IRON IN ARCHAEOLOGY

THE EUROPEAN BLOOMERY SMELTERS

RADOMÍR PLEINER



ARCHEOLOGICKÝ ÚSTAV AV ČR
PRAHA 2000



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ARCHEOLOGICKÝ ÚSTAV AVČR

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ARCHEOLOGICKÝ ÚSTAV AVČR
PRAHA 2000

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Dedicated to the memory
of my father

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PREFACE

I first met Radomír Pleiner at the Archaeological Institute of the Academy of Sciences in 1970 when, as a research student beginning the study of ironworking in Ireland, I made the first of my visits to what was then that slightly mysterious (even, slightly menacing) 'Iron Curtain' city, Prague. Even in the drab aftermath of the Russian invasion of 1968 and subsequent clamp-down by the communist authorities, Prague was a city of beauty and, when not feeling threatened by the presence of a westerner, the Czech people turned out to be a delight. In many repects, I have found them over the years to be very close to the Irish in temperament and innate hospitality, and none more so than Radomír Pleiner with his love of song, good conversation and, of course, beer!

The encouragement that I received from Radomír on that first visit further stimulated my enthusiasm and I became a corresponding member of the grandly-titled Comité pour la Sidérurgie Ancienne de l'Union des Sciences Préhistoriques et Protohistorique of UNESCO. This body was founded at the session of the UISPP held in Prague in 1966, at which Radomir Pleiner was designated Secretary and to find myself named in the company of such as Ronnie Tylecote, Henry Cleere, Kazimierz Bielenin, Elżbieta Nosek, Jerzy Piaskowski and Cyril Smith was indeed heady encouragement for a novice.

Although we were in regular correspondence, I did not have the opportunity to meet Radomír again until 1976 when I embarked on a Švejk-like research anabasis in central Europe. Typically, he managed to provide me with brand-new information which had to be hurriedly inserted as a post-script to my doctoral thesis which was to be examined on my return to the UK. We met again frequently over the years at the conferences which were now being organized on a regular basis by participating members of the Comité and at meetings of a small group set up within it to try to co-ordinate activities. As always, his bubbling enthusiams led to long discussions and ideas for new directions of research.

An indelible memory for me is late October 1989 when Radomir and I returned together to Prague from the highly-successful Ameliówka conference in Poland at a time when the first 'escapees' from the former DDR were taking sanctuary in the BDR embassy there. The city was tense with a feeling that change of some form was in the air and I remember standing with Radomír in front of the National Museum, looking down over a grey and misty Wenceslas Square. Their opinion then was that there might be some political relaxation, maybe in five years, maybe ten. I left Prague on the 2nd of November and, by the 20th, communist Czechoslovakia effectively was no more!

Since then, I have returned regularly to what is now the Czech Republic and spent many happy and instructive hours with Radomír, now professor at the Charles University, collaborating with him first on his major work 'The Celtic Sword' and most recently on 'Iron in Archaeology'. Hopefully, although he absolved his 70th birthday, we will continue on with the second volume dealing with metallography, since his archive of knowledge and information is unparalleled and demands to be set down for others to use. As Secretary of the Comité, Radomír has had the task of collating all of the new research publications and information passed on to him by other members and of publishing it regularly in the Communications. Anyone who is remotely interested in archaeometallurgy cannot but agree that this is probably the most useful of its type and feel indebted to its compiler who, regularly, contributes significantly in terms of his own research.

Radomír Pleiner has since the 1960's made an invaluable contribution to the development of

the study of early ironworking, not just as a scholar, but also as a teacher and as an organizer. This book will be an invaluable resource for many years to come as a detailed and wide-ranging description of the early production of iron, as well as for its comprehensive gathering together of source materials. But I wish to offer a personal tribute also. For those entering the field and wishing to develop their studies, along with those long-established (all of whom, I know will agree with me), it is not possible to find either a more generous sharer of knowledge or a more convivial companion with whom to enjoy it.

Killinchy, N. Ireland, Autumn 1998

Brian Scott

FOREWORD

The story of how this book came to be planned and written is a long one. As the reader will find in the introductory chapter, post-war research began to yield an unusually large amount of evidence for the earliest making of iron. In the 1960's, the need to treat this material in a systematic manner inspired Dr. Henry Cleere to plan the writing of a book entitled 'Iron in Archaeology' which would encompass all of the available sources for both the smelting and smithing of iron. He kindly invited me to collaborate as a co-author and, having been actively working in the field for many years, I agreed with pleasure. However, at that time, my country lay behind the so-called 'Iron Curtain' and it was not easy to co-operate with such a degree of regularity with a western scientist without official permission. Fortunately, perhaps due to a temporary thaw in cold-war relationships, the Academy of Sciences of the former Czechoslovakia judged the project positively and I was not only allowed to begin writing with Henry, but was also offered good wishes for success in my collaboration with a British scholar.

From this starting point, we compiled a summary of the proposed work and I began work on individual chapters, at this time totally unaware of the volume of the future flow of research results and publications. Such a flood of material did not materially alter the proposed form of the book, but was such that, if ignored, would have deprived it of much valuable information and, essentially, made it obsolete even before it was written. Thus, our work continually required updating in the light of fresh work, and this process has continued right up to the time of final setting of the text.

It happened that the initiator of the project, Henry Cleere, became fully involved first with his work as Director of the Council for British Archaeology and subsequently for UNESCO. The weight of his duties compelled him to withdraw from our collaboration, but was he who encouraged me to continue by myself. I did so, and he kindly read and corrected twelve chapters of the 'first generation' of my English texts. Then, numerous supplements and additions were systematically corrected by Dr. Peter Crew. Finally, I entered into a close co-operation with Dr. Brian Scott (whose book 'Early Irish Ironworking' is among the best published recently in the field) who was ready not only to correct my English text in its grammatical and stylistic content, but who has been also a serious and critical reader, calling my attention to many inconsistencies and imperfections which could be avoided. Without him, I do not think that this final version could have been completed.

It eventually became apparent that it would be impossible to keep to the original concept of 'Iron in Archaeology' in its entirety. The second part, ideally comprising the work and techniques of the blacksmith, so richly documented by archaeology and by metallographic research, could not be included. For this reason, a sub-title has been added to this work - 'The Early European Bloomery Smelters' - a signal that the scope of the work has been reduced to the field of the extraction of iron from its ores. A couple of words are needed here. The direct or bloomery process produced in bulk malleable iron and steel (using these terms in their historical meanings). This technology carried within its metallurgical principles, the germs of creation of highly carburized and even liquid iron and the Middle Ages saw the gradual evolution of what can be described as the predeccors of the charcoal-fired blast furnace, delivering cast iron and secondarily-fined malleable ferrous alloys. Thus, when discussing bloomery technology, it was unavoidable to touch on the earliest examples of the indirect process and its installations in various chapters. But, taking the title into account, I decided against a special chapter on the blast furnace, preferring to relegate the subject to a brief discussion in the concluding chapter.

In my view it is also necessary to add something about the structure of the book. Despite the title, it does not represent *sensu stricto* a proper history of ancient and early iron. However, the first two chapters do deal with the discovery of iron smelting and its spread, especially to Europe. Subsequent chapters are devoted to different areas of the archaeological evidence, not overlooking the historical settings, relating to early ironmaking from its beginnings to the High Middle Ages. But the topics are treated from different perspectives and in forms from general outlines to detailed discussions, from the emergence of the first iron-producing regions, through metallurgical installations operating the various stages of the direct process (roasters, smelting furnaces, reheaters) to the products and wastes (blooms and slags). The historical development is summarized, hopefully in an acceptably concise form, in the final chapter.

For all of these reasons, the same sites, regions, features and objects appear in various places, even though appearing in earlier sections. Hopefully, the reader will not see these as unnecessary duplications, but rather as treatment according to the context of each topic under discussion. Nevertheless, I have attempted to keep the text as concise as possible, in the hope that it will be understood as a guide to the numerous sources for the study of the early stages of European iron production.

The field under discussion is what must be termed 'interdisciplinary', treated from the point of view not only of metallurgy, but also of archaeology and history. Because of this, I have added a glossary of technological terms for the non-metallurgist, complemented by a brief glossary of archaeological and historical terms for the non-archaeologist.

The completion of the present work was made possible by the support of the Grant Agency of the Czech Republic (404/98/1564 and 404/00/0548) and by a kind donation on the occasion of the 65th Birthday of Dr. D. Springorum, Verein Deutcher Eisenhüttenleute, Düsseldorf.

If the bibliography appears somewhat extensive, it is because it simply mirrors the steadily growing size of the body of scientific, archaeological, literary and historical research publications. It is incomplete in the time of the edition of the book, and much of new information already has arrived in the meantime. This is good — it is a signal that the archaeometallurgy of iron is advancing.

Prague, Autumn 1999

Radomír Pleiner

INTRODUCTION

The Archaeometallurgy of Iron: A Historiography

There comes a time in any field of human activity when scholars begin to examine its history. The need was felt a century ago to know in detail the evolution of the history of iron which has so deeply influenced the image of human civilization. Interestingly enough the historiography of ironmaking began as a synthesis, a survey of all of the scattered historical, ethnological and sporadic archaeological data which was presented in the broadly-conceived work by Beck (1884), followed, later, by several editions of the history of iron by Johannsen (1924, 1925, 1953). Early historical records referring to the use of iron in the Near East were discussed in several basic papers published in the first half of the 20th century (Belck 1907/1910; Rickard 1939; Przeworski 1939; Witter 1942). The whole series of papers and books dealing with metals in antiquity was crowned by the synthetizing volumes compiled by Forbes (1950; 1964). At the same time, data on surviving methods of primitive iron smelting were being recorded (von Luschan 1909; Klusemann 1924; Crawhall 1933; Hulme 1937; Wright 1939).

In early works, it was normal for the archaeological evidence for ironmaking to be treated only marginally, while the systematic archaeological research on iron smelting sites began on a regional basis. In this respect, we remember the names of J.W. Gilles, a metallurgist (1936) and P. Reinecke, a celebrated archaeologist, the author of the chronological system for Central Europe, who also published a list of ironworks bearing localities in Bavaria (1934/1935). Similar treatises appeared elsewhere; apart from the paper by Gurlt (1884), the contributions by Schmid (1932), Barb (1937), Nihlén (1939) and Hauge (1940) should be noted also.

The first critical review of various features of early ironmaking was presented by P. Weiershausen (1939) who tried to interpret correctly different finds of furnaces from Germany and neighbouring countries as smelting devices used in the bloomery process.

*

Although a great deal of information was brought together in all of these works, the actual trend toward the detailed examination of early ironmaking began during the post-war years. Workers in the modern iron industry began to take an interest, so that in the pages of the leading metallurgical periodicals, such as the Journal of the Iron and Steel Institute, London, or Stahl und Eisen and Archiv für das Eisenhüttenwesen, Düsseldorf, papers dealing with early iron making and working appeared regularly. New monographs, written partly by historians and partly by metallurgists interested in the history of their special field emerged, as did also those by archaeologists who revised *corpora* of old finds in various European regions and started excavations, directed intentionally at smelting sites — Coghlan (1956), Schubert (1957) and Tylecote (1962b) for the British Isles; Pleiner (1958) for Bohemia and Moravia; Rauhut (1957) for Poland; Kolchin (1953) for early Russia. Excavations were undertaken (and subsequently published) in Denmark (O. Voss), Sweden (I. Serning), Hungary (G. Vastágh, G. Nováki and others), Austria (F. Hampl & R.J. Mayrhofer), Switzerland (W.U. Guyan; P.-L. Pelet). Some projects developed into larger research programs. A special large-scale project was launched in 1955 in the area of the Holy Cross Mountains in central Poland, which is dotted with traces of pre-industrial ironworks whose excavation began under K. Bielenin and whose metallurgical evaluation by M. Radwan. A similar project was developed, at almost the same time, in the Sauerland and Mark in Germany (M. Sönnecken). These programs have continued to the present day and have been followed by many other projects which have substantially enriched our knowledge of ancient and early ironmaking centres over all of Europe.

Another phenomenon that emerged during the fifties and sixties should be noted. The materials yielded by excavations such as ores, slags, charcoal residues and refractory linings started to be submitted to scientific examination. Thus, chemical, mineralogical and palaeobotanical analyses were regularly applied to the presentation of results. The value of primary sources as evidence increased considerably, and, in addition, many specialists became involved in complex research work.

Analytical methods came to be widely used in a new approach to the problems of understanding the mechanism of the bloomery process. Moreover experimental smelts imitating the techniques of the ancient smelters in reconstructed furnaces entered the study. Not regarding the first trials organized by Graf Wurmbrandt in Austria (1877), and by O'Kelly in Ireland (1952) and Sadzot in Belgium (1956), experimental smelts have been carried out in the late fifties and early sixties (and subsequently published) in Germany (Gilles 1958a), England (Wynne & Tylecote 1958; Tylecote, Austin and Wraith 1971), Poland and Bohemia (Radwan & Pleiner 1963; Pleiner 1969), Denmark (Thomsen 1964) and in Sweden (Hagfeldt 1966). In 1970, a specialized symposium was held, devoted to the results and the value of evidence of these first campaigns (Pleiner, Guyan & Fabešová 1973). In due course, experimental smelting of iron spread over practically all of the European countries and took place even in America and Africa: in the latter continent within specific programs of reconstruction the traditional practice having been disappeared during the last decennia. The aim was to see at first hand how the bloomery process would work under various conditions and, above all, to test the function of the different types of furnaces which had been excavated and tentatively reconstructed. Then, metallurgists became interested in such 'living laboratories' which offer a close look at the very principles of the reduction of iron ore. Finally, trials were directed to produce (in as authentic a way as possible) slags, blooms, iron sponges, tuyeres, fired structures and refractory materials, comparable in appearance and chemical and mineralogical composition to those found in excavations. These were submitted to same analytical procedures so that calibrated data were obtainable. The resulting information provided the basis for further reconstruction of features uncovered in the field. Metallurgists then became interested in such 'living laboratories' which offer a close loo at the very principles of the reduction of iron ore. In addition, basic data on time consumption and optimal manning of primitive ironworks were yielded.

*

Scholars engaged in studying the archaeology and history of iron have been able to enjoy the help of various associations, especially the Geschichtsausschußdes Vereines der Deutschen Eisenhüttenleute in Düsseldorf which organized annual conferences, and the Historical Metallurgy Group, London, which began to publish a specialized Bulletin (Historical Metallurgy) devoted to the historical problems of both non-ferrous and ferrous metallurgy. In France, the Revue d'Histoire de la sidérurgie, edited by the Centre de Recherches de l' Histoire de la Sidérurgie, Musée du Fer, Jarville near Nancy, published articles on historical and archaeological research.

In the sixties, the activity of individual scholars and groups increased so much that the need arose to record all of the scientific production and to foster contacts between those working in the field which was, later, labelled 'the archaeometallurgy of iron'. Thus, the opportunity was used during the VIIth International Congress of the Prehistoric and Protohistoric Sciences (Prague 1966) to establish the Comité pour la sidérurgie ancienne de l'UISPP as a consultative board consisting of corresponding members, both individuals and groups working in various countries of the World, with W.U. Guyan, Schaffhausen, being elected president and R. Pleiner, Prague, as secretary. Since 1967 Communications of the Comité have appeared twice a year in the periodical Archeologické Rozhledy, Prague (the Archaeological Institute in Prague is the seat of the secretariat). The pages of the Communications inform all interested scholars (of whom there are now about 180 registered) on the work in progress and, above all, of the current

bibliography of books and papers dealing with research results on the early history if iron. The rapid development of the field is clearly mirrored in these bibliographies, with around 80 specialized bibliographical items being recorded annually.

This establishment as well as other organizational activities encouraged further achievements in work already in progress and also stimulated further research. Efforts were made to present the results in front of relevant *fora*. A boom in conferences, symposia, *tables rondes*, workshops, *colloquia* and seminars can be seen from the seventies, although the first session directed towards the history of iron, took place as early as in 1955 (Le fer à travers les âges, Nancy, edited 1956). But the main acceleration can be dated, approximately, to 1968. There are three levels of meetings involving iron in their topic.

The first comprises archaeological, historical and methodological conferences or sessions dealing with the history of technology and of crafts in general: among their contributions, the history of iron appears in various forms. Apart from annual meetings and congresses, about 20 meetings were organized between 1968 – 1990. The second category consists of conferences devoted to early metallurgy. Increasing interest in the development of the metallurgical activities of the past took in also the study of non-ferrous and precious metals and meetings were organized which included, naturally, the making and working of iron. Sessions of the Historical Metallurgy Society, London, are held every year, with themes covering the topic in general or focussing on regional or broader geographical topics (Aspects of Early Metallurgy, London 1977; Journées de la paléometallurgie, Compiègne 1983; Archäometallurgie von Kupfer und Eisen in Westeuropa, Mainz 1986; Archeometallurgy in Central Europe, Herl'any 1997). Prehistoric and early mining has also received attention (Mines et fonderies de la Gaule, Toulouse 1980; Miniere et metallurgía secoli XIII – XVIII, Prato; Minería y metallurgía etc., Madrid 1985; Colloque international de la technique minière, Strasbourg 1988; Montanarchäologie in Europa, Freiburg/Br. 1990). The problems of the Far East were covered in three conferences held in China (The Beginnings of the Use of Metalls and Alloys I – III, Beijing 1981; Zhengzhou 1986; Sanmanxiu 1994). Specific questions have been addressed (e.g. Metals and armament, Paris 1994) and, very important, educational projects have been organized on behalf of postgraduate students and young archaeometallurgists (e.g. Intensive Course at Ravello 1989 and the Summer school on Mining and Metallurgy Archaeology, Certosa di Pontignano and Campiglia Marittima 1991).

Finally, there are meetings and symposia devoted specifically to the metallurgy and working of iron during its historical development. It should be stressed again that several institutions hold meetings of this kind annually, such as the Geschichtsausschuss des Vereins der Deutschen Eisenhüttenleute, Düsseldorf (the Sitzungen take place in various towns in Germany, in recent years abroad as well) or the National Technical Museum in Prague (annual sessions on the history of iron with emphasis on the post-medieval period). Nevertheless, since the seventies symposia convened to discuss selected themes or to present results achieved in various geographical regions have become part of scientific life. During the period 1970 – 1995 around 45 meetings with iron as a central theme were held — in fact more than one per year. Several years like 1983 or 1993 saw three or even four such meetings.

Special topics have been highlighted, in, for example, conferences on experimental iron smelting (1970 Schaffhausen, Die Versuchsschmelzen und ihre Bedeutung etc., or as in 1993 in Eindhoven, a 'jamboree' of iron smelters working in several international or national teams). Special meetings have been held on the principle of the bloomery process (Grängesberg 1972, Vordernberg 1978); on shaft furnaces (Prague 1973); on the transitions from the bloomery to the indirect process, also ironmaking in its broad socio-economical context (Iron and Man in Society, Norberg 1985 and Importance of Ironmaking in the same place 1995; Dal basso fuoco all' altoforno, Bienno 1987); on the earliest iron in Europe (Schaffhausen 1979, or on the craft of the blacksmith (Belfast 1984); on Catalan forge (La Farga Catalana, Ripoll 1993) and on medieval ironmaking (Schwäbisch Gmünd 1994). The discoveries in Europe were discussed in several symposia

(Eisenstadt 1975, Sankelmark 1980, Liblice 1987, Ameliówka 1989, Belfort-Sevenans 1990, 1992) but predominating regional themes have also been addressed (Polish discoveries were discussed at Bochum 1978, the Mediteranean area in San Vincenzo 1983, Africa in Paris 1983, Germany in a workshop at Günzburg 1991, Scandinavia in Stavanger 1979 and Budalen near Trondheim 1991, eastern France in Besançon 1993, and the Carpathian region 1994 in Herl'any).

These symposia and colloquia started as small, round-table discussions normally with only some 20 – 40 participants. Since the eighties. however, large meetings have taken place where up to 50 scholars presented papers and 100 – 150 participants attended. Naturally, these symposia mirror the relevant time in terms of results achieved and methods applied but they may be considered as effective schools in every respect. All this shows the increasing interest in the archaeometallurgy of iron. Universities, institutes and societies have been helped by sponsorship in organizing meetings by many different institutions, including industry.

Two principal effects may be observed when looking back (and forward) over these symposia. First, a significant number of fundamental works and hundreds of very valuable contributions were presented which, after having been published, form a fund of knowledge in the public domain. More than 65 % of meetings have been published within 1 – 5 years, and their volumes contain an immense amount of information.

Second, the meetings were platforms for contact between scholars not only internationally (because the majority were organized on international basis) but also interdisciplinary: study of the early history of iron has not only involved archaeologists and metallurgists, but, in addition, historians, archivists, miners, mineralogists, metallographers, geologists, botanists and chemists, all of whom are frequently engaged in the work of research teams. In due time a group (almost with the atmosphere of a club) arose among scholars from various countries throughout the world; they meet regularly at many of the meetings referred to above and know problems of the field intimately; and they make contacts with the majority of the newcomers who are gradually gravitating toward working on solutions for the problems under discussion.

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Several generations have now devoted much of their lives to the study of the earliest history of iron. These 'generations' have to be seen not strictly in terms of physical age, but rather when scholars began active participation in archaeometallurgical work. The early stage is linked with names of senior masters like J.W. Gilles, B. Neumann, B. Osann, H. Vetters, W.U. Guyan, P.-L. Pelet, E. Salin, M. Radwan, O. Arrhenius, A. France-Lanord, B.A. Kolchin, H. Hingst, R.F. Tylecote, C.S. Smith. Many unfortunately have passed away in recent years although their pioneering work lives on up to the present day.

Since the late fifties and sixties another, now ageing group of scholars began to work intensively on the archaeometallurgy of iron. Coming from both technology and the humanities. The list includes K. Bielenin, J. Piaskowski, Elżbieta Nosek, R. Pleiner, M. Bartuška, J. Kořan; H. Cleere, B.G. Scott, H. Straube, G. Sperl, O. Voss, R. Thomsen, B.A. Shramko, A.K. Anteins, U. Zwicker, F.K. Naumann, M. Sönnecken , B. Gille, J.-R. Maréchal, R. Maddin, G. Nováki, G. Vastagh; Inga Serning and Irmelin Martens.

These were followed by explorators like M. Mangin, A. Ploquin, C. Domergue, Ph. Andrieux, Ph. Fluzin, C. Forrières, R. Halleux, I Keesmann, D. Horstmann, A. Hauptmann, Rosemarie Leineweber; Věra Souchopová, K. Stránský, L'. Mihok, J. Gömöri; A. R. Williams, Effie Photos, P. Crew and Susan Crew, G. McDonnel, P. Craddock, R.M. Ehrenreich, C. Salter, G. Magnusson, P. Kresten, A. Espelund, L. Stanvik, M. van Nie, Nicole Échard; B. Prakash, M. F. Gurin; N. van der Merwe, Rubin Han, T. Amano and many others. These workers come from many countries in Europe, from America, Africa, India, Japan and China as well, who identified new sources and introduced new methods and approaches. The trend continues up to the present day and new personalities are emerging on the scene of the archaeometallurgical research (V.

Serneels, L. Eschenlohr, M. van Nie, H.L. Knau, M. Kempa, Chr. Willms, H. Jöns, Ü. Yalçin, S. Orzechowski, A. Jockenhövel and others), some being archaeologists, some brilliant geologists, mineralogists and metallurgists. In addition to many studies and articles this enlarged forum produced a considerable number of monographs, dealing, for example, with the general development of metallurgy and the principles of the bloomery process, and the detailed publication of excavated bloomery works and regional surveys, from Ireland to Tuscany: it is not possible to comment on all these volumes within this introduction, but they form an integral part of the bibliography.

As an expression of focussed and systematically-organized research, we may note further specific projects, carried out by various institutions. Some have already been noted, but since the late sixties new campaigns have been undertaken. These include study of the Romano-Barbarian bloomery agglomerations which have been investigated in the Masovia region, near Warsaw in Poland; of the early medieval bloomery concentrations in western Moravia and in northern and western Hungary, of metallurgical centres in the Montaigne Noire area of southern France and traces of ironworks of the Roman and medieval periods in Franche-Comté, the archaeol-metallurgical discoveries in Sweden (Dalarna, Jämtland, Norberg) and in Norway (Møsstrond, Trøndelag), and of Iron Age bloomeries in north Wales. In recent years, complex projects sponsored by the Volkswagen Stiftung and carried out by German universities, deserve our attention. These include archaeological excavations and the evaluation of palaeobotanical evidence for the environmental effects of ironmaking, as well as mineralogical and metallographic investigations of metallurgical residues (the Joldelund project in northern Germany, the Schwäbische Alb, the Lahn-Dill region in western Germany; other projects are in planning and under preparation.

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All of these activities have yielded a considerable fund of positive data, but have raised, naturally, further questions. We do have a general image of the spread of the use of iron from the Southeast to Europe. However, the details of this process, its mechanisms and the varying pace in different areas still remain veiled by the uncertain dating of many of the relevant find complexes.

Most of European countries may be considered, nowadays, as mapped in terms of inventories of those monuments connected with the ancient and early metallurgy of iron. Among them are some areas with scattered evidence, as well as regions with concentrations of bloomery ironworks, some of them having been of short-lived prosperity, while others proved to iron-producers over several historical periods, supplying the technical needs by a range of market iron. Modern estimates of their effectiveness form calculations of production based on volumes of residues; They are undoubtedly fraught with uncertainty, due to the fact that the data available are incomplete, if not fragmentary. On the other hand, these calculations allow, nevertheless, a certain imagination on the production in general, which can be critically treated at any time. Certain European areas remain uninvestigated. There is lack of data on archaeometallurgy in Spain and Portugal, in Balkans, and in the entire classical Near East.

Different types of furnaces came to light. In many instances they reflect technological and cultural traditions, and even workshops layouts varied in different regions and between time periods. We do know much of the resource bases, including the ore smelted, and the fuel necessary for their reduction, or the structural materials used by different ancient ironworks. We have collected much information about the products of smelting, iron and slag, the latter being a passport to the deciphering of details of the process. From hundreds of practical trials we have got the feeling that we are beginning to understand, very slowly, physical and chemical principles of the bloomery method — the germ primeval ironmaking as such. However, detailed studies at the heart of the metallurgical processes have shown that bloomery smelting very often involves the seeds of cast iron formation. This is seen mainly from discarded pieces found by chance

among the waste. Nevertheless there are hints which point to hypotheses that certain groups were able to vary the conditions of smelting to favour their production of heavily carburized metal. In fact, discussion continues on Roman cast iron production, stimulated by analyses of certain raw products.

The recent archaeometallurgy of iron has contributed much to our knowledge of the origins of the true indirect method of production, through to the regular making of cast iron and its fining to malleable wrought iron and steel. Investigations into slag play an important role in this respect, since they are directed to distinguishing between bloomery and finery waste (and, moreover, between bloomery and reheating and smithing slags). The roots of the new technology are being traced back as far as the 13th, or even 12th centuries AD.

In spite of apparent successes, the archaeometallurgy of iron was criticized by certain scholars, tending to work on problems, connected with various forms of interrelations between men and materials used and gained by them. The new branch of science is said to be rather introvert, solving its own problems and being distant from efforts of recent archaeologists (Ehrenreich 1991a). I do not agree with this point of view. Certainly, archaeometallurgy is an interdisciplinary field where specific technological aspects are examined, but the bulk of topics is directed to economic and social questions in which men were involved during their historical development. It is sufficient to look at the bibliography. The archaeometallurgy of today cannot be considered merely as a service for historians, but as a spring-well, open to be drawn for information by anybody. And anybody is free to be inspired by needs of humanistic studies and to develop new programs, involving archaeometallurgical aspects.

The presentation of the results achieved to date forms the theme of following chapters of this book. It must be stressed that the other side of the technological cycle, the blacksmith's work, so much elucidated by contemporary archaeological and analytical research, has to be reserved for another volume.

Chapter I

THE BIRTH OF IRON SMELTING

When studying the origins and development of the production of iron, a metal which was to have so profound an influence on technology as whole, answers must inevitably be sought to certain fundamental questions, namely, how, when and where did the making of iron begin?

Any investigation of these questions must start with a critical study of the sources available, both literary and archaeological. The contribution made to this research by linguists is in exploring the words and concepts relating to iron production found in ancient languages. Archaeology supplies the dated objects which help to identify those geographical regions where information about the earliest use of iron may be sought, and a variety of approaches are needed in interpreting the data arising from all of these sources. We are, nevertheless, still far from a definite solution to the basic problem, which is whether the discovery of iron can be ascribed to a single region or whether the technology could have been discovered independently, perhaps at different periods, in several regions. The key to the solution of this problem lies in establishing absolute and relative chronologies for the earliest known iron producing areas.

The earliest finds of iron

The earliest evidence for iron-use so far available comes from the Near and Middle East — ancient Mesopotamia, Anatolia, northern Syria, ancient Armenia, northern Iran, and, in respect of a small number of very early iron artefacts, Egypt.

A survey of the earliest known finds (Waldbaum 1978, 1980) lists fourteen iron objects from four sites which date to before 3000 BC. Grave A at Samarra in modern Iraq yielded a small piece of terrestrial iron from around 5000 BC, while Layer Complex II at Tepe Sialk in northern Iran, dating to the second half of the 5th millennium BC, produced three small iron lumps, apparently used as polishers. Iron beads, one rich in nickel, another nickel-free, were found at El Gerzeh, while a small iron ring came from Armant, both in Egypt. All of these objects have been analysed and, with the exception of the Samarra specimen and one of the beads from El Gerzeh, have been shown to have high nickel contents, up to 7.5%. Despite the arguments by some authors (Piaskowski 1980; Photos 1989) that ancient nickel-rich artefacts should be seen as the products of the smelting of nickel-bearing iron ores, there are strong reasons for believing that these early objects were made of meteoritic iron, which is high in nickel and would have been a natural curiosity. A silent witness to this is the steady decrease in both the frequency and proportion of high-nickel iron artefacts during subsequent periods.

Up to the present day, over twenty finds of iron which can be dated to the 3rd millennium BC are known. These come mainly from Mesopotamia and Anatolia, with only four from Egypt. Analyses of twelve objects show that six were rich in nickel, the remainder being apparently made of smelted iron. They are mostly rusty fragments or indeterminate lumps, but also include small amulets, pendants and inlays on non-ferrous objects. The corrosion products on the bronze dagger hilt from a palace deposit at Tell Asmar (Eshnuna) show that it must have had an iron blade (Frankfort 1950). Another important artefact in this group is a low-nickel iron dagger with a gilded hilt from Royal Tomb K at Alaca Hüyük in northern Anatolia (Fig. 1:1) which is dated to around 2300 BC (Koşay 1966). Iron pins and pendants, probably of meteoritic iron, were found in at least four contemporary grave complexes from the same site. Other finds from this period are listed in the literature (e.g. Forbes 1964, 175 – 276; Aitchison 1960, I, 76 – 110; Waldbaum 1978; 1980).

A number of iron artefacts dated to the first half of the second millenium BC are known from five sites in Anatolia, Cyprus, and Crete. Egypt is represented by a single object only, a large

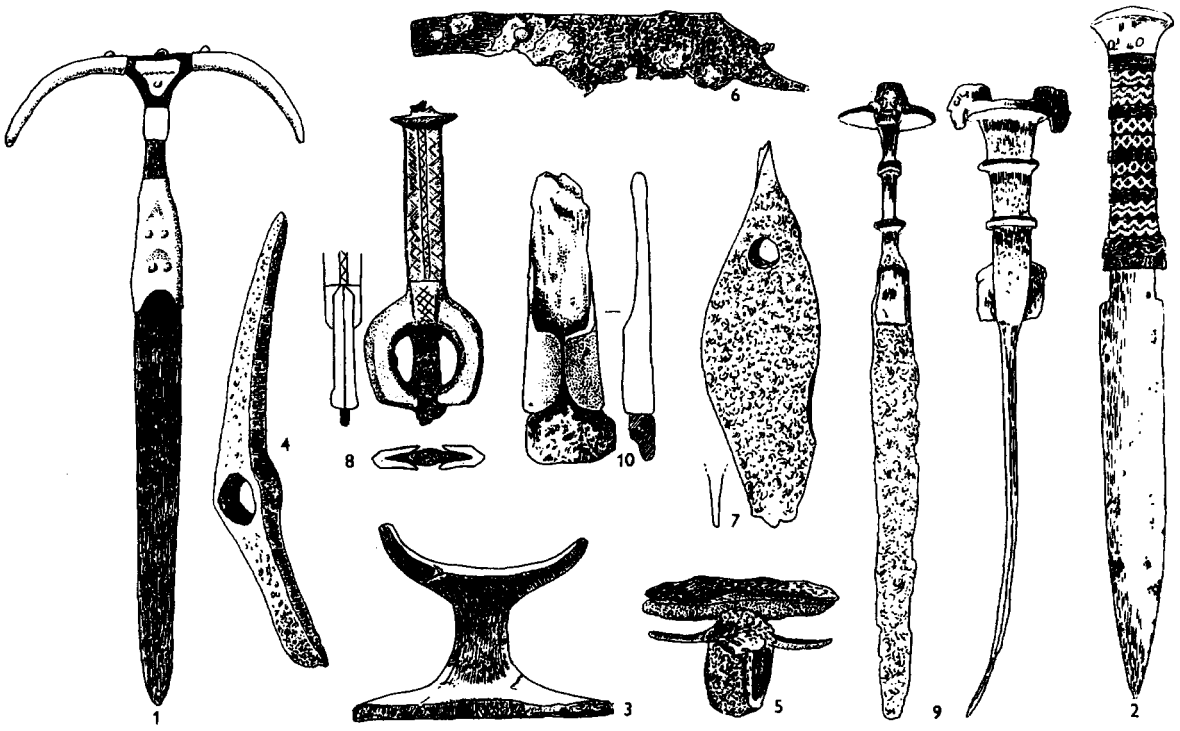


Fig. 1. Selected examples of ancient iron objects from southwest Asia, Egypt, Eastern Mediterranean and eastern Europe. 1 Alaca Höyük, Turkey, an iron dagger with gilted hilt and pommel parts, from a royal tomb about 2300 BC; 2 Thebes, Egypt, the dagger from the Tutankhamen tomb, ca 1350 BC — the hilt is gilded and ornamented with granulation, the pommel is of rock crystal, total length 42cm; 3 Thebes, Egypt. A miniature of a ceremonial headrest from the Tutankhamun tomb, length 5cm; 4 Har Adir, Palestine, iron pick from a settlement, heat treated steel, 12 century BC; 5 Dendra, Greece, ceremonial ring I from a royal tomb. The hoop and the upper plate of the bezel are of iron, followed by lead and silver bezel plates — the hoop light diameter ca 2cm, 14th century BC; 6 Perati, Greece, iron knive with bronze rivets from a cemetery, length 11cm, 12th century BC; 7 Khorsabad, Iraq, a bi-pyramidal iron bar from the store of the Sargon palace, 8th century BC — heterogeneous carbon steel, length 32cm, weight 3.9kg; 8 Luristan, north-western Iran, bronze-hilted iron dagger, preserved length 16cm, 8th century BC; 9 Luristan, short sword with human heads on the pommel, length 38cm, 8th century BC — homogeneous unhardened steel; 10 Boldyrevo, south foothills of Ural range area, Russia, a meteoritic iron adze mounted in copper socket, length 11cm, 18th century BC. References: 1 Bittel 1950; 2 Archaeological Museum Cairo; 3 Aitchison 1960; 4 Maddin 1982; 5 and 6 Varoufakis 1981; 7 Oriental Inst. Museum, University of Chicago, after Pleiner 1979; 8 Pleiner 1969a; 9 Deutsches Klingenmuseum Solingen-Gräfrath (Pleiner 1969d), 10 Terekhova *et. al.* 1997.

spearhead from the XXIIth Dynasty grave K3 at Buhen, the authenticity of which is, however, somewhat dubious (Randall MacIver and Woolley 1911; Wainwright 1932). The circumstances of deposition of amulets and ceremonial weapons in rich graves and temple precincts demonstrates that the new metal was available only to the upper strata of society.

The beginnings of the terminology of iron

How is the arrival of this new metal, which joined copper and other non ferrous metals, represented in language and writing? The earliest terms are to be found, again, in the Middle East, in the Sumero-Akkadian cultural province. Akkadian *kú.an* and Sumerian *an* (inflected form *an.na*) occur in contexts which suggest symbolic iron objects, including daggers. The two

words are identical in meaning according to Sumerian and Akkadian versions of the Rimush inscription which dates from 2300–2200 BC (Hirsch 1963). Legal texts of Shusin IV contain references to the taking of an oath on 'the iron dagger of the god Ningirsu' (Falkenstein 1956, No 205, 45). An axe is described as being made of 'the precious metal which is iron' in the fragments of the so-called Lugalbanda epic which dates to shortly after 2000 BC (Wilcke 1969).

According to Limet (1976), *kú* means either meteoritic iron of heaven or 'a precious blue metal', *an*. This is the equivalent of two synonymous terms, *ašium* and *amūtum* used in the so-called Cappadocian tablets, a set of early Assyrian trade documents from Káneš-Kül Tepe in the Near East, belonging to the period 1900–1600 BC (Garelli 1963, 274–276; Landsberger 1965, 290). This mysterious material, more expensive than silver and gold, was imported from somewhere in Anatolia and, although controlled by the local rulers, was often traded clandestinely. It seems likely that the term relates to meteoritic or smelted iron. In course of time, according to Limet (*op. cit.*), *an* lost the attributes of rarity and high value (*kú*) and acquired a descriptive element *bar*. Interpretation of cuneiform texts suggests that this means 'baked' or 'roasted', in other words, transformed at high temperature. Limet sees this development as reflecting the production of iron by smelting ore. In fact, strong semantic links can be found between metallurgical terms and those for 'heating', 'baking', 'roasting' and 'boiling' in connection with non-ferrous as well as ferrous metals in the later Celtic and Germanic language families, suggesting that terminology reflecting the use of high-temperatures dates at least from the earliest smelting of non-ferrous metals (e.g. Scott 1990, 174ff.).

The Akkadian equivalent of the Sumerian *AN.BAR*, written syllabically as *BAR.zil.li, bar-zil-lu* or *pa-ar-zil- lu* (Bilgiç 1947, No C 33), is an unambiguous term for iron which survived in several forms in various Semitic languages for some two millennia, and which is used for the first time in the Cappadocian tablets. The logogram *AN.BAR* occurs frequently in Hittite texts (alongside $AN.BAR.GE_6$ which is usually interpreted as meteoritic iron). Careful study by Laroche (1957) and Kammenhuber (1969, 437) proved that this word was pronounced not as *parzillu* but as *hapalki*, and was thus of pre-Hittite (presumably Hattian) and non Indo-European origin. According to Melchert, one Indo-European word for iron was apparently *kiklu* (see Muhly *et al.* 1985, 76).

Study of archaeological and linguistic data from the period 1600–1200 BC confirms two facts. First, in spite of the fact that new provenances in Palestine, the Aegean and mainland Greece have been identified, the frequency of occurrence of iron objects increased slightly, although not more than a hundred are known from the whole region, including Egypt (Fig. 1: 2, 3). Second, the circumstances of these finds and the documentary sources indicate that iron continued to be a rare metal which remained under the direct control of ruling groups, whether religious or secular.

During this period Anatolia was the centre of the Hittite confederation where the frequency of occurrence of iron objects increased rapidly. Those found at Alaca Hüyük and in 14th century levels at the capital, Boghazköy, include what are indisputably tools — two trunnion axeheads and some possible knife fragments. However, they throw less light on the subject than a number of textual references to iron which demonstrate that by the 14th–13th centuries BC the metal was relatively common. It continued, however, to be used principally in temples and royal courts, and there are numerous temple inventories of the 13th century, compiled in the reign of Tuthaliash IV, which mention symbolic iron objects and idols (Brandenstein 1943; Rost 1963; Siegelová 1984) suggesting that iron also played a symbolic role in ritual.

References to objects made from iron or meteoritic iron ($AN.BAR.GE_6$) occur occasionally. Sometimes the sources indicate substantial numbers of, for example, iron hairpins, vessels and spears – for example, 10 knives and 56 dagger-blades. Certain tablets (e.g. KUB XLII, 21) refer to from 22 to as high as 66 pieces of iron, presumably blooms or bars (Košak 1982; Siegelová 1986 I, 195). The weight of such objects is not known, but in other documents (e.g. KUB

XXVI.66; KBo XVIII 162 + KBo VII. 24) reference is made to 23–30 shekels (180–216 g) of iron. Ten knives represent 16–40 shekels (120/300g), and a tribute of 56 dagger blades (KBo XVIII. 158) must have represented several kilograms of iron.

Temple inventories, such as the list of seven small iron amulets and solar discs from the Nin Egal temple of Mishrifé-Qatna on the Orontes also occur in northern Syria (Bottéro 1949). The archaeological counterpart of this kind of list is the famous Ugarit -Ras Shamra find, an iron (3.5% Ni) axehead with a bronze socket inlaid with silver and gold (Schaeffer 1939, 107 ff.). The assemblage, which also contained bronze spearheads, dates from the 15th–14th centuries BC. There are numerous comparable finds, among which high-nickel iron continues to figure.

Royal iron

Iron was also the object of royal gifts, as demonstrated by royal correspondence from the Near East and adjacent regions, including a long list from the Tell el Amarna archives (14th century BC), describing a collection of precious bridal gifts from the Mitanni king Tushratta to the Egyptian Pharaoh Amenophis III, and subsequently to Amenophis IV, in the hope of marrying off his daughter (Knudtzon 1915, Nos 22, 25). This assemblage included a number of valuable goods, among them several iron blades and amulets, some of which are described as *habalkinnu*. This word was at one time believed to apply to a special type of iron (or steel), but recent philological research interprets it as a Hittite, Hattian or Hurrian reading of *AN.BAR*. Hittite texts do, however, refer to different types of iron and differentiate between raw metal, as smelted *AN.BAR KI.NE* and the best quality iron it AN.BAR SIG_4 (Siegelová 1986 I, 139).

There is also the well-known letter from the Hittite king Hattusil III who reigned in the first half of the 13th century BC to an unknown recipient, a copy of which was preserved in the archives of Boghazköy (KBo I 14; Cavaignac 1934; Goetze 1940). Lines 20–27 contain the first reference to the deliberate, albeit difficult, production of good quality iron (*parzillu damqu*) daggers which are requested by one of the king's neighbours. Hattusil pleads the lack of available material, saying that he has given orders for their manufacture at a favourable time and that in the meantime, he is sending one iron dagger. This section of the letter, which was at one time the basis for the long-prevalent hypothesis of a Hittite monopoly over iron-production is, in fact a conventional phrase which occurs in other royal documents of the time. It is used, for example, in connection with silver vessels in another letter of Hattusil and about large quantities of bronze nails in a letter from the early Assyrian king Shamshi Adad. The 'strategic monopoly' theory has been effectively refuted by Zaccagnini (1971). Nevertheless, iron and iron daggers were counted as gifts appropriate to royalty. Another document from the palace of Ugarit refers to the request of a certain Zulanni, apparently a local king, for an iron dagger and garments (Nougayrol 1951).

The best example of the importation of iron as a prestige material from abroad into Egyptian royal treasuries and tombs comes from the 14th century BC tomb of Tutankhamen at Thebes. Among the magnificent grave goods are two superbly-crafted daggers, one of gold and the other, with an equally-lavishly decorated hilt and an iron blade. The assemblage also included sixteen minute iron chisels, interpreted as the mouth openers used in funerary rites (*peshesh kefs*), a ceremonial iron headrest and an amulet in the shape of the Eye of Horus set in a gold bracelet (Carter 1927/1933, 2, 105, 122, 135). These artefacts, which are believed to be made from high nickel iron (Waldbaum 1980, 78 – 79, but see Aitchison for a contrary view, 1960, 94 – 97) are evidence of the extraordinary importance and symbolic significance of iron (Fig. 1: 2 and 3).

Iron also occurs in early royal tombs in Crete and in Mycenaean *tholoi* such as those at Archanes and Phaestus, as well as in the Peloponnese at Dendra, Kakovatos, and Volos. All date to the 14th–13th centuries BC, except for the Arkhanes find, which is believed to be Minoan from the 17th century BC. At these sites, rings have been found which have bezels made up of superimposed plates of lead, silver, and iron (Fig. 1: 5). Chemical analyses by Varoufakis

(1981) show that the iron is high in nickel (3–10%), contrasting with the two iron knives from Perati (12th century BC, Fig. 1: 6), where the nickel content is no higher than 0.03–0.05%, typical of bloomery iron. The iron parts of the rings, which appear to have had an apotropaic or magical function, were apparently of meteoritic iron.

It may be said that between 5000 and 1200 BC (i.e. the Chalcolithic and Early and Middle Bronze Ages in the Middle and Near East), iron was an extremely precious metal, occurring in the form of artefacts either with high nickel (and cobalt) contents, or nickel-free. Some Hittite iron smelters (or smelters living in the Hittite lands) continued to struggle against their lack of experience. They tried to smelt various minerals, often unsuccessfully, as can be seen from an unforgeable iron sulphide matte found in 14th century BC Boghazköy, which resulted from an attempt to smelt ferruginous arsenopyrite (Muhly *et al.* 1985). Successful smelts undoubtedly resulted in the manufacture of various artefacts which, however, are rarely represented in archaeological assemblages, while those that have survived are usually badly corroded, rendering them unsuitable for metallographic investigation.

During a period of great cultural development in the Near and Middle East, the terminology relating to iron as a specific metal gradually became standardized, a process which culminated around 1800 BC. This indicates that it was in that part of the ancient world that the new member of the family of metals of antiquity was discovered and distinguished from the other metals and, in due course, produced deliberately and on a regular basis.

The discovery of iron smelting

How was the metallurgy of iron discovered? From the work of scholars such as Wertime (1964), C.S. Smith (1965), Tylecote (1976, 40), and Charles (1980) it is possible to establish the following sequence.

During the Neolithic period (11th to 7th millennia BC in the Near and Middle East), the possibility was slowly recognized for a replacement for traditional natural materials such as stone and bone by another with superior mechanical properties, which could be made available through the use of new technologies. The material which met this demand was copper, which had already been identified and worked in its native form from copper ore veins. Once copper became available in smelted form, it had a profound influence on technological development and the division of labour, the process being admirably illustrated in the region.

Iron did not assume such a predominant role here. It appeared on the scene much later and was slow to achieve a level of technological significance comparable to that of copper. Its progress was especially slow in those regions which may, with some justification, be considered to be its cradle.

The invention of iron smelting has recently been seen as closely associated with the smelting of copper ores. Scientific opinion has rejected the hypothesis of the accidental discovery of the smelting and melting of metals in the oxidizing conditions produced within bonfires or by forest fires above ore outcrops. The two most likely conditions for the invention of metal smelting technology seem to be associated with the reducing atmospheres inside pottery kilns or with the use of charcoal-fed hearths to melt native copper in crucibles when fragments of copper ore, present in the fuel charge, might have been reduced to reddish, shining copper prills.

Copper ore deposits are usually divided into two zones. The upper level, above the water table, is the oxidation zone which contains easily reducible oxide or carbonate ores enriched in copper, while the lower level, which constitutes the bulk of the deposit, is the cementation zone, consisting of sulphide ores, principally of the chalcopyrite ($CuFeS_2$) or chalcocite (Cu_2S) type. The copper content of the non-oxidized ores is much lower that of the oxidized ores (Tylecote 1986, 8). Native copper often occurs in the intermediate zone between the two levels, as is certainly the case in the most important Near Eastern deposits, such as those at Ergani

Ma'aden in eastern Anatolia and Anarak and the Kerman province in northern and southern Iran, and also possibly in Cyprus and the Balkans.

Once the oxide and carbonate ores (the familiar malachites and cuprites) in the upper levels of the major ore bodies had been exhausted, it became necessary to use the poorer sulphides. These required a higher level of technology as the sulphur had first to be removed by repeated roasting and subsequent smelting, resulting in the production of various types of matte and cakes of black copper. These mattes required careful refining, a major difficulty being the removal of non-metallic components by producing a slag. The silica gangue had a higher melting point than copper, while the sulphides contributed further gangue material, and as a result the yield of the process was diminished.

The early smelters appear to have found an empirical solution to this problem. They must have observed that a reddish or brown material, if added (originally no doubt by accident) in sufficient quantity to the ore charge, resulted in better slag production and a higher yield of copper metal. Generations of experience would have shown that the addition of some 30% of this material, iron ore in the form of haematite or limonite, the latter occurring naturally on the exposed tops of chalcopyrite deposits (gossan, *chapeau de fer*), gave the best results. Pure haematite and limonite were also regularly present in polymetallic deposits in the Near and Middle East.

In metallurgical terms, the addition of iron ore was positively beneficial to the copper smelting process, and the iron ore would have been reduced at the same time as the copper ore. When smelting iron bearing chalcopyrite, similar effects might been observed (Hauptmann 1985b). One of the metallurgical phases that resulted was iron(I)oxide (FeO) or wüstite, which at the relatively easily-attainable temperature of 1100°C, combined with part of the silica in the ore gangue to form iron oxide orthosilicate or fayalite ($2FeO.SiO_2$). In other words, the iron ore acted as a flux and the method survived until the beginning of the 20th century in both traditional copper and lead smelting.

This technique had important consequences in antiquity. Copper smelting slag was, in fact, identical with that produced later by bloomery iron smelting, since it had the familiar fayalite and wüstite phases, a high Fe content and contained no more than traces of copper, in the form of remanent sulphides and oxides and occasional metallic grains. Under certain conditions, however, other metallic phases were present – reduced iron particles or fibres of sponge iron. Nevertheless, the conditions that allowed the production of metallic iron in that way were limited, developing only when the oxygen pressure was accidentally low, as when the furnace was blown with primitive bag bellows (Maddin 1982, 14, 16, fig.3). For this reason, iron was slow to be recognized and it took many centuries before the new metal was distinguished, not least because the metallic grains were buried within the slag mass and because they were, like the slag, greyish-blue in colour. It was only as a result of their ductility that they could only be separated from the brittle slag when this was crushed, allowing their silvery lustre to become apparent.

Meteoritic iron appears to have played no part in the invention of iron smelting, although occasional pieces could have been discovered, collected and worked. Falls of meteorites in the Near East were observed in antiquity (Bjorkman 1973) and, despite some recent different views, the use of minute fragments would have been feasible (Classen 1969), as demonstrated by the regular exploitation of Greenland meteorites by the Inuit around 1900 (Buchwald and Mosdal 1985; Craddock in: Wayman *et. al.*1992). This could explain the strong symbolic, magical, even cosmological significance inherent in the earliest terminology associated with iron. Thus, the meteoritic iron could have contributed to the identification of man-made iron in copper slags.

Slags from prominent ancient copper smelting regions in northern Iran, Cyprus, Palestine, and Oman have been shown by chemical analysis to have high iron contents (e.g. Tylecote 1967; Steinberg and Koucky 1974, 152; Rothenberg 1978; Hauptmann 1985a). Recently, Chalcolithic

copper slags from the 4th millennium BC have been published from site N_3 at Timna, Israel, which reveal high iron contents and fayalitic phases and are said to be the result of intentional iron ore fluxes (Segal *et al.* 1998, 223, 233). Metallic crystals and conglomerates have, moreover, been found in several copper artefacts and bronze castings from the eastern Mediterranean and the Caucasus (Cooke and Aschenbrenner 1975; Kotovich 1977). Iron was also the principal impurity in copper slags and cakes produced in smelting experiments (Tylecote and Boydell 1978). The number of analyses available is not high, with some samples examined and dating from the 2nd millennium BC, and further data are needed. It should be noted that the iron in the much discussed copper 'slag' from Çatal Hüyük (7th millennium BC) is in the form of delafossite ($CuFe_2O_2$) and so cannot be considered to be a normal smelting slag (Tylecote 1976, 5–6).

If the hypothesis that iron smelting began as a by-product of developed copper smelting technology, one which seems to fit the available data best, were to be accepted, another question must be posed. At what period did Old World smelters cease collecting iron from crushed copper slags or by separating it from molten copper in crucibles and start to smelt iron ores proper for the deliberate production of the black metal? In her discussion on the possible causes of the accelerated introduction of iron, Waldbaum (1989) suggests that there was a shortage of fuel in the Near East, caused not only by the firing of pottery but also by copper smelting, arguing that the smelting of iron required a lower fuel consumption. However, this is a debatable point of view. Georgia, adjacent to the presupposed focus of the earliest metallurgy of iron, has yielded evidence of intentional and specialized ironmaking, before or around 1000 BC, in four districts (Khakhutaishvili 1987). Unfortunately, no other smelting furnaces are known from Asia Minor and the surrounding regions until the Middle Ages. We may, however, take into account the above-quoted letter KBo I 14 from the 13th century BC, where the intentional (and apparently difficult) making of iron is explicitly referred to. The first mention in classical literature seems to be in Hesiod (*Theogony*, 861–866), a passage which may refer to the smelting of iron ore in a form of bowl hearth. However, some translations use the word 'melting' in the context (West 1988, 28) so that it has also been suggested to refer to the decarburization of cast iron (Scott 1990, 182) which does not seem to be persuading.

It is well known that the bloomery process produces iron which is usually low in carbon or heterogeneously carburized. This is due to the fact that the carbon absorbed by the iron during reduction is completely or partially oxidized by the air flow at the tuyere level of the furnace (see Chapter VIII). It was only much later that ironmakers learned how to take advantage of certain factors which could be used to avoid the secondary decarburization of steel. It is therefore of especial interest to find hard steel objects from early periods, including the 12th century BC pick (Fig. 1: 4) from Mount Adir, Palestine (Davis *et al.* 1985), and blades from several other sites such as Lapithos in Cyprus (Stech *et al.* 1985; Åström it et al. 1986). The same has been noted for Europe as, for example, with the 8th century BC Radzovce knife (Pleiner 1981).

It may be suggested that iron descended into the bath of molten copper where the conditions were different, the iron being protected against re-oxidation, so retaining its steely component. Steel treated in small quantities in this way could have been removed without being attacked by the air stream from the bellows (see Chapter VIII). In the present state of our knowledge, this can be no more than a tentative hypothesis, with the corollary that iron quality declined during the Early Iron Age, since the smelting of iron in bowl hearths led mainly to the production of soft wrought iron containing little or no carbon. This development is illustrated by the wrought iron adzes and hoes from the developed Assyrian Iron Age civilization of the late 8th century BC (Pleiner 1979; Curtis *et al.* 1979) and also by the preponderance of soft iron tools and weapons in the European Hallstatt period (as will be discussed in Chapter II). This may well have been the result of smelting of iron ore on its own. The transition to this technology must have been stimulated by an increased demand for iron products, to replace copper and its alloys in the

manufacture of everyday artefacts.

The spread of iron in south-west Asia and in Greece

It has been shown that the earliest evidence for the manufacture and use of iron comes from eastern Anatolia which, along with adjacent areas of Armenia and Cilicia, formed the initial focus for the technology. A number of very ancient iron objects, isolated both in space and time, have also been found in neighbouring regions, such as ancient Mesopotamia. This region and Egypt, neither of which possessed any iron ore, must have been the earliest consumers of the rare new metal, which was imported from abroad.

Towards the end of the 2nd millennium BC, the situation changed and knowledge of iron-making radiated outwards in all directions. In Syria, for example, where iron artefacts were rare in previous centuries, the change is signalled by relatively numerous finds of iron weapons at the cemetery of Hama (Riis 1948; 1958/59; 1960; 1961/62; 1963), which dates from the 12–10th centuries. Later, during the 9th and 8th centuries BC, small Syrian city states such as Haianu, Qué, Hattina, Carchemish and others, were obliged to deliver tribute to the kings of the New Assyrian kingdom in the form of increasingly large quantities of iron, ranging up to hundreds of talents (several tonnes) in weight (Pleiner and Bjorkman 1974, 292 –293). This is indirect evidence for the development of iron in the Cilician region. At the same time, the natural economy of Syria was distorted by the Assyrian conquest.

In Palestine, further to the south, urban centres suffered in the same way. Iron had been introduced there a little later but on a larger scale, during the 11th to 10th centuries BC, when bronze and copper tools were gradually replaced by iron (Waldbaum 1980, 85). It is apposite here to refer to another widely reported hypothesis regarding a supposed monopoly, this time exercised by the Philistines (*Pelishti*), one of the Sea Peoples who are credited with having introduced iron into this area, and with having denied it to the pastoral Hebrew tribes, as reflected in Old Testament stories. In fact, the pre-Philistine Canaanite population of Palestine was already making limited use of iron. The conquering Philistines simply enjoyed easier access to the prized new metal whose value in crafts and agriculture was beginning to be recognised.

The impact of iron technology further south was brought to a halt by the Egyptian civilization, where a rather paradoxical situation developed. Egypt, which was one of the most ancient and important consumers of prestige iron objects in earlier centuries, had a highly developed copper industry, and as a result blocked the further penetration of iron until at least the 7th–6th centuries BC (Leclant 1956). Amborn (1976) asserts that Egypt formed an effective barrier to the spread of iron technology along the Nile into Africa.

The islands of the Aegean and Greece made the acquaintance of iron relatively early, probably through Asia Minor and Cyprus (Pleiner 1969c, 12–13; Iakovidis 1970). Greece provides a model for the natural evolution of iron usage from a symbolic use, with high-nickel iron set in rings of precious metal, through its use for chieftains' swords, spears and knives (Fig. 2: 1–2) in the Dark Age cemeteries of the Protogeometric period in the 12–9th centuries BC (Pleiner 1969c; Snodgrass 1964; 1971, 213–286; 1980), through to the time when iron currency bars in the form of stylized spits (*obeloi*) were used in internal trade transactions (Fig. 2: 4). Iron production and trade were well organized in the Greek *poleis* of the Classical and Hellenistic periods (Pleiner 1969c, 15 – 32). There are several interesting and coherent Greek literary references, including a Hippocratic text *On diseases* IV 45 which contains an accurate description of the bloomery process. Comments on the nature of metals in other works have still, however, not been completely studied, as, for example, the problem of cast iron and fluxes in Aristotle and Theophrastus (Halleux 1974, 189 – 198: *cf.* Scott 1990, 182 ff., see Capter VIII). Several texts contain comments on blacksmith's workshops and trade.

Moving eastwards from Asia Minor, the economic development of the Kingdom of Urartu is not fully understood. Written sources mention iron as flowing down in the form of tribute into

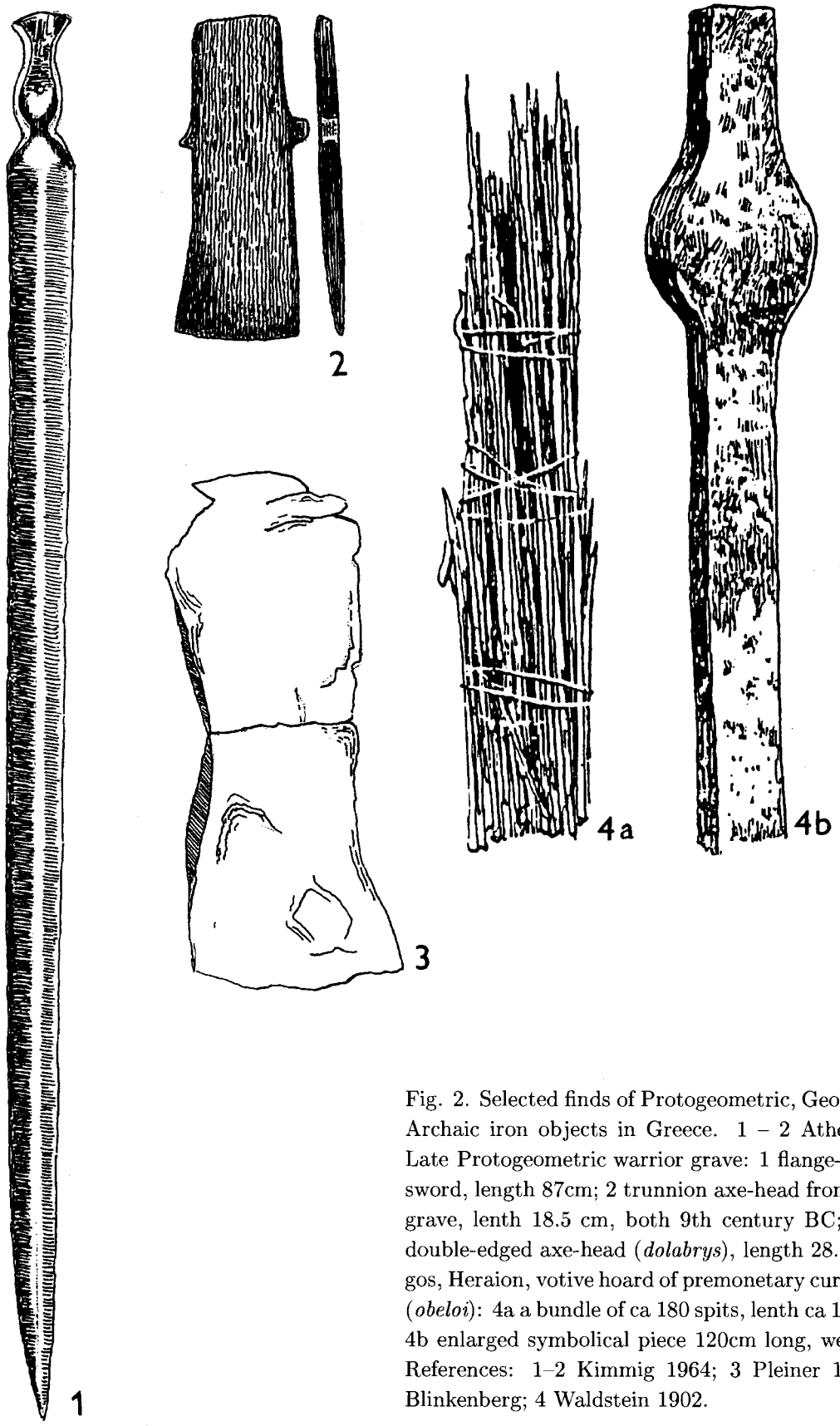


Fig. 2. Selected finds of Protogeometric, Geometric and Archaic iron objects in Greece. 1 – 2 Athens Agora, Late Protogeometric warrior grave: 1 flange-hilted iron sword, length 87cm; 2 trunnion axe-head from the same grave, lenth 18.5 cm, both 9th century BC; 3 Lindos, double-edged axe-head (*dolabrys*), length 28.5cm; 4 Argos, Heraion, votive hoard of premonetary currency spits (*obeloi*): 4a a bundle of ca 180 spits, lenth ca 117–120cm; 4b enlarged symbolical piece 120cm long, weight 73kg. References: 1–2 Kimmig 1964; 3 Pleiner 1969c after Blinkenberg; 4 Waldstein 1902.

the treasuries of the Assyrian rulers as early as the 9th century BC. Two centuries later, the Urartian civilization, then at its zenith, introduced a developed form of ironworking and use into all of the lands affected by its expansion, and particularly into Subcaucasia (Pleiner 1969a). The beginning of this process is still obscure, since there is no evidence available. It may be that a small piece of white cast-iron (3.51% C) from Geoy Tepe on Lake Urmia, dating possibly from the end of the 3rd millennium BC (Burton-Brown 1950), is evidence of a metallurgical accident in a region which later came under Urartian domination and which may have been involved in the birth of iron metallurgy. In nearby western Georgia, the earliest dated iron artefacts begin to appear at the end of the 2nd millennium BC, while bloomeries with bowl smelting furnaces which have been investigated by Gzelishvili (1964) and Khakhutaishvili (1974; 1975; 1987; see chapters III, IV, and IX), appear in the period around or before 1000 BC. On the other hand, iron was still rare in eastern Subcaucasia in the 9th – 8th centuries BC (Pogrebova 1977; Pigott 1977). It seems to have been the power of Urartu which accelerated its use in this part of the world.

In Assyria at the end of the 2nd millennium BC, iron was still reserved for the palace (Pleiner and Bjorkman 1974). Assyrian kings such as Shalmaneser I and Tiglath Pileser I in the 11th century BC owned iron objects such as daggers, while Ninurta Tukulti Asshur had a blacksmith named Marduk bel Ushur at his court. The palace played a decisive role in the distribution of iron for a long period. It would appear that the iron derived entirely from the booty collected from Cilicia, eastern Anatolia and northern Syria in such enormous quantities that it distorted the normal consumption patterns in these productive lands which were the involuntary providers. The 160 tonnes of iron in the form of double-pointed bars (Fig. 1: 7), chains and other artifacts, found in the 19th century by Place in the royal stores at Khorsabad, can be interpreted in this way. The hoard belonged to Sargon II in the late 8th century BC. Metallographic examination of some of these bars and of some implements from Khorsabad has shown that the quality of the iron was in no way exceptional. The bars were made of heterogeneously-carburized steel while the tools were of soft wrought iron (Pleiner 1979; Curtis *et al.* 1979).

Media and Persia had little iron, especially in the south and east, until the 8th century BC. In western Luristan, a famous centre for skilled bronze casting, there was a flourishing industry in the 9th–7th centuries BC producing mace heads, halberd blades and iron daggers with typical zoomorphic pommels which are known almost exclusively from isolated finds (Fig. 1: 8–9). Metallographic examinations on some Luristan blades and mace heads by Smith (1971) showed them to have been made of soft wrought iron with areas of heterogeneous carburization. Although the the daggers show elaborate and skilful jointing of hilt, pommel and blade, there is no trace of heat treatment. The Achaemenid period brought a sudden rise in iron production in the 6th century BC. Persian soldiers started to wear coats of mail, while structural iron clamps began to be used in large quantities in the monumental stone architecture of the Persian kings, as at Pasargadae and Persepolis. This rapid increase in iron production and use may be ascribed to influences from the Assyrian, Urartian, and Manaean cultures lying to the west of Persia (Pleiner 1969a; Pigott 1977).

The Indian sub-continent is separated from Persia by a mountainous region that has not been well investigated, something which led to the formulation of hypotheses based on questionable arguments about the independent invention of iron metallurgy in India (Chakrabarti 1976; 1977) for which there is no solid evidence. They rely on a very loose interpretation of the narrative sources in the *Rig Veda*. The chronology and the direction from which iron spread into India are, however, incontestable. The earliest specimens of iron in India cannot be dated before about 1000 or 1100 BC (Souvenir 1991). Like other cultural influences, iron and it's working technology penetrated India across the Punjab from Persia.

Iron objects occur more frequently in cultural layers associated with NBP pottery on sites in the north of India which date to the 6th–3rd centuries BC. The main centres were the prosperous

city states in the *doab* of the Ganges and Jamuna rivers such as Hastināpura, Atranjikhera, and Alamgirpur. A flow of knowledge of iron towards the south of the sub-continent can be observed around 300 BC. It is interesting to note, however, that bone and copper continued to play an important role alongside iron (Banerjee 1965; Pleiner 1971b).

This situation is reflected in the terminology used for pure copper, copper alloys, and iron in the early Indian languages which remains confused until the later centuries BC. The shifts in the meanings of words like *ayas* and *loha* in the Vedic texts and later in the Pāli canon, which denote copper alloys or – in certain contexts and with special attributes, also iron - document this slow stabilization of meaning (Pleiner 1971b).

The contribution of Indian metallurgists in the form of the high carbon crucible steel known as *wootz* which later became famous as a material for making damascened blades, remains a problem. High carbon (> 1%) steel artefacts have been found in Graeco-Indian contexts at Taxila in northern India, while over a hundred cylindrical iron bars have been recovered from sites such as Sirkap and Taxila. It is to be regretted that these have not yet been subjected to metallographic examination. In the early centuries AD, Indian steel became famous in the Roman world as 'Seric' iron. Nevertheless, *wootz* is considered to be a relatively late innovation of the early medieval period, at several centres in India and Srí Lanka (Bronson 1986). However, views emerged which try to open the problem of an early and independent invention of the wootz-type steel in southern India (summarized by Toussaint 1999). New reliable facts would be needed.

There are more problems in the recognition of the spread of iron and of the knowledge of how to make and use it into other parts of the Old World. Some are discussed briefly in Chapter II which considers the coming of iron to Europe, but we must note here the introduction of the new metal to the far North-East and East. Sporadic occurrences of iron objects dating to the 2nd millenium BC have been recorded in regions north of the Caucusus as far as to the southern foothills of the Urals where artefacts even of meteoric iron (Fig. 1: 10) occur (as at Bichkin Buluk and Boldyrevo — see Shramko 1981; Terekhova *et al.* 1997, 33–37). There are major problems in the precise dating of these scattered objects, but there is little doubt that nomadic steppe tribes of Indo-European stock such as the Cimmerians and Scythians and related groups, knew of iron and used it during the 9th–7th centuries BC, primarily for display weapons, spreading knowledge of it relatively rapidly, via Altay, to the Far East.

It is clear that all metallurgy, whether ferrous or non-ferrous, arose later in the Far East than elsewhere. Rare and isolated objects such as the spearhead with iron blade from Banchiang in Thailand began to appear in the first half of the 1st millenium BC. In this connection, recent results must be noted regarding the situation in China, a region which has been much-discussed in terms of the introduction or independently-developeed technology of iron smelting. New sources reveal that in north-western China in Xinjiang, the first iron artifacts appeared during the 8th century BC, having been brought from the West by Scythian nomads. They are slightly later than a group of bronze axes with cutting-edges made from meteoric iron, some of which have been found in the same contexts as the bloomery iron specimens (Li Chung 1979; Wagner 1993; 1997; 1999). Well investigated meteoritic iron blades of an axe and a dagger-axe in bronze shafts were published by Gettens, Clarke and Chase 1971. They date from the time around 1000 BC.

Rapid development of iron production began around the middle of the 1st millenium BC and is noteworthy for several reasons. In the south and south-eastern regions, the State of Wu large furnaces of the type used for copper smelting consumed ores containing iron and began to produce carburized iron in the liquid state (Wagner 1993, 1997; see Barnard and Tamotsu 1975). Fined iron and steel were then used for the making of weapons, and malleable cast iron was formed into tools, especially agricultural implements the shapes of which followed that of bronze models (Wagner 1997). During the subsequent period of the Han dynasty (206 BC to

AD 263), all production was run on a large scale and fully monopolized by the state.

*

In terms of the spread of iron technology, a reference to the continent of Africa is desirable. Unfortunately the situation is veiled by a heavy curtain of chronological problems, with traditional 'Iron Age cultures' producing little or no iron on the one hand, and collections of radiocarbon dates revealing different values on the other. For example, Holl (1997) claims that four regions in Africa — the territory of the Nsukka-Nok culture in Niger, Egypt, Sudan and Urewe in the Great Lakes — show, relatively speaking, very early iron production said to begin in the 9th–8th centuries BC. This hypothesis is based on unspecified radiocarbon data; no details have been presented. Based on other published material and interpretations (e.g. Tylecote 1968; 1975; 1977; Arkell, Fagan, Summers *et al.* 1966; 1971; van der Merwe 1980), one is inclined to accept the following rough model for the spread of iron technology to the African continent.

After a long period during which mighty bronze-using Egypt imported splendid iron gifts from Asia Minor, it was much later that the region reached the verge of an Iron Age as the result of the influences of Assyrian and Greek cultures (7th–5th centuries BC). The first impressive iron production emerged a little to the south, in Sudan, within the Meroïtic culture which was contemporary, in its earlier phase, with the Hellenistic period in the eastern Mediterranean (4th–3rd centuries BC). The 12 huge slag heaps at Meroë date from the 2nd century BC onwards (Tylecote 1977) and it is hard to believe that this developed industry, which reached its peak during the 1st and 2nd centuries AD (Roman Empire period) was not implanted from the north. Thus, Sudan was either a gate for the channelling of the knowledge of ironmaking south into eastern Africa, or else this industry represents an episode before the activities of the Arabs, moving across the Red Sea in the early Middle Ages. Influences could have been transmitted by another group, the Phoenicians or Carthaginians, who, by about 1000 BC, were firmly established in north Africa and the western Mediterranean and who were using iron by at least 800 BC.

The trans-Saharan Nok culture in Nigeria must have been affected by caravan traffic from the north, with the seeds of iron metallurgy being implanted there during the 4th – 2nd centuries BC, as shown by the slag pit furnaces at Taruga (Tylecote 1968; 1975). To the east, in the region of Agadez, the use of iron is believed to have commenced in the 5th century BC, and slag-pit in Ghana within a broad chronological range from 500 BC to AD 500 AD. The further spread of the technology is obscure. With the exception of episodes of copper mining in certain areas, Africa had no Bronze Age in the proper sense and iron-using populations directly succeeded Stone Age cultures. Sub-Saharan Africa mainly adopted iron during the 8th –19th centuries AD. An enormous research effort must be devoted to the resolution of the history of iron in Africa, the continent which has yielded so much information about traditional, possibly late, bloomery iron smelting.

Thus the most likely birthplace of iron metallurgy would appear to be the Near and Middle East, the technology arising from repeated observations and empirical trials by skilled metallurgical craftsmen working under the favourable geological conditions of the regions that encircled the Fertile Crescent of antiquity. Here, the evolution was a very long one, and one which could hardly have been duplicated elsewhere over a shorter period (Fig. 3).

The stages in the development of iron-use

Initially the art of ironmaking was restricted to a handful of workshops whose masters jealously guarded the secrets of their craft. Metalworking daemons such as Daktyloi and Telchines, whose names are preserved in ancient Greek mythology, may reflect the early existence of highly specialized metalworkers. In addition, the traditions surrounding the iron smelting Tibarenoi

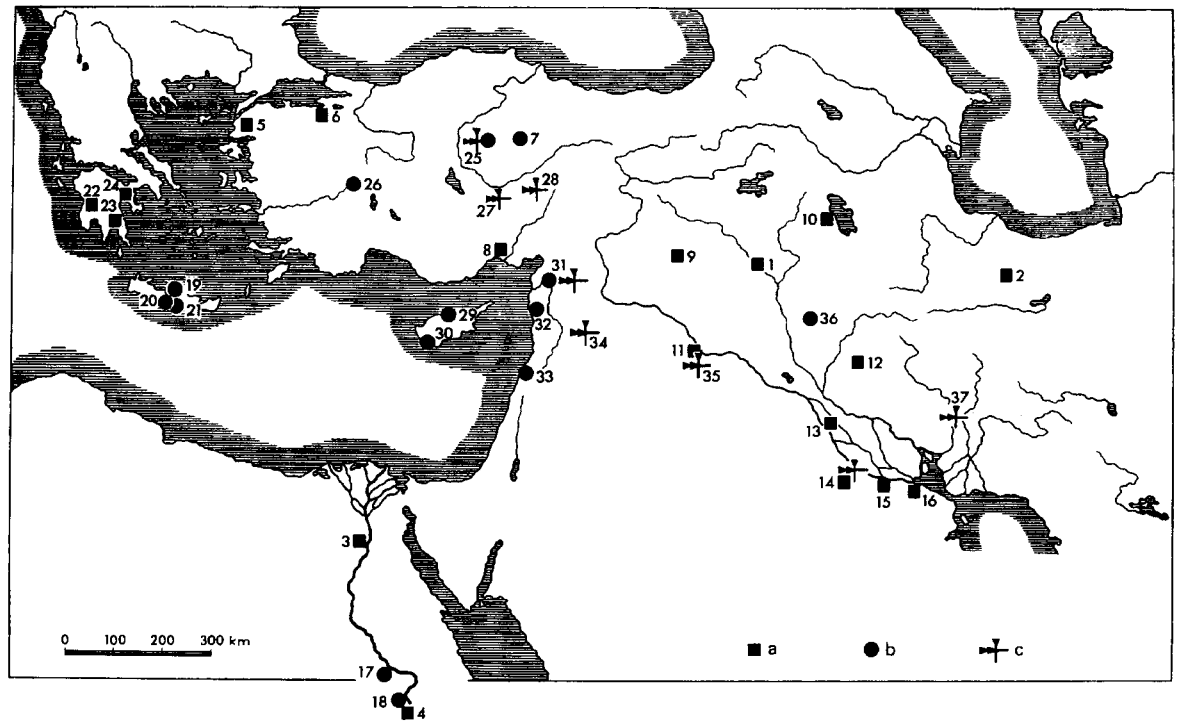


Fig. 3. Iron in ancient south-west Asia, Egypt and eastern Mediterranean in the period 4000–1400 BC. Fourth–third millennia: 1 Samarra, 2 Tepe Sialk, 3 El Gerzeh, 4 Armant, 5 Troy, 6 Dorak, 7 Alaca, 8 Tarsus, 9 Tell Chagar Bazar, 10 Geoy Tepe, 11 Mari, 12 Tell Asmar, 13 Kish, 14 Uruk, 15 Ur, 16 Ubaid. Second millennium: 17 Abydos, 18 Thebes, 19 Archanes, 20 Hagia Triada, 21 Phaestus, 22 Kakovatos, 23 Dendra, 14 Asine, 25 Boghazköy, 26 Kusura, 27 Purukshanda, 28 Káneš, 29 Lapithos, 30 Kourion, 31 Alalakh, 32 Ugarit, 33 Byblos, 34 Qatna, 35 Mari, 36 Nuzi, 37 Susa. Symbols: a — the 4th and 3rd millennia iron objects, b — 2nd millennium iron objects (up to about 1200 BC), c — iron as mentioned in written records (2nd millenium BC).

and especially the Chalybes could well be of great antiquity. Such a monopoly among craft-specialists would have facilitated control by local ruling groups related to the Palace and Temple. The alleged monopolies of this period would have been motivated more by the desire to keep secret the production of a rare material endowed with supernatural powers, rather than by any political or military strategy of the kind attributed to the Hittites.

How did the mechanisms of diffusion of the knowledge of iron technology operate? Some are explicitly set out in written sources, including the royal gift as a form of export and the clandestine trade in iron. In practice, the product of any successful attempt to smelt iron ore would have been whisked away for trading, often to distant lands. During the second half of the 2nd millennium BC, rare iron artefacts began to turn up in regions as distant as Europe and India. It may be suggested that there was a succession of stages in the development of the transport of iron, whether in the form of blooms or artefacts, although it is difficult to believe that this was the only method. In spite of close supervision by the ruling classes, there must have been some movement of specialists. After the destruction around 1200 BC of the Hittite Empire which encompassed most of the iron producing *foci* of the period, skilled metalworkers, who had mastered ironmaking, would have been able to move about more freely. Despite the tendency to keep their technology secret, experienced craftsmen in iron could have begun to communicate with one another and exchange ideas, giving rise to the spread of technology, as outlined above. The new metal gradually came to form part of the range of crafts in the eastern Mediterranean, the islands of the Aegean, Greece, and the countries of the Middle East.

The following stages in the process of the introduction of iron can be identified as being common to the regions under consideration, although its chronology varied from region to region.

The first phase comprises that long period when iron made only sporadic appearances on the human cultural scene and had symbolic and ritual, rather than technological significance. The ownership of this new metal, more expensive than gold and many times more valuable than silver, quickly passed into the hands of the ruling strata of society. Metal from some of the meteorites which were recorded in ancient Mesopotamian literature as having fallen (Bjorkman 1973) was occasionally combined with iron that had accidentally been produced during the smelting of copper ores, and occasional rare specimens might have been transferred to distant regions. This phase lasted three millennia and more in Anatolia and Mesopotamia (5000–1300 BC), but was substantially briefer in neighbouring regions, and in India lasted only from about 1100 to about 700 BC. Theoretically, two sub-phases can be distinguished. In the first iron was available accidentally as a result of the simultaneous smelting of copper and iron ores. The slight increase in the frequency of iron objects in the archaeological record and in written sources indicates that iron was being intentionally made, although as a by product of copper metallurgy. This later sub-phase began in Anatolia perhaps before 1500 BC. The amounts of iron used to make minute artefacts did not exceed a few grams (Pleiner 1966).

The second phase saw iron being produced on a limited scale but on a regular basis, though still as a high-prestige material under the aegis of Palace or Temple. A relatively small number of specialist metal workers and their families or clans were responsible for its production, and the supply to non iron- producing lands was extremely irregular. Iron was offered as royal gifts, and was only made available to the upper strata of society. Its use for technological purposes was very limited, although most ceremonial weapons were capable of practical use. The few metallographic examinations that have been carried out on material from this period provide evidence of the production of steel. It is still debatable, however, whether iron was being produced from the smelting of iron ore on its own. This was the era when iron was measured in shekels (quantities in tens or multiples of ten grams) and, in its final phase, iron circulated in *minae*, (1*mina, man.na, mná* = about 0.4kg).

This period could be well described as an Initial or Proto-Iron Age, although not, archaeologically, in strict chronological terms since it coincides with Late or Final Bronze Age. In Anatolia it covers the period 1300–1100/1000 BC when shekels of iron, about 16g each, and *minae*, less than 0.5kg each, are recorded in contemporary cuneiform documents. For Mesopotamia and Syria it is dated to around 1400 – 1200/1100 BC, in Cyprus, Greece and Urartu to 1200 – 900/800 BC, in Transcaucasia 1000 – 800 BC, in Persia 900 – 700 BC, and in India 700 – 400/200 BC. It is considerably shorter than the preceding phase.

The third phase is the Early Iron Age proper in the technological and socio-economic sense. The technological applications of iron are obvious, with the appearance of four basic types of implement, knives, axes, chisels, and sickles. This does not mean, however, that control of iron by the ruling classes ceased. In places it may have been relaxed to some extent, but the distribution of iron continued to be regulated by palace and temple rather than by the free market. It was mainly the ruling classes who profited from iron in this phase, and they armed their soldiers and made use of iron as a means of applying social and political pressures. It is likely that this explains the demotion of iron from being the metal of heaven to a symbol of fear and evil. The phrase *patar parzilli ša šarri* (King's iron dagger) became a synonym for the royal army in 9th – 8th century Assyria and the phrase 'to put into iron fetters' occurs on many monumental inscriptions of the period (Pleiner and Bjorkman 1974, 288, 298 – 300). It was an impure metal in Hebrew tradition, while the Indo-European world viewed it equally harshly, despite the fact that it alleviated daily toil. The Persians and Indians saw it as a gleaming metal of torture and painful purification while, for Hesiod, (8th– 7th centuries BC) the Iron Age, the fifth age of mankind, was inferior to all those which had preceded it. This identification of bad

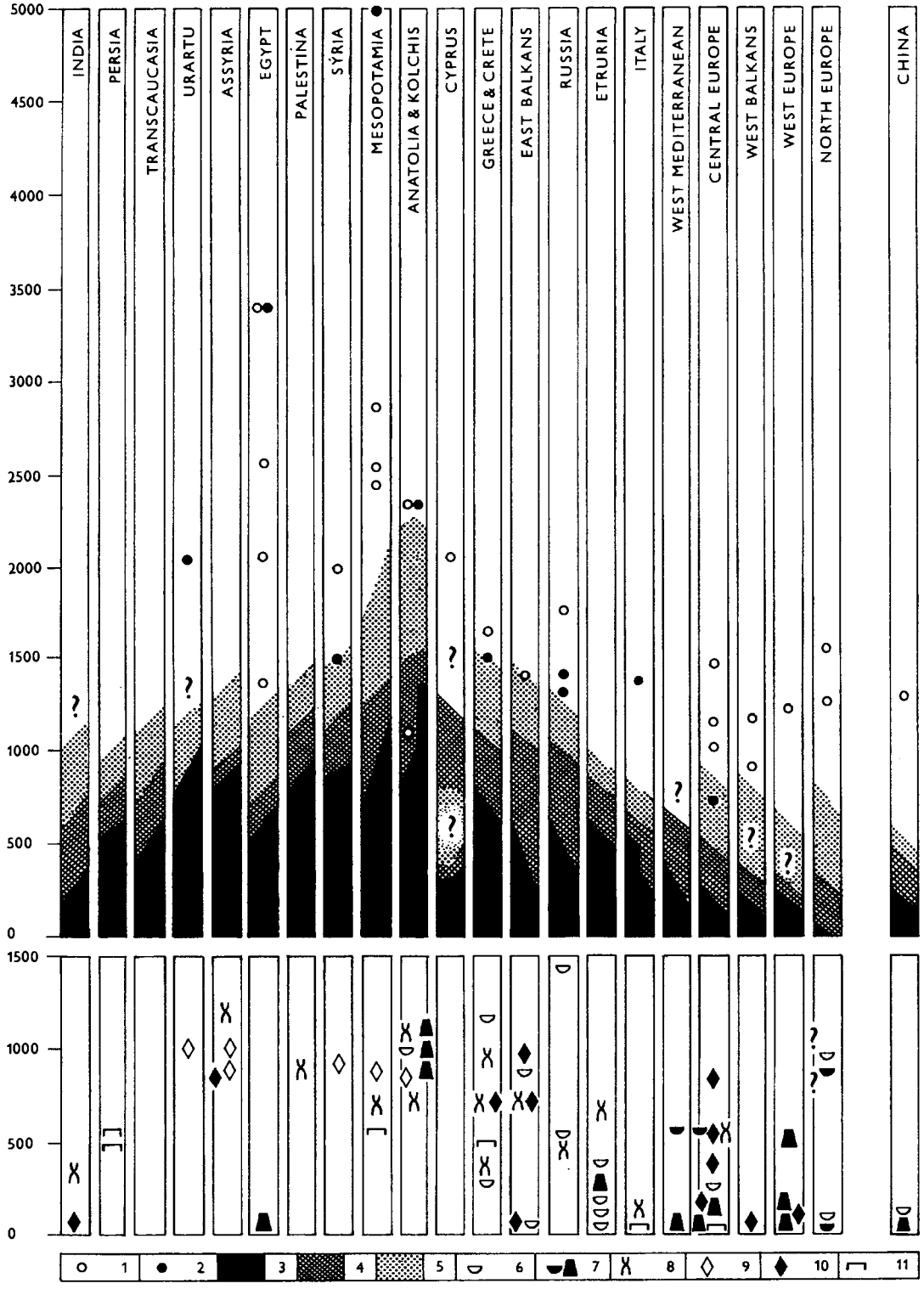


Fig. 4. Stages in the development of the use of iron in anient south-west Asia, Egypt, eastern Mediterranean, and Europe. Symbols: 1 iron objects with elevated nickel content; 2 iron objects, terrestric or unidentified; 3 fully-fledged civilization of iron, 4 the beginning or early Iron Age; 5 sporadical occurence of iron in the Bronze Age; 6 iron slag; 7 smelting hearth/furnace; 8 forge, blacksmith's tools; 9 tributes in iron; 10 iron ingots or bars (of any shape); 11 structural iron in the architecture.

times with iron is consonant with similar pejorative views of the metal and its associations in other cultural regions.

Apparently, iron was no longer being smelted in association with copper by this time, as is indirectly demonstrated by the greater amount which was available, counted in tens to thousands of talents of iron, 26 to 30kg each, i.e. tonnes to hundreds of tonnes and exemplified by the mass found in the palace of Khorsabad. Wrought iron was being used for implements and bloomeries have been discovered in eastern Georgia at sites such as Choga, Charnali, Legva and others (Khakhutaishvili 1974; 1987). Of importance from the technological point of view is the extension of iron working into the forging of wire and sheet and the use of iron rivets. Plastic hot-forming had already reached a high level of virtuosity, as shown by the swage-forging, cutting and jointing of ornamental elements on Luristan short swords (Pleiner 1969d; Smith 1971). The western areas of the Near East have also provided evidence of secondary carburization and quench hardening.

The rise in mass-production (talents to thousands of talents, tonnes to hundreds of tonnes) in certain regions had an influence on the economy. Iron was used for the payment of tribute and taxes in Assyria and became the means of exchange, as in premonetary currency such as the famous Greek *obeloi* and *drachmai* which was used in domestic transactions (Pleiner 1969c, 15–17). These were stylized tools — ritual iron spits, often in bundles (Fig. 2: 4). Metal currency of this kind was characteristic of many areas just before the advent of struck silver coins, and underlines the increased economic and technological importance of the metal.

The Early Iron Age thus dates approximately to 1000/900 – 700/600 BC in Anatolia, Syria, Palestine, Greece and Urartu, 700– 600 BC in Persia, 700 – 500/400 BC in Egypt and Transcaucasia, and 400/200–100 BC in India.

The fourth phase is represented by the fully-fledged iron-using civilizations. Mass-production was the rule in smelting centres, which must have been located in areas with sufficient supplies of fuel and ore. Tools were manufactured using sophisticated techniques, such as the deliberate combination of wrought iron and steel in blades, martquenching and the introduction of tempering. The range of artefacts available increased to between 60 – 100 or more types, including ploughing implements, while large quantities of structural iron began to be used in monumental buildings. Blacksmiths began to specialize as toolmakers, armourers, swordsmiths and cutlers. Certain types of steel, such as Chalybean, Lacedaemonian, Tarsian, Cilician, and Syrian, became renowned for their quality and were traded over long distances at different prices (Oppenheim 1967). Iron had by now become 240–360 times cheaper than silver.

The chronology of the four phases of the geographical spread of the use of iron (which can be extended to the evolution in Europe) represents the most serious evidence for the initial epicentre of iron smelting having been situated somewhere between the eastern Pontus, eastern Anatolia and Cilicia in the Near East (Figs. 3 and 4).

Chapter II

THE COMING OF IRON TO EUROPE

When considering the spread of ironmaking technology, it can be seen that Europe lagged behind the Near and Middle East by more than a millennium. Technological progress had been accelerated there by the availability of copper and bronze, and it was the Bronze Age with its economic achievements which witnessed highly significant developments in social organization — the evolution of early states. Iron was slow to replace non-ferrous alloys and remained in a subordinate role, possibly until a shortage of tin (and/or fuel) provided the impetus for it to play a more important part.

In Europe, by contrast, iron was introduced before the advent of more highly-developed systems of social organization. The natural environment of Europe laid stress on the significant contribution which iron and steel tools could make in deforestation and the associated processes of woodworking. In the initial phases of European iron use, as in the Near and Middle East, it was reserved for the ruling classes. But it much more quickly exerted considerable influence on industrial production and thus made gave a major impulse to the creation of more advanced social and economic structures.

From Greece to the Baltic

Iron made its initial impact upon Europe in the form of high value artefacts, widely distributed in space and time, in the eastern regions of central Europe – the Balkans, the Carpathian basin, and then, via Bohemia as far as Scandinavia. It is not impossible that from the western Balkan area, another route branched off towards Russia. An example of a stray and, by any standard, isolated find is that of a beak-shaped iron dagger hilt from Gánovce, in northern Slovakia, which was found stratified in a ritual well of the Early Bronze Age Otomani culture (Vlček and Hájek 1963). Archaeological association indicates a 15th century BC date, whilst the subsequent ^{14}C measurements gave a date as early as the 17th century BC. Analysis showed that the rust contained no nickel, while the three coniform rivets possibly resemble Mycenaean style (Fig. 5). This is the earliest iron object so far found in central Europe and dates from a period when iron was still a precious metal even in the Near and Middle East.

In fact, the early iron-using civilizations of Late Mycenaean and Geometric Greece referred to in Chapter I might provide the starting point for the iron bearing routes northwards. One of these seems to have followed the Vardar valley where the fortified settlement at Vardaroftsa in Macedonia yielded iron slags which have been dated to the 12th–11th centuries BC (Davies 1926/1927). Unfortunately, the published analyses do not permit their identification either as bloomery slags or smithing waste.

Early finds from eastern Romania such as the socketed axehead from Lăpus, an iron knife from the third Rozavlea hoard, a flange-hilted sword from Banat, a dagger from Tirol and the iron bracelet from Bobda, all of which date from the period 13th–11th centuries BC, deserve attention (László 1977; Boroffka 1991). An unidentified and poorly-stratified slag find reported from Susani, cannot be included with these pieces with any certainty. There are a few finds of the same date-range from eastern Romania which have been claimed to be linked with another possible transmission route for iron, directly via the Bosporus from Anatolia (Boroffka, *op. cit.*, 29). These include the knives from Meri and Cindeşti but, above all, slags from the settlement at Peteni and from Cernat. The 11th century BC find complex from Cernat, interpreted as a metalworker's smithy, was made up of a bronze spearhead, a founder's ladle, several iron tools and 12 rod-shaped iron bars.

Another early group of iron objects from northern Bulgaria comprises the flange-hilted iron swords from Popovo, Topčii, Omarčevo and Krušeto (Toncheva 1980), and a knife, pin and pair of tweezers, all of iron, from a tumulus grave at Vajze in eastern Albania (Fig. 6:4).

Further northwards, in the Alpine zone, small awls and rings have been reported from Hötting and Völs. From Bohemia come some iron rings, chisels and fragments from the period HA–HB_1, the most important of which is the iron rod, sticking in a copper cake which forms part of the HA bronze hoard from Suchdol, near Prague (Pleiner 1981, 116). Unfortunately, the analysis of this curious and important artefact (Fig. 6: 2) is so far not available.

Among iron finds from Saxony, a 1kg piece of iron from Heegermühle near Eberswalde deserves attention. This used to be identified as a large chisel but recently has been interpreted as a form of iron bar (Bukowski 1981a). Its date has also been revised from HC to Montelius III (11th century BC) which might be considered somewhat of a surprise, although the find circumstances are charged with difficulties. More to the west, a small iron awl from Baageroosterelde, Netherlands, was found on a timber trackway in a peat bog, and is dated to the mid-14th century BC, on the basis of dendrochronology (Charles 1984).

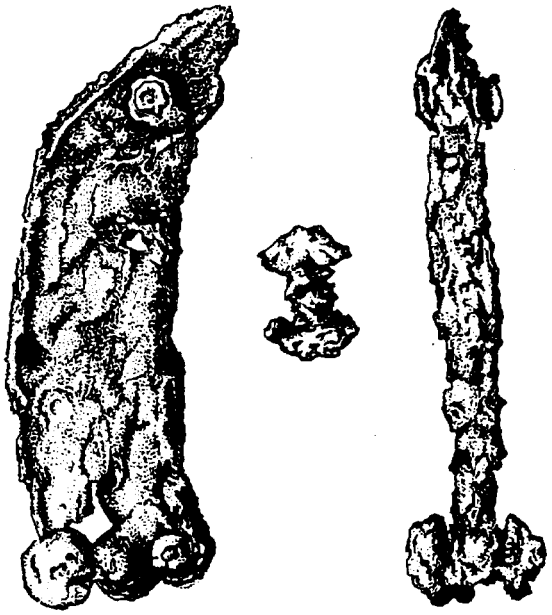


Fig. 5. The earliest iron object in Central Europe: Gánovce, Slovakia, an iron dagger hilt (15th century BC). The rivets are plated with bronze, length 9 cm. No nickel content. After Vlček and Hájek 1963.

In northern Europe, the earliest Danish iron objects are apparently represented by the knife fragment from Grödeby and by what were reported to be ornamental, as thought, iron inlays on bronze razors from Arnitlund and Kjöldbymagle (Stjernqvist 1961, 77–84). However, the recent analytical work has revealed that both of these inlays are, in fact, of pure copper (Voss, pers. comm. 1998). Apart from the well-known piece of iron from Simris, several iron fragments from Bronze Age graves and stone settings in southern and central Sweden have been reported recently (Hjärthner-Holdar 1993, 32). Some are dated by radiocarbon, while three are dated by the typology of accompanying objects to Montelius III–IV (end of the 2nd millennium BC), the others into the wide span of Montelius IV–V.

The spread of occurrences of iron along the geographical axis from the Balkans to Scandinavia constitutes the next phase of introduction around or after 1000 BC, during the HB period of the European Bronze Age. Further Romanian evidence seems to support the idea of a direct Anatolian influence (Sandars 1971; Boroffka 1991). Sites such as Babadag II, Hărman, Sintimbru, Mediaş, Galiţa Dervent and Hirşova in the eastern part of the country have all yielded iron slags (unfortunately not analysed). Babadag even produced an iron bar, while from Sinçraieni comes an iron bloom. The number of iron objects from various Bronze Age contexts (Fig.6: 3) has now reached about 20 (Székély 1966; Olteanu 1971; Boroffka 1991).

It seems that traffic bearing iron by routes situated to the west was less frequent, although the situation is not very clear. Occasional finds of iron have come from Albania, the north-west Balkans (Čović 1980) and the Caput Adriae region of northern Croatia and Slovenia and include

the flange-hilted sword from Škocjan-St. Kanzian (Fig. 6: 1), and items from Ruše Maria-Rast, Sisak and Šarengrad (Rieth 1942, 12–15; Alexander 1972, 99–101). A single iron knife was found in an Urnfield context at Ginzheim, near Mainz, while a spherical object made of iron sheet has been reported from a cremation grave near Dortmund (Brink-Kloke 1994, 23, 84).

In spite of territorial gaps, it can be asserted with reasonable justification that it was influences from the south-east which brought knowledge of the working of the new metal into the regions both south and north of the Balkans which were, at that time, inhabited largely by Indo-European Dorians, Venetians and Illyrians.

The subsequent decline of the Bronze Age (Hallstatt B_3) marks a critical stage in this process (Kimmig 1964; Pleiner 1981). In central Europe, this was the period when ornamental iron inlays on bronze sword hilts were in favour (Fig. 6: 11–12) and when iron bracelets, knives and sword blades made entirely of iron appear (Fig. 6: 13). At the same time, objects made entirely of iron began to occur alongside bronze artefacts of the same type. We must take particular note of the iron knives, spear heads and pins dispersed throughout the Urnfield cultures which are characteristic for central and eastern Europe. Although more than 100 iron objects are known from Hallstatt B complexes (Kimmig 1964; Pleiner 1981, 1982; Patek 1984), this did not, however, constitute an Early Iron Age as these objects continued to be associated with the upper echelons of society, as prestige goods.

The question of ironmaking sites belonging to this early period arises. To date, none have been found in central Europe, but the possibility of iron having been made on a very small scale somewhere in the south-eastern foot hills of the Alpine massif or in the northern periphery of the Carpathian basin cannot be ruled out. Indeed, some scholars believe that metal workshops or bronze foundries using iron and steel chisels for engraving non-ferrous castings existed at this time (Bouzek 1978). An indisputable loaf-shaped iron bloom weighing 2.43kg was discovered by Furmánek at Šafárikovo-Tornal'a in southern Slovakia (Pleiner 1981, 121; Furmánek 1988), in a HB_3 pit at a settlement of the Kyjatice culture. The relatively large amount of metal would have been sufficient for the manufacture of at least three sword blades, several axes or about a hundred knives. Furmánek suggests that some production of iron took place in Slovakia before 800 BC, although there is no direct evidence for this at present.

In contrast, in the Mäleren area of Sweden, there are at least three sites which are claimed to be bronze foundries and iron smelting works. Hällby has produced three stone-set bowl hearths some 20–40cm in diameter, with associated wüstite-fayalite slags and a highly carburized bloom fragment. At Hallunda, a rather large hearth, 60–80 cm in diameter yielded 450g of iron-rich slag, as well as copper slag-containing metallic prills, while there was a small heap of fayalite-wüstite waste with embedded, partly carburized iron particles and a hearth also containing slag at Linga. The Hallunda site is interpreted as showing occasional ironmaking by multi-skilled metalworkers familiar with bronze and copper work (Hjärthner-Holdar 1993, 62 - 99). While radiocarbon dates indicate an overall time-span for these sites from the Bronze Age to the Middle Ages, those calculated on samples related to the ironmaking belong to the period 1500–380 BC for Hällby, 1071–400 BC for Hallunda and 968–357 BC for Linga; Hjärthner-Holdar prefers the earlier dates, although Zimmermann (1998) is inclined to ciriticize the interpretation of the above dating. It is thus fairly difficult to ascribe those installations only to Montelius IV as the author wanted, to the subsequent Montelius V–VI, or even to the Nordic Early Iron Age which includes the period between the 7th and 4th centuries BC. Nonetheless, it is clear that the traffic from the Balkans and central Europe continued throughout the entire Bronze Age.

To the eastern steppes and beyond

Studies suggest that iron first emerged in the eastern steppes and forests to the north of the Black Sea and Caucasus during the 2nd millennium BC (Grakov 1958; Shramko, Solncev and Fomin 1965; *iidem* 1977; Shramko 1981), but the dating of monuments is less precise than for

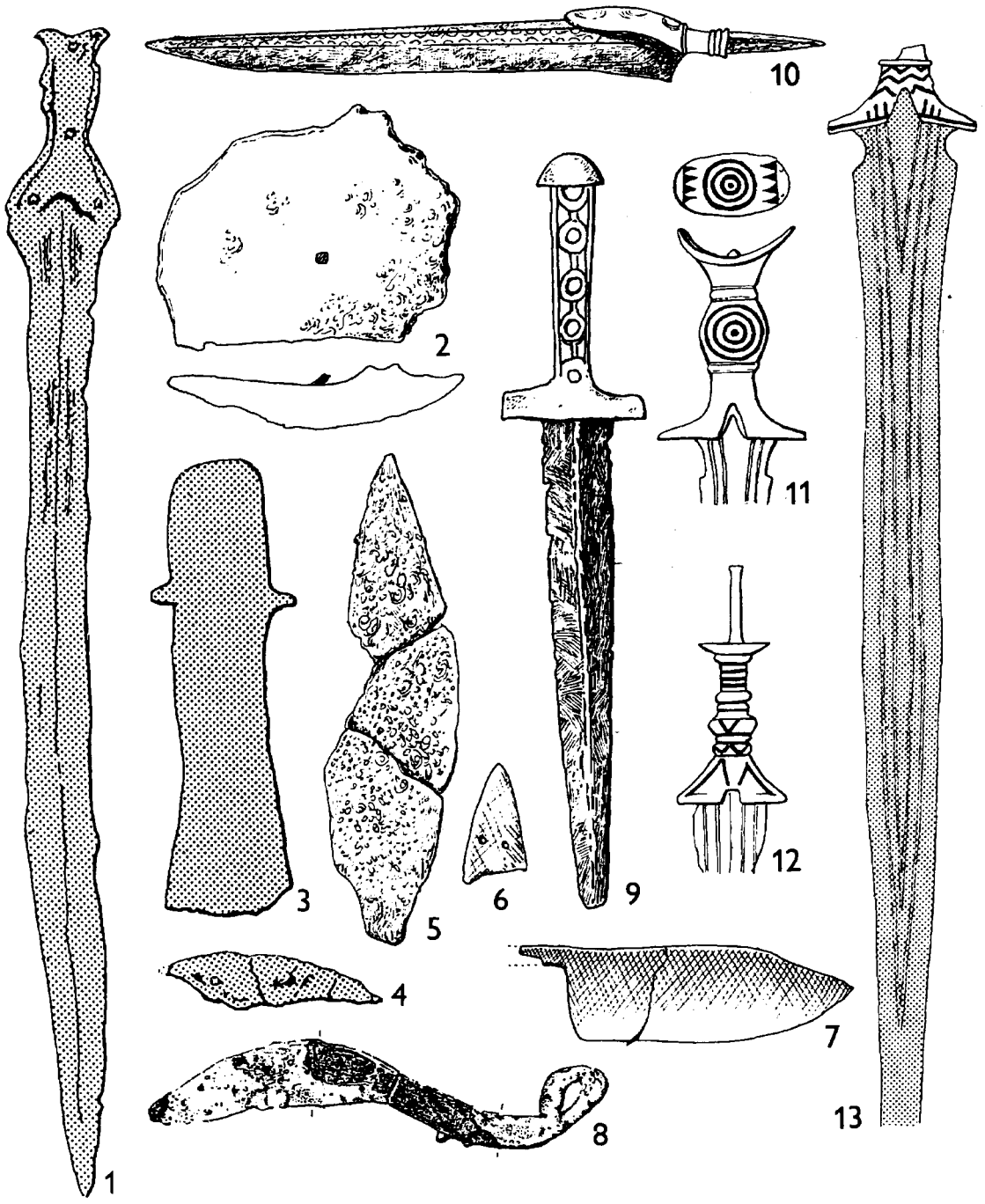


Fig. 6. Selected Late Bronze Age iron objects from Europe. 1 Škocjan – St. Kanzian, Slovenia, flange-hilted sword, length about 50 cm. 2 Prague-Suchdol, bronze cake with a sticking fragment of an iron rod, from a hoard. Dia. 10 cm. 3 Bîrlad, Roumania, trunnion axe-head, length 18 cm. 4 Vajze, Albania, knife, from a grave, length 8 cm. 5 Bichkin-Buluk, Russia, a point with elevated nickel content from a tumulus tomb, length 15cm. 6 – 7 Quéroy, France, arrowpoint and knife-blade from a cave. 8 Radzovce, Slovakia, knife from a settlement, hypereutectoid steel, length 21cm. 9 Gamów, Poland, bronze-hilted iron dagger from a hoard, length 22 cm. 10 St. Aubin, Switzerland, iron knife with bronze mounting, length 18.5cm. 11 – 12 Bronze swords with iron inlays inhilts: 11 Unterkrumbach, Germany; 12 Mörigen, Switzerland. 13 Mörigen, bronze-hilted sword. Approximate chronology: 5 18th century BC, 2 12th century BC, 1 about 900 BC, 3, 6 – 7 about 800 BC, 8 – 13 8th century BC. After various authors, see Frühes Eisen in Europa 1981.

central Europe. The blade from Bichkin Buluk in the Kalmyk steppe (found in a grave, accompanied by a copper axe, Fig 6: 5), which contains 3.65% Ni and 0.1% Co, is dated to about 1800 BC. It is thought to have been made from meteoritic iron, the origin of which is naturally unknown. A similar date is proposed for two iron objects — a 'chisel' and the cutting-edge of an adze (Fig. 1: 10) — from Boldyrevo I, a site of the Chalcolithic early Pit Grave culture in the Orenburg region at the southern foothills of the Ural (Terekhova *et al.* 1997, 33–39). Examination has shown that the handle of the adze was made of pure copper, while the iron cutting-edge, which contained kamacite and taenite (5.3–5.5% Ni and 0.52% Co) but no slag inclusions, must be identified as being meteoric iron, as well as the chisel with 9.45% Ni and 0.67% Co.

Curiously enough, the earliest objects made from smelted iron occur well to the north, in the area of the upper river Don. A primitive copper and iron knife or dagger formed part of the burial assemblage in a tumulus grave at Gerasimovka, dated by radiocarbon to the l8th century BC. Moreover, there are some iron awls from the Voronezh region at Voronezh and Semidvorki which are ascribed to the early Timber Grave culture (14th century BC). Iron slags dated to the same period, were claimed to have been found in a hearth-like installation in Voronezh, but no details are available. The cemetery of Tchastyye Kurgany, near Voronezh, yielded another awl, dated to the period 11th to 10th centuries BC and the same chronological span is suggested for some small iron objects (awls, blades) from a burial at Volosovo, near Murom, further to the north in the lower Oka river valley.

The southern area of the lower Dniepr river has also yielded early iron. At Lyubovka, an iron knife in a tumulus grave of the Sabatinovo period dates to the 14th–12th centuries BC and iron daggers with bronze hilts from sites at Stepnoye and Malaya Lepetikha-Shirokaya mogila belong to the 10th–9th centuries BC. At Krasnopolskaya, Uman', iron-rich slags containing 58% Fe were found in an open smelting hearth. When considering the geographical distribution of these isolated finds (about 20 in number) it must be noted that they form a pattern which links up with the western Black Sea coast, following the rivers Dniepr, Psyol and Vorskla towards the upper Don and lower Oka regions and, possibly further north-east, to lake Galitch and the Vychegda valley. This geographical tract which crosses the territories of the Ochre grave and Timber grave cultures must have been active during the whole of the 2nd millennium BC.

Surprisingly, finds of early slag finds have been reported from far to the north of Russia, in the regions of the Kostroma and Vychegda rivers. The most important of these is at the 8th century BC site of Umileniye on the northern shore of lake Galitch where sunken-floored huts II and III and several fireplaces yielded 'slagged crucibles and bloomery iron' (Foss 1948, 59, 61). This, and a similar find from Vanvizdinskaya, is regularly quoted in the literature but unfortunately, no analyses have been presented.

During the 9th–7th centuries BC the regions adjacent to the northern coast of the Black Sea were inhabited by Cimmerians, an Iranian folk, who were the predecessors of the Scythians. Later, they came under pressure from the Scythians and expanded to the south-west, forming the Thraco-Cimmerian family of Indo-Europeans. One group, however, invaded Anatolia and brought about the fall of the Lydian kingdom. It has been claimed that the Cimmerians were skilled ironworkers who produced iron and steel blades (some of them with bronze hilts, Fig.6: 9), axes and spearheads. A group of Late Bronze Age bronze-hilted daggers with cruciform hilts have been found scattered throughout Hungary, Silesia, Moravia, Austria and Romania in HB_3 contexts (Podborský 1970, 153*ff* and figs. 25–26). These were at one time related to the 'Cimmerian iron route', to which considerable importance was attributed (Berciu 1963) but are now believed to be merely occasional enrichments of the Central European iron inventory (Fig. 6: 9). It seems now that these steppe populations played a more important role in the spread of iron to inner Asia and the Far East (Wagner 1997; 1999).

The Cimmerian and subsequent Scythian periods from the 8th to 5th centuries BC, saw a

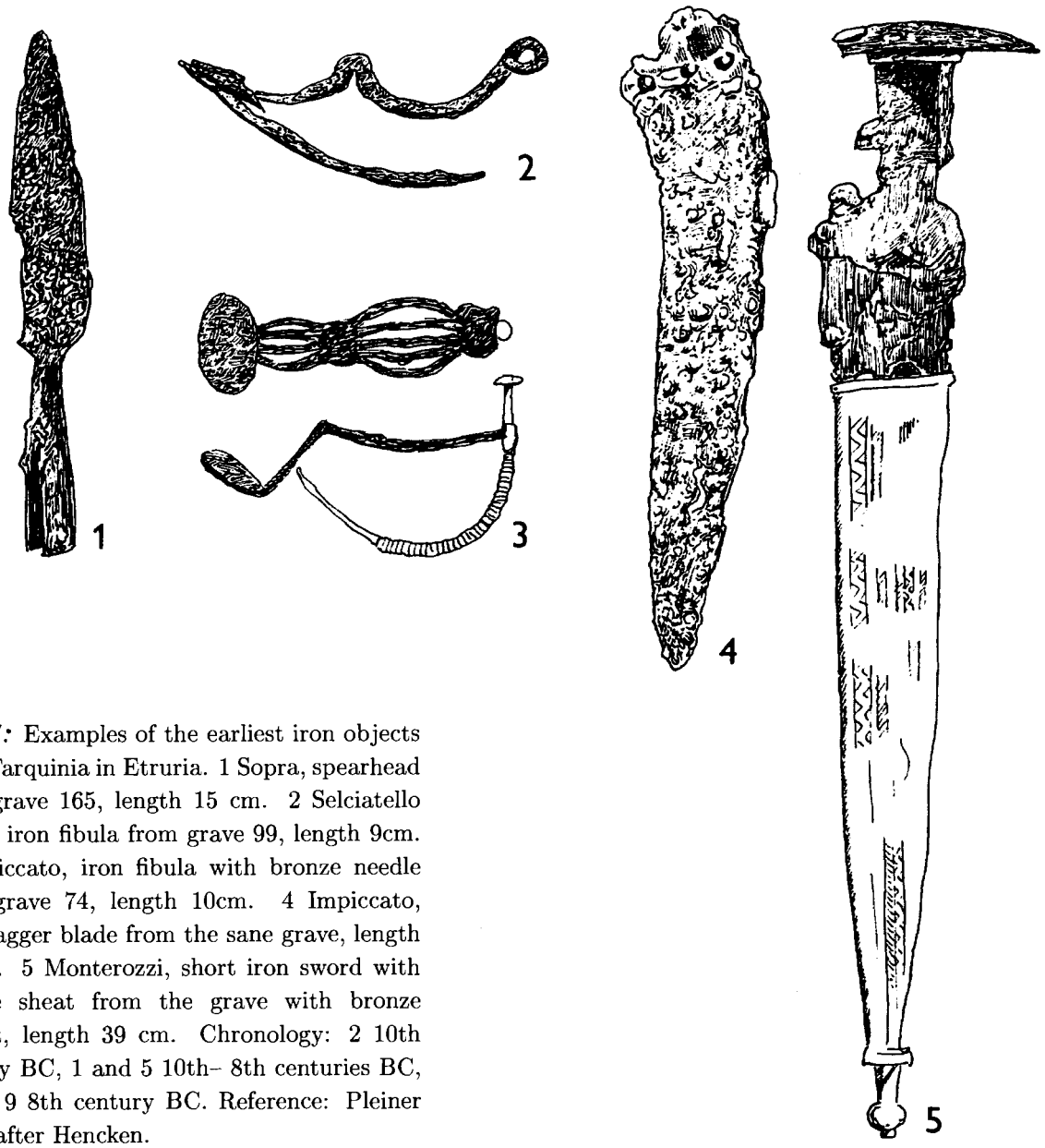


Fig. 7: Examples of the earliest iron objects from Tarquinia in Etruria. 1 Sopra, spearhead from grave 165, length 15 cm. 2 Selciatello Sopra, iron fibula from grave 99, length 9cm. 3 Impiccato, iron fibula with bronze needle from grave 74, length 10cm. 4 Impiccato, iron dagger blade from the sane grave, length 24 cm. 5 Monterozzi, short iron sword with bronze sheat from the grave with bronze helmet, length 39 cm. Chronology: 2 10th century BC, 1 and 5 10th- 8th centuries BC, 4 and 9 8th century BC. Reference: Pleiner 1981, after Hencken.

rise in the numbers of working iron tools and weapons in the steppes and woodlands of Ukraine and Russia.

Italy and the western Mediterranean

The route by which iron technology was brought to Italy was a slightly later development. There is lack of 2nd millennium BC finds, except for an iron ring from the 14th century BC grave 23 at Castelluccio near Syracuse, Sicily and an iron rod-shaped object with steatite pommel from a collective burial at Montrox, Sardinia (Delpino 1988). In fact, there is little evidence for iron in Italy before 1000 BC, when it was introduced to the southern part of the penninsula, although the picture is by no means clear. Apart from several isolated objects, attention should be given to small iron rings found at Mullino della Badia in a site of the 10th century BC Pantalica Sud III culture. On the coastal mainland, the earliest iron objects are roughly a century later, while in Campania and Basilicata, it was not until the 8th century that artefacts such as the swords,

knives and spearheads from Torre Galli, Torre di Mordillo, Canale, and Santa Maria d'Anglona (Malnati 1984) and the few iron fibulae from the cemetery of Sala Consilina (de la Genière 1968) make an appearance. In none of these cases is the origin of the metal known, and although we can note old finds of iron slags and/or furnace remains from Coppa Nevigata-Manfredonia in southern Italy, the suggested chronology of 10th to 8th centuries BC for the site has not been firmly established.

Chronologically, some of these Italian finds are pre-Greek, whilst others must be attributed to the direct influence of the Greek colonization that began in the 8th century, by which time an iron-using civilization had been definitely established in Greece. Excavations of an 8th century settlement on the Euboean island of Pithekoussai (Ischia) produced evidence of ironworking in the form of a smithy with iron slags and tuyeres, whilst another phase, dating from the 7th century BC, also produced specimens of Elban haematite which indicates that bloomery iron smelting may have begun (Buchner 1969; Snodgrass 1980, 369).

The iron ore of Elba is associated with Etruscan ironmaking on the west coast of Italy. Firmly dated evidence for this industry comes from a later period, but it is significant that the sporadic use of iron is attested in the Etruscan area as early as the 10th century BC. Phase IA of the Tarquinia Selciatello cemetery produced iron rivets in a bronze sword hilt (grave 73) and iron fibulae (grave 99, Fig. 7: 2; Hencken 1968). Iron objects continue to increase in number from that time onwards, when influences from Greece and Asia Minor can be identified, as shown by the Tarquinia Monterozzi and Impiccato cemeteries (Fig. 7). By the 8th century BC, iron was being used for swords, lance and spear heads, ornaments and harness in Umbria and Picenum, to the east of Etruscan territory and the 8th–7th centuries BC warrior graves from Novilara are noteworthy for their iron *falcatae* and other types of dagger. However, certain regions to the south of Etruria remained somewhat backward. In Latium, for example, iron ornament is very rare indeed before the 7th century and iron did not replace bronze until as late as the 6th century.

One fact should not be overlooked. At the same time as the Etruscans on Elba were developing the large-scale exploitation of iron ore, the shore of the Bay of Baratti close to Populonia, Tuscany, began to be covered by layers of iron slag which buried earlier Etruscan tombs of the 7th century BC (see chapter III).

The widespread use of iron appears to have been brought to Italy above all by the Greeks and Etruscans, although it is difficult to determine the extent to which the Etruscans can be held responsible for bringing it from Asia Minor. It should be noted that the Latin word for iron, *ferrum*, is not of Indo-European origin, originating presumably in Akkadian and Semitic roots (*parzillu, barzel, ferzom*) which might provide a link with Etruscan origins, if the Eastern theory is accepted. In archaeological terms, however, whatever the origins of the Etruscans, it was from their lands in Italy that the knowledge and practice of ironmaking and working radiated out in all directions, including to the northern regions, which became familiar with the new metal during the 8th century BC in the Bologna II and Este cultures. The question remains as to whether iron technology also crossed the Alps at this time since the metal had already been introduced all over central Europe. Nevertheless, the passage from the south to north played an important role in the spread of innovation centuries later.

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During the 8th century BC, which constitutes a remarkable turning point, there was some levelling-up in the use of iron between south-eastern, eastern, southern, and central Europe. This resulted from several basic technological stimuli which can be related to migrations of artisans and the supply of metal. The transmission of knowledge often operated in the opposite direction to the ethnic movements, southwards to the Carpathian basin, Balkans, and Apennines.

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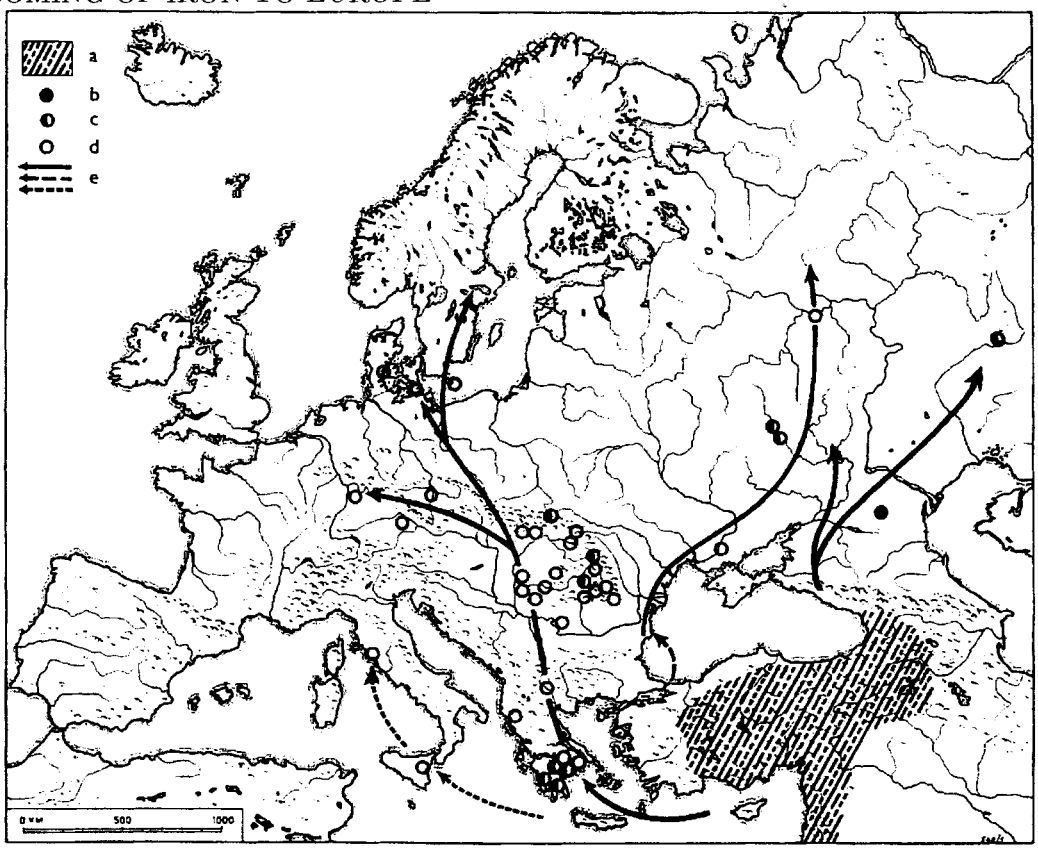
It was in the same third phase of the Hallstatt B period that iron reached western Europe, not only by overland Continental routes. Greek and Phoenician traders had brought iron artefacts and technology as early as the 8th century BC to the west coast of the Iberian penninsula and to the Golfe du Lion. Iron production spread to the interior in the 7th to 5th centuries BC, as shown, for example, by the remains of bloomeries (unfortunately not published in detail) from Cortes de Navarra in the Ebro valley (Maluquer de Mottes 1971). Iron did not reach the north-west of the penninsula until Celtic raiding began, although it did spread along the coast to the eastern and north-eastern foothills of the Pyrenees. There, as well as in southern France, Mediterranean and continental influences might have joined during the 8th–7th centuries BC (Mohen 1980; Rovira; Janin and Chardenon in Recherches sur l'économie du fer, 45–64). At that time, Late Bronze Age groups began to adopt iron sporadically at that period (Fig. 6: 6–7).

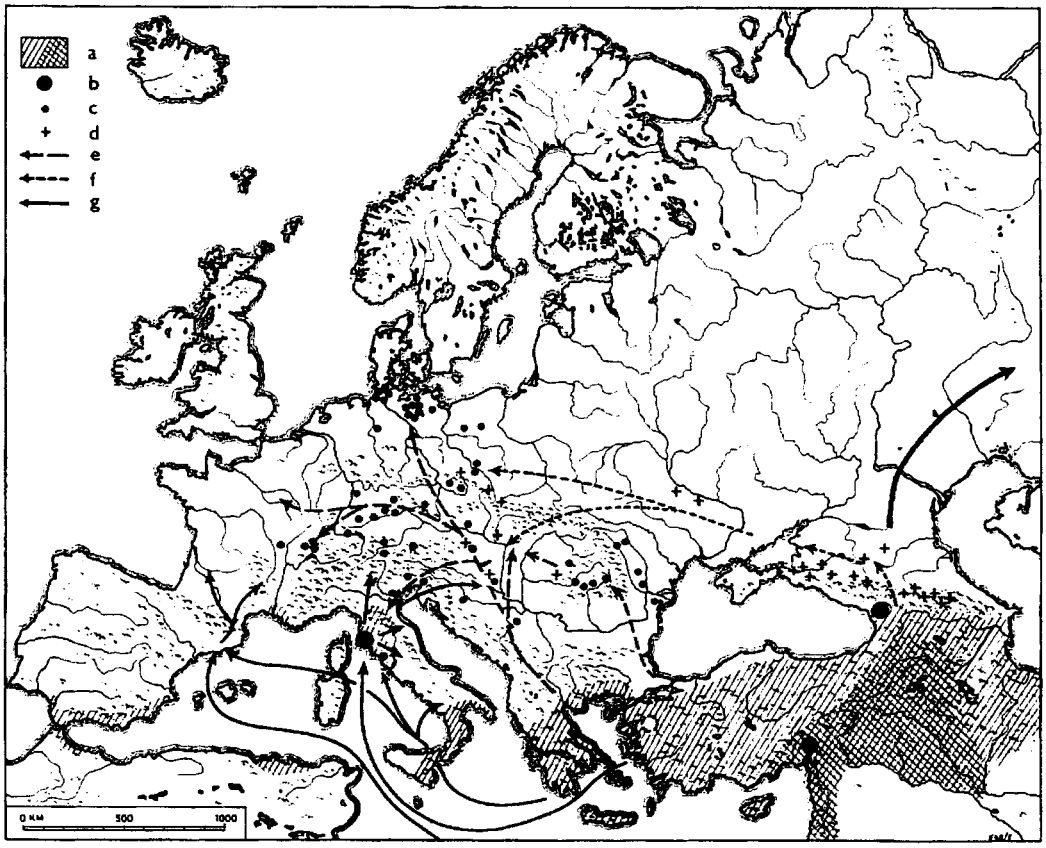
From that time onwards iron technology spread to cover the whole of France, including Brittany, supported by influences from the regions north of the Alps. By the 7th and 6th centuries BC, iron artefacts begin to appear in Britain (Alexander 1981; Tylecote 1986) and even further to the west, in Ireland (Scott 1990, 41) which, like most of Britain, was to be settled by Celtic peoples. It is worth noting here that the Celtic language family shares a root for the name for 'iron' with the Germanic languages – Celt. **isarno*, Germ. **isarna* which stands in contrast to Slavic *železo* and Greek *sideros* and others, evidence of the complexities surrounding the introduction of iron to Europe (Scott 1983; 1990, 180). Tentative reconstructions of the routes and directions of the spread of iron and its technology are shown in Figs. 8 and 9.

The European Early Iron Age

Thus, in the lands to the north of the Alpine massif, the Hallstatt C and D and the early La Tène chronological phases in central Europe may be classified as the Early Iron Age proper. The archaeological evidence still shows the majority of the iron available being used by the upper classes of society. Nevertheless, from that period, weapons and tools, such as axes, knives, punches, chisels and sickles were made entirely and exclusively of iron. New artefact types began to emerge, including components of of horse trappings, wagon mountings, and spits and the first blacksmith's tools, such as heavy hammers, anvils and pincer-tongs, such as those from the cave at Býčí skála in Moravia, from Yablonovka in Russia and Wicina in Silesia (Pleiner 1962, Fig. 10; Shramko 1969; Bukowski 1981a, 72; 1981b), appear in the archaeological inventory of metal objects. In fact, in Central Europe during the Hallstatt C and D phases, some 30 kinds of iron artefacts were manufactured, and the first double-pointed iron ingots (dating to the end of this period, about the 5th century BC — Pleiner 1980, 391–392) such as those from Biskupiń, Witów and Maszkowice in Poland, Býčí skála cave in Moravia, Leipzig -Wahren in Saxony, Heuneburg in Württemberg and Mont Lassois in eastern France began to circulate.

Fig. 8. The spread of the use of iron to Europe. Above: from the Early up to the Late Bronze Age. Symbols: a – the area of the beginning Iron Age in the Near East (15th - 11th centuries BC); b – objects with attested elevated nickel content; c – finds of the 15th – 13th centuries BC; d – finds of the Late Bronze Age (beginning of the 1st millennium BC); e – presumed directions of the spread of the earliest iron objects. Bottom: Directions of the spread of iron and the knowledge of iron metallurgy at the decline of the Bronze Age. Symbols: a – areas with a developed civilization of iron; b – evidence of iron smelting; c – the most important iron objects of the 8th century BC; d – Bronze Age irons of eastern types; e – presupposed Thraco-Venetian route; f – Cimmerian route; g – Greek and Phoenitian routes.


a
b
c
d
e
0 KM
500
1000


a
b
c
d
e
f
g
0 KM
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1000

At this time, traces of the first bloomery works emerge among the archaeological assemblages of the central European Urnfield and Tumulus complexes. In the past, numerous sites have been claimed as Hallstatt period bloomeries, but the chronological and functional evidence does not stand up to critical examination. There are, however, three sites — Smolenice Molpír, Čečejovce and Králová — of the HC/HD periods, situated in the eastern Urnfield province, which may be interpreted as ironworks, but the evidence is still questionable.

Slags (unfortunately not analysed) were found at a place excavated inside the fortified area of the 7th century BC site at Smolenice-Molpír in western Slovakia. Heterogeneously-carburized iron blooms (Fig. 62: 2), iron scrap, socketed and trunnion axes and semi-finished knives were found close by (Pleiner, unpublished; Dušek 1966). A red-burnt hearth, found nearby, was apparently not associated with these finds, as originally considered, since analogous features appeared within the settlement area, without any slag finds. The unfortified site of Čečejovce in eastern Slovakia is also interpreted as a smelting site, in spite of the absence of any hearths or furnaces *in situ*. However, the occurrence of bloomery slags with a characteristic fayalite-wüstite texture, of outcrops of limonitic ore and of a piece of heterogeneously-carburized iron bloom (0.01 up to 0.8/0.9% C) 0.587kg in weight seems to constitute sufficiently good evidence (Mihok 1994).

An iron smelting hearth lined with lumps of bloomery slag found in the corner of a sunken-floored hut, was reported from Králová, northern Moravia, in 1930. No documentation has survived but charcoal is known to have been found in the hearth and, close by, pieces of high grade haematite of the Lahn-Dill type, deposits of which occur nearby. This site, an open settlement of the local Hallstatt cultural member of the Urnfield family, is dated by pottery to the HD period (5th century BC, see Pleiner 1958, 81–82).

The site of Waschenberg in Lower Austria belongs to the transition zone between western and eastern Urnfield cultures. Five open bloomery hearths, a charcoal pit, an area for ore-roasting and two features which were interpreted as smithies were excavated within a fortified area (Pertlwieser 1970; see chapter IV below). An iron sponge found in one of the hearths shows an area carburized to 0.4% C. As at Králová, the rich HD pottery assemblage dates to the 5th century BC. There is, again, the question of the Swedish sites at Hälby, Hallunda, and Linga, discussed above with their stone set hearths and slags, claimed to be from the period before 1000 BC. In fact they could be dated, by aid of other quoten radiocarbon measurements, to later centuries, up to the 4th.

It should not be overlooked that at the same time the Etruscans on Elba developed a large-scale exploitation of iron ore and the shore of the Baratti bay close to Populonia, Tuscany, began to be covered by layers of iron slag (see chapter III).

One point worthy of note is that in contrast to the Swedish sites, the few central European bloomeries or ironworks seem from their contexts to have been fully engaged in ironmaking, and not combining ferrous and nonferrous operations. There is also an interesting phenomenon to be registered from metallographic studies of artefacts of the period, namely that the quality of iron produced decreased through time. Among the earliest iron products from the Near East to Ireland, all-steel blades very often come to light. As but one example, we can cite the 8th century BC knife from Radzovce in southern Slovakia (Fig. 6: 8) which was made of homogeneously-carburized steel with 0.8– 0.9 % C and 0.494 % Cu (see Pleiner 1986, with further references to steel artefacts of the period).

Theoretically, advanced copper smelting with the regular use of iron ore fluxes might have yielded some carburized iron, not only in the slag but also in the copper cake, where it would have been perfectly protected against secondary decarburization. However, recent metallographic research on some 200 specimens dating from the HC–HD periods shows that the majority (over 61%) were made from ferritic wrought iron or heterogeneously-carburized metal. All-steel artefacts are rare (about 15%) and the subsequent carburization of cutting edges can hardly be

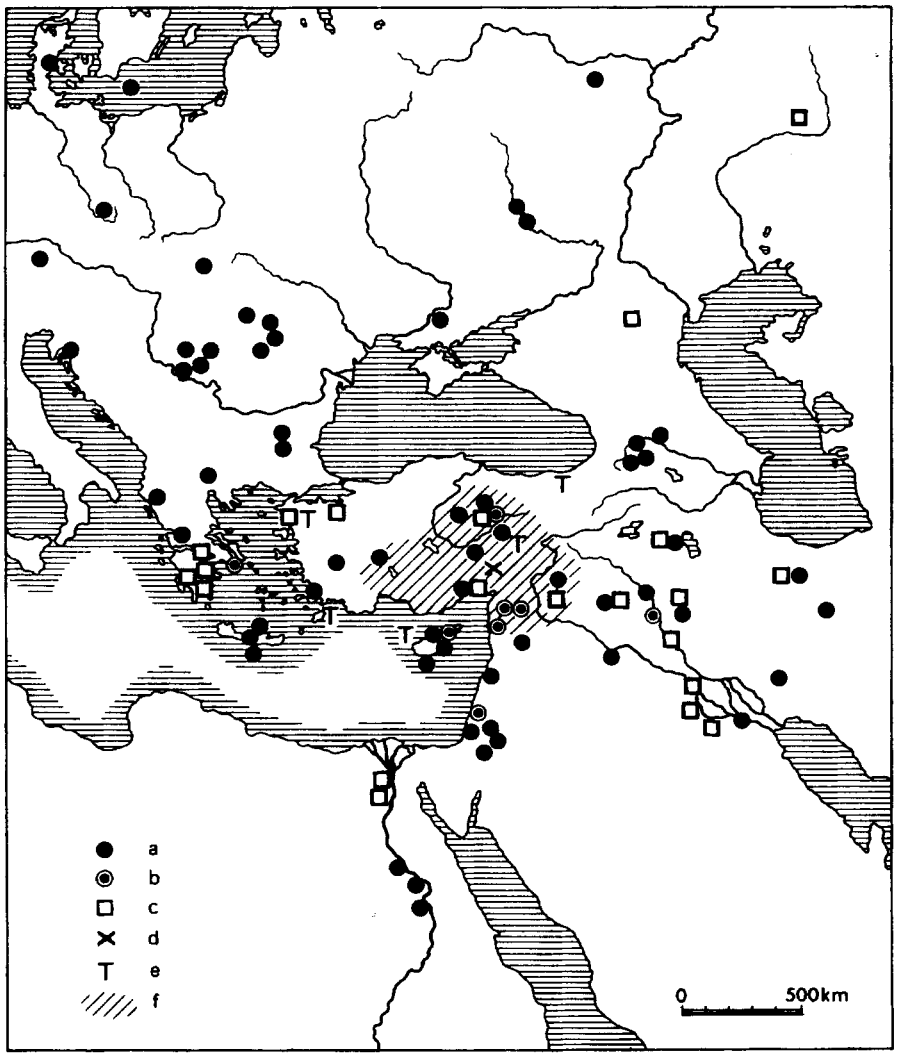


Fig. 9. Summary map of distribution of iron from about 4000 up to about 1000 BC in South-west Asia and Europe. Symbols: a – iron objects and places with written records concerning iron; b – sites with larger assemblages of iron objects or evidence of systematical use of iron; c – iron objects with elevated nickel content; d – Kizzuwatna, the area with the earliest written evidence of iron smelting; e – tradition related to the beginning of ironmaking; Hittite area with numerous written documents concerning the use of iron (after about 1500 BC).

described as systematic (about 15%). One explanation, namely that smelters of that period operated exclusively with iron ores, seems obvious. Under the conditions of the primitive bloomery process the quality of the iron produced and worked was not easily controlled and in the main, a decarburized metal resulted. Further experience was necessary to allow for the deliberate making of steel and its separation from the uncarburized areas of the bloom. This was a task for the next generations of iron-smelting folk.

Iron and the early Celts

Somewhat surprisingly, it was the technological approach and practice of southern Europe which had a very strong influence on the Celtic peoples on their early sites on the upper Danube and in eastern France. As a result of the establishment of close contacts with the rapidly-developing civilizations of the Etruscan and Italic peoples, the Celtic world became the most progressive in terms of European iron technology. It is relevant to comment here on the use of iron by Celtic peoples between the 5th and 3rd centuries BC.

Direct evidence in the form of smelting furnaces and bloomeries is very scarce for the earliest period. There is a find from Hillesheim in western Germany of the stone-set base of a feature which, when reconstructed, can be interpreted as the predecessor of a domed furnace more than 100cm in diameter with an opening, possibly the traces of an arch on the south-eastern side. The furnace, which produced much iron rich slag (over 50% iron), had been destroyed and was overlaid stratigraphically by a tumulus of the Hunsrück Eifel culture II A1 (Haffner 1971), so that the remains must belong to the HD period (about 500 BC). There are no further indications of ironmaking in the wider vicinity and thus, this one site seems inadequate support for the idea of contemporary large-scale iron production in the 6th and 5th centuries BC, controlled by rich Celtic princes who supplied Greek and Etruscan consumers with iron and received luxury goods in return.

This hypothesis results from the conflation of two separate groups of data, on the one hand the occurrence of high-grade iron ore deposits in Celtic lands north of modern Mainz and on the other, the occurrence of 6th–5th century BC rich princely graves containing luxury goods from the Mediterranean, including a group on the Middle Rhine associated with high-grade haematites (Driehaus 1965). Similarly, the Saar cemeteries, near the outcrops of minette ores should, but do not show an iron inventory resulting from striking local metallurgical activity (Pittioni 1966). There is no direct evidence to justify the view that groups on the periphery of the Celtic world at that time owed their temporary prosperity to iron production. In the mid-1st millennium BC, the southern world had no need to look northwards to distant barbarian rulers for its iron, even though that the situation was to change shortly afterwards.

It seems likely that the enormous growth which we see in Celtic iron production came after the collapse of the princely society represented by these rich burials, in other words during the late 5th to 2nd centuries BC. Until now, the evidence remains indirect but eloquent, and two observations support this assertion. First, there is the relatively sudden appearance of thousands of double-edged iron swords in Celtic inhumation cemeteries, accompanied by spearheads, shield fittings and other iron gear. The number of these finds has no equal, either in the preceding periods or in contemporary societies elsewhere. It seems that these weapons are closely associated with the historical expansion of Celtic raiding groups. Their quality was variable as metallographic examination has demonstrated, but they were formidable in battle. The fact that a significant proportion of the swords were of good-quality metal suggests that the celebrated comment by Polybius (II.33) concerning the bending of swords of Celtic warriors during the 3rd century battles in northern Italy was somewhat of an exaggeration (Pleiner 1993a).

The second observation relates to the occurrence and distribution of hoards of double-pointed iron bars or ingots forged together from smaller pieces or blooms of heterogeneously-carburized metal, each weighing several kilograms. In Germany, the Bechtheim hoard, for example, consisted of 60 ingots, the Sauggart hoard of 24 (151kg), and the Rodalben hoard of nine (42kg). Most of these hoards have not been dated, but some of the associated finds provide a chronological framework. Those found at Heuneburg and Mont Lassois came from 6th–5th century contexts, whilst those from the *oppidum* of Manching in Bavaria were discovered in early 1st century cultural deposits (Pleiner 1980, 392–393, Fig. 7). This would indicate, contrary to some earlier views (Kleemann 1961), that the majority of these ingots, along with comparable materials such as sword-shaped ingots or 'currency bars' from both Continental and British hoards, belong to the La Tène period. And we should not overlook the huge amounts of iron that went into the production of the large iron nails which held together the timber components of *muri gallici* (Pleiner 1980, 462).

The early history of iron in Europe shows how it was gradually adopted and assimilated into the material culture over some ten to twelve centuries until it became, in the fullest sense, the base for a fully-fledged material technology. The process gathered pace in the 8th century BC, then in the 5–4th centuries BC, and again at the end of the 2nd century BC, by which date,

the period of the Celtic *oppida*, a fully-developed iron-using civilization can be observed for the first time. The specific environment and historical development in Europe provided the right conditions for iron metallurgy to evolve very quickly, in an unusual if not unique way, stimulated both by fruitful influences from the south and by the creative potentional of the Celtic and other folks. As a result, the technology had a profound effect on economic and social structures.

Chapter III

THE PRINCIPAL IRON-PRODUCING REGIONS OF EARLY EUROPE

The economic and technological evolution of societies which resulted in a growth in demand for iron as an idustrial metal, with a resulting increase in iron output, took place largely among those peoples who had already progressed to a full, technological Iron Age. In addition to the early pattern of scattered smelting sites catering for the needs of individual communities, new regional ironmaking centres, capable of outputs of iron that were more than sufficient for local requirements, appeared in those regions with abundant resources of good ore and fuel. In the course of time, some became famous throughout the ancient world.

It is not always easy to recognize such regions in the field. The main indicator is a concentration of evidence for early smelting, in the form of slag heaps or furnace groups, in clearly defined geographical areas. These operations may have taken place over a relatively long period, so that a time factor must be taken into account. However, chance isolated discoveries of furnace remains or smelting debris may eventually prove to be indicators of hitherto unknown concentrations of such sites.

A note of caution needs to be sounded about the compiling of distribution maps of ironmaking sites. A number of sites plotted on a large scale map may give the impression of a region where concentrated iron production took place when, in fact, they were localized, small scale operations supplying strictly local markets and subordinate to an overall farming economy over a long period. This was the situation in Bohemia in the Romano-Barbarian period, and probably also applies to the sites of the Jurassic ridge of east-central England in the Roman period.

So far as Europe is concerned, over thirty major regions have been identified, characterized by their high outputs of iron which was distributed over a wide market area. The largest of these have been known since the 18th and 19th centuries, their immense slag deposits often having been quarried away for recycling in order to exploit the high iron contents in contemporary blast furnaces, or for the metalling of roads, a process which continued up to the middle of the 20th century. The archaeological evidence in such regions has largely disappeared, creating problems of interpretation for present-day investigators. In some cases, however, extensive campaigns of fieldwork, involving survey and recording of slag deposits and mines and the excavation of ironmaking settlements, have allowed estimates to be made of production tonnages for entire regions.

In this chapter we propose to present some basic information on the main iron-producing regions of early Europe in roughly chronological and geographical order.

The earliest iron smelting regions

There is a lack of smelting sites relating to the beginnings of iron metallurgy in the Near and Middle East. Nevertheless, important information has come to light in modern western Georgia, ancient Colchis, on the edge of Asia Minor. It is possible that the ironworks there had a close relationship with those on the Pontic coast (with their 'Chalybean' tradition) and with those of eastern Anatolia, a region which saw the unfolding of crucial events in the birth of ironmaking.

Four groups of bloomery works have been discovered in the Black Sea coast region of Georgia, the ancient Colchis. They are called according to river valleys: Chorokha region near Batumi, typified by the site at Charnali, the Choloko-Okhamuri district with type sites at Zjikhandjuri and Tseckhlauri, the Supsa-Gubazeul bloomery concentration centred on Askana, Mziani and Nagomari, and the Khobi-Okhomuri group comprising the sites of Choga type (Gzelishvili 1964; Khakhutaishvili 1974; 1987). Within these four areas, 28 bloomeries (Fig.10: 4), equipped either with a single furnace or with twin units have been excavated (Fig. 11). Most are attributed to

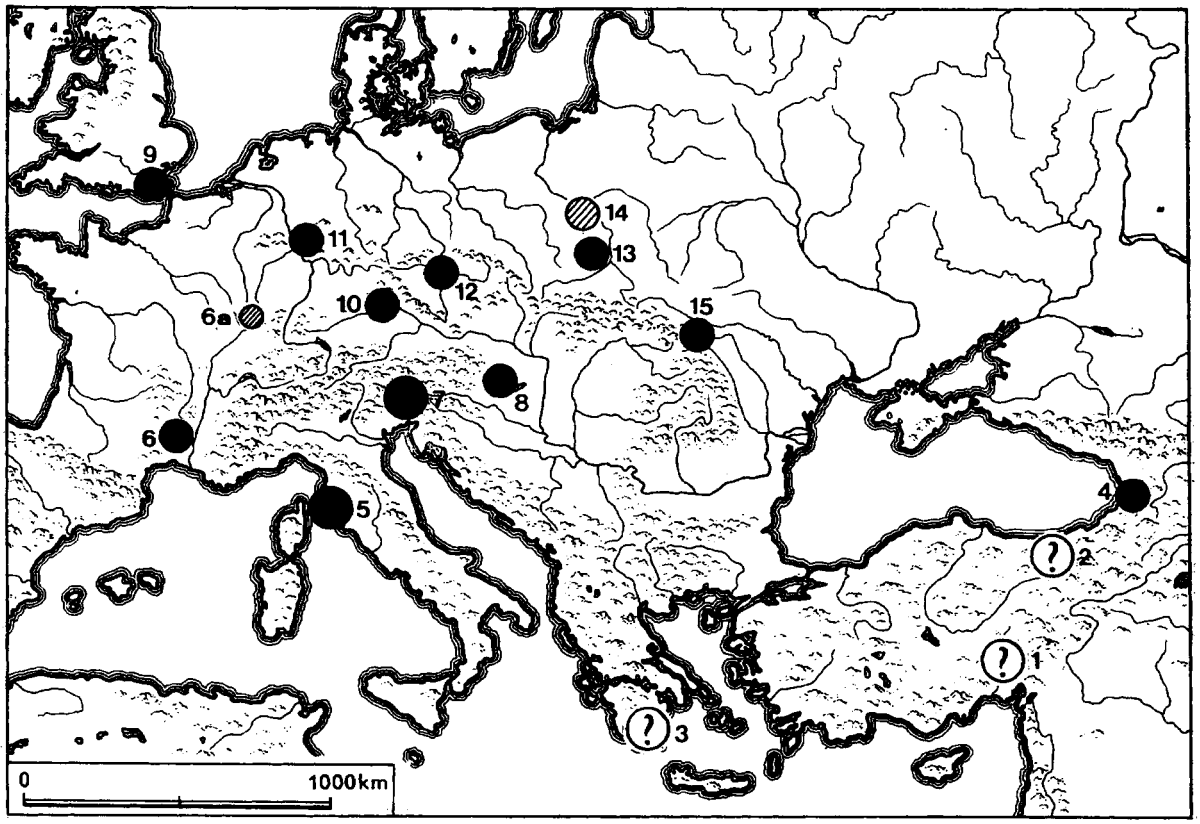


Fig. 10. Major producing regions of antiquity and the European Iron Age. 1 Cilicia - an area including the Hittite Kizzuwatna; 2 traditional Chalybean area; 3 Peloponnese - the source of Lacedaemonian iron; 4 Western Georgia (Colchis) — groups of smelting sites of the period around 1000 BC; 5 Elba — Populonia, 2nd half of the 1st millennium BC. La Tène period production: 6 Hérault and Montagne Noire, the beginnings; 6a Yonne, the pre-Gallo-Roman beginnings; 7 Noricum; 8 Burgenland; 9 Weald of Sussex, the pre-Roman beginnings; 10 Kelheim; 11 Siegerland; 12 central Bohemia; 13 Holy-Cross-Mountains, the La Tène period beginnings; 14 Masovia, the La Tène period beginnings; 15 Novoklinove. The dots represent the approximate geographical position of the producing region, not the exact extent of the area; places with question mark indicate incloplete sources or indirect evidence concerning the production of iron.

the early 1st millennium BC on the basis of archaeological finds, radiocarbon dates, and archaeomagnetic measurements. The Supsa group exceeds, however, the above chronology in physical dates: Askana 15th – 12th centuries BC, Mziani II 15th – 6th centuries BC, Mshvidobauri 14th – 12th centuries BC, and Nagomari 18th – 9th centuries BC (for problems, concerned with the dating of individual ironworks and furnaces see Chapters IV an IX respectively). Nonetheless, western Georgia is one of the earliest iron-smelting regions of antiquity yet identified. Production was based on local haematites and coastal magnetite sands which are relatively poor in iron and required careful dressing by flotation.

The Mediterranean upsurge

One of the most impressive centres of iron production is located in the central Mediterranean region, on the island of Elba (ancient Aithalia and Ilva) and in the area around ancient Populonia on the Etruscan mainland. Large slag heaps have been recorded, especially in the northern and eastern coastal parts of the island at Procchio, Rio Marino, Capo Paro and at Porto Azzuro

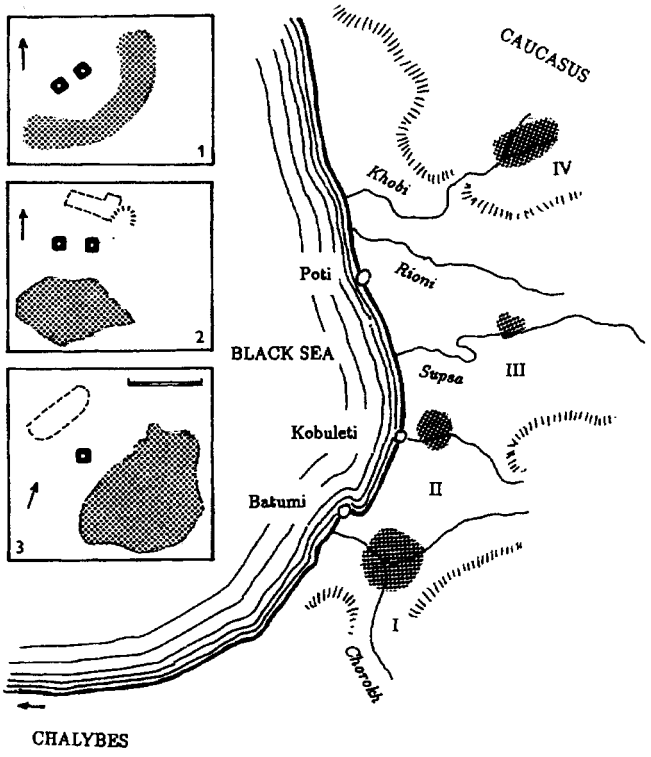


Fig. 11. Ancient Colchis, the earliest extensive iron producing region (centuries around 1000 BC). Left: Types of ironworks excavated — 1 Legva, 2 Charnali II, 3 Mziani II, hatched: smithing platforms. Map: I–IV, principal concentrations of the iron smelting evidence (dotted). After Khakhutaishvili 1987.

where very high-quality haematites have been mined presumably since the Greek colonization of the 8th – 7th centuries BC. Samples of Elban ore are also said to have been found at an iron working site on the island of Pithecusae (Buchner 1969; Ridgway 1973). According to Diodorus (5. 33), a shortage of fuel eventually obliged the ironmakers, Etruscans at that time, to transfer their smelting activities to Populonia, on the mainland opposite Elba. There, a layer of slag varying from 2m to 20m thick covered an area of some 2km square around the Bay of Baratti. Between 1920 and 1925, also later, these slags, estimated at 2 million tonnes, were exploited on an industrial scale for resmelting in the blast furnaces at Piombino, and as a result only a few traces still remain, notably on the beach at Baratti.

The rare fragments of furnace lining or slagged stones that remain in the surviving debris on the beach area have yielded charcoal which has been submitted to radiocarbon dating which has suggested a wide time-span. The accumulations of slag buried earlier Etruscan domed tombs of the 7th century BC. Among the relatively abundant literature on this region, we may note the works of Simonin (1858) and Minto (1943) and, more recently, Sperl (1981) and Voss (1988). On the beach at Baratti Bay, Voss excavated the remains of a smelting furnace which may be reconstructed as of slag-pit type (see Chapter IX, Pl. I: top). Its position within a massive slag layer is dated by radiocarbon to the period around 170 ± 70 BC. The bottom of the layer, some 140cm below, dated to 465 ± 100 BC and thus falls into the Etruscan period (between the 5th and 2nd centuries BC). In addition, stray furnace fragments indicate the presence of another type of smelting device, stone walled and producing tap-slag, which may be later, relating to production in the Roman period (Voss 1988).

Ancient historians such as Diodorus (5.33), Livy (28.45), Strabo (5.2.6) and Pliny (34.51), as

well as various commentaries (e. g. *Servius ad Aeneidem* 10,174) refer to large-scale production on Elba and in Populonia, and it is evident that the Greek communities of the central Mediterranean, the Etruscans, and the Romans were all heavily dependent upon this region for their iron. Voss (*op.cit.*) estimates that about 2 million tonnes of slag were deposited at Baratti bay near Populonia over some five centuries of the pre-Christian era and that around 500,000 tonnes of iron had been produced. Recently, Crew (1991b) has questioned both these calculations and the limited dating evidence, arguing that some of the slags may be of mediaeval (Pisan) date and that some result from copper smelting. However, large Roman slag heaps occur around the bays of Elba (Coretti 1991), while the mediaeval bloomeries so far excavated indicate only a rather small scale of production. At the Bay of Follonica, to the south of the Baratti area, abundant traces of iron smelting have been found (Francovich 1990; Tizzoni and Tizzoni 1992), with more than 20 sites dating to pre-Roman or Roman times. Thus, Elba, Populonia and their hinterland formed a prominent production region in classical antiquity.

Metallurgical activity in Tuscany decreased in the 1st century AD, but Italic *negotiatores* organized large-scale production in the near vicinity of Narbonensis in France, on Celtic territory. The large bloomery slag heaps (Pl. II) of the Montagne Noire, north of Carcassonne, so much damaged by modern industrial exploitation, have yielded undisturbed debris at Les Martys. Recent excavations there uncovered between 24 and 72 thousand of tonnes dating to the second half of the 1st century BC. Pottery associated with the slag indicates Mediterranean connections, and large capacity shaft furnaces were in operation from the very beginnings of this activity (Domergue *et al.* 1993). The question remains as to whether the local Celtic inhabitants participated in any way in that industry, given the fact that the Celts developed their own iron technology in Europe.

Little is known about the archaeology of the ancient Greek iron production both on the Aegean islands and mainland. Unexplored huge bloomery slag heaps, some of them showing traces of radioactivity, are situated in several places close to the Thracian coast. They date from the Late Hellenistic period (2nd century BC, after Bassiakos, Jutland Conference 1999).

The Celtic 'ferriers'

La Tène period ironmaking of the later European Iron Age, primarily that of the Celtic population, is attested by many bloomery sites found over the whole Continent and in the south-east of Britain. A significant number have been found in regions which later developed into major production centres in the Roman and mediaeval periods (Fig. 10).

Foremost among these was Noricum (Pliny 34.51) where a number of inscriptions relating to commercial transactions from the walls of the *tabernae* of Magdalensberg in Carinthia (Egger 1961) testify to the long-distance trade and export of iron and steel products, mainly in four characteristic forms, *incudes* (anvils), *unci* (hooks), *anuli* (rings) and *secures* (axes), the possible equivalents of ingots or semi-products. The market covered the whole of Italy and reached as far as north Africa. The names of the traders are Roman, but some Celtic forms appear also. The metallurgical activity, however, was apparently carried out by the Celtic *Norici*. On the evidence from rescue excavations in the Görtschitz valley, in the vicinity of the Magdalensberg oppidum, slightly domed or shaft furnaces with 3 – 5 air inlets were in use (Glaser 1995). Several sites have been discovered accompanied with large and voluminous slag heaps. The high-grade manganiferous limonites of the region were smelted and contributed to production of highly carburized metal of excellent quality of *Noric* steel, so famous throughout the Roman world (Horstmann 1995).

Immediately to the east of Noricum lies the modern Burgenland, where considerable evidence of ancient ironmaking has come to light. In recent years, large domed furnaces of the La Tène period have been excavated at several sites, including Unterpullendorf 1 and 2, Weppersdorf and Klostermarienberg (Pl. III; Bielenin 1977a). It has been postulated that several hundred sites

which have produced ancient slag are of La Tène date (Kaus 1977) and that this area formed a part of the Noric iron producing region, although the evidence is somewhat sketchy.

Our knowledge of the character of iron metallurgy in Gaul is not well developed, despite classical references to the Bituriges and Petrocorii, tribes renowned for their ironworks (Caesar BG 3.21; 7.22). Iron slags and mines have been reported from the Massif Central (Roumilhac and Roumilhac 1969), but no details have been published. Some other vestiges were noted in the work of de Tryon-Montalembert (1955/56) but without any systematic evaluation. Of greater importance are the recent results of rescue excavations in the Yonne valley around Clérimois, which proved that relatively large-scale production, later to become well- known in the Gallo-Roman period, began in this region long before the Roman occupation, some time after 200 BC (Dunikowski and Cabboi 1995).

In his *Commentarii de bello Gallico*, Caesar makes reference to the economic and ethnographic characteristics of the lands and peoples of his campaign. He showed his awareness of the wealth of iron of the Weald of south-east England in a well known passage (5.12). Like Noricum, this became an important iron-producing region in the Roman period. Excavations and field work in the Weald have so far identified eleven pre-Roman ironmaking settlements, some of which, like Cow Park, Minepit Wood, Pippingford Park and Broadfields, were equipped with domed furnaces (Cleere and Crossley 1985, 41, 54). In other parts of southern England, iron production was developed to a limited extent only (Ehrenreich 1991b). According to a preliminarily announced report by Halkon (1997) there were discovered about 50 archaeometallurgical sites in Yorkshire, north of the river Humber estuary (Home-a-Spalding Moor) comprising slag heaps, tap slag, blooms and furnace hearth bottoms of a surprisingly early date, achieved, however, by radiocarbon (450 – 230 and 600 – 380 BC). Any comments would be premature at the present stage of investigation.

At the northernmost limit of the territory later incorporated into the Roman Empire as the province of Raetia, there was a flourishing Celtic iron producing centre at the confluence of the Danube and Altmühl rivers in Bavaria, within and in the vicinity of the Michelsberg *oppidum* at Kelheim. Remarkable fields of pits, associated with the exploitation of the local brown ores and dating to the La Tène period, have been discovered there (see chapter V), and enlarged domed furnaces have also been excavated (see chapter IX; Schwarz *et al.* 1965/1966; Behaghel 1939; Burger and Geisler 1983). Iron production did not continue into the Roman period, but was subsequently revived in the early Middle Ages.

On the northern Celtic periphery, far from the Roman *limes*, other iron producing regions began to evolve early. The most important of these was the Siegerland, along the river Sieg, a tributary on the right bank of the Rhine. About half of the known sites, some 200 in all, have been dated to the La Tène period (Gilles 1957). Bloomeries equipped with large domed furnaces have been excavated at Obersetzen, Gosenbach, Engsbach (which produced in the region of 40 furnaces), Minnerbach, Trupbach, Alchen and Silberquelle (Stieren 1936; Behaghel 1939; Gilles 1936). The ores being smelted were good quality manganiferous limonites and siderites.

It was suggested by Driehaus (1969) that the ore deposits on the opposite bank of the Rhine near Waldalgesheim were of considerable importance in this period. In his view the great richness of the Early and Middle La Tène chieftans' burials in this area must have been connected with the production of and long distance trade in iron. It must be said, however, that to date there has been no direct support for this theory in the form of dated field evidence. Instead, traces of early iron-making actvities, apparently of Celtic origin, are being stated in south-western Germany, in the Schwarzwald region. Surveys and excavations are in progress (Gassmann and Hübner 1998).

Much smaller in extent but nonetheless distinct in terms of La Tène settlement is the small group of ironmaking sites in western central Bohemia, near the town of Nové Strašecí, to the west of Prague. Seven sites have been identified in an area of 4km^2 and slag-pit and bowl

furnaces were excavated at Mšecké Žehrovice (Pleiner 1958, 101 – 103). In the late eighties, part of a La Tène period settlement, earlier than the known *Viereckschanze* was excavated at the same site. Although layers of bloomery slag were discovered in several areas, no smelting furnaces came to light (Pleiner 1998). At Mšec, a complete workshop with a arrangement of slag-pit furnace hearths was discovered (Pleiner and Princ 1984). The ore source has not been clearly identified, though it may have been pelosiderites or limonitic geodes from sandstone and sapropelite deposits. The production of sapropelite bracelets, a commodity exported over the whole of central Europe and which characterizes the La Tène period in this area, coupled with ironmaking, suggest that this may have been one of the first 'industrial' regions of prehistoric Bohemia. A geographic concentration of sites with unidentified iron slag has recently been identified in north-west Bohemia (Salač 1990) but evidence for smelting remains scarce and the existence of a bloomery production district is not proven so far.

In the Carpathians, to the south east of Mukachevo in Ukraine, a concentration of thirteen early ironmaking sites has been identified, although the ores exploited are unknown. One site, near the village of Novoklinove, has produced three groups of slag-pit furnaces (with 59, 32, and 42 units respectively) which indicates substantial iron production intended to supply a wider area (Bidzilya 1970). The dating covers a wide range in the centuries before and after 0 AD, and the site has yielded pottery from the late La Tène period (2nd to 1st centuries BC). It is possible that this activity may be attributable to Celto-Dacian smelting groups.

Roman iron smelting industries

At the beginning of the Christian era, with the establishment of the Roman military border along the rivers Rhine and Danube separating Roman territory from that occupied by Germanic tribes, the Celtic world was partitioned into two spheres, each at different stages of development (Fig. 12).

Roman iron metallurgy continued from the earlier period to be organized on a large scale, either by senior Imperial officers known as '*procuratores ferrariarum*' in the principal production districts, or supervised on their behalf by major strategic units, such as the Roman Navy in Britain. Some of the ironworks were leased to private enterpreneurs, entitled '*conductores ferrariarum*', who employed their own personnel.

During the Early Empire (1st – 2th centuries AD), Roman iron production was transferred from mainland Italy to the provinces. In some cases the existing nuclei there were further developed, while in others ironmaking began as a new industry.

*

Noricum continued to flourish during the Roman Imperial period and its outstanding steel, smelted from manganiferous limonites or siderites became renowned throughout the ancient world. It is celebrated by classical authors in technical treatises and geographical works (Pliny 34.51; Strabo 5.1.8; Antonine Itinerary) and in poetry (Ovid, *Metamorphoses* 14. 711 – 712; Horace, *Carmina* I.16; *Tristes et irae quas neque Noricus deterret ensis*; Martial, *Spect.*, 23.1; *Epigr. lib.* 4.55 and 11 – 13; Rutilius Namatianus, *De reditu suo* 1. 351 – 353). In archaeological terms, it is the heartland of Noricum around the Hüttenberg of Carinthia, that is best known for its traces of Roman underground mining (also epigraphically attested in inscriptions). There are also reports of many slag heaps, although not described in detail, near Lölling, Semlach, and Hüttenberg itself (Schmid 1932). At the end of the 19th century, furnace remains were found at Hüttenberg-Preisenhof and Lölling (Schmid 1932; Malzacher 1965; Sperl 1985), but were not closely dated.

The managment of the Roman iron industry in Noricum was closely parallelled by that in Pannonia and in Dalmatia where an area in western Bosnia, in the valleys of the Japra and Sana

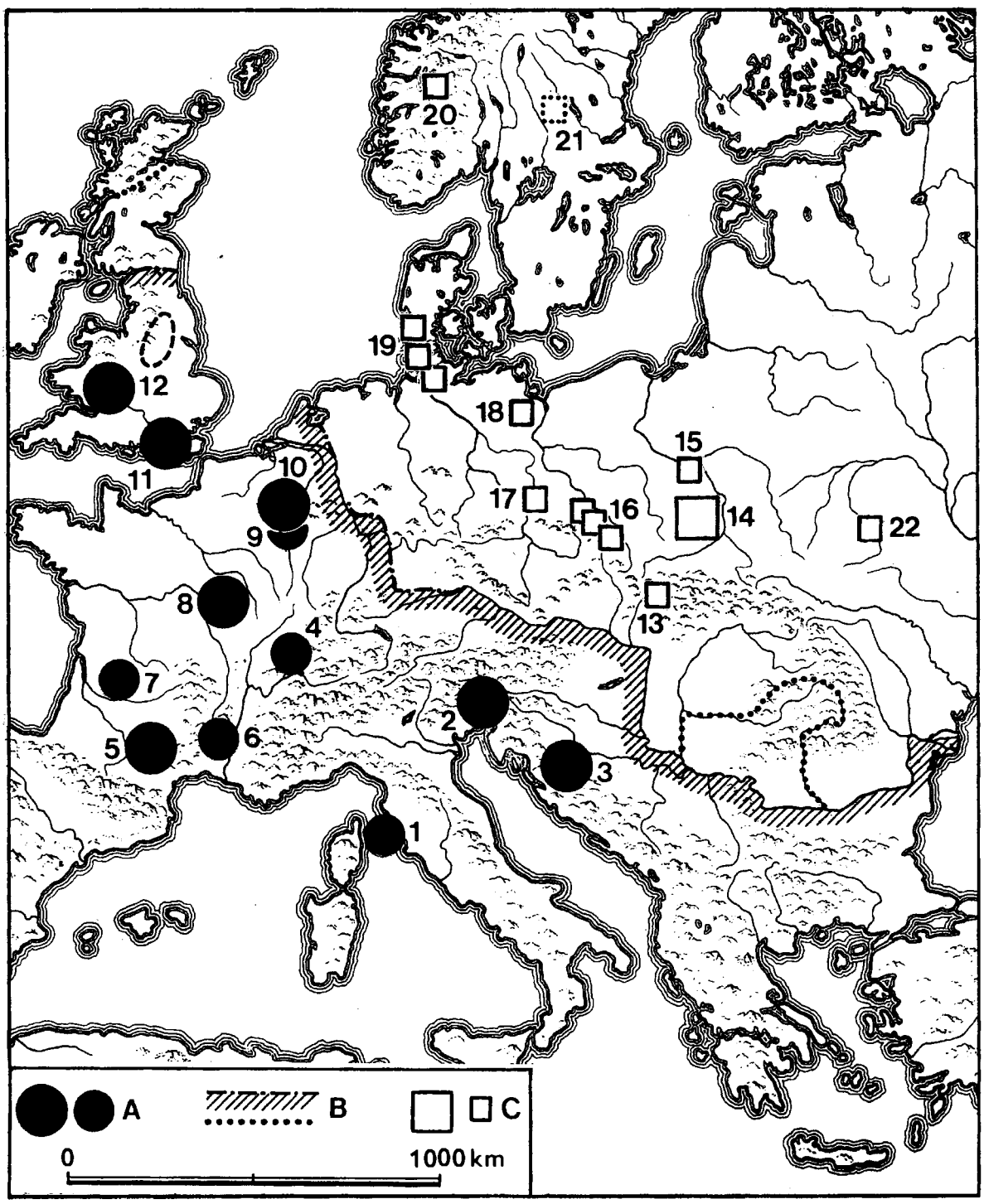


Fig. 12. Prominent iron production districts of the Roman period. Roman centres: 1 Elba – Populonia; 2 Noricum; 3 Dalmatia - Japra and Sana valleys; 4 Vaud; 5 Montagne Noire; 6 Hérault; 7 Périgord; 8 Yonne; 9 Meurthe-et-Moselle; 10 Namur – Dinant; 11 Weald of Sussex; 12 Forest of Dean; the sites of the Jurassic Ridge are situated northwards. Barbarian extensive producing regions: 13 Varín; 14 Holy-Cross-Mountains; 15 Masovia; 16 Silesian smelting agglomerations; 17 Lusatia; 18 West Mecklenburg; 19 Schleswig-Holstein and West Jutland; 20 Trøndelag ; 21 Jämtland; 22 Volynhia and Zhitomir region. Symbols: A Roman, Gallo-Roman and Romano-British districts; B the Roman military border (as in the 1st millenniun AD); C Barbarian extensive ironmaking regions (scattered ironworks are not presented).

rivers near Prijedor, is worthy of note. A rather imprecise description of the slag deposits in this area suggests that they may contain some 2 million tonnes (Pašalić 1965). There were probably major producing areas elsewhere in this part of the Empire, such as in Dacia at Sarmizegetusa, but little field evidence is available. According to the epigraphic evidence, the works were managed by fiscal officers, the *procuratores ferrariarum* or by private tenants, the *conductores ferrariarum*, in all of these regions.

There is a very well-explored iron-producing region known from north-west Switzerland, in the in the Canton of Vaud (Pelet 1973; 1993). It is not extensive, only covering some 2km^2 between Vallorbe and Sarraz, north of Lake Geneva, but contains some fifty slag heaps, varying in size from 80 to 400 m^3. Fourteen ironworks with 24 furnaces (two of them dated to the La Tène period) were excavated at Bellaires, Prins Bois, and Bossena. Their combined output of iron is estimated to have been in the region of 922 tonnes.

Roman smelters were also very active in Spain. Two large slag heaps at Los Roqillas in Zamora Province in the Sierra de la Culebra range, one 90m in diameter and 5 – 6m high and the other 40m in diameter and 3m high, have been investigated and published (Larrazabal 1996). They include Roman pottery and tiles and date from the 2nd to 4th centuries AD.

The Roman Empire was supplied with a considerable quantity of iron by Gaul, and this is reflected in a number of inscriptions relating to the organisation of the industry. The administrative centre was apparently at Lugdunum (Lyon), the seat of a *procurator* of ironworkers. In addition to his area of responsibility, there was another level of iron production activity, that of the local Celtic nobility, represented by the *arca ferrariarum* (Sablayrolles 1989a). There are a number of districts known as *ferrières*, where early iron slag has been heavily exploited for resmelting from the 19th up to the mid-20th centuries. As a result, the archaeological remains have been almost completely obliterated and so provide only fragmentary data.

An example already introduced is the Montagne Noire in southern France, with its 27 huge Gallo-Roman slag heaps, including Les Martys and Les Forges (de Tryon-Montalembert 1955/56; Sablayrolles 1982). Nonetheless, recent surveys have revealed huge intact slag heaps of Roman date (2nd to 3rd centuries AD) at Col d'Espérou and Carreleit with several satellite ferriers. The slag debris at Les Martys and Leprade Basse comprise as much as 1.5 million tonnes, dating from the period 50 BC – AD 270. Early sites such as Camp Naout and Fargues commenced operations at the beginning of our era (Sablayrolles 1989b; Rebiscoul 1989).

Bloomeries such as Vélieux, Roc de la Balme, Mailhac and Aigues Vives, all in the Massif Central, used to be dated primarily to the Gallo-Roman period, but little supporting evidence is available (Roumilhac and Roumilhac 1969).

Other centres of mining and ironmaking are known from Périgord and the Bourges region, the ancient *civitas* of the Bituriges and the Petrocorii (Strabo 4.2.2). Lying roughly within the triangle formed by Limoges-Périgueux-Angoulême, they consist of slag heaps and the remains of shaft furnaces, several of which have been excavated, as at Mesnardes, Mérigaud and Busserolless (Barrière 1972), with another 60 Roman smelting sites having been recorded within an area of 90km^2. At least 150,000 tonnes of slag from the original territory of the Bituriges Cubi were exported in modern times to modern blast-furnace plants (Dumasy 1994; Dieudonné-Glad 1994).

Extensive sites of this kind are known from further to the north-east, in the Yonne region and in the adjacent region of Nièvre, around Vézelay (de Tryon-Montalembert 1955/56; Lacroix 1963; Monot 1964; Bouthier 1982). Traces of ore mining and some 54 slag heaps, up to 15m high, have been recorded at Tannerre en Puysaye, Joigny, Vieille Ferté, Vézelay, and elsewhere. These heaps would originally have contained around 300,000 tonnes of slag before they were mined for resmelting in blast furnaces. This is the equivalent of 75,000 tonnes of iron which would have been available for distribution to the markets of the Roman world. The recently excavated ironworks at Clérimois (Dunikowski and Cabboi 1995) show that when the large domed furnaces were in operation there in the earlier Gallo-Roman period (1st – 2nd centuries AD according to

pottery and coins) with claimed beginnings in the late La Tène period according to radiocarbon analyses (see Chapters IV and IX). When the large domed furnaces were in operation one complex produced around 419 tonnes of iron, leaving behind more than 6000 tonnes of slag.

Systematic surveys in nearby Morvan have revealed an iron-producing region said to be of medium size and comprising several hundred sites of which only some can be dated to the Roman and Mediaeval periods. It includes *ferriers* or smelting sites as well as areas where mining and dressing was carried out. Activity is classified into four types according to the geomorphology of the locations where it occurred. It is suggested that bloomery units concentrate in 11 zones, each with 10 – 20 worskhops, within three production districts: Auxois, the Thoste plateau, and central Morvan. However, only two sites have been excavated and little can be said about the character and size of individual localities, known only from field survey. In Thoste, the site of La Comme Philippe 08 revealed the remains of four furnaces whose walls were built from slag blocks, while at Lécussy were found Mediaeval stone-reinforced smelting units of the 13th century AD. The bulk of the mining and metallurgical evidence seems to be date to the Roman period, with production presumably directed by the *Civitas Haeduorum*. It is possible that this activity was a part of that of the larger production centre of the *Sennones* in the Yonne valley (Mangin *et al.* 1992).

There is evidence in north-eastern France for Gallo-Roman iron mining and production in the tribal territory of the Celtic *Leuci* in the *département* of Meurthe et Moselle, between Bar le Duc and Nancy. It was formerly believed that this included some pre-Roman ironmaking, as at the Camp d'Affrique although a mediaeval date for this site is now thought more likely. Some fifteen sites producing bloomery slag are reported at Neuves Maisons, Tone, Pont à Mousson, and the surrounding areas (Deroche 1982). Leroy (1997) presents a list of 255 sites in the Lorraine, with two concentrations between Nancy and Thionville where unspecified iron slags and/or ores were found. They are mostly undated, although there are 52 sites of the Gallo-Roman period where slags were found in association with *villae rusticae* and 26 mediaeval sites of the 6th – 14th centuries.

Although to a large extent destroyed to obtain material for modern blast furnaces at Charleroi, the enormous slag heaps between Dinant and Namur in south-west Belgium are worthy of mention. It is reported that one large slag heap near Namur contained 8500 m^3 (equivalent to about 1 million tonnes) of waste material dating to the Roman period. The local ore deposit, principally limonite, was easily accessible, since it lay just below the surface (Voigt 1959; van Doorselaer 1971).

Across the English Channel, the iron-producing region of the Weald is one of the most thoroughly-investigated in recent years. A boom in iron production began there immediately after the Roman invasion of AD 43 and continued at a high level until the mid-3rd century. Some sixty sites (including thirteen Iron Age and seventeen Mediaeval) have been recorded as a result of recent research in a region encompassing some 1560km^2. Waste material, of which at least 60 % was bloomery slag, was usually deposited in banks along the many small rivers in the region, as at Bardown and Beauport Park, the largest site so far identified, where most of the material was removed for road metalling in the 19th century. Successive layers of materials from different stages of the ironmaking process indicate that activity was cyclic, probably seasonal (Cleere 1971a; 1976; 1983). It has been estimated that some 89,000m^3 (equivalent to 278,000 tonnes) of slag from the six main sites represents 89,000 tonnes of iron produced, in other words, an average annual output of 550 tonnes (Cleere 1976; Cleere and Crossley 1985). Tiles bearing the stamp of the *Classis Britannica* suggest that the fleet was responsible for supervising the work of the Wealden industry, on behalf of the Imperial procurator, since the Weald was in all probability an Imperial estate.

There is less precise information about the Forest of Dean on the border between England and Wales, where mining and ironmaking began on a large scale later than in the Weald, probably

in the early 2nd century AD, but continued until the end of the Roman period in Britain, in the early 5th century. The region is known for its mining (see chapter V) and for its slag deposits, in beds often up to 4m thick, as at Peterstow, Bridstow, and Whitchurch. Some sixteen sites, on which limonitic ores were being smelted, have been identified spread over an area of about 100 km^2. A Roman road, metalled with iron slag, leads from the mine at Wigpool towards Wedston-under-Penyard, the ancient Ariconium (Schubert 1957; Bridgewater 1968; Bick 1990). Ironmaking began again in the mediaeval period and continued until relatively recent times (Bick 1990). Much of the Roman slag was quarried away in the 16th and 17th centuries, being taken north up the river Severn for resmelting in Shropshire and Worcestershire.

The third area, where scattered Iron Age (La Tène) and Roman smelting occurred, is the Jurassic ridge, a region in the western part of the east Midlands, south of the Nene river. It is being studied in detail by recent programmes (Schrüfer-Kolb 1999).

The barbarian ironmaking areas

In contrast to the large scale of Roman production, the Germanic tribes, living in a rural civilization, adopted east Celtic or even earlier slag-pit furnace types which they used in small-scale, decentralized smelting operations. In Bohemia, for example, virtually all of the larger villages had their own family of smelters who provided the population with basic tools and weapons. According to Tacitus (Germania 6) there was no surplus of iron, even for military purposes (*ne ferrum quidem superest sicut ex genere telorum colligitur*).

An exception was to be found to the north of the great bend of the Danube river, where a Celtic-speaking tribe of ironmakers, the Cotini, lived to the rear of the Marcomani and Quadi. They did not escape the attention of ancient writers such as Tacitus (Germania 43: *Cotini, quo magis pudeat, et ferrum effodiunt*), and paid tributes both to the Germans and Sarmatians. Ptolemy of Alexandria in his Geography (2.11) drew particular attention to iron mines (*sideroruchеia*) which he located somewhere in the lands of the Quadi.

In relation to this, a relatively small area, still only partially investigated, at Varín, east of Žilina in northern Slovakia should be noted. The smelting of haematite ores resulted in the accumulation of seven heaps of slag and furnace debris heaps measuring up to 10 – 20m in diameter. In addition, a number of banks of slag on forested slopes in this area have been identified, although they have not as yet been studied (Pieta nad Moravčík 1983; Pleiner 1985). Excavations revealed that the furnaces had been totally destroyed, perhaps intentionally, but the numerous furnace fragments and tap slags permitted the reconstruction of large shaft furnaces, built out of brick-like blocks standing to well over 1m in height. These are somewhat unusual among Romano-Barbarian contexts, differing from the Barbarian slag-pit furnaces which appear everywhere else in the in surrounding territories. Pottery finds belong to the Púchov culture of the 1st – 2nd centuries AD, which was much affected by Celtic influences, or even immigrants. It is possible that these establishments, which also occur further to the east on promontories of the High Tatra range, may be identified with the Cotini.

With the exception of the Cotini, decentralized Germanic iron metallurgy began, in some cases, to concentrate in several regions within '*Germania Libera*', presumably in an effort to increase production and was achieved simply by deploying ever-larger assemblages of traditional slag-pit furnaces which were designed to be used for one smelt only. Such a way of working may be described as 'extensive', as distinct from the 'intensive' work in the Roman world which was based on large, long-lived shaft furnaces. Fields of tens and even hundreds of hearths appeared in those areas, filled with characteristic slag blocks, which were not removed after the smelting was completed, but left *in situ*. Ironworks of this kind have been discovered in various parts of Germany, such as at Westerholz, with 118 hearths (Dehnke 1968), Merzdorf near Uhyst, with 55 hearths (Wetzel 1982, 1986, 1996; Schneeweiss 1996), and Wolkenberg in the Lausitz (Spazier 1996; 1997; 1999), where many other clusters have recently been under excavation. Scattered

ironmaking sites appear in the same area in Altmark, Brandenburg, Pommern and Usedom (Leube 1992). In south-west Mecklenburg, slag-pit furnace concentrations have been discovered on at least 93 sites. At Göhlen, between 15 and 17 clusters with more than 600 slag-pit furnaces have been excavated, while others have been identified through geophysical survey. In Moravia, excavations at the site of Sudice revealed three furnace groups comprising a total of 76 hearths (Ludikovský and Souchopová 1978).

The largest region of this type is the Holy Cross Mountains, to the east of Kielce in central Poland where around 6000 ironworks have been recorded in an area of some 600km^2, comprising at least 300,000 individual smelting hearths containing slag blocks (for slag-pit furnaces, see chapter IX). Of course, no slag heaps would have built up, but it is known that some 100,000 tonnes of these blocks were re-smelted at the Bytom ironworks in the years before 1939. Systematic research started in 1955 under the direction of Radwan and Bielenin. In addition to many sites with between 4 and 50 hearths, a number of much larger ones, such as Słupia Stara 2 and 4 (Pl.VIII) and Słupia Nowa 2 and 6 and Jeleniów 1 each with 100 – 130 hearths, have been investigated. The largest found to date is at Świętomarz, which had 231 furnaces. The larger furnace groups were arranged deliberately in planned layouts, with two separate banks laid out in three or four rows (Figs. 17 and 18). In many cases, furnaces cut through each other stratigraphically, indicating an effort to maintain the *focus* of operations in small batteries which were gradually shifted in a particular direction. Such features strongly indicate organized working and more than forty such sites have been excavated. This industry was based on haematite and limonite ores (the underground mine at Rudki is discussed in Chapter V). Bielenin (1974, 1992) has estimated that the region produced 8100 tonnes of iron over about four centuries, although the majority of these 'organized' sites seems to date to the 2nd – 3rd centuries AD (for chronological problems, related to archaeological and radiocarbon dating see Chapter IV and IX). It is not out of the question that they delivered iron to customers in the south, while the smelters who created the smaller, irregular clusters supplied Germanic groups over a wide area (Bielenin 1992; Orzechowski 1991). It seems that the region of the plain of Sandomierz, east of the Holy Cross Mountains was the settlement hinterland of the production areas which yielded among others Roman imports including hoards of coins, dating mostly from the 2nd century AD (Orzechowski 1999).

In Masovia, to the west of Warsaw, lies another vast and contemporary ironmaking region which was discovered in 1967 and has been under investigation since then. About 70 ironmaking sites have been identified in an area of 300km^2 and some, such as Biskupice with 917 dispersed hearths, Pruszków and Pęcice have been excavated. The total number of furnaces so far located is around 1300 and it is estimated that the total in the region probably numbered 100,000 – 150,000 (Woyda 1977; Bielenin and Woyda 1978). The slag-pit furnaces were fed with bog ores and date from the Late La Tène to the 3rd century AD, with maximum production having been achieved in the Romano-Barbarian period (1st to 2nd centuries AD — Pazdur *et. al.* 1981; Orzechowski 1991). So far there is no detailed publication of this work.

There were other concentrations of Romano-Barbarian ironworks in Lower Silesia, around the confluence of the Odra and Barycz rivers. Some sixty sites with slag-pit furnaces have been found over an area of about 800km^2. The main sites were at Tarchalice (formerly Tarxdorf), with 73 hearths discovered to date, and Psary, with a similar number (Hołubowicz 1956; Różycka 1971; Mamzer 1984). Further to the east, contemporary ironworks operated in the vicinity of Opole (Dobrzeń Mały: Pawlowski 1979).

The Schleswig-Holstein area of northern Germany, from Jutland in the north to Hamburg in the south, represents a special example of early ironmaking activity. It is difficult to describe this as a discrete ironmaking region, since the 200 known sites (of which 40 have been investigated) are scattered with varying intensity over a very wide area. Nevertheless, in comparison with other parts of Germany, the relative abundance of ironmaking remains in this region demonstrates a

more resolute approach on the part of the inhabitants towards the production of iron from local deposits of bog ore. The results of many years of research (Hingst 1952; 1955; 1957; Hinz 1952) show that about 25 % of the predominant slag-pit furnace type belong to the pre-Roman Iron Age, 50 % to the Romano-Barbarian period (for example, Padenstedt, Joldelund, Goldebek and Husum), and 17 % to the Middle Ages. The later furnaces are characterized by the crescent-shaped slag heaps surrounding them, as at Stitz which dates to the 10th – 12th centuries AD. All of the slag-producing sites are closely linked with small bog ore deposits near streams, although slag has also been found in graves in cemeteries of the period. Since 1990, research has been directed at some of the iron-smelting areas in Schleswig-Holstein in a broad-based project. Preliminary reports have been produced on some groups of slag-pit furnaces at Joldelund which were located by geophysical survey. However, the intensity of production relating to the 4th – 5th centuries AD has to be analysed with care because of suggested relationships of furnace groups with individual farms that seem to indicate rather small-scale local operation (Jöns 1992; Backer *et. al.* 1992).

Special mention should be made of the Danish sites. Drengsted yielded 47 slag-pit furnaces of the late Romano-Barbarian period (Voss 1964; Abrahamsen 1965), but the largest iron-producing area in Jutland seems to have been the region of Snorup near Varde (Pl. X). Geomagnetic survey located numerous clusters of the remains of slag-pit furnaces over an area of some 35 hectares, one consisting of 800 slag pits with many cases of stratigraphical superimposition. A total of 3000 furnaces has been estimated for the area, of which some 1000 have been excavated. Radiocarbon dating spreads over a wide range between the 1st and 7th centuries AD (Voss 1995; Zimmermann 1998), the bulk apparently having been in operation during the 2th - 4th centuries AD.

At present, a late Romano-Barbarian site from the beginning of the 4th century AD is under examination at Heeten in the Netherlands, just north of the old Roman frontier. Rescue excavations brought to light a cluster of 17 slag-pit furnaces, but careful geological core sampling within an area of some 5.5 hectares leads to a preliminary estimate of some 45 – 50 tonnes of slag blocks and a production of 9 – 17 tonnes of iron blooms, one of which, weighing 11.5 kg, was found in the well of the settlement. The reheating and working of the blooms is considered to have taken place at the site of Wesepe some 4km away (Groenewoudt and van Nie 1995; Joosten *et. al.* 1998).

Thus, the major barbarian iron producing regions would obviously have yielded impressive quantities of iron. However, even the most prolific barely achieved 10% of Roman production levels. Moreover, practically no technological ideas crossed the barrier created by the Roman frontier.

The Migration Period disintegration

The decline of the Roman Empire paralysed its iron industry. Some large production districts such as the Montagne Noire and the Weald ceased to operate after the late 3rd century AD, although activity continued in others. Noricum was still producing good steel during the 5th century and supplied the *fabricae armorum* in northern Italy (Nerger 1992), while smelting was still carried on in the Forest of Dean (Bick 1990). In certain regions, often after a hiatus, large-scale operations were replaced by smaller ironworks as, for example, at Yonne and the last phase of activity in the 3rd – 4th centuries AD at Clérimois (Dunikowski and Cabboi 1995).

The fall of Roman power resulted in the disruption of social and economic networks. Some groups survived although living poorly, while others simply disappeared. Whole populations moved and society returned temporarily to much more simple patterns of civilization, sometimes having been reduced to basic nuclei. Much iron was buried in hoards, especially by the Romans as they abandoned their military borders. Much of this was never recovered for re-use, as was the case of the Roman fort at Inchtuthill in Perthshire, Scotland, where several tons of iron nails

were buried by the departing garrison (Angus *et al.* 1962). Non-Roman ironworks of the time produced iron only to meet basic requirements and the Romans aimed to deprive the local and newly coming inhabitants of such valuable sources of raw material.

The interlude of the Migration (5th to 6th centuries AD) and Merovingian (7th century) periods in western Europe and the British Isles can, in general, be termed a 'Dark Age' in terms of our detailed knowledge of contemporary ironworking. In the former Roman provinces, smelting was continued in minor ironworks. In Switzerland, at Bellaires, Bossena and Prins-Bois several pairs of furnaces dating from the 6th to 7th centuries, yielded less than about 30 tonnes of iron (Pelet 1993), while the two contemporary furnaces at Boécourt would have produced about 1 tonne (Eschenlohr and Serneels 1991). At Montcherand, nine furnaces operated during the 5th – 8th centuries AD (Abetel 1992) and at Frouard in northern France, a small ironworks with two furnaces operated in the 5th – 6th centuries AD, and another with five furnaces, dating to the 8th – 9th centuries, has been discovered at Ludres (Leroy 1988, 1997).

In the European *Barbaricum*, the situation is very unclear. The extensive production areas in the centre of the Continent also declined gradually, although interesting individual features can be noted. At Březno in north-west Bohemia, where total excavation of an area of 7 hectares revealed a complete Migration Period village of the 6th century, a single slag-pit furnace was found in the central area, possibly the remains of one smelt performed by an itinerant or guest smelter who delivered just a few kilograms of iron to the community (Pleiner 1995b).

Nevertheless, the north of Europe, Scandinavia, began its rise to pre-eminence in iron making at this time. Recent research in Norway (around (Trøndelag), relatively far to the north, has shown that concentrations of ironworks with slag-pit or bowl furnaces formed the foundations for subsequently-productive regions, with clear evidence of a 'boom' during late Romano-Barbarian times (*cf.* Espelund 1987; Stenvik 1991). In Jämtland, in central Sweden, iron production during the 3rd – 5th centuries AD possibly reached as high as several thousand tonnes (Magnusson 1986).

The advance in the Middle Ages

During this turbulent period, small, scattered ironworks continued to supply local communities with their basic technical needs, although they were at the time of only limited capacity. Gradually, new political and economic groupings appeared and, with them, the new structures which allowed iron production to increase to meet the growing needs of the emerging Mediaeval civilization. Economic forces powered the recovery or establishment of ironworking in those regions which offered the best conditions, namely abundant and good quality ore, wood for charcoal and access to markets. In many cases, the potential of regions which had been abandoned, was rediscovered, while that of many others was newly discovered. A large number remained at the level of minor suppliers of iron, while others grew in importance, increasing their productivity and thus helping to shape the development of the European iron industry (Fig. 13).

The study of Mediaeval iron producing districts is only patchily developed, and our knowledge is based predominantly on written sources supplemented by some recent archaeological projects of field survey and excavation, often broadly based.

*

Taking into account the fragmentary nature of the sources, we may offer the following broad description of developments. The most significant source of iron in early antiquity, the island of Elba, seems to have been abandoned for about 1200 years. In the 11th – 12th centuries, the city of Pisa revived iron smelting there and extended it to the region around the bay of Follonica on the coast of Tuscany. In comparison to ancient times, exploitation proceeded in a rather limited

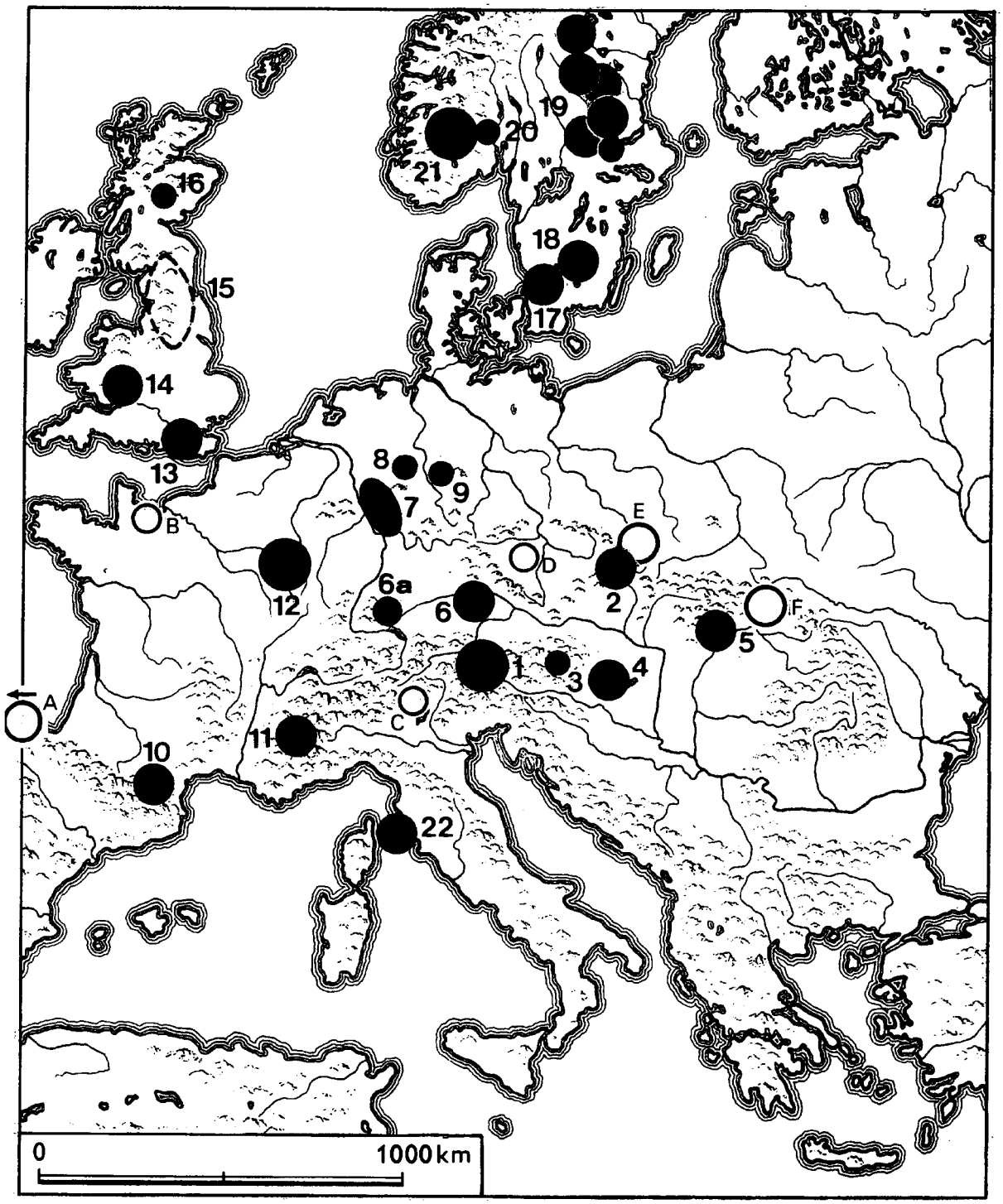


Fig. 13. Fig. 13. Major pre-industrial iron-producing districts in Europe during the early Middle Ages. 1 Styria, since the 10th century AD; 2 West and North Moravia; 3 Hirschwang-Prein, 11th – 12th centuries AD; 3 Burgenland and Western Hungary; 4 Bükk, 11th – 12 Centuries; 6 Upper Palatinate (Oberpfalz); 6a Schwäbische Alb; 7 Westerwald, Lahn-Dill, Siegerland, Märkisches Sauerland, 8th – 13th centuries; 8 Wietze; 9 Harz; 10 Pyrenees (Arièges); 11 Western Alpes (Allevard); 12 Bourgogne and Champagne; 13 Weald of Sussex, 7th – 13th centuries; 14 Forest of Dean; 15 Jurassic Ridge sites in England; 16 Rannoch, Scotland; 17 Halland, Sweden; 18 Skåne; 19 Central Swedish districts (Norberg, Jämtland, Dalarna *etc.*) and adjacent eastern Trøndelag in Norway; 20 Gudbrandsdalen, 21 Hardangervidda, Waldres; 20 Elba under Pisan hegemony, 13th century and onwards. Mediaeval iron producing regions known so far principally from written sources (white symbols): A Spanish iron from the Basque countries; B Normandy; C Italian Alpine regions (Brescia, Bergamo etc.); D Bohemian centres based on the Ordovician ore deposits; E Upper Silesia; F Slovenské Rudohorie (Hungarian iron).

fashion. Some 22 sites, situated in the hills of the island, have been registered and some of them excavated (Coretti 1991). Survey and field work has also located mediaeval sites on the coast of Tuscany, south of Populonia (Francovich 1990; Tizzoni and Tizzoni 1992), where open hearths resembling the post Mediaeval Corsican type were in operation, with production estimated at some 16,000 tonnes of iron. Apart from this, exploitation and smelting of iron ores began in northern Italy in Subalpine valleys such as Monte Scalfi in the 11th century and in the areas round Bergamo, Brescia and Bellona. New archaeological record comes from the environment of Bienno (Tizzoni 1999).

Gaul had been the most flourishing of the Roman provinces, but the renaissance of more intensive ironmaking seems to have come about later there than in other areas. In certain parts of the country, such as Normandy, there were peasant communities (*ferrons*) specializing in the art of making iron, who survived until the 14th century. But as a rule, the capacity for the manufacture of iron passed under the control of feudal landlords, who often donated such property to the church, in particular to monastic foundations. Chief among the beneficiaries were the Cistercians who, from the 11th century, took the lead in developing the industry (Verna 1995). Cistercian production was concentrated in Champagne, in the forest of Othe, and at Chaume and Wassy amongst others, but they also promoted ironmaking at their daughter establishments in other regions.

Small excavations have been carried out in the Veluwe region of the Netherlands which yielded more than 50 sites of the 7th – 9th centuries AD, with slag heaps in forrested areas and mining pits on their periphery (Joosten and van Nie 1996). It seems to exceed the small-scale local production.

In the south-east of France, in the Dauphiné, the Carthusian order played a similar role as, for example, at Grenoble and Allevard. Little archaeological information is available to date, although in Morvan, ironworks of the 13th century have been excavated at Lécussy (Mangin *et al.* 1992). Further south, Ariège, beside the Pyrenees, grew to be an iron producing region. On the other side of the mountains, important districts were developing around the Bay of Biscay in Guipuzkoa and the Basque region (see Gorrochategui *et al.* 1995), forming the basis for the later, celebrated Spanish production of iron, so well-represented in custom documents of the western ports.

Britain was abandoned by the Romans in the early years of the 5th century and production of iron decreased in quantity during the Anglo-Saxon and early Norman periods. There was an upturn after AD 1000, as a result of monastic activity, principally that of the Cistercians, as well as promotion by the Crown. The Forest of Dean was the major iron smelting district although operations there increased only slightly in the 11th century. From AD 1244, however, the granting of royal privileges stimulated the development of ironworks significantly (Hart 1968), while the Weald of Sussex began once more to produce on a larger scale during the 13th century to supply the important market of London (Schubert 1957, 108 – 109).

Ironworks of the 13th century have been excavated at Alsted and of the 14th century at Minepit Wood (Cleere and Crossley 1985, 100 – 104). New concentrations of ironmaking capacity emerged in Wales, and in the Midlands, especially around Leeds, Sheffield, and Furness. Archaeological research has discovered a smaller iron-producing region of the late Mediaeval period (13th – 16th centuries) in Perthshire in Scotland (Aitken 1971). Some 24 sites with over 140 slag heaps (from 7 to 12m in diameter) have been recorded around Loch Rannoch and traces of furnaces are reported from Grund na Darachan, Upper Hill, Bridge of Gaur and elsewhere.

Despite these developments, however, the demand for iron in Britain could not be satisfied and imported iron Swedish, Spanish and other Continental sources flowed in through the North Sea ports.

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The European iron industry shows dynamic developments in Germany, in other words, East Franconia, which, in AD 962, became the centre of the 'Holy Roman Empire'. In certain regions, striking levels of activity become evident, in some cases as early as the 7th – 10th centuries. Let us consider first the broad geographical tract whose axis constitutes the river Rhine and its tributaries, including the headwaters of the Danube.

A complex research project being conducted in Württemberg is now yielding quite new data on the Schwäbische Alb region (Szöke 1990). About 130 smelting sites of the so-called Frickenhausen-Linsenhofen type have been identified, producing small clay shaft furnaces (50cm in diameter) supplied by forced draught through tuyeres. Slag is located close to numerous mining pits which are 3 or more meters in depth. These ironworks, which are dated to the 7th – 8th centuries, exploited high-grade ores and, apparently for the first time, also lime fluxes. A later group of the so-called 'Metzingen' type sites of the 11th – 12th centuries, is very important due to the fact that they have produced blast-furnace slag and pieces of cast iron. At Metzingen-Kurleshau, an ironworking complex has been uncovered by excavation (Hauptmann 1993; Kempa and Yalçin 1995; Beiträge 1995). South of this area, in Switzerland, is the monastery of St. Gallen, which, according to numerous 9th century documents, collected taxes in iron (*tremissae ferri*) from the surrounding area. There is no evidence in the vicinity for any related ironworks, but later, in the 11th – 12th centuries, concentrations of iron-producing workshops, called '*Eisentäler*' (iron making valleys) emerged in northern valleys such that of the Durach river (Guyan 1991).

To the north of the upper Rhine and the Danube, lies the Siegerland, so important in the La Tène period and the Westerwald where, in the Nister valley near Lautenbrück, 64 slag heaps have been recorded in an area of 76km^2 (Weiershausen 1939). The resources of these regions continued to be exploited into the Middle Ages, the ores used being manganiferous limonites and siderites (Gilles 1957). Around a hundred localities, with mediaeval slag heaps standing up to 2.5 m high, including sites at Plittershagen, Nauholz and Obernau, have been reported.

A third important region was that of the Lahn-Dill river basin where the remains of ironmaking form two distinct groups, one along the Möttbach near Dietenhausen, and the other centred around Dillenburg and Weilmünster. The iron-masters there were known as *Waldschmiede*, since, between the 11th and 14th centuries, they operated in forested areas, away from the river valleys with their sources of power. Written sources attest to the payment of taxes in the form of iron as early as the 10 – 12th centuries, as was the case for the monasteries of Fulda, in the west, with a reference for 912 and Lorsch in the south with one for 1187. There is also a 13th century reference to *fora ferri* or 'iron markets' (Heymann 1951; 1954; 1955; 1958; Herwig 1951; 1958). Some of the Lahn-Dill slag heaps (later subjected to modern exploitation) are crescent-shaped (16m in diameter and over 1m high) and arranged around the furnaces.

The Lahn-Dill region has been the subject of a long-term research program, the survey phase of which has revealed 325 bloomery sites, with partially-destroyed slag heaps, located around the Dietzhölz valley. The remains of shaft furnaces with provision for slag-tapping, surrounded by slag heaps (e.g. site B 88) and a smithy (B 85) have been reported (Jockenhövel 1992; 1995; Willms 1992). It was suggested by Willms that the individual smelting places migrated in due time in a cycle system which was caused by local deforestation from charcoal making (the same idea was expressed by Souchopová considering the 9th century AD ironworks in the Moravian Karst). Most of the monuments in the Lahn-Dill area date to the Middle Ages (7th to the 14th centuries).

Further to the north lies one of the most carefully-studied mediaeval iron-producing regions, that of the so-called Märkisches Sauerland, lying around the towns of Lüdenscheid, Kierspe, and Olpe, extending as far as Altena and reaching the southern part of the modern Ruhrgebiet industrial centre. Thanks to the indefatigable field work and excavation of Sönnecken (1971 for summary), some 500 groups of slag heaps have been recorded in an area of over 1000km^2.

These heaps, of which over 1100 are known, are 10 – 12 m in diameter and 60 – 70cm high, each containing 60 – 70 tonnes of slag, and occur in groups along the banks of streams. Excavation has uncovered many ironmaking establishments with smelting furnaces, roasting and reheating hearths, and charcoal deposits. They date to two main periods, the minority from the 8th – 9th centuries and the majority from the 10th – 13th centuries. In the Bergisches Land region, new surveys have revealed at least 6 smelting sites near Asmannskotten, as well as minepits and charcoal stores (Tutlies and Stapel 1992). The region has deposits of excellent specular haematites (*Eisenglanz*) and limonites and the iron produced was traded through markets at Dortmund and Cologne and the Hanseatic ports.

The successors of these local bloomery establishments in this region were known as *Massenhütten*, to which has been attributed the capability of producing blooms or cast iron pigs although the latter is held to be more likely in the light of recent studies. The sites of these ironworks shifted from the hills and slopes down to the stream valleys in order to take advantage of water flow to power bellows, grindstones and hammers. A large establishment of this kind has been investigated at Haus Rhade (Sönnecken 1977). Some *Massenhütten* have been recorded in the Agger valley, the earliest so far being Agger 10 from the 13th century (Knau and Sönnecken 1986; Knau 1992). Other similar plants, revealing furnaces which should be properly be labelled as *Flossöfen*, predecessors of the blast furnace, are still coming to light. These are proving to have been stable operations which were conducted over several generations during the 13th – 15th centuries and include the sites of Wehe, Wippertal, Hemecke, Jubach near Kierspe (Sönnecken and Knau 1994), and at Kerspe (Jockenhövel and Willms 1998).

A smaller and, in the view of Schulz (1972), less important ironmaking district has been surveyed further to the north-east of the Märkisches Sauerland, between Hannover and Celle, in the basin of the river Wietze. It covers about 3.5km^2 and includes 359 sites with slag, in heaps measuring 7 – 15m in diameter (in rare cases up to 30 m) or beds. Smelting was based principally on bog ores, but so far no intact furnaces have been found. The remains are dated to the 13th – 16th centuries, and the output was apparently all consumed by the city of Hannover.

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Iron was produced on a large scale in several regions north of the Alps. The output of the Styrian Erzberg in Austria (Erzberg, Admont) was of comparable importance to that of the Middle Ages. Somewhere in this area may have been located the renowned '*fossa ruderis in monte Gamanara*' which was put at the disposal of the archbishops of Salzburg by local rulers in AD 931 and again in AD 972 and, later, by the emperor Otto II in AD 982. Excavations are in progress at a number of bloomery sites, but no detailed information has yet been published.

Considerable evidence has been recorded at Kelheim (7th century) and near Augsburg (9th century), where iron ore was mined extensively (see chapter V). Reference is made to slags in the various reports (Frei 1977; Geisler 1991; 1995).

The Oberpfalz region of southern Germany is an area of 30 – 90km ^{2} between Bayreuth and Regensburg with deposits of cretaceous limonites with iron contents of 50 % Fe and more. It was one of the most important iron mining and production districts of the Middle Ages, having its main centres in the neighbourhood of Amberg and Sulzbach. Iron is known to have been made at the Erzberg, near Amberg, at the beginning of the 10th century, but the main activity was in the High Middle Ages (14th – 16th centuries). It is estimated that eleven mines had an output of 121,000 tonnes of iron ore in the single year of 1596. Many hammer-mills associated with bloomeries are known to have been working on the banks of streams in the area (Ress 1950), but there is as yet no information on slag heaps and furnace sites as any form of systematic field research is lacking.

In any survey of early European iron producing regions, one cannot overlook the Harz, renowned primarily for its silver and copper mining, but where ironmaking is also known to have

taken place, as at Düna, Werla and Osterode (Kolb *et al.* 1986). Unfortunately, the present state of research precludes the compilation of any form of concise survey of sites or production parameters. It is, however, known that ironmaking was being carried out by Cistercian and Dominican monastic establishments as early as the 13th century.

The progressive centres of the North

As already noted, Scandinavia was, from the mid-1st millennium AD, among the most active areas of iron production. The Skåne, Halland, the hinterland of Kalmar and the Taberg and Kind areas of southern Sweden have all produced many finds of slag and furnaces (mainly open smelting hearths). These are concentrated largerly to the south east of Laholm, where more than 130 sites were recorded originally (Nihlén 1939), the number having increased in recent years to 600. Two types of slag heap have been observed, the smaller being 5 – 8m in diameter and 50cm in height, the larger 10 – 15m in diameter and 1 – 1.5m in height. The larger heaps are thought to be later in date, although there is no precise dating evidence. Written sources refer to iron production in 1197 at Tvåker where the ores used were bog and lake limonites.

More clearly-defined iron producing regions developed further north in Västergötland with 400 known sites, in Västmanland, Jämtland and Härjedalen with 1000 known sites (Magnusson 1977, 1986, 1995), and Närke (Hansson 1989). Activity ranges in date from pre-Viking times up to the Middle Ages, the dominant area having been Dalarna, the *Järnbäraland* described by Sverre Sigurdsson in 1177. Most of the 1000 iron-producing sites known to date lie to the west of Lake Siljan (Hyenstrand 1974), where limonite ores and magnetite sands were extracted from from lake and river margins. Some thirty sites have been investigated archaeologically, and all have produced evidence of smelting hearths and slag heaps of varying dimensions. The latter are classified into three groups — 10 – 12 m diameter and up to 1.5 m high, 3m x 4m and 40cm in height and 7m diameter and 30cm in height. The best known districts are Sunnanäng which is perhaps the most important, Dysdalen, Gryssen and Dykmyra (Serning 1973). Activity, mostly dated by radicarbon, centres on the period AD 700 – 1000, with a few earlier and later establishments. The shaft furnace at Dysdalen, which was encased in a wooden superstructure, has been dated to 1200 – 1500. The finds in Dalarna as well as in adjoining Gästrikland, Hälsingland and Jämtland may be connected with a group of mediaeval sites in the east Trøndelag in Norway (Stenvik 1991).

Just to the south of Dalarna, some 100km from Stockholm, is the Norberg region, which became one of the most important iron producing regions of the High Middle Ages and early modern period. It is mentioned in a document of 1354 in connection with taxes imposed upon the iron industry. In archaeological terms, the beginning of its rapid rise is admirably illustrated by one of the earliest *Massenöfen* or *Flossöfen*, with associated installations for the production of cast iron, which was excavated by Magnusson (1985) at Lapphyttan, north of Norberg. The site has been dated by radiocarbon, thermoluminiscence, and pottery to the 12th – 14th centuries.

Iron-producing regions also developed in the Mediaeval period in Norway where research activity has recently focused on the Hardangervidda region in the centre of the country (Martens 1972; 1981; 1988). About 200 sites have been recorded in an area of 8 – 9km^2 and nineteen have been excavated. The excavator makes reference to heaps containing up to 5.2 tonnes of slag (equivalent to an iron production of 1.8 tonnes) and estimates that about 4 tonnes of iron (i.e. 400 blooms) must have been produced annually in this region in the 6th – 8th centuries and again in the 10th – 11th centuries. It would appear that this iron, which was made in open hearths as well as in low shaft furnaces lined with stone slabs (Pl. XX), was exported to the lowland areas. Another region in Norway where iron production developed at around the same time (although the dating of the remains is very uncertain) lay further to the east, in the upper valleys of Valdres and in Gudbrandsdalen, in the so-called 'iron valleys' where chains of bloomeries used open hearths for smelting bog ore. Hauge (1940; 1946) has recorded over 100 sites including those

at Myrhaugen, Kleivseter, Fagstad and Skåtalien. Well-organized surveys and test excavations have been carried out in other regions of Norway and a number of preliminary reports include descriptions of remains at Dokkfløy in Oppland and Gausdal in Valdres (Larsen 1992; Narmo 1996), of 121 smelting sites in Hallingdal (Bloch and Nakkerud 1992) and 191 sites in Setesdal (Rolfsen 1992). Mediaeval iron smelting is attested archaeologically in Trøndelag north-east from Trondheim as well (Espelund 1991a).

Even Iceland and Greenland, far across the seas from Scandinavia, have been the subjects of broad-reaching surveys. In Iceland, three ironmaking districts, Thósárdalur in the south, Fkótsdalshérad in the east and Fnjóskadalur in the north have been identified (Fridrikkson and Audardóttir 1992). There, small-scale production flourished between the 13th and 15th centuries, coming to an end during the 16th century. Smelting was performed in huts, presumably as a seasonal activity and reconstructions suggest that the bloomery furnaces were built of cut turf blocks and reinforced with wooden planks. In Greenland, very limited production was carried out by the Viking settlers as, for example, at the Brattahlid farmstead. Activity came to an end as the colony, cut off from the outside world, succumbed to the hostility of the indigenous peoples.

New iron smelters in Europe

After the Dark Age of ironmaking between the 6th and 8th centuries, a period for which we lack any significant information, new peoples appeared in Central Europe. Among the immigrants were the colonizing Slavs, the nomadic Avars who subsequently settled, and the Hungarians. All of these groups showed a tendency to concentrate their iron production in regions particularly well-endowed with raw materials, a feature which manifested itself surprisingly soon after the period of stabilization.

In Ukraine, an 'iron bearing' sandy island in the river Bug near Gayvoron (Bidzilya 1963), yielded workshops with 21 furnaces and 4 roasters. This site may provide evidence that a certain degree of specialization and concentration of production was taking place as early as the 7th century. However, before any further judgement can be made, a systematic survey of the whole area is required.

The western Slavs developed advanced socio-economic structures at a relatively early date, as the example of Great Moravia in the 9th century shows. Their material culture reached a high level of development, with successes in the field of iron metallurgy supporting progress in other technological fields during the 8th and 9th centuries.

Three ironworks, dating to the period before AD 800, have been discovered in northern Moravia, on the loess bank of a stream some 3km from Uničov, in the vicinity of outcrops of high-grade magnetite and haematite veins on promontories of the Jeseník mountain range. In terms of the number of sites, this was not a large operation, but its importance lies in the intensity of production. One site at Želechovice was excavated completely and yielded 24 fairly large underground furnaces of Slavic type which had been carefully planned and laid out as a battery and used repeatedly (Pleiner 1955; 1958, 208 – 224).

Identical banks of the slag tapping Želechovice type of furnace were discovered in an iron bearing forested region of western Moravia at Olomučany, in the Blansko district. Here, production continued with a short interruption until the 11th century, the iron having been smelted on the slopes where slag and furnace debris were deposited. It is evident that this region was important as a supplier not only of the main settlements of the Great Moravian kingdom, but also, later, to the feudal state of Bohemia of which Moravia became a part after the Hungarian raids. Archaeological excavations are still in progress at Olomučany and elsewhere in the region (Souchopová 1986, 1996). In fact, an iron industry flourished in the valleys around Blansko during the whole of the *Stuckofen* and early blast-furnace periods, lasting up to the 19th century.

On the plains of the former Pannonia, another population appeared at the same time as, or just after the Slavic colonists. The previously nomadic Avars in some cases entered into confrontation with the Slavs, while in other zones of contact, into a peculiar symbiosis. It is very difficult to distinguish the ethnic background of iron smelting workshops under these conditions. Thus, while Avar furnaces of the 7th – 8th centuries are believed to have been excavated at Tarjánpuszta (Gömöri 1977/78), the attribution is not wholly certain. The same may be held to be true for the Magyars or Hungarians, a steppe folk who appeared in the Carpathian basin about AD 900 as a cluster of nomadic tribes who settled down very quickly, the whole process lasting but a few generations. Again, in the field of iron making and working, the Magyars absorbed much knowledge from the indigenous Slavic inhabitants as their vocabulary related to these crafts shows. Because the style of their furnaces is extremely similar, even identical, to those found in modern Hungary where the early mediaeval population was mixed, any consideration of the language spoken in the workshops seems irrelevant. At any rate, the Kingdom of Hungary, established during the 10th century, introduced strict control over the output of ironworks on its territory and the *Castra ferri* or *vasvár* were the posts where taxes on ironmaking were collected (Heckenast 1966). An iron-producing region based on the local limonites and siderites emerged slightly later in northern Hungary, in the Bükk mountains near Borsód, to the west of Miskolc and extended over the border with modern Slovakia (Füryová *et al.* 1990). Eighteen sites of the 11th – 12th centuries have been reported to date, with some having been excavated (Nováki 1966; Heckenast *et al.* 1968). Of these, the sites at Imola and Trisz were ironmaking establishments with two or three embanked furnaces extremely similar in form to the 9th century AD furnaces from Olomučany.

Further west, on the border between Hungary and Austria, there is a considerable concentration of slag and of furnace sites, as well as of fields of mining pits in the forests around Sopron and in adjoining Burgenland. The whole area, which contains sedimentary limonites and siderites, covers about 700km^2. Over fifty sites have been recorded (Barb 1937; Ohrenberger and Bielenin 1969; Nováki 1969; Gömöri 1977; 1988; Gömöri and Kisházy 1985), some of which (Tarjánpuszta, Sopron, Köszegfálva, Veszprém, Nemeskér, Szákony, Somogyfajsz, Unterpullendorf and Dörfl) have yielded slag heaps as well as smelting furnaces. With the exception of Tarjánpuszta-Vasasföld, the sites are of 10th – 12th century date and supplied the mediaeval market centres at Eisenstadt and Vasvár. At that time the area was under Hungarian control, but a Slavic technological substrate had existed there from before 895 when the Magyars invaded the Carpathian basin and Pannonia. There are toponomastic relicts among the contemporary place names of eastern Austria and Carinthia (adjoining Slovenia) which incorporate the now-obscured roots of Slavic terms. Original Slavic terms to be found there include iron = železo (Selezna, Selessen a.d.Gurk), ore = ruda (Rudenich, Rudnigbach, Raiding, Reidlinsberg) and mine pit = jáma (Gaming, Gamingbach). The present forms come from the time after the period of the Bavarian occupation in the 8th century.

It is possible that the successors of the Slavic smelters have been responsible for a smaller group of ironmaking sites in the Schwarza valley in Austria, near the Rax Mountains around Hirschwang-Prein and dating to the 11th – 12th centuries (Mayrhofer and Hampl 1958). Some thirteen furnace sites are spread over an area of about 10km^2, while fifteen smelting furnaces which were fed with limonitized ores have been investigated at Payerbach and at Hirschwang where the installations resemble Slavic furnace banks.

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As can be seen, the number of bloomery smelting regions increased across Europe during the Middle Ages. At the same time in certain localities, the smelting of iron was shifted down from the hills and slopes to the valleys with their running water, the potentional source of great energy to power machinery. It was in the valleys that the first seeds of the blast furnace plants

germinated, signalling an increase in the intensity of activity. This was followed subsequently by a reduction in the number of productive regions, coupled with a rise in the productivity and capacity of those which remained.

Chapter IV

BLOOMERY IRONWORKS

Even the simplest ironmaking required certain specific and basic operations to be performed and some of had to be conducted using special equipment and installations. An assemblage of such installations constitutes a bloomery ironworks.

The basic production unit was the bloomery smelting furnace and it is a fact that individual furnaces uncovered by archaeological excavation are often thought of as representing the whole process of ironmaking. In fact, they would invariably have formed a part of a larger complex, which could have included some, if not all, of an inventory of units where raw materials (iron ore, charcoal, clay for building or repairing furnaces) were prepared and stored, where ore was dressed and/or roasted (in furnaces and hearths and on platforms), where charcoal was made (pits, heaps), where the crude furnace product was further worked (reheating hearths, smithing hearths, anvils and tools) and where finished or semi-finished products were stored. It must not be forgotten also that dumps of process refuse, such as ore gangue or fines, smelting and forging slags, and fragments of dismantled furnaces form a part of these complexes since it was almost always dumped, along with domestic refuse, near to the working site.

Thousands of furnaces or hearths have in the past been excavated, effectively as isolated finds (see Chapter IX) and for a very long time, no attempt was made in the great majority of cases to search for the associated remains of other processes. Even where features relating to the complete ironmaking process have been investigated, little attention has been given to the non-technological elements of settlements where iron making was carried out. This has resulted in our having only an imperfect picture of the status and organization of labour and of the commercial aspects of the industry. In recent years, however, this lack has been recognized and addressed by researchers.

In most geographical regions of Europe, the ironmakers and their activities would have been exposed to the effects of the weather, necessitating the protection of raw materials and process plant from wind, rain and frost. This raises the question of whether or not shelters and buildings might have existed on early bloomery sites, although where these were temporary or flimsy, it is difficult to find surviving traces in the field. Similarly, we must consider also the buildings in which ironworkers might have lived. And information of this kind is essential if any attempt is to be made to estimate the manning requirements of early iron industries. Analysis of living accommodation can also produce valuable clues about the social and economic basis of a specific industry, and can throw light on the vexed question of whether ironmaking at any site or in any region was a seasonal occupation or was carried on continuously throughout the year.

It is a reasonable assumption that early ironworkers, especially those operating on a limited scale, would have wished to have all of their facilities as close as possible to where they were working. In contrast, where iron production in a region was on a very large scale, we may expect to see evidence for the development of a measure of specialization. Certain operations, such as ore preparation, charcoal production, reheating processes and the finishing of iron products, can be shown in such cases to have been carried out at locations some distances from the smelting areas, with materials having been transported from one site to another in the process chain.

It will be seen from what has been said, that some diversity may be anticipated in the layouts of bloomery ironworks, and this is borne out by the results of archaeological research. In some cases, the remains of workshops and their layouts bear the marks of certain conventions, resulting in what may be called a 'type', specific to time and territory. The examples in this chapter have been selected from among a very large number and are presented in roughly chronological order. They relate both to specialized workplaces and to what, in modern terms, would be considered to be 'integrated works'. They have been chosen also to reflect the evidence that they can

provide about working capacity and the organization of workforces.

The earliest excavated ironworks

In the course of archaeological research on early ironmaking in Georgia, a number of small-scale bloomery ironworks with one or two furnaces have been investigated. One of these, at Kvemo Bolnisi, south of modern Tbilisi, was an ironmaking complex, housed in a rectangular enclosure defined by two dry stone walls. An area measuring 11.5m x 8m was covered with a mixture of soil and iron slag. Against the northern wall was a bowl smelting hearth, set in stone, with a slag dump covering some $15m^2$ located 4m away. To one side, between the furnace and the slag heap, was a pile of good quality haematite some $4m^2$ which contained several hundred kilograms of ore. Near the ore dump were found three stone slabs, which are interpreted as pads for posts which, together with the stone walls, supported a light roof structure (Fig. 14: 1). The dating of this small-scale ironworks is a matter of debate. The excavator tends to assign it, on the basis of pottery finds, to the 14th – 13th centuries BC (Gzelishvili 1964, 31 38). However, in the light of other finds from the vicinity, including some burials, he admits that the date-range may be broader, from the 13th to 7th centuries BC. This chronology is based on Schaeffer's (1948) high dating, whereas the lower chronology of Piotrovskiy (1949) and Pogrebova (1977, 143 – 148) indicates younger dates comparable with those for other Georgian bloomery furnaces. The ironworks at Kvemo Bolnisi shows signs of being of developed form and so a younger date, perhaps in the region of 1000 BC or after, would be easier to accept.

The most recent synthesis by Khakhutaishvili (1987), including more than 30 newly-excavated bloomeries from 28 sites, shows a systematic pattern. They consist of one or two bowl furnaces, often paired like twins, on the top of slight elevations or ridges, accompanied by oblong (rarely circular) stone-paved or red-burnt areas which are probably roasting or reheating installations, and with fan-shaped spreads of slag debris on the slopes (Fig. 11). Tuyeres and crushing stones for ore or for some unidentified flux appear in the stratigraphy. Despite their early dates, these sites give the impression of developed, systematically-arranged plants which definitely must have had predecessors somewhere in neighbouring areas, especially in the south.

The best preserved complexes are the workshops at Charnali I and II, Askana I and IV, Mziani II and III. The dating of the remains in this region, which is situated close to the Black Sea coast north of Batumi, is based on archaeological data as well as on radiocarbon. While the archaeology indicates the centuries after 1000 BC (9th – 7th), the latter show much earlier periods and wide ranges from the 14th, even 17th – 11th centuries. What is suspicious in this respect are the significant differences in dates for individual paired furnaces, especially in the Charnali group, and the differences of several hundred years among samples from one single furnace which occur in the Mziani group. Nevertheless, despite these difficulties, the Georgian ironworks may still be considered the earliest so far identified.

*

The central European ironworks discovered at Waschenberg in Upper Austria (Pertlwieser 1970; 1971), is more soundly dated, in this case by the pottery assemblage which assigns it to the Late Hallstatt period (HD — *ca.* 5th century BC). What remains of the site lies on the tip of the spur of a headland, defended by five ditches. The centre of the site has been destroyed by modern gravel extraction, but it was possible to excavate the southern part, between ditches 1 and 4, revealing the plans of several houses. An iron-smelting area was discovered in the south-east corner and consisted of eleven bowl furnaces (Fig. 14: 2; see Chapter IX), arranged irregularly over an area of roughly 40m square. Three charcoal burning pits (see Chapter VII) were found on the northern edge of the site, as well as two places where the siderite nodules smelted on the site were calcined (Chapter VI), to the south-east.

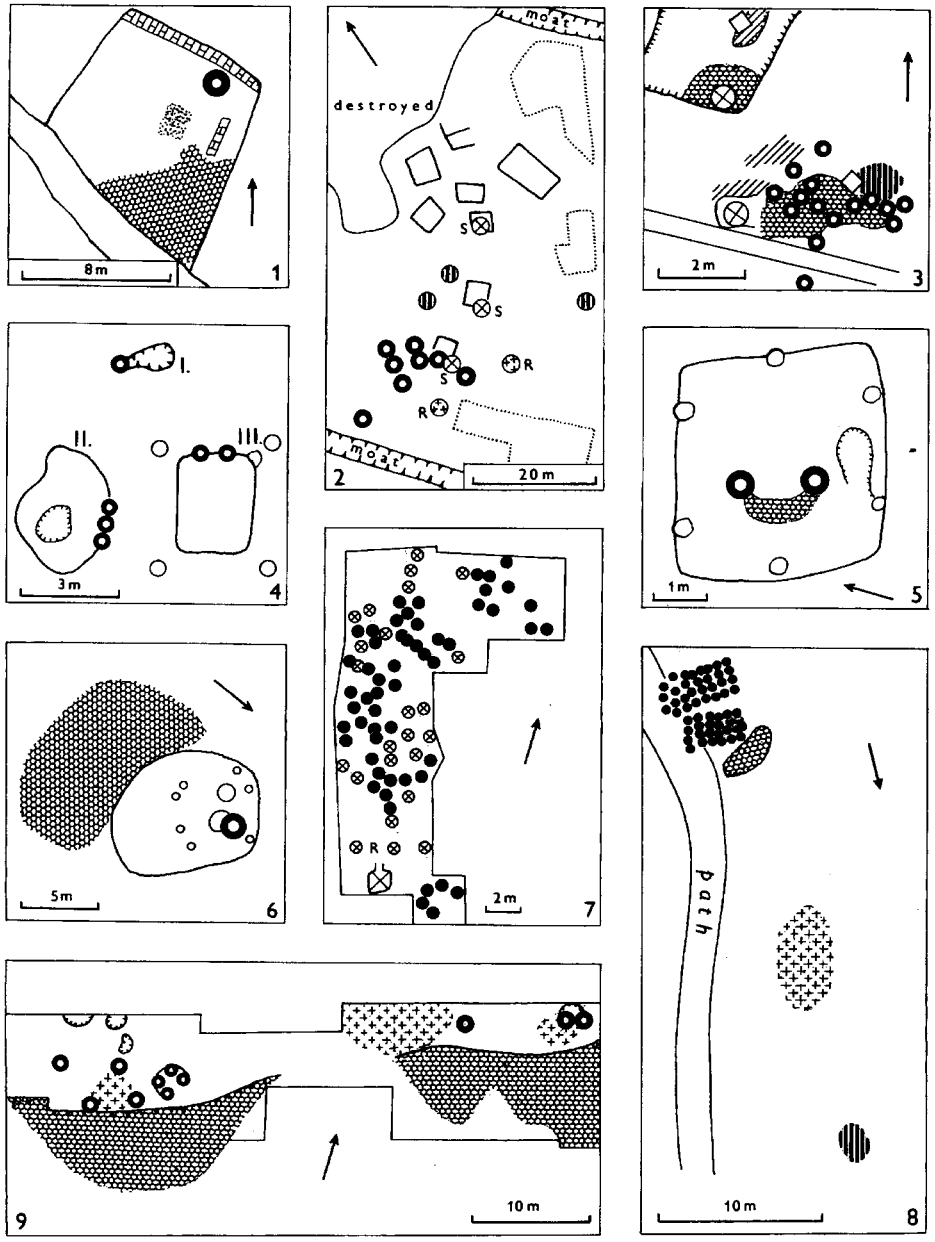


Fig. 14. Layouts of some ancient and early bloomery ironworks. 1 Kvemo Bolnisi, Georgia, a bloomery with one bowl furnace, ore, slag waste, 10th century BC; 2 Waschenberg, Austria, an iron making and working complex, about 500 BC; the symbols for various features are not to scale; the furnaces and hearths followed possibly in several phases; 3 Mšec, Bohemia, a small slag-pit furnace field (about 3 phases) and a smithy of the 2nd century BC; 4 Ořech near Prague, Bohemia — sunken-floored bloomeries with slag-pit furnaces of the early Romano-Barbarian period: I No 15, II No 14, III No 35; 5 Křepice, Moravia: a sunken-floored house with 2 slag-pit furnaces in the centre, 3rd century AD; 6 Pippingford, England, a Romano-British bloomery, 3rd century AD; 7 Isernbarg near Hatten, NW Germany, a Romano-Barbarian slag-pit furnace cluster with reheating places; 8 Jeleniów, Holy Cross Mountains, Poland, site 4: an organized slag-pit furnace cluster, Romano-Barbarian period; 9 Olomučany, Moravia, ironworks site 98/I, 9th century AD. References: 1 Gzelishvili 1964; 2 Pertlwieser 1970; 3 Pleiner and Princ 1984; 4 Motyková and Pleiner 1987; 5 Peškař 1962; 6 Tebbutt and Cleere 1973; 7 Hayen 1968; 8 Bielenin 1960; 9 Souchopová 1986. For symbols see Fig. 20.

Three other features were identified as smithies, with fire-reddened hearths containing smithing slag and posthole alignments which indicate that they were covered by light shelters. Two of these (M and R) were situated on the northern edge of the ironworking area and one (S) in the centre was closely associated with a smelting furnace (S_1). An anvil stone was set in the gravel surface immediately to the south of both features. A fragmentary, carburized arrowhead and other pieces of iron were found in a depression close to forging hearth S_2. It is justifiable in this case to postulate the existence of a permanent specialized ironmaking complex consisting of three distinct smelting groups, working either simultaneously or successively and preparing their own charcoal, roasting the ore required, smelting it and working up the product. This is typical small-scale production works.

One of the early bloomeries that has been attributed to the historic European Celts was excavated in central Bohemia, at Mšec (Pleiner and Princ 1984). Dating to the second half of the 2nd century BC, this works covered some $70m^2$ (8m x 9m) and consisted of a small area of 6m square containing eighteen slag-pit furnace bottoms, with three phases of stratigraphy. Smelting began in a shallow pit containing one or two furnaces, and further units were subsequently added nearby, dug into the slag debris that had already accumulated. To the west of the smelting area, a permanent reheating hearth (1m x 0.8m) showed signs of heavy burning and was filled with blocks of smelting slag, which had become fused together. On the northern edge of the site were two other areas with clearly differentiated functions. One was a 1.1m x 0.5m area of burnt-red clay containing a considerable amount of magnetic ore fractions, which was almost certainly the place where the roasting of the ore was carried out. The other was covered with a thick deposit of charcoal, and probably represents the site of the charcoal store. A large stone on the boundary between the furnace area and charcoal spread is interpreted as having been used as an anvil in the initial rough forging of the hot iron sponge after it had been taken from the smelting furnaces, as the soil around it was permeated with magnetic flakes.

Close by, to the north-west of the furnace area, was a sunken floored hut (4.4m x 3.5m) in the southern section of which was a raised platform (80cm x 60cm) covered with charcoal and typical cakes of smithing slag. This was the smithy proper, and perhaps was where semi-finished blooms or other artefacts were worked up. A depression in the centre of the hut, which was also filled with slag and magnetic hammer-scale, housed a large anvil stone (Fig. 14: 3). It would thus appear that operations connected with smelting and the reheating of the raw spongy bloom were carried out in the open in the front of the smithy building. It has been estimated from the weight of the slag blocks found on the site that a single smelt would have produced 1 – 3kg of unworked iron. Since furnace 1 showed that it had been repaired at least once, it has been suggested that each furnace was used twice and that the total output of the works would not have exceeded 150 – 350kg of iron.

This complex is significant for several reasons. First, it is an example of the very early use of the slag-pit furnace (see Chapter IX) by the eastern Celts. Second, it represents a group of smelting furnaces which were used for only one or two smelts and then replaced by other units in the same restricted area. The stubborn insistance on the erection of the new furnaces in the same place is worthy of attention, because it will be observed frequently in other cases. Third, the ironworks at Mšec represents a typical 'open air' smelting site with small-scale production and of a form known from the later Romano-Barbarian settlement in Central Europe. In addition, we can see there another contemporary feature, the sunken-floored bloomery housed in a hut.

A completely different model of ironworks appears in the north-west of Wales. Excavation of the fortified settlement at Bryn y Castell (a very small hill-fort with a dry stone rampart 40m x 25m), revealed several phases of iron smelting and working. The remains comprise a small shaft furnace (No. 20), outside the walls close to the northern entrance, with bloomery slag debris. Archaeomagnetic estimates indicate a date around 50 BC for this feature. Contemporary smithing activity took place inside the fortified area, in a circular hut with stone foundations

in which smithing waste was found. Later, in the early 1st century AD, a similar furnace (No. 208) and a reheating installation (No. 200) were worked at the opposite end of the enclosure. Behind those features there were remains of a smithy (structure 3) which had been levelled (Fig. 15: left).

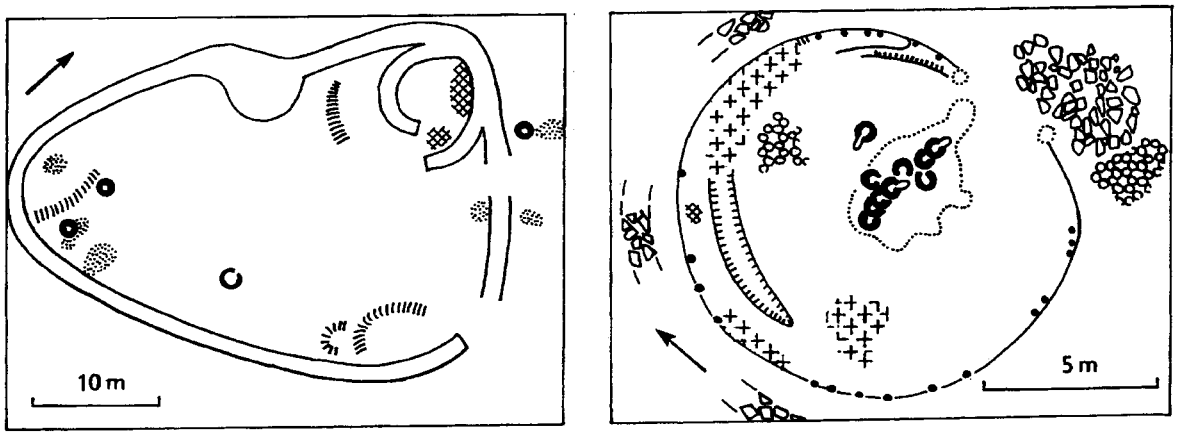


Fig. 15. Welsh Late Iron Age bloomeries. Left: Bryn y Castell Hillfort, two furnaces inside and one furnace *extra muros*, slag (dotted) and smithing debris (cross-hatched) in the snail-shaped feature. Right: Crawcwellt West, a furnace sequence in a stake-wall roundhouse, raw ore close to the smelting area, roasted ore at the circumference, smelting slag inside and smithing waste outside (balls). About 1st century BC and early 1st century AD. Reference: Crew 1987 and 1989.

Another workshop was discovered outside the walls, some 30m to the NE. It contained several damaged furnaces and/or hearths, a dump of roasted iron ore, many plano-convex hearth-bottoms, hammerstones and a stone anvil. This works was used during two phases between the early 1st and 3rd centuries AD. A circular, stone-set structure characterized the site in the later phase (Crew 1987). The Bryn y Castell complex represents one of few early iron making and working sites in Wales so far excavated and studied. It is very difficult to estimate its role in the native economy of the region. Since the 1200kg of mixed bloomery and smithing slag is not yet open to comparison with yields from other production sites and regions, our present state of knowledge permits only the interpretation that the small-scale of iron production was somehow tied to a local estate.

Excavations, still in progress, at the nearby open settlement site at Crawcwellt has revealed ironworks using high-phosphorus bog ores, with a complex sequence of round stake-wall houses. Inside the buildings at site A was a sequence of some 15 furnaces, some of which had been re-used as reheating hearths (Fig. 15: right). These are of the same character as at Bryn y Castell being non tapping, with walls some 15 – 20cm thick and internal diameters of 25 – 30cm and with a single 3.5cm diameter blowing hole at 90 degrees to the furnace arch. An external slag dump contains some 1.4 tonnes of smelting and reheating residues, calculated to be the result of some 300 smelts (20 smelts per furnace) which produced about 0.6 tonnes of raw blooms (Crew 1989). More recent work at site J has revealed a similar sequence of buildings and three external slag dumps, estimated to contain 2 tonnes of debris. Fieldwork in the surrounding area

has discovered other similar sites dating to the last century BC and the early 1st century AD, all using local bog ores.

At Clogher in Co. Tyrone, excavation of a hillfort complex which was the seat of the kings of the Argialla uncovered a smelting and smithing site lying just outside the outer bank and ditch. There were traces of three (badly damaged) bowl furnaces, while close by was a stone-built reheating hearth and a large anvil stone (Scott 1990, 160 and 167, Plate 6.5.7). Post-holes in the area indicated some form of light cover. The smelting and smithing activity is dated by calibrated radiocarbon to AD 390 – 620 and was probably directed towards supplying the needs of the inhabitants. A working complex comprising smelting hearths and slag dumps was dicovered in the interior of a circular structure at the monastic site of Reask, Co. Kerry, from the second half of the 1st millennium AD (Scott 1990, 161, figs. 6.5.5 and 6.5.6). Such small-scale production with smelting and smithing activites taking place in the same area typifies Irish ironworking from the first introduction of the technology until well into the Middle Ages (Scott 1990, 158 ff.).

Early large-scale works

However, at the close of the pre-Christian era, ironworks which operated on a large scale to supply early urban civilizations emerged in the south of Europe. The huge spreads of slag debris in Populonia, so severely damaged by later industrial exploitation, have yielded fragmentary residues of iron smelting furnaces, but not any ironworking complexes. But in southern France, in the area of the Montagne Noire, a team led by Domergue has investigated and published an interesting open-air smelting area dating to the second half of the 1st century BC at the site known as Martys-La Domaine des Forges (Domergue *et. al.* 1993; Domergue, Jarrier and Tollon 1999).

Excavation of three foci where iron smelting furnaces came to light (Fig. 16: 1) showed that they lay over earlier accumulations of slag debris. One consisted of two stone set-bases for large shaft furnaces (F 1 and F 2) which stood side by side and belonged apparently to the same ironworks. A second complex consisted of a battery of three furnaces of the same type (F 10, F 11, and F 12) which had been built along the edge of an artificial terrace some 10m long and 80 – 90cm high constructed from large stones and which probably were protected by a light shelter. Behind this workshop was another terrace set in stones, and, at a distance of some 10m, a stone walled charcoal bunker (*charbonière*) II which would have provided one or both of the smelting units with fuel. To the east, between two further parallel stone settings, the third complex, consisting of furnace F 20 and an adjacent forge or smithing hearth F 20A was discovered (Fig. 16: 1; Fig. 60). Excavations are still in progress and finds of further installations are to be expected.

These smelting workshops, equipped with voluminous shaft furnaces, indicate well organized, large-scale production which, from the evidence of associated pottery with Latin lettering, would seem to have been carried out by a group of Italic or Roman entrepreneurs (Domergue *et al.* 1993, 362 – 364). The earliest slag heaps, which were still intact, comprised between 20 to 25,000 and 60 to 70,000 tonnes. The production and working of iron continued within the Gallo-Roman industry up to the end of the 3rd century AD, but the remains from this period were heavily damaged by modern industrial exploitation which lasted until 1966.

No complete workshops were known from the territory of inland Gaul before rescue work in 1990 and 1991 by Dunikowski and Cabboi in the territory of the ancient Senones in the Yonne region (Dunikowski and Cabboi 1995). Ironworks showing three chronological phases were excavated beside a stream, with the middle phase believed to include the late La Tène and Gallo-Roman periods. The workshop called ferrier 1 (Fig. 16: 2) was a large depression 20m x 80m (not fully excavated in the south) with an irregular bank, where three pairs of domed fur-

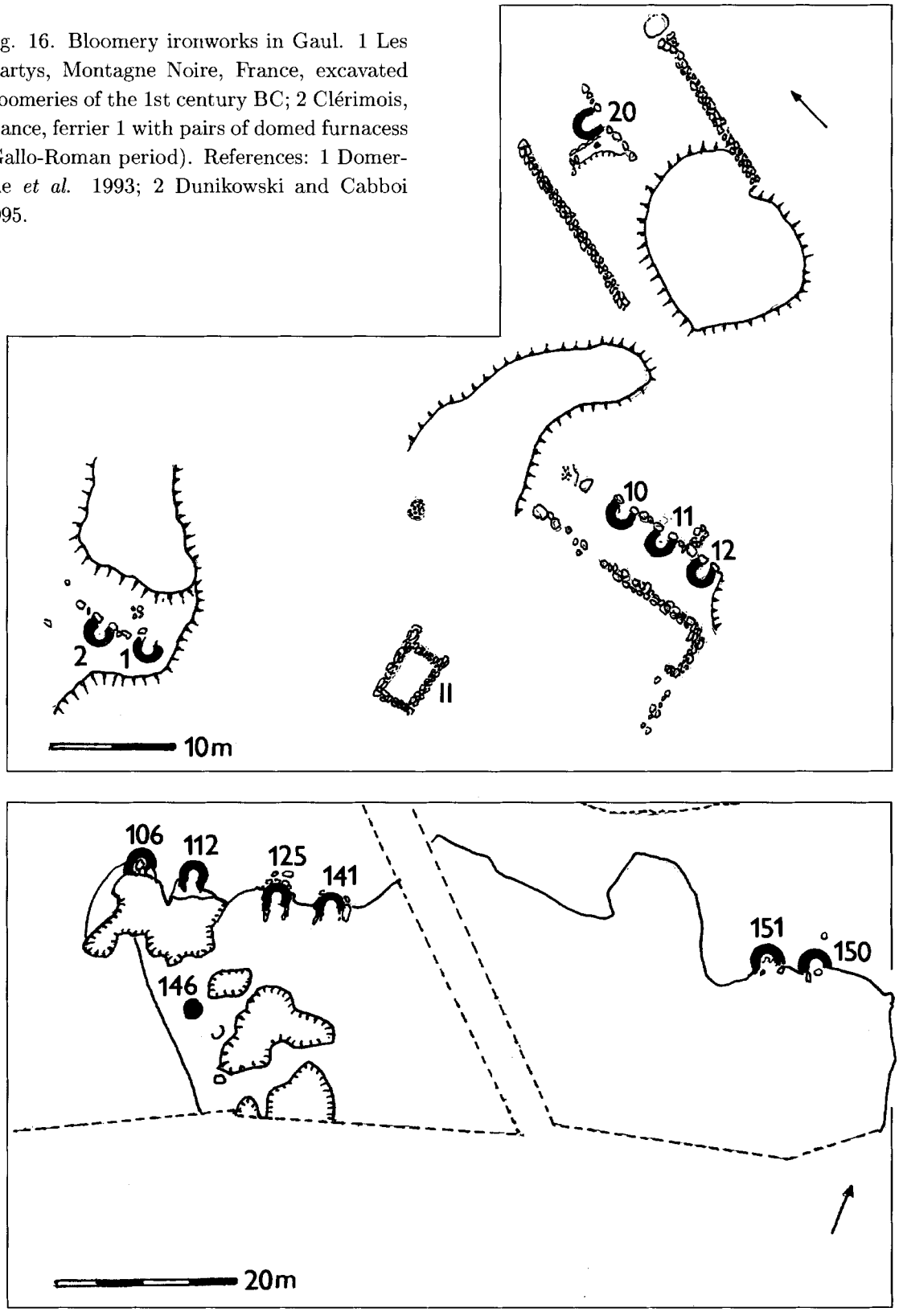


Fig. 16. Bloomery ironworks in Gaul. 1 Les Martys, Montagne Noire, France, excavated bloomeries of the 1st century BC; 2 Clérimois, France, ferrier 1 with pairs of domed furnacess (Gallo-Roman period). References: 1 Domergue *et al.* 1993; 2 Dunikowski and Cabboi 1995.

naces, labelled 'batteries' B, C, and D, were set in distances of 3m and 40m respectively. Slag and furnace lining has filled up this depression and as a result, a very low heap was detectable on the surface before excavation started. The pottery from this filling belongs to the 1st and 2nd centuries AD, which is in concordance with a hoard of 16 Roman coins from pit 147, situated within this ferrier (comprising coinages from Tiberius AD 23 to Antoninus Pius AD 161, see Amandry in: Dunikowski and Cabboi 1995, 111). Radiocarbon measurements cover a time space from 230 BC – AD 180. The averaging of ferrier 1 chronology presenting it as 86 BC – AD 41 seems to be inadequate; the stratigraphy of pit 147 (coin hoard) is, unfortunately, not presented. Ferrier 2, some 30m to the east, also was a depression (35m x 25m, slag and furnace debris in its filling). A pair of domed furnaces was situated out of the depression about 15m northwards. Pottery finds date this complex to the 1st – 2nd centuries AD, while radiocarbon indicates a range of 90 BC – AD 50. Further to the east there was ferrier 3a – b with at least two phases of existence in the earlier as well as the later Gallo-Roman periods but, as to its isolated furnaces and a feature what might have been a forge, not showing any clear pattern of individual ironworks. A charcoal burning area with 4 charcoal pits, dated by sherds from the 3rd century AD, appeared north of ferrier 3a – b. Another pair of larger furnaces was discovered 10 – 12m to the north-east (described as ferrier 4); these are dated solely by radiocarbon which shows a surprinsingly early period in the range of 140 – 20 BC.

According to estimates, the large (domed) furnaces of ferrier 1 consumed 215 – 290kg of ore and the same amount of charcoal each and yielded 50 – 100kg of unworked iron per smelt. This ferrier is believed to have produced 6280 tonnes iron slag and some 2500 tonnes unworked iron in total. An iron ore mining zone is being presupposed westwards of all the ferriers. It seems that the ironworks at Clérimois, in the territory of the Senones tribe, represent at least a medium-scale production when compared with the contemporary huge Roman slag heaps in the Yonne valley in the south (*op. cit.*, 131).

With regard to furnace 'batteries' we should note in passing the four large domed furnaces uncovered at Laxton, England which stood side-by-side, belonging apparently to one workshop (Jackson and Tylecote 1988, Crew 1998).

We shall now turn our attention once more to the small-scale production of the first centuries AD, which have left characteristic remains in central Europe in particular.

Bloomery ironworks in sunken-floored huts

Smelting furnaces in circular houses have been already noted for Crawcwellt in Wales, but in this section, we will discuss the those found in the more or less rectangular features, generally described as sunken-floored huts (9 to 12m square). The subterranean parts of such structures, the pits, are similar to those accepted as having been dwelling houses of the period, but they may well have been much simpler in construction. They would, however, have been roofed over, since the access of rain would quickly have reduced their floors to quagmires, bringing iron production to an abrupt halt. On the other hand, good ventilation was essential, since the combustion gases from the furnaces, rich in CO and CO_2, would been dangerous in such enclosed spaces.

The first examples of works of this kind were discovered shortly before World War II in central Bohemia, at Mšecké Žehrovice and Chýně, south-west of Prague (Pleiner 1958, 110 – 114; 1980, 400 – 401, fig. 11: 10). Chýně I produced a pit, which, on excavation proved to be somewhat oval in shape, measuring 1.5m x 2m by 50cm deep, with a slag-pit furnace 35cm in diameter at floor level set into the wall at each end (Fig. 17: 1). A slag block removed after one of the smelts lay to one side of furnace 1.

There were two larger sunken-floored bloomeries at Chýně II, the better-preserved being about 3m in diameter and 60cm deep. Three slag-pit furnaces were set into the north wall, and the hearth of a fourth was set into the floor, in front of them. This fourth furnace represents an earlier phase of working, after which its shaft was removed when the workshop was enlarged.

Facing these and set into the south wall, was another furnace of slightly different form, with a wider, sloping frontal aperture. This is interpreted as being the reheating furnace, designed so as to facilitate manipulation of blooms into and out of the furnace.

These sites represent a tradition for the layout of bloomeries, attributable to late La Tène culture, which continued through to the succeeding Romano-Barbarian period in the 1st century AD. A number of sunken-floored bloomeries of this type have been excavated in recent years in the same region to the south-west and east of Prague, as well as in northern and north-western Bohemia. They so closely resemble late La Tène establishments that it seems reasonable to infer that they were operated by original Celtic ironmaking groups who had been assimilated by the incoming Germanic peoples.

Some ten sunken-floored workshops of this kind, dating from the 1st century AD, have been excavated at Ořech, to the south west of Prague, not far from Chýně (Motyková and Pleiner 1987). Some were small rectangular pits with a single slag-pit furnace set into one wall, while others were larger, roughly rectangular in plan housing between two and four furnaces and several retained traces of their front walls and entrances. Structure 5 at Ořech is worthy of particular note for its four large postholes, one at each corner of the pit, undoubtedly remains of the supports for a roof. It was not possible to detect similar structures elsewhere on the site as the original surface had been scraped away by heavy earth-moving equipment.

There were three furnaces in structure 14, set side by side into the east wall of the pit which measured 3.5m x 2.75m by 1.65m deep, with a depression 1.2m x 1m by 70 – 80cm deep at its centre, in front of the furnaces (Fig. 14: 4; Fig 37; Pl. III). Only a very small team could have operated in such a confined space and it is likely that only one furnace would have been worked at a time. Such production sites of this time must have been in operation over considerable periods, since there is clear evidence of worn-out furnaces being replaced by new ones, sometimes after the pit had been enlarged by digging out the walls into which the earlier furnaces had been set.

Three workshops of this type were investigated at Ořech, the most informative of which was No 5, a pit measuring 3.3m x 3.6m by 22 – 34cm deep as excavated, although sections through the inset furnaces showed that it had originally been at least 70 – 80cm deep. The floor of the south-eastern area contained traces of between eleven and fifteen slag-pit furnaces, four of which were set into the south-east wall and still survived although their front walls had been broken down (Fig. 17: 2). The succession of furnace-bases provides clear evidence that this wall had been moved further to the south-east of the interior on at least three occasions in order to accommodate new furnaces. It remains an open question as why the smelters insisted on keeping their furnaces in the same place in each hut. This structure was the only one to have produced two depressions with process functions, located in the north-west area of the floor. These were shallow oval pits measuring 83cm x 72cm and l00cm x 94cm respectively and each was about 10cm deep. The inner surfaces of the pits were baked red and one contained charcoal and ore waste, the other haematite ore. Two ore samples were analysed, one of which proved to have been roasted, the other unroasted. It can be suggested that these pits were used alternately for roasting and for storing the ore and fuel charges for the furnaces.

The site of Říčany, several kilometers south-east of Prague comprised part of a late La Tène settlement and a later Germanic smelting area which extended some 200m along a stream in three distinct sections. Seven sunken-floored bloomeries dating from the 1st century AD were excavated (Kuna *et al.* 1989). The workshops were small (some 6 – 9m^2) and must have been sheltered by roofs. As at Ořech, there were pits with single furnaces such as feature 55 which had a slag-pit furnace with an original height of 80 cm in the side wall, as well as those equipped with two or more furnaces. The largest smelting hut was feature 16 with traces of 10 slag-pit furnaces, six of them set into the walls of the hut, representing the last phase of the workshop (see also Ořech, feature 5). The remains of other units appeared on the floor showing that the

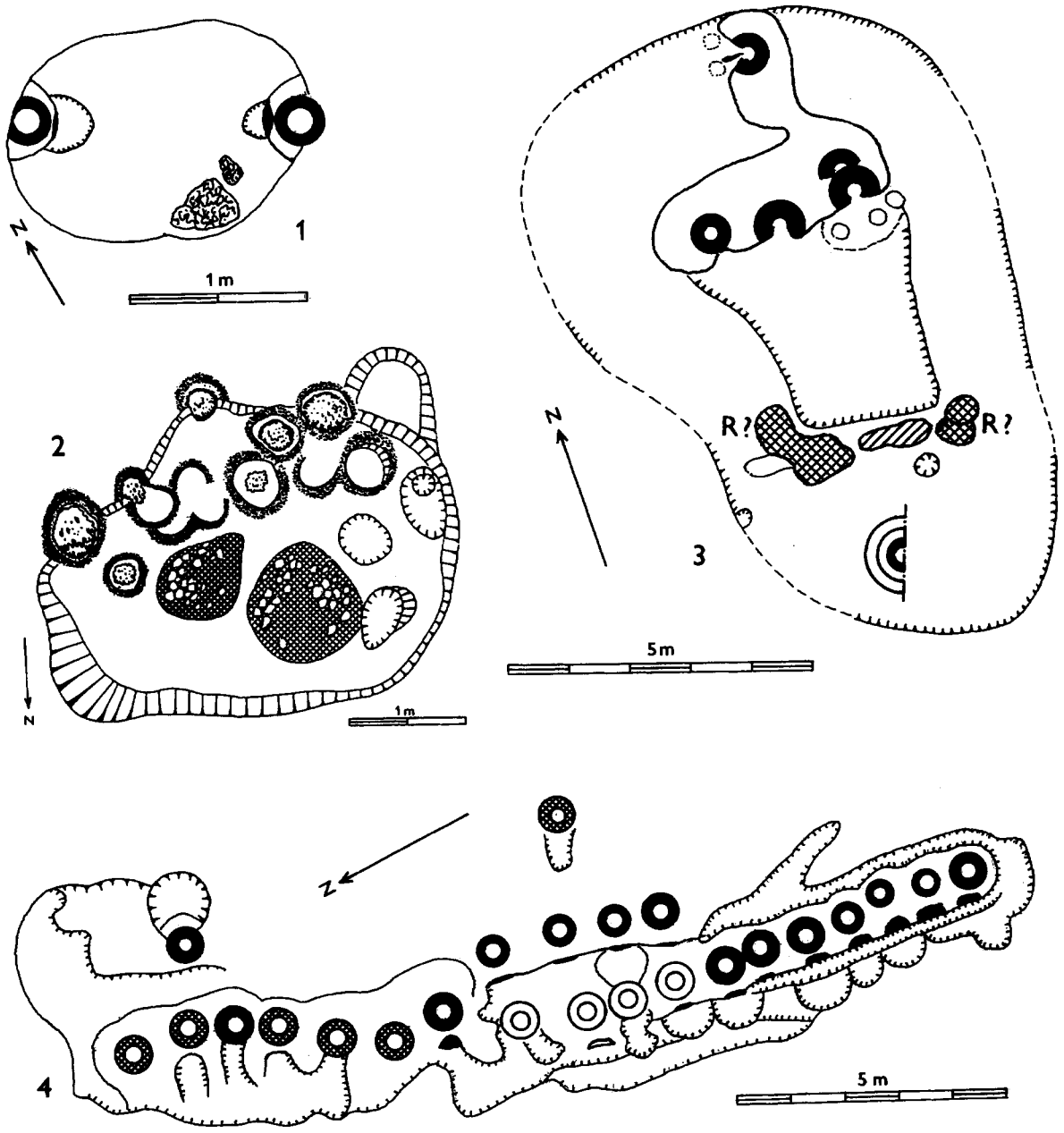


Fig. 17. Plans of selected European bloomery works. 1 Chýně, Bohemia, sunken-floored bloomery I with two embanked slag-pit furnaces, Late La Tène, 1st century BC; 2 Ořech near Prague, Bohemia, sunken-floored bloomery 5, early Romano-Barbarian, 1st century AD, several phases of furnace operation, in front of the abused furnaces charcoal, ore, gangue and stones; 3 Ashwicken, England, 2nd century AD; grid: cinder in presumed reheating hearths, hatched: hammer-scale; 4 Želechovice, Moravia, bloomery furnace system of the 9th century AD; furnaces in the left wing (grid) removed during Schirmeisen's excavation in 1935, empty circles: furnaces devastated during the function of the plant, second line of the furnaces: units of the later phase, discovered and excavated in 1951. References: 1 Pleiner 1958; 2 Motyková and Pleiner 1987; 3 Tylecote and Owles 1960 (slightly schematized); 4 Pleiner 1955 (schematized).

pit must have been enlarged and new furnaces installed. Despite the fact that large numbers of bloomeries of this type are known, production in furnaces with such restricted capacities must be regarded as representing small-scale activity, albeit concentrated. Nevertheless, a chain of such settlements, such as those represented by Dubeč and Počernice, could have supplied a wider settlement area or micro-region with iron (Vencl *et al.* 1976; Pleiner 1958, 144 – 145).

Many further sites of this type are known from central Bohemia, as at Jinonice and Stodůlky in the Prague region and Tuklaty and Třebovle in east-central Bohemia (Pleiner 1958; 1960) and from the north and north-west of the country, including Březno near Chomutov (Koutecký 1984), Lovosice (Pleiner and Salač 1987, and Kyjice (Smrž 1979) where several ironworks, one with seven furnaces, operated (Pleiner l958; 1961; Pleiner and Salač 1987). It is interesting that these bloomeries, so typical in their dimensions and form and equipped with the same type of furnace, were not dependent on one single type of ore. While the ironworks to the south-west of Prague consumed Ordovician haematites, those to the east smelted local bog-ores which were relatively low in phosphorus. Further examples of this form or organization are known from Germany and some of the ironworking features excavated at the site of Gera-Tinz may be interpreted as sunken-floored bloomeries (Dušek 1967), while similar installations have been excavated at Hagenow, Barkow and Leuben in Mecklenburg (Leube 1992).

A modified version of the sunken-floored bloomery plant comes from Křepice, southern Moravia (Peškař 1962). A typical Romano-Barbarian six-post sunken house 3.65m x 3.4m by 55 – 80cm deep was found to contain two slag-pit furnaces, the shafts of which had been demolished. These were not set into the walls of the pit but were free standing, facing each other in the middle of the room as shown by the small layer of furnace refuse that lay between them (Fig. 14: 5). An oval depression, measuring 1.9m x 0.6m by 20cm deep, of unknown function was found in the floor near the southern wall of the pit.

The sunken-floored workshops discussed above resembling the dwelling huts represent a specific type in the very centre of Europe (Bohemian lands). However, worth of mention are two features of the contemporary Zarubincy culture in the Ukraine, discovered at Remezovcy in the region of Lvov. Site II yielded a recltangular pit 2.5m x 4m; in its NE corner there were embanked 5 furnaces in the wall (not well documented). Site XII was a circular pit with one slag-pit furnace in the NW wall (Bidzilya *et al.* 1983, 34, figs. 12 and 13; Pan'kov 1993, 82, fig.8). At Lyutesh (Kyiv region), an oval shallow working pit (1,2m x 1.6m, 40cm deep) housed en excentrically placed, not embanked, furnace base in the floor (Bidzilya *et al.* 1983, 34 – 35, figs 11 and 20).

Iron smelting in these sunken-floored workshops obviously represents small-scale production to meet the requirement of a few local settlements. The restricted working space (4 – 12m square) indicates relatively small teams. Although many such workshops contain more than one furnace, it seems clear that only one furnace would have been in operation at any one time, the others being under repair or prepared and awaiting use. In no case were more than four in service during a single phase of the life of the workshop. Ethnographic observations, especially from India (Cleere 1963b; Ghosh 1964; Prakash and Igaki 1984), have shown that there were probably two smelters – the 'ironmaster' and his assistant (frequently his son or elder brother). There would also have been bellows-operators or 'blowers' as all of the furnaces in the sunken-floored workshops were blown by bellows. These workers are likely to have been members of the ironmaster's family or neighbours who also carried out other ancillary functions, though not necessarily in the smelting workshop itself, and alternated in operating the bellows. In the small units containing a single furnace it would appear that only the blower could have worked inside the pit, the furnace being charged from the outside by other members of the team. In general terms, five or six people would have constituted a smelting team, but no more than three could have worked inside the sheltered pit.

A similar layout was observed at the 2nd century AD Roman working site of Holbeanwood

in the Weald of south eastern England (Cleere 1971b). No slag-pit installations were discovered here, but instead, six shaft furnaces had been set into the walls of a working area which comprised an elongated rectangular depression measuring 3m x 1m by 80cm deep. Three furnaces with hearth diameters of 25 – 30cm had been built into each of the two main walls and one survived to a height of 65cm. Several showed signs of relining and tapped slag still filled shallow depressions in front of two of them. The fact that a large posthole was located immediately in front one of the furnaces shows that it had gone out of use before the final phase of working, and it is suggested that no more than two furnaces (one at each wall) would have been in operation at any given time. As with the central European examples above, these furnaces would have been charged from outside the depression. A line of postholes on the axis of the depression and parallel to the two rows of furnaces is taken as evidence for it having been covered by a pitched roof of some kind, although there was no evidence of any form of wall. A second group of six furnaces, similarly laid out, was excavated some 5km away and a third was identified, though not excavated.

*

Iron smelting within buildings, but on a different pattern to that of the Romano-Barbarian sunken-floored bloomeries, or Welsh ironworks under circular roofs is known from the Roman settlement at Ahrweiler in western Germany (Gilles 1961). The bases of at least three shaft furnaces, which had been renewed on several occasions, were found inside a room of stone building 1, which measured 10m x 8m. The adjacent slag heap extended beneath the wall of this building. Other furnace remains come from within building 3, but overall, the description of the excavated remains is completely inadequate and it is thus impossible to obtain a clear picture of the situation. Gilles carried out one of the first estimates of production volume on the basis of the amount of slag uncovered, a very modern approach for his time. He estimated that the 192.5 tonnes of slag in one of the heaps represented an iron production of 116 tonnes (an average of 1.35 tonnes per year). These figures seem, however, to be very high in the light of recent experimental work. By the way, small roofed ironworks were announced from Norway and Iceland (see below); the clima played there a role without any doubt.

Returning to ironmaking plants situated in depressions, we must not overlook the site of Ashwicken in Norfolk, England (Tylecote and Owles 1960; Tylecote 1962b; 1986) where an L shaped 'island' was found in the centre of the northern part of a large hollow (9m x 13m x 70cm deep). This took the form of a block of clay with five shaft furnaces set into it. A sixth, free-standing, furnace was found in the southern part of the hollow. Between the clay block and the isolated furnace was a hearth measuring 1m x 0.6m, filled with partly-reduced ore (cinder), which was believed to have been redeposited. Close to this hearth and to two other dumps of cinder was a deposit of hammer-scale measuring 1.5m x 0.3m, which indicates that reheating operations took place at some stage in the working life of this installation (Fig. 17: 3). Roasted siderite ore was found scattered over the whole area, but the roasting process itself is thought to have been carried out elsewhere. In its final phase, the pit was filled up with 350 tonnes of slag, representing an average annual output of 75 tonnes over a period of six years within the 2nd century AD. No consideration was given by the excavators to the possible existence of any kind of shelter or roof protecting the depression from the elements.

Roman period open-air bloomeries

Of course not all ironmaking installations of the Roman period were located in hollows or in sunken floored huts in line with the central European model. The majority of furnaces were erected in the open air, although possibly sheltered, and were frequently located close to sunken-floored or free-standing houses. To date, Roman bloomery workshops are unfortunately known

only from the periphery of the Imperium. No first rate process plant has so far been excavated in the major producing districts. The reason would seem to be that they were originally located in areas which were so severely devastated by modern industrial exploitation of the slag heaps which they produced.

The early 1st century AD Romano-British workshop at Pippingsford Park in the Weald of south-east England is worthy of mention (Tebbutt and Cleere 1973). It was situated on a levelled platform measuring 9m x 8m which had been partly dug into a hillside (Fig.14: 6). Within this area were found a stone-walled shaft furnace with an internal diameter of 50cm and an elongated smithing or reheating hearth measuring 70cm x 50cm, also set in stone. Several postholes surrounding both features indicate the presence of a light shelter. To the south lay a slag heap of about 11.5m^3 which covered another hearth).

Ferrier 3b at Clérimois, Yonne (Dunikowski and Cabboi 1995, 70 – 80) with the scattered remains of three furnaces radiocarbon-dated to the period AD 150 – 350 and 330 – 450, and a hearth, presumably a reheating installation, dating from AD 180 – 320, belongs to the period of decline of Roman Gaul as confirmed by associated pottery. It is difficult to see any clear workshop pattern, despite the fact that the charcoal for these furnaces was prepared nearby to the north. Activity at this site was presumably on a small-scale only.

Excavations at Oulches, in the ancient territory of the Bituriges Cubi in central France, revealed a Gallo-Roman bloomery of the mid-4th century AD, with ore-dressing traces and consisting of remains of two thick-walled shaft furnaces (internal dia. 1m), an oblong smithing hearth, another stone-walled hearth of unknown purpose, and of a water-pool, fed with water by a pipe, dug in the clay and lined with wood. This pool contained a different kind of slag, glassy, low in iron and enriched with lime; this waste should represent a thousandth in comparison with usual heavy bloomery slag of the site (Dieudonné-Glad 1997; Mahé-Le Carlier *et. al.* 1998).

Another ironmaking and working operation of limited scale was uncovered at the Roman *vicus* of Bliesbruck in N France (Forrières, Petit and Schaub 1987). The furnaces had been destroyed, but from within the artisans' quarter came hearth remains, lining fragments, slags, some with embedded traces of roasted pisolitic ore and bloom and iron fragments. This '*petite sidérurgie*' was apparently intended to meet local needs only.

Beyond the Roman *limes* system, in the world of the Germanic tribes, many open-air bloomeries, which regularly produce local variants of the slag-pit smelting furnace, have been uncovered. In regions such as Bohemia, they are contemporary with sunken-floored ironworks, showing that they were operated by smelting groups whose traditions or conventions were somewhat different. The furnaces, sometimes grouped in units of two or three, were placed outdoors, without any traces of postholes indicating shelters, but in the close vicinity of houses, as at Prague-Roztoky. In some cases, these workshops included charcoal pits, roasting platforms and reheating hearths. We may note three sites dating to the 1st – 3rd centuries AD which were excavated to higher-than-average standards at Gera-Tinz in central Germany (Dušek 1967). A total of 21 furnaces in 16 workshops, three of which consisted of 2 or 3 units, were located in a relatively small area of 200 m^2. In the light of the time-range involved, it is likely that production was on a limited scale only. The 1st – 2nd centuries AD site at Kadaň-Jezerka in north-west Bohemia (Kruta 1972) revealed 33 furnaces, 3 reheating hearths and 3 houses spread over 1 hectare, an area 50 times larger than at Gera-Tinz and again, it would seem that activity was restricted in scale.

We should note also the late Romano-Barbarian period (3rd – 4th centuries AD) ironworks at Tuchlovice in west-central Bohemia. The bases of six small clay-built shaft furnaces which had no slag-pits, but instead, flat hearths and tapping holes were uncovered. These were situated in front of a free-standing rectangular house, along with 5 elongated, shallow and red-burnt reheating hearths, filled with charcoal and small pieces of iron slag, which flanked the smelting area (Pleiner 1958, 176 – 188, fig. 49).

Slag-pit furnace clusters

Small clay-built shaft- and slag-pit furnaces could easily be reconstructed at the end of a smelt. However, the removal of the raw blooms which were an intimate admixture of iron and slag resulted in considerable damage to the shafts themselves. The method of working therefore had a significant effect on the decision as to whether the damaged furnaces should be rebuilt, as has in many cases been shown by excavation, or a new furnace erected nearby following demolition of the earlier structure. In the latter case, which indicates a trend towards efforts to increase production, groups of tens or even hundreds of furnace hearths were gradually built up in well-defined areas to create dense 'fields' or clusters of furnaces. The La Tène ironworks at Mšec described above is a modest example of this phenomenon.

Most of the larger ironworks of this type are to be found to the east and north of the Roman military *limes*, in the barbarian hinterland — Germany, Moravia, Poland, the Carpathians and Ukraine. Their chronology in some cases shows an early phase around the beginning of the Christian era, but the bulk commenced operation in the middle or late Romano-Barbarian period. These furnace 'fields' are generally irregular in layout, having developed haphazardly as new smelting units were installed. At Hatten on Streekermoor, near Oldenburg in north-west Germany (Hayen 1968), for example, 55 smelting furnaces were associated with 25 reheating hearths which were scattered, seemingly at random, among them, over an area of 120m^2 in a strip measuring 20m x 6m. No slag heaps had accumulated, since the slag blocks were usually left *in situ* in the hearths after the reduced iron, still hot, and the superstructure had been removed (Fig. 14: 7).

At the 3rd — 4th centuries AD settlement at Westerholz, Kr. Rothenburg, in the same region, 118 slag-pit furnaces were arranged in two rows, each 25 – 30m long, with seventeen possible reheating hearths distributed among them and four charcoal-burning heaps 25 – 30m to the east (Dehnke 1970). Two post-built houses were excavated but their chronological relationship to the furnaces is not clear. Furnace hearths were, however, found inside the northern house and there was evidence of metal working inside the southern house which was the more severely damaged.

The site of Göhlen, Mecklenburg, has been excavated recently, but only preliminary reports have been produced to date (Wollschläger 1992). Within this Later Romano-Barbarian iron smelting area, three sunken-floored houses were found, along with at least 17 furnace concentrations or clusters comprising several to several tens of furnace slag-pits over the excavated area. The site has also yielded slag heaps which seem to represent broken-up slag blocks in which the smelters searched for remaining fragments of iron sponge. Smithing hearths and anvil stones surrounded by hammer-scale also came to light. Some square-shaped stone settings, also containing magnetic particles, may have been used during smithing and/or roasting operations.

Many of the features at Göhlen are similar to those discovered at Snorup, north of Varde in western Jutland. It is very difficult to see individual workshops in the more than 40 clusters of slag-pit furnaces which are spread over 35 hectares (Voss 1995, 1996). Some 1500 furnaces have been excavated and the results of field survey, aerial photography and geophysical prospecting suggest that at least 4000 may have existed originally. Many of the furnaces overlap stratigraphically, being superimposed over earlier slag blocks in pits and radiocarbon dates indicate a long period of operation, from the 4th to the 6th centuries AD. In this complex area, following geomagnetic survey and excavation, only site E 11 yielded furnaces showing any form of arrangement in their placing. Here, 14 relatively isolated slag-pit furnaces were laid out side by side (4 + 4 + 2 + 4) in a line some 25m long (Pl. X, see Voss 1995, 135, fig.4.), giving the impression of a workshop or focus where smelts were carried out in an organized operation, connected with economy of farmsteads, manifested by freestanding long houses (Nørbach 1999). A smithy outside the area cited in the preliminary publication was excavated. It consisted of a red-burnt hearth containing a cake of smithing slag *in situ*, 2 depressions filled with hammer

scale and 6 postholes representing a rectangular structure. A hoard of about 200 axe-shaped steel bars (presumably of Norwegian origin) and 6 iron lumps was found in one of the houses in the south-western area of the site (Høst-Madsen and Buchwald 1999).

It is not possible to describe here all of the ironworks of this type which have been discovered to date, although we may draw attention to Psary (Mamzer 1984), Tarchalice and Opole in Silesia (Bielenin 1977b), to Milanówek, Biskupice and others in Masovia, west of Warsaw (Woyda 1977) and to Joldelund in Schleswig-Holstein (Jöns 1997). It is not easy to distinguish individual ironmaking *foci* among the furnace-clusters on these sites. The southernmost 'unorganized' slag-pit furnace clusters of the Romano-Barbarian period (in three groups) were excavated at Sudice in western Moravia (Pl. VI, see Ludikovský and Souchopová 1978).

In this respect, the best illustration is provided by the iron production in the Holy Cross Mountains (Góry Świętokrzyskie) in central Poland (see also Chapters III and IX). The region shows examples of some unusual variations in this type of site, and also a considerable evolutionary development (Bielenin 1974, 144 – 192; 1991). There are examples of irregular layouts of differing sizes ranging from four furnaces at Gardzienice up to 52 at Worowice 2, covering areas of between 2 and 20m^2. The furnace hearths lie close together, sometimes even on top of one another, which suggests that the smelters deliberately chose to work within strictly delimited areas and 'unorganized' sites of this kind represent about one third of the total excavated.

More than sixty sites, two-thirds of those excavated, are of what can be termed the 'organized' type — regularly laid out in rectangular areas notable for the systematic way in which

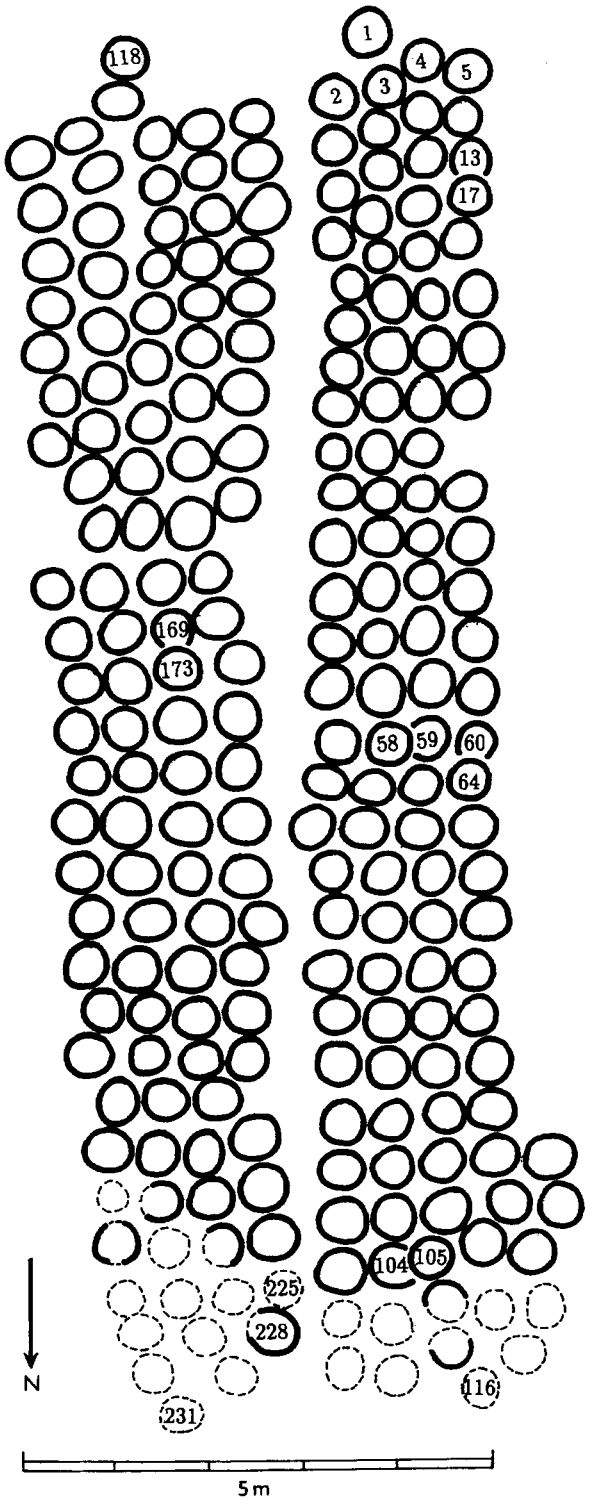


Fig. 18. Świętomarz, Holy Cross Mountains. The largest 'organized' slag-pit furnace cluster with 231 units, some of them in stratigraphical superpositions, Romano-Barbarian period. After Bielenin 1992.

individual furnaces were placed. Within these areas are many lines and rows of furnaces, sometimes overlapping one another. Each line contained between two and five furnaces so that a rectangular 'field', which contained 30 – 115 furnaces, would have developed by sets of furnaces being successively moved in a particular direction. There were ususally two sets of furnaces (exceptionally, three) with a narrow gap between them, giving twin batteries. The most common arrangement was 2 x 4 (eg. Słupia Nowa 6 Pl. VII: bottom; Słupia Stara 3, Pl. VIII: bottom) i.e. each battery consisted of four furnaces in line, a feature found on 72% of the organized sites. Other layouts are rarer — 2 x 3 at Słupia Stara 4 (Pl. VIII: top) Słupia Nowa 1 and Starachowice 1, 2 x 5 at Ciąstków 1 which produced 85 furnaces, and Nieczulice with 91 furnaces, or even 3 x 2 as at Jawor Solecki.

It would appear that in general, the layout of sites resulted from the way in which work was organized. Individual batteries probably represent the working areas of two (or in one case three) smelting teams responsible for operating a line of two to five furnaces, of which between one and three might have been in operation simultaneously. Once smelting had finished in all of the furnaces in a line, the shafts were demolished and levelled and both teams would have moved forward, setting up a new line some 50cm away from the previous one. This process was repeated from ten to thirty times before the site was abandoned. In summary, an establishment of this kind may be interpreted as representing two or three working campaigns although it is difficult to determine whether these were spread over one or more years. It is possible that a campaign would have begun with only one or two furnaces in operation.

It is noteworthy that the regularity of these layouts was sometimes disturbed. For example, a battery (or both batteries) may begin with with one to three furnaces, change to the common 2 x 4 format, revert to the earlier disposition in the middle of the 'field', resume the common 2 x 4 layout, and finally become irregular again at its lower end (Fig. 19). These irregularities are difficult to explain. It may be that the abnormal lines, whether at the start, in the middle, or at the end, have some kind of ritual or ceremonial significance, connected with the initiation of activity. Again, the insistance on having furnaces in the same place and within a clearly-defined area leads one to consider the possibility of this reflecting a ritual motive.

It must be admitted that nothing is known for certain about the organization of smelting campaigns on such sites, although it was most probably dependent upon social and religious constraints and customs. Similarly, nothing is known about the relationships between the two or three working teams that have been postulated to explain their layouts. It is however, worth looking at recent smelting practices among the Hausa people of West Africa who organized annual *campements de fer* into the present century. During their ironmaking campaigns, all of the furnaces were destroyed after each smelt. The furnace of the headman (*sarkin zango*) was flanked by the furnaces of his dependents and his relatives respectively and this group constituted a single bloomery unit. Similar groups belonging to colleagues (*bara*) of the headman were ranged close to the main one and in this way, twenty or thirty furnaces would be operated in a single campaign (Métallurgies Africaines, Échard ed. 1983, 217.).

The sizes of the furnace clusters in the Holy Cross Mountains vary considerably. While Gardzienice 1 had only four furnaces laid out irregularly, Świętomarz contained no fewer than 231 in the regular 2 x 4 layout and covered some 82m^2 (Fig. 18). The average number of furnaces per site excavated is between 90 and 100 (Bielenin 1974, 174) and such ironworks would have produced about 1. 5 – 1.8 tonnes of iron from 18 tonnes of ore and 20 tonnes of charcoal.

Ancillary installations have been examined on some of the sites and those at Jeleniów 4 will serve as an example. Some 7m to the north of the furnace 'field', which contained 86 furnaces organized in the 2 x 4 layout, an oval area measuring 6m x 3m and 0.5m deep, permeated with magnetic fractions, was found. These could have originated either from ore roasting or from the reheating of the reduced iron bloom. A further 7m away lay a charcoal burning pit (Fig. 14: 8) measuring 2m x 1m x 0.5 m deep (Bielenin 1960). The majority of sites have been damaged by

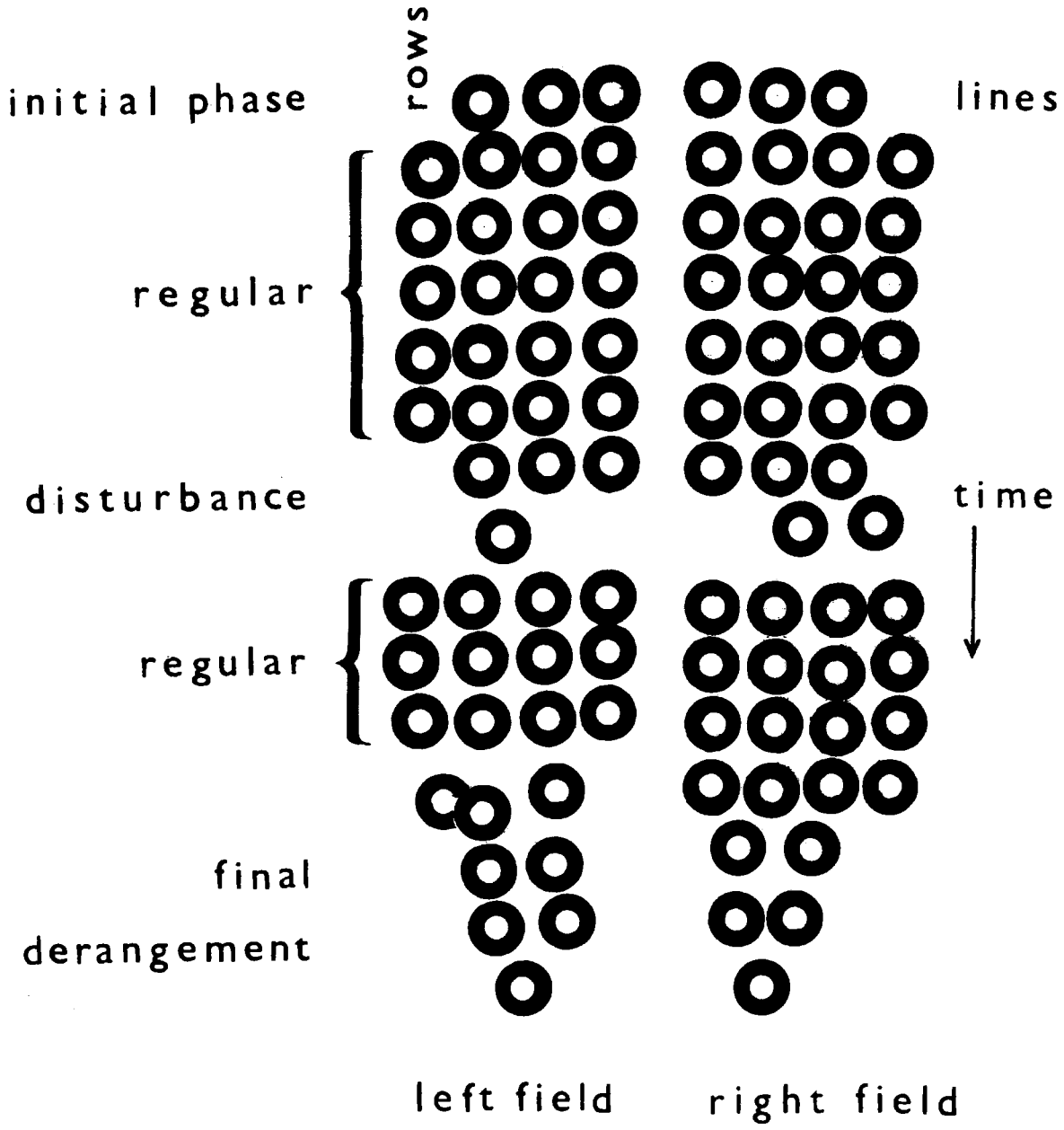


Fig. 19. Holy Cross Mountains, Poland. General system of subsequent setting of slag-pit furnaces in an organized field. After Bielenin 1974.

agriculture and the original surfaces, which would have retained evidence of other activities, can be observed only rarely. Nevertheless, some like Łomno 23, Jeleniów 1 and Skoszyn 3 have yielded traces of smithing areas close to furnace fields (Bielenin 1987).

What concerns the chronology of individual ironworks, twenty six sites yielded pottery fragments of the late La Tène and Romano-Barbarian Przeworsk culture. Five assemblages, originating in the 'unorganized' clusters or furnace fields were dated from the period of the 1st century BC to the 1st/2nd centuries AD (Częstocice, Gardzienice, Kowalkowice, Kunów, and Wymysłów 1, see Bielenin 1992, 167 – 175). Radiocarbon dates from Częstocice indicate, however, the period 300 BC – 100 BC, as for the site of Bolesyzn as well, which is a heavy discrepancy, attacking the entire historical scene; moreover, Boleszyn produced pottery solely of the 1st – 2nd centuries AD. The large, so-called organized clusters or ironworks date from the 1st to the 3rd centuries AD. The ^{14}C datings of four bloomeries reduced this range, in average, to the 2nd cetury AD, taking into account samples from two furnaces at Nowa Słupia 11, two at Grzegorzewice, two at Jeleniów, and three from Łazy 6 (Jeleniów wrenches out of the range giving 85 BC – AD 30, see Bielenin 1992, 175 – 179, after Pazdur). The time span for one single smelting place, resulting from differing dates of individual furnaces, exceeds 200 years. Understanding that the variations have to be ascribed to experimental error of the method and that the result may offer very wide ranges, as the pottery dating does, it must be kept in mind that, for example, the ironworks at Łazy 6 (range of 225 years, having been yielded from dates of three furnaces in various positions within a densely arranged cluster) operated one, at least two working seasons (Fig. 18; Fig. 19; Pl. VII: bottom; Pl. VIII).

It has recently been suggested that the unorganized slag-pit furnace clusters represent a rather small-scale of metallurgical activity directed towards supplying local communities with iron from the 1st century BC to the 2th century AD (Bielenin 1992; Orzechowski 1994). Under this hypothesis, the large, so-called 'organized' works whose *floruit* was the period from the mid-2nd up to the mid-3rd centuries AD (Orzechowski 1999), would have been operated by very skilled groups of smelters, presumably with trading links to the region of the Roman frontier to the south. The boom in production which they represent could have been influenced by the disturbances resulting from the Marcomanic wars, although in any case, the consumer-base must have covered a much wider area than the immediate environment.

Organized furnace 'fields' of the form described above are typical for the Holy Cross Mountains region. Some comparable examples have, however, been reported from further east in the Carpathians, where the 2 x 4 format was used at Novoklinove (Bidzilya 1970); unorganized slag-pit furnaces come from Volynia in the Zhitomir region at Kikhti and Pidvisoke (Pańkov 1992; 1993, 106 – 107, figs 16 and 17)). The most impressive are the sites I and II at Uman' with four unorganized dense slag-pit furnace clusters (36, 68, 14, and 58 units; see Bidzilya *et al.* 1983, 41 – 48, figs 15 – 19). They date from the 2nd/3rd centuries AD. In theory at least, the latter might have some connection with the presence of the Ostrogoths in the plains of eastern Europe. In Germany, a layout of 1 x 4 was reported from Merzdorf, near Uhyst in Lusatia (Wetzel 1982), but the ironworks was unfortunately destroyed by opencast coal mining and only traces survived. Among the unorganized slag-pit furnace 'batteries' at Wolkenberg, in the same region, one group shows signs of a more regular arrangement (site 26, Spazier 1996; 1997; 1999). It seems that this phenomenon can be followed in a vast geographical tract from the Ukrainian steppes to the Elbe river, reaching its most developed form in the Holy Cross Mountains area to the east of the Wisła river.

The emergence of smelting installations of this kind in non-Roman Europe in the first four centuries AD indicates a response to a perceived need to increase the production of iron within the capacities of the various socio-economic systems.

Early mediaeval furnace-batteries

Some early mediaeval ironworks, especially those connected with the technological culture of the early Slavs, represent an approach that is diametrically opposed to that described above. Instead of new groups of furnaces being built up over short periods, early Slavic ironworks were based on batteries of permanent furnaces, set alongside one another with their furnace arches all facing in the same direction. Excavated bloomeries give the impression of having been carefully planned enterprises, with the furnaces set into soil banks so that they were well-protected and insulated and easy to repair by replacing the internal lining. Such units had the capacity for perhaps in excess of one hundred smelts and they clearly represent an intensive mode of iron production.

The most impressive example of this type of establishment is that found at Želechovice in northern Moravia (Pleiner 1955; 1958, 208 – 224; 1962a, 181 – 185). A bank into which nineteen furnaces were set, facing outwards to a ditch-like feature, had been constructed on a loess stream terrace (Fig. 17: 4; PL. XIV and XV). Bellows were placed at the rear of the furnaces, connected to the hearths by inclined, fixed tuyeres (see Chapter IX). The furnaces were very robust and capable of sustaining many successive smelts, with several bearing clear traces of having been repaired (e.g. furnace XVIII). After a time, however, the five furnaces in the central section became too degraded to be repaired. They were therefore demolished, and this part of the bank was cut back, with four new furnaces being constructed behind the original five.

The same sequence of events may be observed in the northern section of the battery where one new furnace (XXI) was erected. Another isolated furnace (XX) was built behind the new furnaces in the central section. The complete battery extended over some 20m and was about 6m in overall width. Pottery finds associated with the furnaces date the process plant to the end of the 8th century AD, corresponding to the pottery found in a rectangular pit 8 (3.5m x 2. 75m x 50cm deep) located by a test trench 150m to the east. In a corner of this pit was a cauldron-shaped depression, 75cm deep, the filling of which was permeated with haematite ore fines, bloomery slag and charcoal, indicating that it had some function as part of the smelting activities. Whether it belonged to a larger settlement remains unknown since there was no possibility of carrying out wider excavations at the site.

It is obvious that all of the furnaces were not operated simultaneously and that there would have been furnaces in operation, in waiting, and under repair at any given time. There were no slag heaps in the cultivated area around the site, but the ditch was filled with slag, which was also strewn over neighbouring fields. Assuming that a minimum of 5kg of iron resulted from each smelt, sixty smelts per year would represent an annual production of 6 – 7 tonnes and the site might be interpreted as showing evidence of the activities of a larger and specialized group or clan of iron smelters. A similar establishment was discovered at Dolní Sukolom, some 1km to the north of Želechovice (Pleiner 1958, 206, fig. 54).

Identical batteries of inset furnaces of the Želechovice type were found at Olomučany, near Blansko in western Moravia (Souchopová 1986, 16 – 22, figs 4 and 6). The two batteries were smaller, consisting of seven (98/2) and eight (98/3) furnaces respectively (Fig. 21: 1; Pl. XVI). Although of exactly the same design, they were fed with a different kind of iron ore, limonites from weathered siderites of the west-Moravian Karst area, while the Želechovice ironworks were based on high grade maghemites of the Lahn-Dill type deposits from the promontories of the Jeseníky ridge.

At Olomučany, a workshop area which replaced the two furnace batteries in the second half of the 9th century has some puzzling aspects to it. An artificial terrace (not fully excavated) measuring at least 55m x 10m was levelled out on the same slope to the north-east, above the original batteries, and here two distinct types of smelting furnace were constructed, although the chronological relationship between them could not be established in the absence of proper stratigraphy. The first type is represented by the hearths of five free-standing shaft-furnaces, laid

out across the whole platform. In the centre of the platform was an oval working pit measuring 2.7m x 1.95m and 60cm deep, which had a battery of four furnaces with thin front-walls (Fig. 14: 9; Pl. XVII; see Chapter IX) set into its sides. Another furnace lay some 8m to the east, set into the rim of the platform where three deposits of roasted ore, 15 – 20cm thick and containing *1, 5, and 8m^3 respectively, were also discovered. The bed below furnace II contained 902kg of* slag, which represents between 54kg and 270kg of iron and the total amount produced by the furnaces on this platform, which was undoubtely supplied to the communities of the emergent Great Moravian Empire, is estimated to have been in the region of 1620kg (Souchopová 1986, 23 – 37).

No special reheating hearths have so far been discovered at Olomučany, although a special feature occurred in front of the remains of shaft furnace VI. Here, two split iron blooms had been buried, and were found embedded in soil which had been burnt red showing that they were still hot at the time. The blooms which each weighed 2.5kg must have been reheated, forged and split *in situ*. Another set of four Želechovice-type furnaces comes from Senička in Northern Moravia (Dohnal 1982), although their dating poses problems. The furnaces are definitely of the type dated elsewhere by pottery to the end of the 8th century. At this site, however, no pottery could be associated definitely with the battery and, in fact, a pit dating to the high mediaeval period was excavated nearby during the rescue campaign.

Outside Moravia, a battery of four furnaces dated by pottery to the 11th century was found at Hirschwang in Austria (Mayrhofer and Hampl 1958, 18 – 22, figs 14 and 15). The shafts were square in plan and set into an artificial clay bank. Bellows were sited to the rear, with slag being tapped or removed through front arches into circular depressions. Behind the furnace battery was a pit filled with charcoal, while a slag heap, only partially investigated, lay in front of it. Excluding the slag heap, the whole installation covered an area of 3.5m x 4m. A small field anvil, suitable only for the shaping or repair of tools, was found among the debris. Despite the later date and some minor differences, this installation is very reminiscent of the Želechovice ironworks.

Bloomeries equipped with embanked furnaces were often sunk into hillsides or slopes, with openings in the front. The Hungarian ironworks at Imola and Trisz in the Bükk Borsód production region in the north of the country illustrate well this type of system in the mediaeval period. Workshop 1 at Imola (Nováki 1969) contained one furnace with a thin front-wall set into a niche measuring 3.5m x 4.5m and cut 80cm into a slope. A small stock of iron ore was found in the south-west corner and there were two baked and reddened areas on the floor, which may have been reheating hearths. Another reheating hearth or fireplace was found outside, some 150 m to the south-east, but this is believed to have belonged to another establishment.

Very similar furnace and workshop types to those in the Bükk and in western Moravia have been excavated in western Hungary, close to the Austrian Burgenland. Gömöri (1988) has published a preliminary report on the 11th century site at Szákony where at least 8 ironworks situated in small oval or rectangular pits (1.5m x 2m) with 22 shaft furnaces (in different states of preservation and stratigraphical positions) set into their walls have been discovered (Pl. XVIII). Each of these workshops was equipped with 1 or 2 furnace units which would have operated during one chronological phase of its existence.

South of Lake Balaton, at Somogyfajsz in the county of Somogy, part of a sunken-floored ironworks with 22 underground furnaces was excavated, yielding also four iron blooms of 2 – 3.5kg in weight (Fig. 45). The works consumed bog iron ore quarried nearby at the Korotenai brook. The dimensions and shapes of the furnaces are again similar to the Imola, Nemeskér and Olomučany types. The chronology is based on radiocarbon and archaeomagnetic dating as well as on associated archaeological material, and places the site in the 10th century AD, the period of rule of the local duke Fajsz. At Sopron-Potzmannsflur in the county of Sopron, four furnaces similar to those from Somogyfajsz, were excavated. These were not placed in working pits, but

instead arranged side by side in a kind of battery. The site yielded tube-shaped tuyere nozzles, inserted into gate panels. Archaeomagnetic determinations and associated pottery cited in the preliminary report (Gömöri 1995) indicate a date in the 10th century AD (Gömöri 1996).

We must not overlook the recently-excavated ironworks discovered at Trøndelag in Norway (Espelund 1987; Stenvik 1991), although they are not easy to date, with radiocarbon estimates spanning the centuries between 200 and 600 AD, the later Roman, Migration and early Mediaeval periods. The area has revealed a novel design of slag-pit furnace, numbers of which were arranged side by side in batteries with heaps of roasted ore behind them, the slag having been dumped down the slope below the furnace bank. Settlement features have been found adjacent to furnaces at Storbekken in Budalen (Stenvik 1991), while specific features, stone-set depressions known as 'rosettes' but not yet clearly interpreted, surrounded the batteries of smelting furnaces at sites such as Heglesvollen. To date, information on these Norwegian discoveries comes mainly from preliminary reports.

Mediaeval paired furnaces

A modification of the battery pattern comes in the form of furnace pairs or twins which survived in single phase workshops. In fact, the best system for a smelting plant would seem to have been where two teams worked, one preparing or repairing one furnace while the other carried out a smelt. As we have seen above, this model is an ancient one, appearing in the very early Georgian ironworks. Furthermore, pairs of Gallo-Roman domed furnaces were recorded at Clérimois (ferriers 1 and 4) and twins come from the Late Roman or Migration Period pha-

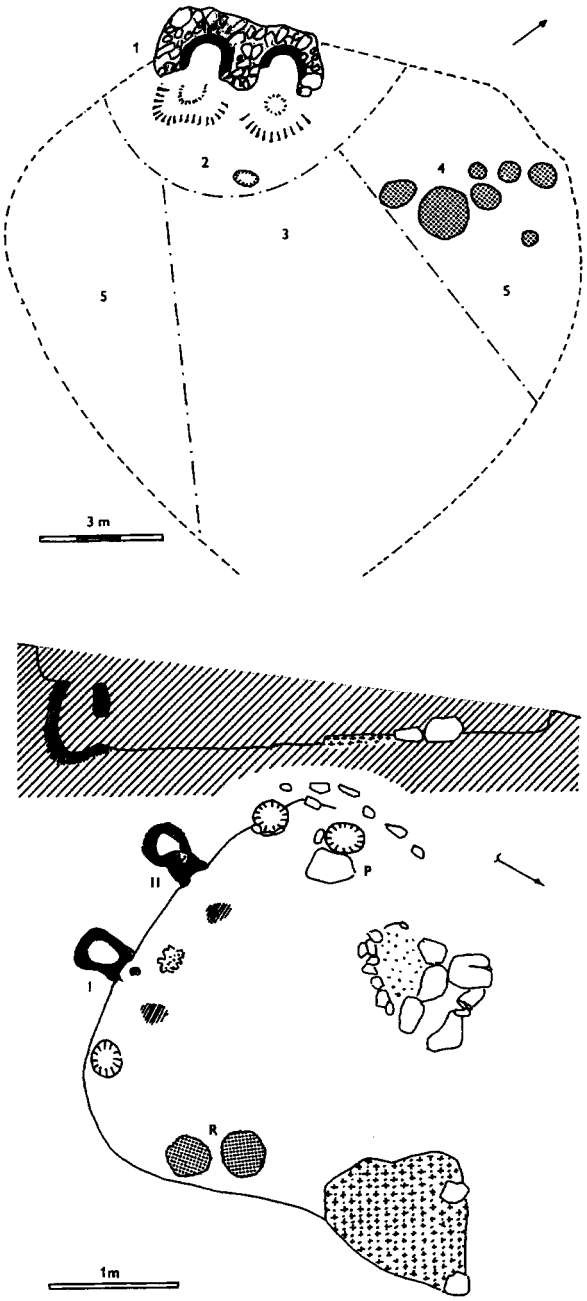


Fig. 20. Examples of twin-furnace ironworks. 1 Boécourt, Jura, Switzerland, 7th century AD (1 furnaces; 2 operating zone; 3 principal refuse; 4 roasters, 5 secondary debris); 2 Gemerský Sad, Slovakia. References: 1 after Eschenlohr and Serneels 1991; 2 after Füryová *et al.* 1990.

ses at Bellaires in Switzerland. The 'two-furnace' pattern has been noted at many of the ironworks described here, sometimes being masked by earlier or later furnace destruction in the same workshop. The following early mediaeval and mediaeval ironworks reveal the 'pair system' very clearly.

During the early Middle Ages in the 6th – 7th centuries AD, this kind of ironworks emerged in northern France and north-west Switzerland. An example was uncovered at Frouard, near Nancy in France (Leroy 1997, 73 – 74, fig. 34) where two relatively large shaft-furnaces were set side-by-side at a distance of some 4m into the bank of a partly-sunken working terrace which measured 13m x 11m. The slag debris was deposited to the north, not far from the furnace arches. Three reddened patches of earth and an area covered with charcoal were observed around the working zone.

The best example, fully-published by Eschenlohr and Serneels (1991), is the 7th century site at Boécourt in the Jura. A pair of stone-set bloomery furnaces (reconstructed height estimated at over 100cm) was erected on a slight slope and the excavators suggest the following sequence of construction: furnace 1 (north-west) was built first, then, to its right, furnace 2 which, after a period when both were in operation, continued in service; furnace 1 was abandoned. The furnaces were blown with clay tuyeres, some lateral and others inserted obliquely into the large clay tapping-arches which faced south-east. The working area, showing surface traces of charcoal, lay in front of the furnaces and covered some $140m^2$ (ca 11m x 12m). Some 5500kg in total of typical tap-slag debris, was recovered from parts of this area also. To the north of the working area, adjacent to furnace 2, seven roasting hearths (0.2 – 1m in diameter), were recognized, each filled with calcined pisolitic ore (Fig. 20: 1). No traces of reheating hearths were found in the work place, but typical cakes of smithing slag were used as building material, together with stones in the construction of furnace 2, showing that smithing activity took place nearby. It is worth of noting that similar installations dating to the 6th century and comprising furnaces III – IV, and XIX – XX had previously been discovered during excavations by Pelet in Bellaires I and III (Pelet 1973, 1993). Excavations in the same area, at Montcherand, have revealed successions of bloomery furnaces in existence during the 7th and 8th centuries AD, but the operation of distinct pairs is difficult to recognize (Abetel 1992).

Another good example of this type of ironworks is Gemerský Sad on the Slovak side of the Bükk region (Füryová *et.al.* 1990). Workshop 1 was a levelled plateu 3.5m x 3m, embanked in a very gentle slope. Dug into the rear were the shafts for two smelting furnaces of an Imola type (original height ca 90cm), the clay fronts of which were still preserved, leaving oval openings at the bottom. In front of these openings red-burnt areas indicated where the manipulation of glowing iron and slag conglomerates had taken place. In the eastern part were two circular fire-places in the floor (30 – 40cm in dia.), probably used for roasting or reheating. A store of iron ore lay at the shallow end of the platform, and the presence of post holes indicates the existence of some kind of shelter (Fig. 20: 2). Workshop 2 was of the same type, but had been more badly damaged. Set into its floor were found 6 furnaces which had subsequently been demolished when the working place was extended up to slope to a point where the pair of two last furnaces to be operated were still standing. Several kinds of iron ore from various places in the vicinity were smelted at the site, including bog ore, haematite and weathered haematite/siderite of which samples have been analysed. Köszegfálva in W Hungary yielded bloomery ironworks with paired furnaces and slag heaps in front of them (Fig. 21: 3).

In the Swedish Tranemo area, in the region of Kind in southern Sweden, a smelting plant consisting of a pair of stone-set furnaces adapted for slag tapping has been excavated. The slag had been deposited to one side, while a store of roasted ore, dated by radiocarbon to the period around 800 AD, lay behind the furnace pair. To the west was an adjacent heap of smithing slag and the remains of a 9th century hearth-like feature. Several charcoal pits were discovered close by, but radiocarbon shows that they were of a later date (11th century, see Englund 1995).

In 1995 an excavation revealed a pair of small stone-cased furnaces, placed some 1m from each other at Jernvirke-Tvååker in Halland, S Sweden (Pl. XI: bottom). One of them seems to be connected, in its hearth level, by a low arch with what seems to be a forepit. The internal shaft or hearth diameter is given as 30cm. The incomplete information comes from Vellev (1994) and Buchwald (1998, 13, fig. 4). Bog iron ore with 72 – 86 % Fe_2O_3 was smelted at the site (*op. cit.*, table 2).

Four bloomeries (labelled as DR 1, DR 9, DR 13, and DR 63) were excavated in the Dokkfløy valley, Norway, which, with one exception, reveal remains of paired furnaces of the Møsstrond type, having been placed side-by-side in distances 1 – 2m; tapped slag was removed, deposited on both flanks. Their volume varied from about 2000m^3 to 8000m^3. Reheating and/or smithing hearths used to be situated in front of the furnace archs (DR 9, DR 63). As to the exception, mentioned above, the ironworks DR 13 consisted of three smelting units, arranged in a line, facing to a smithing hearth and slag heaps both on the NW side and at rear. Narmo (1996, 93 – 133, figs 35 – 46) suggests that the bloomeries were sheltered. Radiocarbon dates indicate the 13th – 14th centuries AD.

Ironworks with furnace pairs can be interpreted as representing the organized labour of two working teams of smelters. In the majority of cases, the furnaces were of restricted capacity, attesting to a rather limited scale of production. On the other hand, the larger process plants with batteries of bloomery furnaces of between 4 and 20 units reflect more complicated organizational systems of manning and may be evidence of the existence of larger specialized social groups such as extended families or clans of ironworkers. In any case, the evidence so far available indicates that these iron producing undertakings were of medium size.

Other mediaeval bloomeries

Other ironworks of the early and later Middle Ages in the various European iron-producing regions do not seem to conform to any specific pattern. As was the case in many earlier ironworks, the various process components — one or more smelting furnaces, roasting and reheating hearths and stores of ore and fuel — are distributed in an apparently haphazard way over areas that vary considerably in size, with slag usually being dumped in relatively small heaps close to the working area. Nevertheless, before the introduction of water-driven forges and the first blast furnaces, concentrations of such smelting works in certain regions of Europe supplied markets with the majority of their iron during the 8th – 13th centuries.

As to the Late Saxon period, a complicated situation appeared at Ramsbury (Wiltshire, England) where a depression of about 16m x 18m housed ironworks, dating, according to archaeological finds and radiocarbon tests (Haslam *et al.* 1980). Stratigraphically it revealed five chronological phases: the earliest involved remains of two bowl furnaces, a 'smithing hearth' (possibly reheater) and traces of calcined siderite ore; the second phase involved furnace 3 and another post-reduction hearth, then, after a hiatus (phase 3) in the function of the bloomery (traces of post-holes in rows indicate the existence of a structure) the third phase of evidence consisted of furnace 4 and an anvil stone platform placed nearby. Repeated relinings of the bowl furnaces indcate a long-termed small scale activity. The last phase represents the period of abandoning the workshop.

In the Hirschwang-Prein region of Austria, referred to above, an ironworks, in this case dating to the 10th – 11th centuries was excavated (Mayrhofer and Hampl 1958, 7 – 13, fig. 3). A smelting furnace had been set on a mound of clay measuring 4.25m x 2.75m which housed two hearths on either side of its front. Two further hearths were situated to the front of this mound, where the remains of another furnace, in this case free-standing, were identified. Slag was dumped on a heap located to the west of the installation. The chronological relationship of the free-standing furnace to the main installation has not been established, but excluding the slag heap, the whole set up covered about 65m^2 (Fig. 21: 2).

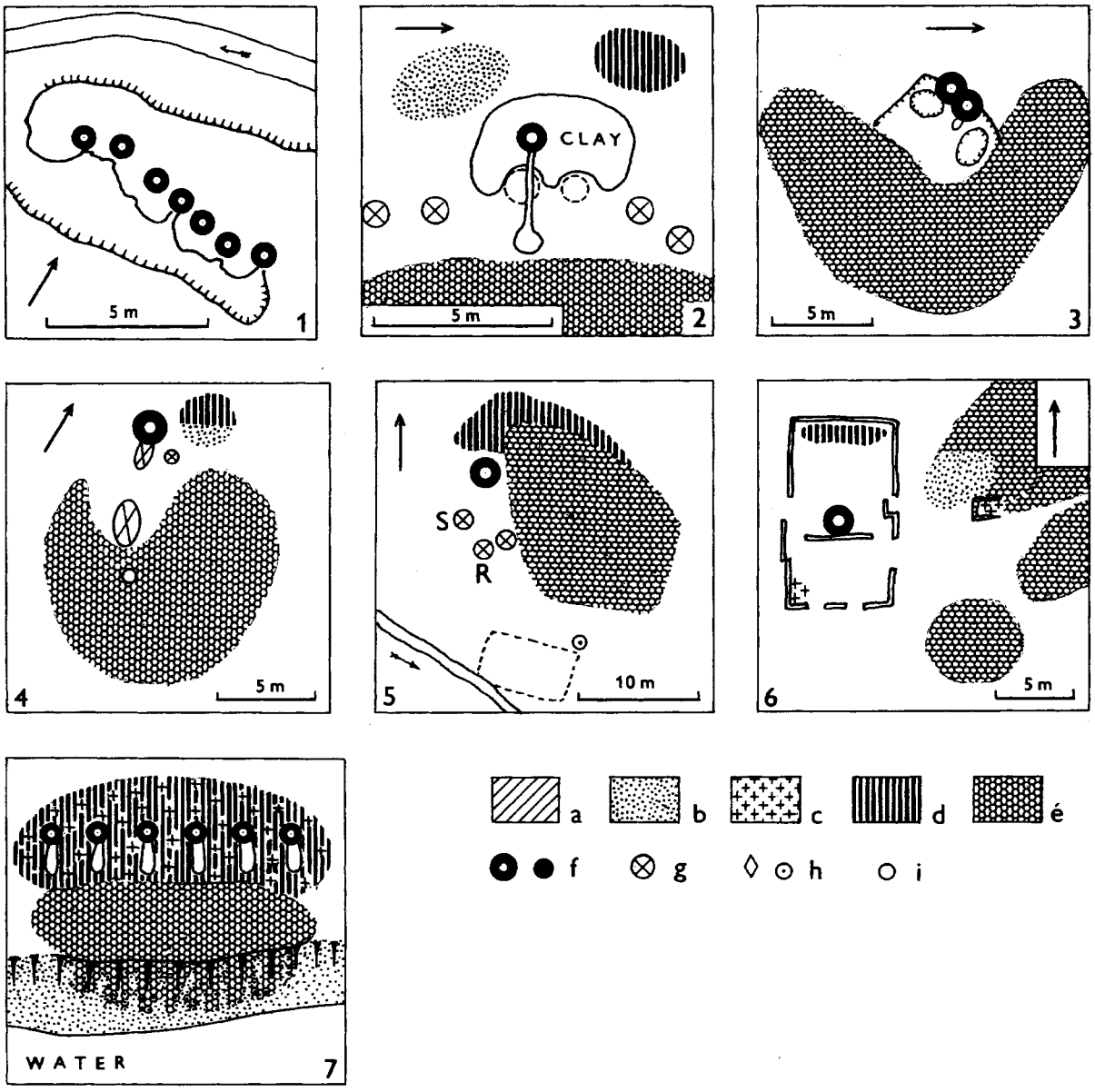


Fig. 21. Layouts of some mediaeval ironworks in Europe. 1 Olomučany, Moravia, a battery of underground furnaces at site 98/2, 8th century AD; 2 Payerbach 1, Austria, shaft furnace in a clay block, 11th – 12th centuries; 3 Köszegfálva, W Hungary, a twin of embanked furnaces, 11th – 13th centuries; 4 Grossendrescheid, Germany, bloomery complex Am Walde 1, 11th – 13th centuries; 5 Bargen, Switzerland, bloomery complex with a bowl furnace and hammer-mill site, 15th century; 6 Minepit Wood near Rotherfield, England, scheme of the later bloomery plant phase, 15th century; 7 Sweden, a type of a bloomery ironworks on the lake shore. References: 1 Souchopová 1986; 2 Mayrhofer and Hampl 1958; 3 Nováki 1966; 4 Sönnecken 1971; 5 Guyan 1965; 6 Money 1971; 7 Magnusson 1987. Symbols for Figs. 13 and 18: a hammer-scale; b ore; c roaster; d charcoal deposit; e slag deposit; f smelting furnace; g hearth (R reheating, S smithing), h anvil, whetstone; i other kind of hearth.

Some of the 10th – 13th century ironworks, for example in the Sauerland of western Germany, were very small. The Wilsmicke site, near Gerlingen/Olpe consisted of a smelting furnace, a $2m^2$ heap of charcoal, a stock of roasted ore in front of the furnace and a reheating hearth which measured 0.6m x lm and contained some hammer scale. Excluding the slag heap which lay to one side, the whole establishment covered only $18m^2$. A similar works, at Linackers Kante, consisted of a smelting furnace, with an oblong reheating hearth alongside, and stacks of charcoal and roasted ore (Sönnecken 1971, 35 – 36). At Am Walde 1, near Grossendrescheid (*ibid.* 17 – 20) an area of $90m^2$ was sufficient for the layout of a smelting furnace, charcoal and ore stacks, two hearths (functions not clearly established) in front of the furnace and a fan-shaped slag heap (Fig. 21: 4). Tens of bloomery complexes have been unearthed in Sauerland.

During research work carried out in the adjacent Lahn-Dill area, an ironworks of the second half of the 13th and beginning of the 14 centuries AD was excavated at the site labelled as B 88, near Ewersbach. It comprised the base of one single shaft furnace with a tapping channel heading to the north, surrounded by a fan-shaped slag heap to the east containing 6.99 tonnes of slag, an area where ore had been crushed and an accumulation of haematite ore some 5 m to the north, in front of the smelting unit. The find of a pair of iron tongs 57cm long is worthy of note. The site is interpreted as the works of specialized smelters, who moved seasonally from place to place (Lammers 1995).

It would be possible to quote other examples of ironworks of similar size and layout from other parts of Europe. In view of the amounts of slag found in association with them, these establishments seem to have worked quite intensively, despite the fact that they were operated by small teams of five or six smelters, possibly all members of the same family.

A bloomery site excavated at Sunnanäng in Swedish Dalarna (Serning 1973, 65 – 84) covered a large area of some $500m^2$, including the three associated slag heaps. In other respects, however, it was laid out in a similar fashion to the examples cited above, with seven open-air smelting furnaces and seven smithing hearths, which presumably operated during the different phases of the life of the settlement. Deposits of ore and an ore/charcoal mixture were identified near furnace 3.

There were already been quoted mediaeval bloomeries with paired furnaces in the Dokkfløy valley in Oppland of Norway (Larsen 1992; Narmo 1996) which are claimed to be sheltered by a kind of timbered building. The same appears in the Møsstrond area in Telemark, the bloomeries of which are a little earlier, from the 11th – 13th centuries AD, but usually such a plant consisted only of one smelting unit (sometimes in stratigraphical superposition). The ironworks are rather small covering an area about 100m square, which included slag debris (layers or very low heaps), ore and charcoal layers, sproadically what is called anvil stone. For examples see the sites of Hovden 5, Homvassbekken, Martinvika (Martens 1988, 51 – 69).

A different type is represented by the 15th century smelting and forging plant excavated at Bargen, north of Schaffhausen in Switzerland (Guyan 1965). Within 4 – 5m of the south of the base of a stone-built smelting furnace, there were three smithing or reheating hearths, which are suggested to have been operated at different phases of the life of the site. Slag was dumped to the east, creating a large flat heap measuring 15m x 10m and 45cm thick. This was subsequently covered almost completely by a bed of charcoal of the same thickness and measuring 12m x 15m. A 6m x 4m area to the south of this complex was marked out with stones and produced a rotary whetstone, while an oak hammer-beam was found between this feature and the bloomery (Fig. 21: 5). Guyan interprets this as being a hammer-mill operated by a water wheel, since it lies only 1.5m from the Durach stream. There is no evidence of there having been any form of mill-pond and it is suggested that the bloomery was not blown by a water powered bellows. Roasted limonite was used in the bloomery, but no roasting facility was reported as having been discovered.

Another late mediaeval ironmaking complex with a different layout is that of Minepit Wood

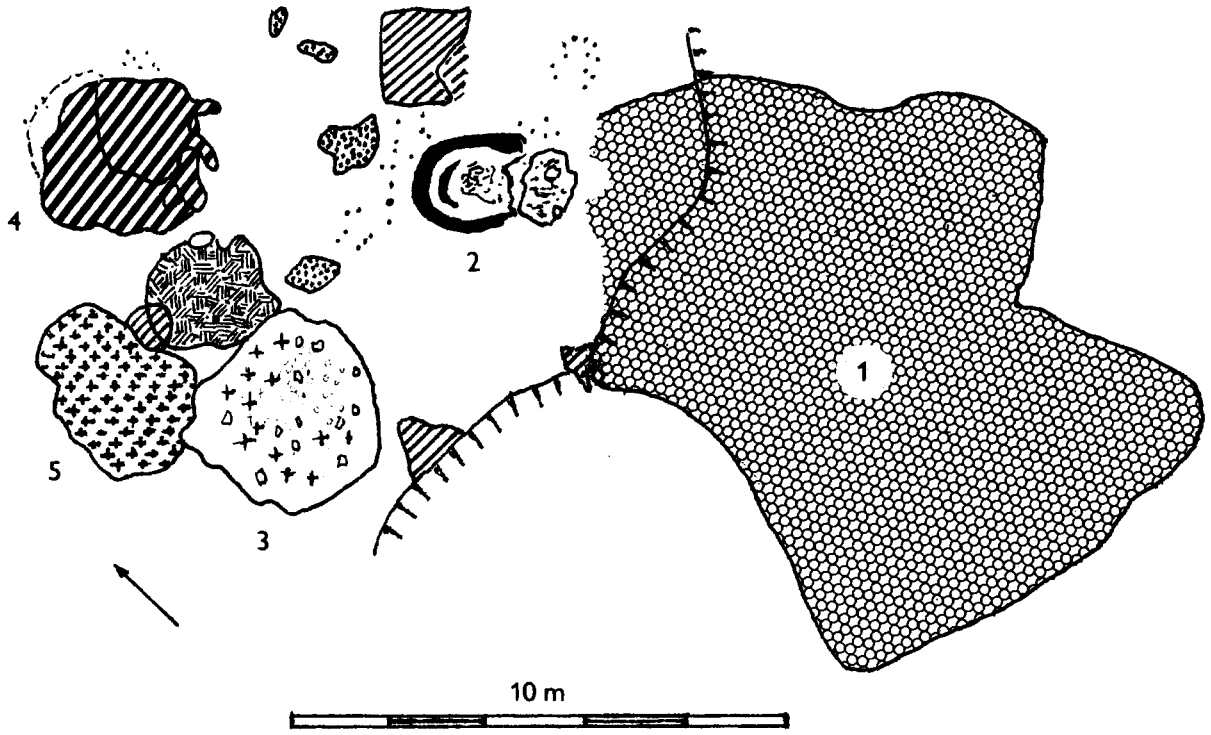


Fig. 22. A pre-blast furnace ironworks at Metzingen-Neuhausen. 1 deposit of a glassy slag; 2 furnace base; 3 layers of crushed slag, limy stones and ore; 4 charcoal store; 5 roasting place. After Kempa and Yalçin 1995.

in the Weald of south-east England (Money 1971), situated close to an early Romano-British bloomery (Money 1974). Two phases were identified in the mediaeval establishment which dates from the 15th century (Fig. 21: 6). The earlier produced the remains of a smelting furnace and two slag heaps near which was a sunken roasting hearth. The bloomery was more complex in its later phase, with the furnace being rebuilt and housed in an 8m x 11m timber-framed building with stone foundations. There was some smelting debris outside the entrance to the building, but most was dumped on a third slag heap to the north-east. A dump of charcoal was found against the north wall and a small deposit of roasted siderite ore in its south-west corner. The earlier roasting hearth was replaced by a U-shaped hearth outlined in stone, which, when excavated, was found to have a heap of unroasted ore in it. Roasted ore refuse partly covered one of the earlier slag heaps and the whole working area measured some 400m^2. To the south of the building which housed the smelting furnace was another structure (probably unwalled) with a scatter of limestone at its entrance. It is possible that this had been used as a flux, since a small amount of vitreous slag with a low iron oxide content was found on the third slag heap. It was not possible to establish the type or dimensions of the furnace and no estimate was made of the output of the plant, although an attempt was made to reconstruct the form of the building (Rigold, in Money 1971, fig.10).

The earliest blast furnace ironworks

Although the theme of this chapter is bloomery ironworks, it seems to be unavoidable to close it without some brief comments on the earliest plants where the indirect process was practised.

Several decades ago, the regular smelting of cast iron was believed to have been first introduced to the Rhineland during the 14th century. Recent archaeological discoveries, however,

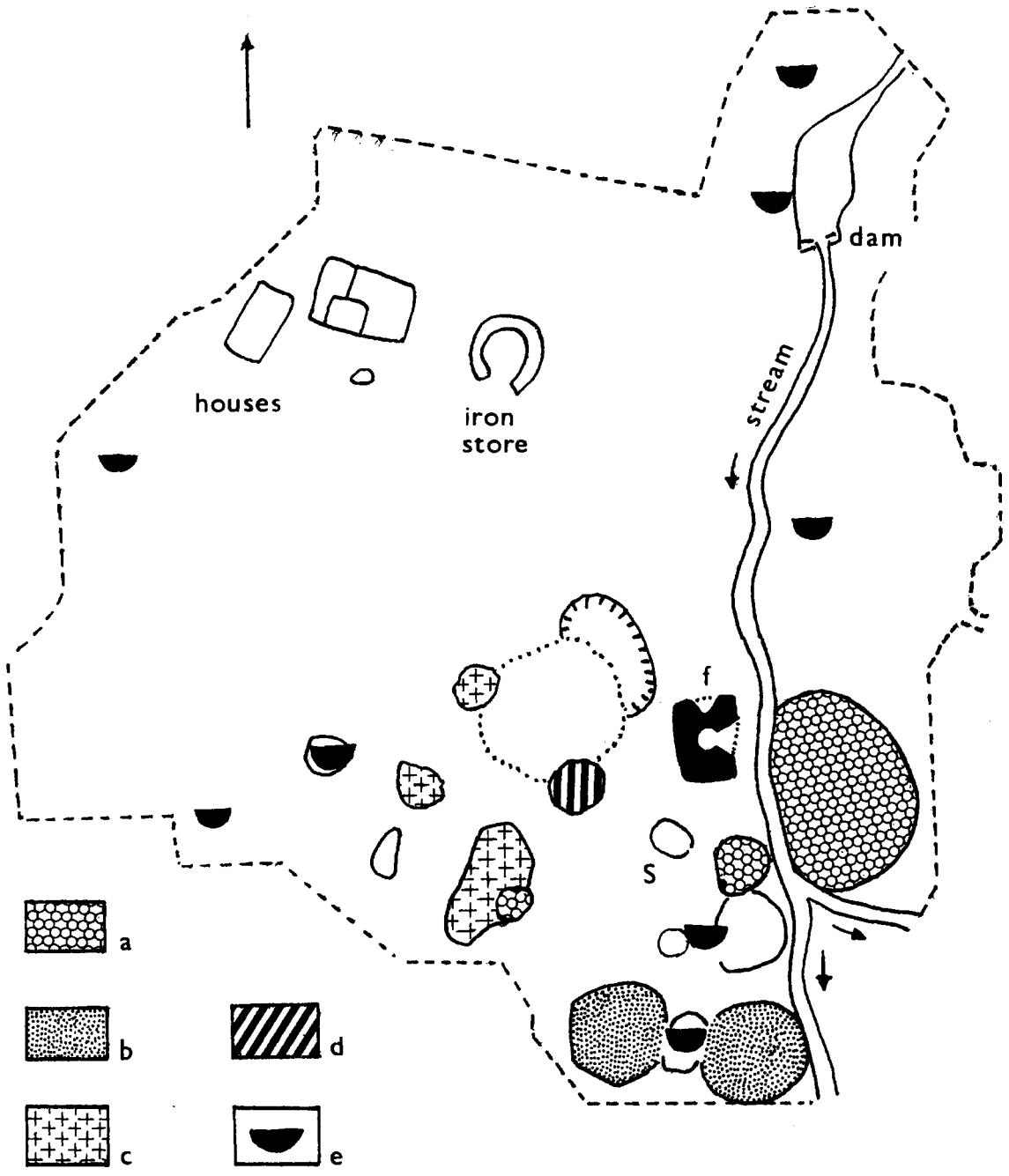


Fig. 23. An early *Flossofen* furnace plant at Lapphyttan, Norberg area, Sweden. Symbols: f furnace; S roaster; a glassy slag; b possibly finery slag, c iron ore; d charcoal store; e finery hearth. After Magnusson 1985.

have thrown new light on the beginnings of this revolutionary change in ironmaking technology. Despite data from several European regions including the upper Rhine valley and Scandinavia, the process of adoption of the indirect method of iron smelting is far from being definitely explained. It does seem to have been preceded there by a certain period of experimentation which is traceable at least as far back as the time around AD 1000. Several process plants of the new type have been excavated and evaluated analytically, and we shall include the most important of them in this survey, roughly according to their chronological position. This may sometimes be a little puzzling, because available dates are often only radiocarbon measurements. Fluctuations in the radiocarbon calendar leads to uncertainties when other forms of dating are not available for purposes of comparison.

In the early 1990's, a research project conducted in the Schwäbische Alb in south-western Germany produced, apart from bloomery remains of the Migration and early Mediaeval periods, several ironworks which diverge from the usual pattern in terms of their products. Excavations at Metzingen revealed the base of a clay-built reduction furnace (outer dia. 150cm x 170cm) with 50 tonnes of slag debris deposited on a steep slope below. Nearby, to the west, were a store of iron ore and a roasting hearth, as well as a charcoal dump (Kempa and Yalçin 1995). The slag from the site is glassy, with an iron content below 5% and is, in fact, the product of a blast furnace. Tongue-shaped lumps of phosphorus-rich iron (0.7 to 2% P) showing levels of carburization between 0.94 and 2.5% C, were found in the slag heap. The metallographic structures indicate an iron-carbon alloy with austenite, ledeburite and cementite (Hauptmann and Yalçin 1992). There is a problem in determining the air-supply for the furnace uncovered as the plant is situated on the edge of a slope and no trace of the use of water power to drive bellows could be identified. Thus, the furnace must either have been very high to produce the necessary chimney effect and secure high temperatures, or else must have been equipped with numerous tuyeres as was the case in some eastern installations such as at Velikiye Bolgary (Efimova 1958) and, in fact, numerous clay tuyeres were found at the site. Radiocarbon dates established a chronology from the 11th to 12th/13th centuries. According to surveys, there are at least 30 sites of this type in the region (Fig. 22).

The ironworks at Haus-Rhade near Lüdenscheid, Märkischer Kreis (Rhineland) was excavated in the early 1960's (Sönnecken 1977), but did not attract any special attention at the time (Pl. XXI: top). A stone-walled smelting furnace with an inner hearth diameter of 150cm (the lining had been demolished) was situated close to the Kierspe stream which apparently drove a water wheel behind a stone wall on its western side. The furnace was surrounded by two kinds of slag, one heavily fayalitic with a 50% FeO content, the other a glassy, low-phosphorus slag with an iron content of some 4 – 6% and 30 – 50% SiO_2. This mass contained spheroidal cast iron particles with graphite flakes. It was formerly believed that the furnace, called a '*Massenhütte*' was able to deliberately produce either blooms or cast iron. Recently, however, the heavy iron-rich slag has been interpreted as finery waste (Sönnecken and Knau 1994). At a distance of about 20m from the furnace, a stone-walled smithy was subsequently excavated, producing tools and other iron items. The ironworks at Haus-Rhade is dated by pottery to the period from the late 13th to 14th centuries AD, later confirmed by radiocarbon dating. The smithy apparently worked in the later phase, since the associated pottery dates from the 14th to 15th centuries. In the light of further discoveries in the same region, there is no doubt that this was one of the very early blast furnaces of '*Flossofen*' type. Several '*Massenhütten*' which date from the 13th – 15th centuries were located in the area of Lüdenscheid and Kierspe, for example at Wippertal, Hemecke and Wehe. The most important of these is the ironworks discovered in a stream bank, now at the bottom of an empty dam on the Jubach river (Knau and Sönnecken 1993). The stone-walled base of a smelting furnace of outer dimension 4.7m x 4.7m (internal hearth diameter 170cm, lining removed) was accompanied by 6 finery hearths (Pl. XXI: bottom). The smelting slags were glassy, siliceous and apparently low in iron, while the finery waste was heavy

and contained much iron (analyses still unpublished). The composition of a lump of semi-fined iron (*Massel*) was determined as 2% C, 2.59% Si, 0.5% P and 0.5 – 0.6 % Mn, its structure showing both lamellar and globular graphite. As at Haus Rade, the pottery and radiocarbon dates indicate the period of production as covering the 14th to 15th centuries, although deposits in the close vicinity yielded some 13th century sherds. Recent excavation work at Kerspe by Jöckenhövel and Willms (1997; 1998), the detailed publication of which is in progress, has revealed the damaged ironworks with remains of two primitive clay-built blast-furnaces, with water-driven bellows.

The ironworks at Lapphyttan near Norberg in Sweden (Fig. 23), investigated completely by large scale excavation in seventies and published in 1985 (Magnusson 1985; Björkenstam and Fornander 1985) is now famous. A smelting plant covering some 0.5 hectares was discovered, the central feature of which was a stone-walled furnace (*Flossofen*) with preserved lining in the form of a bosh (outer dia. 5m x 5m, basal hearth diameter 40cm, Pl. XXII). It was situated by a stream bank with a dam and a water reservoir to the north (Fig. 23) to allow for the supply of air by water-driven bellows. Excavations uncovered three heaps of blast furnace slag (3 – 5% FeO, ca 50% SiO_2, with a low phosphorus content of 0.0 to 0.06% P_2O_5). Manganese contents centred either around 11% or 3%, indicating the use of two kinds or iron ore from different mines in the region. At the tapping hole of the furnace, white and grey cast iron droplets (3 – 4% C, about 0.03% P) were found. The cast iron was fined in stone-lined finery hearths of dimensions 80cm x 50cm, seven of which were reported and the finery slags, deposited as 4 piles of debris, were, again, rich in iron (about 50%). The finery process yielded wrought iron of the *osmund* type (0.160 – 0.585% C), samples of which also came to light.

It is clear that the site of Lapphyttan represents a fully-developed and organized plant where the indirect process of iron smelting was performed on a considerable scale for export via Stockholm, Gävle and other ports. It is dated to a very early period with radiocarbon measurements giving average values for the 12th to 14th centuries, while thermoluminiscence measurements made on refractory linings indicate the period AD 1250 – 1400. Was the smelting and fining at Lapphyttan the product of indigenous development in a most effective ironmaking area (*bergslaget*, Magnusson 1994), or the result of cultural and commercial interaction between western Germany and the North, by way of the vigorous 13th century traffic through the Baltic Hanseatic ports? We may note the other, equally early sites, which have been discovered in Sweden at Vinarhyttan and Juteboda (Serning 1985), although it is not possible to comment on the announcement of radiocarbon dates from the blast furnace site at Moshyttan near Nora which give values from the 10th to 12th and from the 12th to 15th centuries (samples 1, 4.1, and 2, see Wetterholm 1996, 165), since no other data concerning the site and its installations have so far been published.

The present state of research both in the Rhineland and in Scandinavia forces us to keep the problems surrounding the introduction of blast furnace technology to Europe under review.

*

From all of this, we can see that prehistoric and mediaeval bloomeries differed substantially in their layouts, forms, and areas occupied, as well as in their internal concepts, and the organization of those manning them. Naturally, they also differed in their production capacity, although such estimates must be treated cautiously and critically, even though they offer the basis for a sort of rough classification. For instance, the amounts of bloomery slag calculated to have been produced by individual workshops can be informative, in spite of possible errors.

Small ironworks may be characterized by levels of 0.5 – 1.5 tonnes of waste as at Mšec, Bryn y Castell, Crawcwellt and Olomučany. Medium size plants such as individual sites in the Holy Cross Mountains, Boécourt, Ewersbach and Želechovice, left from 5 – 30 tonnes of slag, while installations including Martys, Clérimois, Ashwicken and Ahrweiler, with intensive production,

were responsible for dumps of waste comprising hundreds and thousands of tonnes. The amount of bloomery slag surviving allows a rough calculation of output of iron, usually taken to be on average around 25 % of the weight of slag.

Chapter V

IRON ORES, MINES AND MINING

The use of the word 'mine' in the title of this chapter is perhaps somewhat misleading, since 'mines' in the accepted modern meaning of the term — extensive underground systems of galleries, adits, and shafts or large opencast excavations — were rarely used in the prehistoric and early mediaeval periods for the extraction of iron ores.

Iron occurs in the form of oxides and other compounds at low levels in every type of soil, and more concentrated deposits are also very widespread. As a result of physical and biochemical processes over geological time, iron-bearing minerals tend to concentrate near the surface of the earth, and also, in the form of weathered outcrops, in the upper levels of bodies of other metal ores, such as the sulphide minerals of copper (gossans). Since iron ores were so easy to extract, prehistoric man, with his initially limited requirements for iron, was not compelled to undertake complicated underground mining operations, unlike those working with other metals, such as copper, lead, silver, and gold, who had already been exploiting underground ore bodies for a very long time when iron smelting began. He collected high-grade ore on the surface or excavated it at the surface outcrops of deposits. As the applications of iron grew, however, so did the demand for iron ore, and consequently early ironmakers would have been obliged to adopt the more sophisticated techniques of underground mining in order to ensure supplies of iron ore in sufficient quantity and quality. The methods of iron ore mining were, of course, always determined by the nature and morphology of the ore deposits being exploited.

Ore deposits

Minerals with metallic contents high enough to permit the economic extraction of metal are known as 'ores'. Given that knowledge of metallurgical technology increased over time, what may have been judged economically feasible as sources of metal by earlier generations of metalworkers may not today be accepted as such by modern specialists. For the earliest metallurgists, it was not so much the quantity of ore that was the decisive factor, but much more the quality of the mineral and, in the case of iron, they would not normally have attempted to exploit ores containing less than 55 – 60 % Fe. Deposits of ores which which are suitable for exploitation are known as 'ore bodies'. Again, the minimum economic size of an ore body is dependent upon the technology available and its socio-economic background, so that relatively small deposits that were readily worked in antiquity would not be considered viable today.

Ore bodies result from processes taking place in the magma, which becomes heterogeneously saturated with metallic materials. One method of ore formation is through magmatic differentiation. As the temperature of magma decreases, the solubility of metal-bearing constituents also decreases and they begin to segregate. Magmatic deposits of this kind are to be found in igneous rocks. Another mechanism is the pneumatolytic entrainment of particles of metal bearing components of the magma by gases such as chlorine and fluorine, to become interbedded as ore heads. When the transport medium is thermal water, the resultant ore is termed hydrothermal.

Ore that has accumulated at the boundary between a volcanic feature and the rocks surrounding it forms contact deposits. Minerals often force their way upward under pressure, filling crevices and fissures in the strata, and in some cases working their way to the surface, to produce ore veins. Following chemical attack on soluble rocks such as dolomites, metallic minerals may be altered, resulting in the creation of metasomatic and contact metamorphic deposits. The permeation of porous rocks changes them to disseminated deposits. Larger local agglomerations, known as ore 'pockets' or 'lenses' were exploited by the miners of antiquity by means of pits or shafts.

Erosion and denudation of the surface of the earth causes such primary ore bodies to become displaced and form secondary sedimentary deposits in sands, gravels, and clays. As a result, ancient miners were confronted with subterranean layers and beds of sedimentary ores. Certain metals such as gold and metallic ores such as cassiterite (tin ore) and magnetite (iron ore) were subjected to further displacement in particle form by the activity of water and became readily accessible as placer deposits in streams and rivers.

The ores of iron

The creation of metal from a heavy stony material (ore) was the miracle achieved by one of man's first pyrotechnological skills. Metallurgy began with the reduction of metallic copper from its ores and we have already seen that the earliest production of iron was closely associated with the smelting of copper ores. It is now widely accepted that the accidental production of particles of metallic iron would have resulted from the smelting of chalcopyrite ores with a significant iron content or from the deliberate addition of iron ore to copper smelting furnaces as fluxes to facilitate slag formation.

Iron ores were recognized as such by man early on, since its limonitic form ($2Fe_2O_3.3H_2O$ or $Fe_2O_3.2H_2O$) were products of the weathering of the upper oxidation zone of chalcopyritic copper ores ($CuFeS_2$). This process was greatly assisted by biochemical processes, in which *Thiobacillus ferroxidans* played an important role.

Limonite or brown ironstone (*Brauneisenstein*), is one of the oxide ores which would have been of great importance in early iron metallurgy, since it occurs in the form of a weathering layer (gossan) that seals the upper surfaces of deposits of ores of other metals, such as copper and lead, and also of other iron ores, such as haematites, carbonates and silicates. It was easily identifiable and, of even greater importance, easily reducible using early metallurgical technology. There are many types of limonite (which also occurs as a distinct ore formation). Certain rocks, especially limestones, and tertiary sands and other sedimentary deposits contain layers of limonite in the form of geodes or nodules or as globular grains (ooliths, pisoliths — so-called 'pea-ores', *Bohnerze*, *minette*). Deposits of this kind are known from many regions of Europe, for example in the south-eastern Alpine regions, southern Germany, Lorraine and Belgium and have been exploited for ironmaking since the Iron Age. Good quality limonites may contain up to 60 % FeO, and certain localized deposits contain 0.5 – 2% manganese or 0.1 – 0.2 % phosphorus (as P_2O_5), while others are practically free from impurities.

River flood plains, water meadows, blanket bogs, river banks, and regions of lakes and marshes, above all in the great North European plain, stretching from northern France to northern Russia, contain sedimentary deposits of iron hydroxides and limonites known as **bog iron ores**. In some regions, notably Scandinavia, the variety known as 'lake-ore' is still in the process of formation today as the result of sedimentary processes in iron-rich waters. Bog ores are porous and easily reducible, but their iron contents vary considerably, so that only enriched or selected ores could have been utilized by early ironmakers. They usually have high phosphorus contents (0.5 – 3%), and often manganese as well and have been used since the Iron Age, especially in those areas where there was no easily-accessible source of higher quality ore. In the early Middle Ages they were very widely exploited in northern Germany, Poland, and Russia.

Goethite FeO(OH) is a hydrated iron oxide containing up to 60% Fe, which was also used in certain regions in antiquity. Goethites, like limonites and bog ores, vary in colour from brown and ochre to a lustrous black.

Haematite or hematite (red iron-stone, *Roteisenerz*) Fe_2O_3 is a very good oxide ore, containing up to 60 – 70% Fe and is usually (but not always) low in manganese and phosphorus. It is often the main constituent of vein- or lode-iron ore, below the weathered limonite layer and also occurs in pockets of metasomatic limestones. There are several forms of haematite, including clayey, oolitic, and filamentose. Specular haematite or iron-glance is a lustrous form, while

kidney ore is reniform with a metallic lustre. Haematite has been smelted from very early times, possibly because it sometimes occurs in close association with red copper oxides (cuprites), to which it is similar in external appearance. It is worth noting that where the choice was available, this high quality ore was usually preferred by early ironmakers working on a modest scale and it was not until increasing consumption demanded more intensive working that the more abundant, but lower quality, limonites and bog ores were exploited.

In many regions haematite and its weathered form, limonite, are to be found as the conglomerate known as **ferruginous sandstone** (*Eisensandstein, Ortstein*). In this type of formation, the iron contents are usually low, of the order of 10 – 20 %, but in some cases there are local enrichments where the 'reddles' and 'buckshot' seem to have been welcomed as a source of raw material for small-scale ironmaking operations, since quantities of ferruginous sandstone have been found among debris at central European Celtic and Romano-Barbarian bloomery ironworks where there was no identifiable major ore deposit in the immediate vicinity.

Magnetite (Fe_3O_4) is the highest grade of iron ore, containing over 70% Fe. It is black or blue-grey in colour and magnetic. It occurs as a primary constituent of igneous rocks, as intrusions in metamorphic rocks such as the *skarn* ores of Scandinavia, and even in sedimentary residual clays and in placer deposits (the 'black sands' of northern Asia Minor, Africa, New Zealand, and elsewhere). Its dense texture makes it difficult to reduce, and at one time it was generally held that magnetites were not used by ancient ironmakers. It is now accepted that the ore could have been used in a roasted form in early bloomeries. Magnetite sands are recorded as having been collected for smelting by indigenous ironmaking groups in West Africa and elsewhere at the end of the 19th century, while they were exploited in eastern Macedonia (Photos *et al.* 1989). There is also good reason to believe that the north Pontic magnetite sands, in the land of the legendary Chalybes, were smelted in antiquity. In Europe it has been shown that high-grade magnetites were being smelted, mixed with haematites, in 8th – 9th century bloomeries such as Želechovice, Dolní Sukolom and Brníčko in northern Moravia (see chapter IV). **Ilmenite** $FeTiO_3.nFe_2O_3$, a type of magnetite of high titanium content, occurs, for example, in Norwegian beach sands, and may have been used in antiquity for iron smelting.

Siderite (spathic ore, chalybite, *Spateisenstein*) is a yellowish, brownish or grey iron carbonate $FeCO_3$. In most cases, it occurs in hydrothermal veins or sedimentary deposits, being transformed by weathering on its upper surface to limonite. It may contain up to 50% Fe, which can be partly substituted by manganese (2 – 9%), while the phosphorus content is usually low (0.01 – 0.02%). After roasting (which converts it to haematite), siderite constituted a valuable charge for early bloomery furnaces in regions such as the Weald of south-eastern England, Styria (Erzberg in Austria), and the Siegerland (Germany). Oolitic and clayey forms which have high alumina contents are known as **sphaerosiderite** and **pelosiderite**.

Hydrated silicate ores of the **chamosite** and **thuringite** type $Fe, Mg_3Al_2SiO_5$ occur in Switzerland, central Bohemia, and central Germany. They were of importance to early iron smelters in the form of their weathered limonites. In Africa primitive iron smelters often used **laterites**, rich in iron and alumina: 40 – 50% Fe_2O_3, 22 – 44% SiO_2, 10 – 15% Al_2O_3 (Métallurgies Africaines 1987; Keesmann *et al.* 1983). Laterite are products of tropical climate and may also occur in other parts of the world where, in the geological past, relevant conditions prevailed. They were certainly among the earliest exploited in Ireland where their high aluminium and titanium contents mark them out (Scott 1990, 154).

All of the types of iron ore referred to above may appear not only in their pure forms but also as mixtures, for example when ooliths occur together with haematite and goethite.

The reduction of iron from **pyrites** (FeS_2) and the other sulphide ores such as marcasite and pyrrhotite was one time considered impossible, because of the undesirable mechanical properties conferred on the iron by the high sulphur contents (hot-shortness). Recent work at the Butser Iron Age Farm in England has shown, however, that natural weathering of nodules of

marcasite that are common on the Chalk Downs of southern England effectively converts them to limonite, and these have been successfully smelted in a reproduction bloomery shaft furnace (P.J. Reynolds, pers. comm.). It is possible that pyritic ores were used in antiquity, at least locally, in the roasted form (see Chapter VI), since roasting would drive off most of the sulphur in the ore.

Iron ore deposits in Europe

There is no place in this survey of early iron smelting and its archaeological remains for an exhaustive account of the deposits of iron ore throughout the world, or even in Europe. Iron ore is very widespread in its occurrence, as already noted, though in terms of the modern iron and steel industry the number of economically viable deposits is dwindling and European iron mines are being closed.

The ancient ironmaker, with his small-scale production, was in any case not dependent upon the rich and large ore bodies that have become so important in the modern world. His requirements could easily be met from very small deposits of bog ore or weathered limonite and haematite outcrops in the immediate vicinity of his settlement. Ancient ironmaking is frequently attested in areas where modern surveys of mineral resources make no reference to the occurrence of iron ore. This does not mean, of course, that the major deposits were neglected in antiquity. The archaeological record shows that many of them were discovered by early prospectors and worked, especially when there was a demand for more intensive iron production. In such cases, ironmakers would be drawn to these areas, probably abandoning their localized small-scale smelting operations. The following are the most important iron ore deposits known to have been exploited by ancient and mediaeval ironmakers.

The high grade specular haematites and magnetites in the metamorphic limestones of the island of Elba off the west coast of central Italy (Dessau 1974) were exploited at least as early as the Greek colonization of the 8th century BC (Buchner 1969). They subsequently played an important role in the Etruscan, Roman, and Pisan periods, according to many ancient authors and mediaeval documents.

Further north, smelting of the ores of Noricum yielded the *ferrum noricum* which was so highly prized in antiquity. These were largely Silurian metasomatic siderites and associated weathered limonites, notable for their high manganese contents. They were worked from the late La Tène period onwards near Hüttenberg in Carinthia, and also later, in the Middle Ages, at the Erzberg (Ore Mountain) of Styria where ore extraction is currently coming to an end. The Burgenland of eastern Austria, below the eastern foothills of the Alps, has less important deposits of sedimentary clay ironstones in nodular (kidney) form which occur in the sands and clays of the Oberpullendorf Becken (Schmid 1977). They were collected from the surface and mined as early as the La Tène period, and continued to be an important source of raw material for ironmaking throughout the Middle Ages. These deposits extend into western Hungary.

Iron ores are also known from Bavaria and Swabia. The 'dogger' pockets and lenses of tertiary limonite were first mined by Celtic ironmakers, and also on a small scale in the Middle Ages. The Swabian Cretaceous limonite ores (*Alberze*) around Amberg and Sulzbach, which contain up to 50% Fe, were the basis of substantial mediaeval and post-mediaeval mining operations (Schwarz *et al.* 1965/1966; Ress 1950, 205). In Württemberg, to the south-west, several kinds of iron ore (oolitic limonites and high-grade goethite *Eisenschwarte*) were exploited through the La Tène, Alamanian and early mediaeval periods (Beiträge 1995, 24 – 31).

Iron ore deposits, veins of haematite, siderite and goethite in the subalpine regions of Italy (Val Camonica) were exploited at the decline of antiquity, in the 7th century AD, and in the Middle Ages (La miniera perduta 1999).

In Switzerland, the sedimentary Jurassic limonites around Gonzen in the Jura were worked in antiquity. La Tène and Roman ironmaking centres have been investigated, first in the Bernese

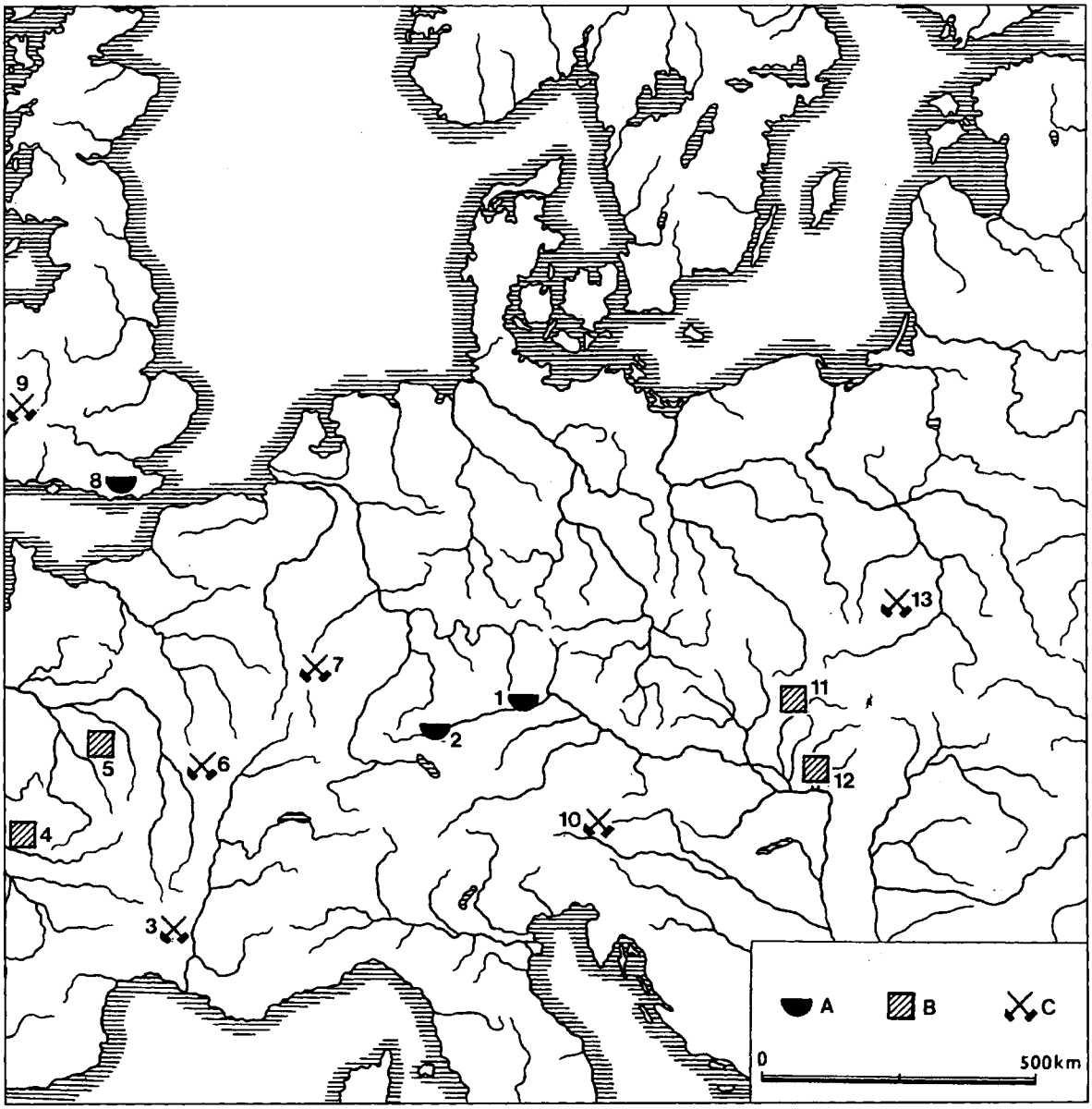


Fig. 24. Ancient iron mines as attested by archaeology or written records. 1 Kelheim, 2 Donaumoos, 3 Hérault, 4 Petrocorii, 4 Bituriges, 6 Thoste, 7 Camp d'Affrique (?), 8 Weald of Sussex, 9 Forest of Dean, 10 Hüttenberg, 11 Cotini, 12 Sidéorucheia of the Quadi, 13 Rudki (Holy-Cross-Mountains). Symbols: A Opencast work, B Written remarks, C Underground mining.

Jura and later in the Jura Vaudois, north of Lausanne, by Pelet (1973, 1993) and by Eschenlohr and Serneels (1991). The dogger oolitic limonites of the Schaffhausen region were probably being worked in the Migration period, and were certainly used in bloomery ironworks and hammer-mills in the 15th century (Fehlmann and Rickenbach 1962; Guyan 1965).

Two important ore-bearing regions lie further north, to the east of the Rhine valley. Siegerland, with its Devonian hydrothermal veins of siderite and weathered limonite outcrops (40 – 67% Fe, 0.2 – 15% Mn) was known to Celtic ironmakers (Stieren 1935: Hauptmann and Weisgerber 1983). The Lahn-Dill area, to the south of the river Sieg, is rich in high grade Devonian sedimentary haematites and limonites, with up to 45 – 55% Fe and was being exploited by the Middle Ages. They are being submitted to detailed analysis carried out as a part of a research project started in 1990 (Willms 1992).

A band of Lower Silurian (Ordovician) iron ore deposits in Bohemia stretches from the south-east as far as Prague, and was of considerable importance until the end of the 19th century. It is made up of sedimentary oolitic haematites, limonites, and chamosites and, despite its high phosphorus content, was exploited — principally in its weathered form — from the La Tène period onwards (Pleiner 1958). Two iron ore deposits in Moravia are worth mentioning. Bands of high-grade Devonian exhalation magnetites/haematites were being smelted in the 9th century AD (Pleiner 1955; 1958, 213 – 214), a time when weathered ores containing 60 – 80% Fe_2O_3 were available for smelting. They are part of the Jeseníky ore tract (Freiwaldau — Frývaldov) important for mediaeval export. In western Moravia, around Blansko, limonites occur in the Jurassic limestones, and smelting began here in the late Romano-Barbarian period (3rd – 4th centuries) and continued right up to the present century.

The Slovakian Ore Mountains (Slovenské Rudohorie), which are rich in epigenetic Triassic siderites and weathered limonites, were certainly being exploited in the Celtic and Romano-Barbarian periods, according to comments by Tacitus and Claudius Ptolemy, and archaeological research has recently started in this area. Further south, on the border between Slovakia and Hungary, the Paleozoic and Mesozoic limonites of the Bükk Mountains were being worked in the 10th – 11th centuries (Gömöri and Kisházi 1985).

In Poland, the Kielce-Radom region has Lower Devonian and Upper Triassic siderites, haematites, and limonites, which began to be used in the La Tène period. The extensive Holy Cross Mountains iron production was based on these ores.

In the British Isles, the most important iron ore deposit in antiquity was that of the Weald of south-eastern England (Worssam in Cleere and Crossley 1985). Iron was being made there from the 1st century BC, as shown both by excavations and by the reports of Caesar in his *De bello gallico*, and there was also an important industry here in the mediaeval and early post-mediaeval periods. Bedded siderite nodules and limonites are found in Cretaceous clays and sands over a considerable area. The limonites in the dolomites of the Coal Measures of the Forest of Dean, lying on the border between England and Wales north of the Severn Estuary, were being worked by the Romans, and continued in use well into the early modern period (Tylecote 1962a; 177 – 179; Bridgewater 1968). In Ireland, the interbasaltic laterites of Co. Antrim were probably being smelted from the start of iron-use in the later 1st millenium BC, while the extensive siderite deposits around Lough Allen in Co. Leitrim were exploited through to the early 18th century AD (Scott 1990, 154) and perhaps later.

In Spain, very important ore deposits occur in the northern part of the country (Bilbao, Somorostro) where siderites and haematites, as well as weathered limonites constitute one of the largest European resources. Little is known about their use in antiquity. Smaller sedimentary ore accumulations in the Ebro valley and elsewhere were exploited by local smelters. Limonitic gossans of the famous non-ferrous deposits at Rio Tinto may also have been a potential source for ironmaking.

French iron ores, occurring in many areas, especially around the Massif Central, for example

in the Montaigne Noire (Sablayrolles 1989b), Nièvre (Bouthier 1982) and in the departement of Yonne (rich limonites and goethites, see Monot 1964, 280 – 282) or Morvan (Mangin *et al.* 1991), were used extensively, especially in the Gallo-Roman period and subsequently in the Middle Ages, many of them having been exploited in Cistercian ironmaking activity. The ores of the Franco-Belgian border region, including minettes and haematites, were also used in the early metallurgy of iron (e.g. Cauet and Mathieu 1989; Leroy 1997).

Sweden is one of the European countries that still supplies ore to the modern iron and steel industry (though in decreasing quantities), mined from the famous magnetite deposits of Lappland around Kiruna and Gellivara. The earlier ironmakers in Sweden made use not of these rich ores, but of smaller deposits located much further south. It was thought at one time that only bog- and lake-ores of the type widely exploited during the winter season in post-mediaeval times were used. But more recent work (Arrhenius 1967), based on the analysis of ore and artefact samples, has shown that weathered outcrops of magnetite and haematite were being exploited at a very early period. Magnetite sands occur on lake shores in Sweden, in Dalarna for example, and were collected for smelting in the Viking period (Serning 1979, 52 – 61).

In the east of Europe, in steppe and forest-steppe zones of Ukraine, mainly bog ores were exploited from the Iron Age onwards (Bidzilya *et al.* 1983, 20 – 26).

Many other iron ore deposits in Europe have had to be omitted from this survey, which has concentrated on those which are of greatest importance for the study of early ironmaking. There are, moreover, thousands of sites where archaeological research has attested ironmaking activities in regions where modern geologists and mining engineers would not recognize the existence of significant iron ore resources. Careful plotting and analysis of these sites would serve to demonstrate dramatically the mineral wealth of Europe and its importance to the European economy from prehistoric times through to the Middle Ages and beyond.

Iron mines

There is a striking disproportion between the scanty evidence for early iron ore mining on the one hand and the wealth of archaeological information about iron smelting on the other. The explanation for this is self-evident. Iron ores are, as we have seen, widely scattered over the entire Old World and were easily accessible to the early ironmaker, whose requirements were, for the most part, so modest that they could be met simply by collecting ironstone outcropping from the known ore bodies. Shallow opencast workings would quickly be obliterated by subsequent cultivation or other activities, leaving no trace in the archaeological record. Small deposits could be identified and worked out by early ironmakers, leaving no evidence of their existence or working. Little is therefore known about ancient iron ore mining in comparison with the copper, lead, silver and gold mining of antiquity, which began in the Chalcolithic period in the Near East, the Mediterranean lands, and the Alpine massif and were highly organized, technologically well-developed, and often comprehensively documented by modern research. Opencast mining at varying levels of intensity was the predominant method of ore extraction for a long period, and it may be assumed generally to have been confined to the area in the immediate vicinity of the ironworks.

Opencast workings

Some reports on field investigations of ancient opencast ore mines have been published, but with a few exceptions, these are not detailed studies.

On the moors between Ingolstadt and Neuburg, near the Danube in southern Germany, there is a plain known as the Donaumoos. Near the village of Karlskron, strings of shallow pits, with diameters ranging up to 10m and surviving to about 0.5m deep, some of them filled with water,

have been studied. They would have served to gain access to bog iron ores in tertiary sands lying 10 – 20cm below the surface. These have been interpreted as iron-ore pits and associated with the La Tène bloomery ironworks in the neighbourhood (Seitz 1938, 461, figs. 3 and 4).

A very clear picture of Celtic opencast iron ore extraction comes from investigations at Kelheim in Bavaria, within the ramparts of the Michelsberg *oppidum* (Schwarz *et al.* 1965/66). An area about 1km^2 is dotted with irregular pits and pit-complexes with re-entrants and bays. They are 5 – 15m wide and up to 0.7m deep. The ironmakers were apparently in search of limonite nodules, which occur in pockets in the chalk. Some radiocarbon dates suggest that this activity took place around 190 ± 120 BC, although one date gave a date of 90 BC – AD 230, which is surprising since there are no Roman finds from Kelheim. The Celtic pits, cut through by later workings, were this exploitation recommencing in the early Middle Ages (see below).

With regard to Gaul, it is suggested that there was a mining area at Clérimois, in the territory of the Senones (Dunikowski and Cabboi 1995, 39). Some 20m to the west of the Celtic or Gallo-Roman ferrier 1, 13 pits were excavated, one of which (pit 16) measured 7m in diameter and was 2m deep. These pits produced fines from limonitic ore.

In France, one of the regions best studied in terms of aerial and field survey is Morvan where fields of mining pits, referred to as 'minières' have been observed (Mangin *et al.* 1992, 75 – 135). The shapes of the opencast workings depended on the forms of the ore outcrops which were, in some cases, exploited by quarrying (Grand Champs, Chaudemain), or by digging long trenches. In the area around Thoste, these trenches reach 80m in length, are 3 – 4m wide and are preserved to depths of 20 – 70cm (*op. cit.* figs. 36, 39, 45). These traces of mining are in close proximity to ironworks and are believed to be, for the most part, Gallo-Roman although precise dating is difficult.

Trenches presumed to be of Roman date and extending up to 1km in length have been reported from Zamora in Spain, between Braga and Astorga (see Larrazabal 1996, 169 – 170).

At Petley Wood in the Weald of south-eastern England, some shallow pits, measuring 15 – 20m in diameter and tapering toward the bottom, have been interpreted as being associated with Romano-British ironmaking (Worssam in: Cleere and Crossley 1985, 15 – 16). Funnel-shaped pits 2 – 4m in diameter and 3m deep which cut through a layer of iron ore nodules have been sectioned at Herstmonceux and Rotherfield in the same region (*ibid.* 263) but no dating evidence was found. There is a large number of pits around the large Romano-British ironmaking establishment at Bardown, also in the Weald (Worssam in *op. cit.*, 1 – 30), some as much as 25m across, with several exhibiting a characteristic keyhole plan. One group lies across a track metalled with iron slag and which leads directly into the centre of the Bardown site. All are, however, water filled, and so no investigations have been possible.

In Sweden thousands of small pits (*skarpingar*), which are believed to be associated with iron exploitation (Serning 1979, 56) are still visible. They have not been explored or dated, but it is thought that at least some are from the Nordic Iron Age and Viking periods. Early mediaeval elongated opencast mining pits in rows (about 4m deep, total length 82 km in the Veluwe region of the Netherlands (Joosten and van Nie 1994) have not been excavated as well. The ore mined was high grade lepidocritic 'rattle stones' (Joosten and Kars 1999, 247).

We should make brief reference to an opencast mining site outside Europe. Many years ago a report was published on traces of iron ore workings far to the east, in southern Siberia, in the region of Tuva, near Minusinsk, where weathered carbonate ores were being exploited. Opencast pits were reported from sites such as Sharlan Tey and Kyzil Ezim, forming 80m long chains of pits with diameters varying between 1 and 15m at the latter site. Copper ores of the malachite and azurite types were being mined as well as haematites. One pit, at Kara Sug, is worthy of special comment, since it bears traces of fire and it is possible that this may be evidence of the use of fire-setting to fragment and soften the rock. This site produced some pottery sherds that have been dated to a surprisingly early period, the 3rd – 2nd centuries BC. Diggings following

a lode of magnetite ore found at Chevarlyk and Ak Ezim, measuring 3m x 3m and 4m long, are claimed to represent prototype adits (Sunchugashev 1969, 104 – 110, figs.48 and 50).

Evidence that opencast mining was sometimes carried out on a very large scale in China, has been produced by Li Kuo Li (Hartwell 1966, 48 – 49). The rock was attacked by fire-setting followed by cooling, and it is estimated that 37,000 tonnes of ore were exploited there annually in the 11th century AD.

Some of the iron mines started as open cast extractions, followed by underground work (see below).

Underground mining

Although opencast mining predominated for iron ore extraction in the prehistoric and mediaeval periods, there is evidence that in some areas ore was mined underground. In the written sources, the fullest information is provided by the *Geography* of Strabo, dating from the end of the 1st century BC/early 1st century AD. He knew the locations of the celebrated iron ore mines (*metalla, sidéreia, sidérourgia, sidérorucheia*). These included those of the Chalybeans (then known as Chaldeans) near Pharnacia on the Black sea coast of Asia Minor (12.3.19), the Greek island of Chalkidiki, where he refers to an abandoned mine for both copper and iron ore (10.1.9) and, at the other end of the Mediterranean, the vicinity of Hemeroscopeion in Iberia, also a coastal region (3.4.6.). No archaeological evidence has come from these regions, but the fact that an ancient geographer, who was acquainted with underground mines for the ores of silver and lead, draws attention to them makes it legitimate to assume that these were not mere surface workings. Strabo also refers to iron ore mines in regions where archaeological fieldwork has produced evidence of ancient ironmaking, and these will be discussed when these areas are dealt with below.

Shafts and galleries dug into iron ore deposits in Gaul are mentioned in several reports, but unfortunately, only fragmentary data are available. More systematic exploration is currently being organized in central parts of Gaul. Subterranean Gallo-Roman galleries have been reported at Courcelles Frémoy and Thoste, near the *oppidum* of Alésia in Burgundy (Mangin 1985, 31 – 33). In the ironmaking region of the Morvan, traces of haematite and goethite mining have been recorded at several sites but some of them, as at Brosse Josselin, may have been opencast operations (*carrières*), trenches or bell-pits (Mangin *et al.* 1992). In southern France, shafts and galleries from the same period have been found at Vélieux and Roc de la Balme in Languedoc (Roumilhac 1969).

The Bituriges of central Gaul were renowned for their underground iron ore mining. In describing the siege of Avaricum (near modern Bourges), Caesar comments admiringly on their galleries (*cuniculi*), saying that they were extremely skilled in work of that kind because they operated large iron mines (*magnae ferrariae*, BG 7.22.2). Strabo, too, refers to the iron ore mines (*sidérourgia* of the Bituriges Cubi and, to the north of them, the Petrocorii (4.2.2). The Leuci were considered to be the leading iron ore miners of northern Gaul. Reference is made in the literature to Gallo-Roman galleries which may be of later date at several sites, notably Chavigny, Houdemont, the Forest of Plaimont, and the Camp d'Affrique, but without any details (Deroche 1982). On mediaeval mines in the region, see below.

The iron industry of Gaul appears to have been well organized at several levels and based on underground ore mining. After the Roman conquest it came under direct Imperial control, as shown by epigraphic evidence. The headquarters of the *procurator ferrariarum* was at Lugdunum (Lyon). In the 2nd century, operation of the iron ore mines was transferred to private companies and entrepreneurs *conductores ferrariarum*, who paid royalties to the Imperial *fiscus*, or perhaps to local Celtic authorities supervised by the Gallic Council (*iudex arcae ferrariarum*, see Sablay-

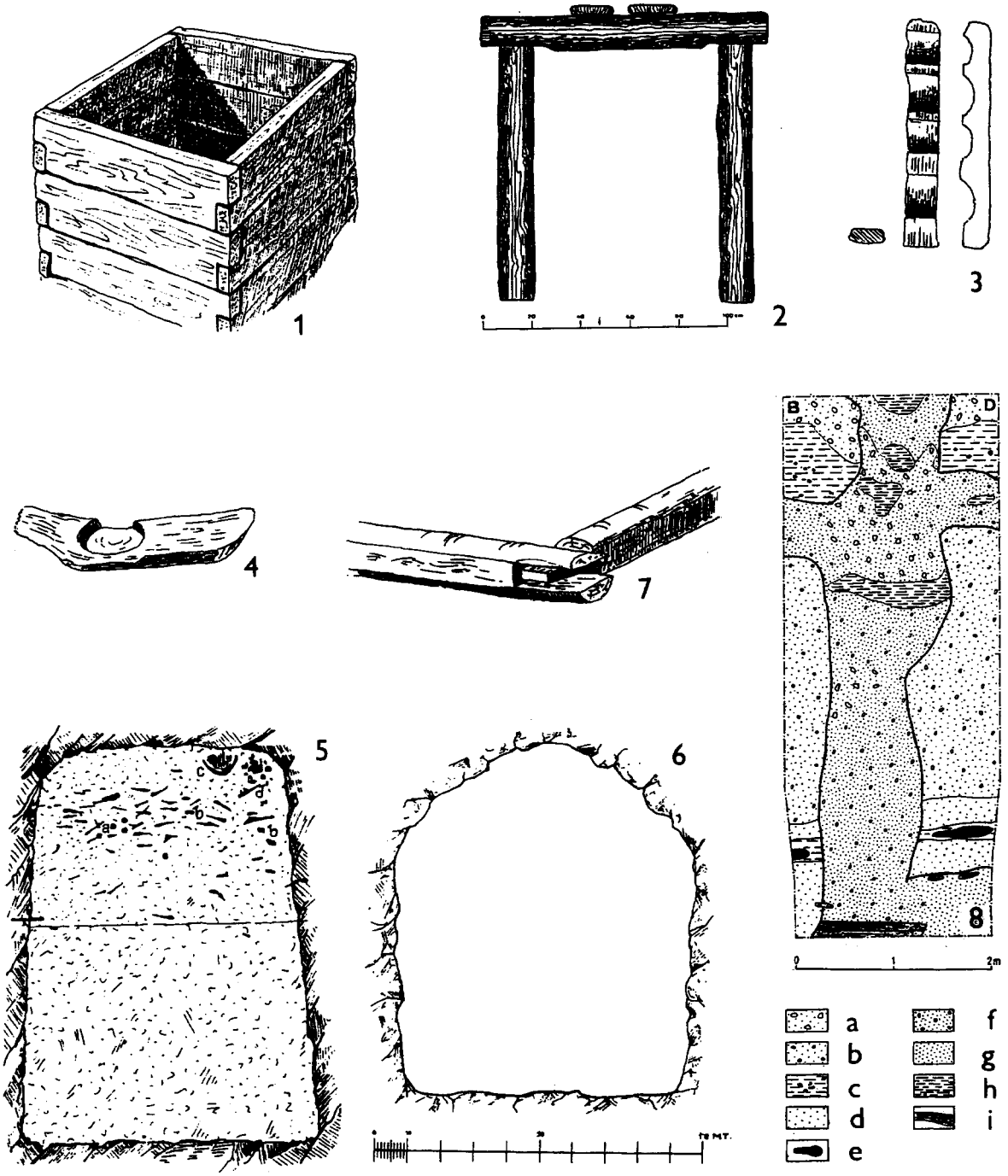


Fig. 25. Traces of ancient and early iron mining in Europe. 1 – 4 Rudki, Holy-Cross-Mountains of Poland, Romano-Barbarian iron mine, about AD 200: 1 Reconstructed frame-work of a shaft, 2 Three-piece timber set of a gallery, 3 Fragment of a ladder, 4 Foot support of a timber leg from a gallery; 5 Hüttenberg, Austria: Knichter Grube, Roman mines of the 3rd century AD — section of rock-cut gallery with human bones and other finds; 6 Hüttenberg-Wilde Keller — section of a rock-cut gallery; 7 – 8 Griesbach — Forst Steinkart, Bavaria, early mediaeval iron mine, 9th – 10th centuries AD: 7 Fragment of shaft timbered frame-work; 8 Shaft of an excavated iron mine. Symbols: a Coarse quartz gravel, b Greenish gravel, c Clay with iron ore nodules, d Fine sand, e Iron ore lumps, shaft filling, f Mixed gravel and sand, g Disturbed fine sand, h Clay, i Timbering. References: 1–3 Bielenin 1974, 1978, 4 State Archaeological Museum, Warsaw (Pleiner 1965b), 5 – 6 Schmid 1932, 7 – 8 Frei 1964.

rolles 1989a).

A better picture of Roman mining techniques is offered by the ancient territory of Noricum (Styria and Carinthia in modern Austria), which was celebrated for its iron products, exported widely in the ancient world, from the La Tène period onwards (Egger 1961). Iron ore workings (*sidérourgia*) there are mentioned by Strabo (5.1.8). Mining at the end of the 19th century cut through Roman adits and galleries in several places near Hüttenberg (Schmid 1932, 177 – 180, figs 4 – 7). Ore pits and an adit, 48 – 50cm wide, inclined downwards at an angle of 18-20°, were observed at Scharfenstein-Watsch. At intervals it widened out into special niches measuring 1m x 1.6m and 65cm deep, cut into the limestone. A weathered form of siderite known as *Blauerz* was the favoured ore.

A gallery of trapezoidal section (Fig. 25: 5) which was discovered at Knicht, north of Lölling, was about 1.6m high and 1m wide and reached a depth of 22m at a distance of 78m from the surface. The scattered remains of two human skeletons testify to an ancient disaster. It has been dated by coin finds to the second half of the 3rd century AD. In addition to pottery vessels and an oil lamp, two iron chisels or gads were found, still embedded in the rock (Fig. 27: 2 – 3). Another Roman gallery, 1m wide by 1.7 – 1.8m high with an underground shaft, its walls still bearing the marks of picks, was discovered at Wilde Keller. Roman rock-cut adits without timber shoring were found some 9 – 10 m below the surface at Zosnerkogel (Fig. 25: 6). These, and other Roman mines in the vicinity, are mentioned in the *Itinerarium Antonini* of the 3rd century AD (revised in the 4th century), which refers to iron ore pits near Candalicae, just to the south of modern Hüttenberg (Schmid 1932).

As in Gaul, these subalpine Roman iron mines were run by specialist entrepreneurs. Inscriptions of the 1st and 2nd centuries from Friesach, Hohenstein, Tieffen bei Feldkirchen, and Aquileia relate to *conductores ferrariarum noricarum.* Their influence seems to have extended to parts of the neighbouring provinces of Pannonia and Dalmatia, although the latter had its own administrative centre at Siscia (Sísak). Ancient iron ore workings, including an adit to a limonite mine said to be 300m long at Lubija, and inscriptions relating to *procuratores* and *conductores ferrariarum* are discussed by Pašalić (1954) and Sergejewski (1963). *Conductores ferrariarum* are also reported from Sarmizegetusa in ancient Dacia (Romania). Cleere (1983) has discussed the organization of the iron industry in the western Roman provinces in the Early Empire.

In addition to the opencast workings in the Weald referred to above, Iron Age and Romano-British iron ore mining is represented by some largely undated opencast and underground mines in the Forest of Dean. At Coleford, a large hollow about 18m x 28m was dug to reach the limonite vein, which was then followed by galleries. There was a similar mine at Great Doward. The Lydney Park Mine (Schubert 1957, 42, fig 6: above) was a sloping shaft with pick-marks on its walls that was quickly abandoned. Coghlan (1977, 15) suggests that it was operated on a trial basis for a short time in the 3rd century. The well-known opencast workings or 'scowles' were also dug to extract the Forest of Dean limonite ores. The Bream example is possibly Roman, since 1st and 2nd century coins have been found there, but none of the 'scowles' has yet been properly investigated. The surface workings at Wigpool Common are undated, but the existence of a slag metalled road connecting this site with the Roman settlement and possible administrative centre at Ariconium (Weston-under-Penyard) favours a Roman date for these workings (Bridgewater 1968).

The influence of Roman mining technology using underground working spread to some areas of barbarian Europe, across the *limes.* As already mentioned, Tacitus (*Germania*, 43) writes of the Celtic speaking Cotini, a specialist iron-producing tribe, who *ferrum effodiunt*, mined their iron somewhere to the north of the bend of the central Danube. In the 2nd century AD Ptolemy of Alexandria knew of and emphasized as exceptional the iron mines *sidérorucheia* in the lands of the Quadi (*Geogr. 2.11*). These have not so far been identified, but they may be within the

area of the Slovakian Ore Mountains. It is not known whether this ore was exploited opencast or underground. Underground working cannot be excluded, since an underground iron mine proper has been discovered and investigated at Rudki, near Kielce in Central Poland, in the major iron-producing centre of the Holy Cross Mountains (Góry Świętokrzyskie).

The Rudki mine (Fig. 25: 1 – 4, Pl. VII: top) is an isolated exception in the barbarian lands. A shallow hydrothermal deposit of siderite, overlain by weathered haematite and haematitic clay (*śmietana*, cream), with 50 – 70% Fe_2O_3 and low in phosphorus (0.05 – 0.14% P_2O_5), began to be mined opencast earlier this century. Traces of ancient log-timbered subterranean shafts and galleries came to light in the course of that work in 1933, and were examined scientifically from 1956 to 1959 (Bielenin 1974, 97 – 126, figs 48 – 64; 1978). Excavation showed that at least two shafts located 55m apart and reinforced with timber shoring had been sunk to the ore body. They were slightly inclined, at an angle of 80^o to the horizontal, and had been deformed by soil pressure. They reached the dolomitic substrate at depths of 16m and 18m respectively. The shafts were extended by galleries that were lozenge-shaped in section, varying in height between 1.3m and 1.87m, as estimated from the many timber props (pine, poplar, birch, beech) that were found and their widths varied between 0.76m an 1.2m (Fig. 25: 2). Mining started from the bottom and worked upwards.

The many timber elements found in the excavation were diverse in form and function, and included props, braces, and planks 3 – 5 cm thick. The functions of other planks which varied in length between 0.7m and 1.4m and in section between 15cm square and 20cm x 30cm were not clear. One charred piece of timber may have been associated with lighting or with the use of fires for ventilating the galleries. The soft nature of the surrounding rock or, better, clay made digging the ore an easy task, and many wooden wedges and picks and two small wooden shovels (Fig. 27: 4) were found, but no tools of iron (Bielenin 1974, figs 61, 63). The exact dating presents difficulties. Older radiocarbon dates for timbers found in the mine conform better with the archaeological sources (beginning of the 3rd century AD) than the new data indicating the period about AD 100 (Goslar and Pazdur 1991).

Recently, initial or alternating open cast mining of high-grade haematites, siderites and goethites, followed or combined by underground work, was described from Bienno-Piazzalunga in the Val Camonica, northern Italy (Morin 1999). An inclined gallery (some 30m long and 0.56m to 1.2m wide, and 10m high) was apparently the result of the overhead or underhead stoping in four etages, leaving a giant narrow slot in the rock. The stope face at the deepest end was only 1m high, less than 1m wide, and some 3m long. The open cast traces represented chains of ditches, about 2m wide and 2m – 3m deep. The date of the Piazzalunga mine is based on radiocarbon dates which indicate the 15th century AD.

*

It would seem from these examples that underground mining was primarily used in areas of large-scale iron production in antiquity, and, after a gap, again in the mediaeval period when the same pattern of small-scale ironmaking based on opencast exploitation of weathered outcrops can be observed alongside more efficient underground mining in regions where the iron production was intended for a wider market. However, the methods of mediaeval underground mining differed considerably from those employed by the Romans, with alignments or extended layouts of ore pits (German *Pingen*) being characteristic for the period. These pits are the depressions created by the backfilling of series of individual shafts (*Duckelbau*) laid out densely over the ore field. This was a somewhat wasteful and labour consuming technique but it had the advantage of not requiring large manpower and elaborate technical equipment. There are several excellent examples from Europe. In the neigbourhood of Oberpullendorf in the Austrian Burgenland, no fewer than 22 such fields of ore pits, each with on average 200 pits, have been recorded at sites such as Zerwald, Djela Wald, Podvornica and Herrschaftsfeld. Some of these,



Fig. 26. Reutern, Germany. Part of a the mine-pit field at "Brunnholz". Symbols: a Mine-pits up to 1m depth; b Mine-pits up to 2m depth, c – d Gangue heaps, e Excavation 1964. After Frei 1964.

such as the Djela Wald field, have been properly surveyed, but the results of trial excavations carried out there not yet been published. The dating is not firmly established, but it seems likely by analogy with dated examples elsewhere that this was mediaeval working. The pits in their present state are 5 – 10m in diameter and 0.5 – 2m deep, and are edged with crescent-shaped heaps of excavated gangue and overburden from the local clay ironstone deposits (Schmid 1977; Meyer 1977). Not too far away, at Kópháza in Hungary, over 227 bell pits (*Pingen*) were mapped within an area of 30,000m^2. Their diameter ranged from 2 to 12 m with a maximum depth of 1.5m. One was excavated in 1989 and dated by radiocarbon to AD 1190±120. It was a narrow shaft 1m wide which was followed to a depth of 6.7m but no timbering was observed. Limonite concretions with goethite as the major component were reported from the fill (Gömöri 1989b). Unexplored remain fields of minepits, presumably mediaeval, in the Blansko region of Moravia. One of the best examples of mediaeval iron ore mining comes from the region around Augsburg in Bavaria, where 23 groups of ore pits with a total of 11,000 individual pits, have so far been recorded (Frei 1966; 1977). In their present form they are 3 – 7m wide and between 0.5 – 2m deep (Fig. 26) and usually have heaps of waste from the underlying tertiary sands and gravels, often crescent-shaped, around their rims. The ore being exploited was a limonite, occurring in the form of geodes weighing up to 12kg and containing up to 70% Fe_2O_3, with from 0.97 – 7.6% Mn heterogeneously distributed. These pits occur as very dense concentrations in the forests and in some places, up to sixteen have been found per 200m^2. True shafts were investigated in areas of the Augsburg region, at Rauher Forst-Dachsberg, near Augsburg and at Steinkart, Kr. Griesbach, with a pit having been excavated at each site (Fig. 25: 7 – 8). The former revealed an 8m deep funnel-shaped shaft, 4m in diameter at its mouth, widening out at a depth of 4m, where ore nodules and geodes were being dug out from a seam. The miners then apparently decided to dig further down, and at the bottom opened the shaft out into a gallery, the mouth of which was found, though not excavated. This shaft is unfortunately undated. The Steinkart shaft was, however, radiocarbon dated from its timber shoring to the early mediaeval period (830 ± 120 AD). It was similar to the Rauher Forst-Dachsberg example, with a square vertical shaft which had been dug to a depth of 5m and lined with a framework of oak and beech. Again, there was an attempt to run small galleries from it, part of the way down the shaft, but the main gallery began from the bottom, at 5m. The galleries were also shored with timber and fir props and ceiling members were found inside. Frei suggests that these relatively simple shafts may have been operated by small teams of miners, and estimates that the digging of one shaft would represent the work of three men for one week, the annual output of a team being in the order of 18 tonnes of ore.

The Augsburg evidence is admirably complemented by the research work carried out by Bavarian archaeologists and geologists in the area of Kelheim, a Celtic *oppidum* at the confluence of the Danube and Altmühl rivers (Schwarz *et al.* 1965/1966). Their work in this area revealed a magnificent example of Celtic opencast iron ore mining (see above) as well as mediaeval minepits of characteristic type (circular depressions 4 – 5m in diameter) which represent the 2m deep shafts dug to follow beds of limonitic geodes in the chalk and subsequently backfilled. One section revealed an early mediaeval shaft with a radiocarbon date of AD 570 ± 60 which cut through a Celtic pit. The shaft was followed to a depth of 12m without reaching its base, and so it was not possible to establish whether there were any horizontal galleries. These pits are very densely clustered and, unlike the Celtic ore pits, they spread over the interior and the exterior of the *oppidum* and its surroundings. A list of such sites was published by Reinecke (1934/35), who believed them all to be of La Tène date. A third type of ore pit was recognized at Kelheim, considerably larger (7 – 20m diameter), again with crescent shaped spoil heaps, and scattered over a much wider area. They might be expected to be later in date, but none have so far been excavated.

Another region in Germany where fields of clustered iron ore pits occur is the Schwäbische

Alb in Württemberg, especially in the vicinity of Reutlingen, Weilheim a.d. Teck and Essingen. There are many systems of mediaeval and post-mediaeval mining pits, mostly in the form of irregular trenches, 2 – 3m deep, bordered by gangue heaps. Szöke (1990) describes about 40 groups of iron ore pits, many of them with crescent shaped gangue rims, the best-preserved being 4 – 5m in diameter and 2m deep. They occur either in clusters or, very often, in chains 200 – 500m long and indeed, in one case, the line of pits can be followed for a distance of 2km. This mining activity can be dated to the 9th century AD. Szöke believed that these were opencast workings, but on the basis of his description, they may be interpreted as small shafts or *Duckelbau.* Excavations revealed only two very primitive shafts, situated side by side, 110cm diameter and 5m deep in one case, 2.75m deep in the other. They followed a layer of '*Eisenschwarte*' ore in flint-bearing clays near the locality known as Weiherwiesen near Tauchenweiler. These may be earlier than the 11th century, possibly even early Alamanian from the 4th century, as the contents and stratigraphy of their fillings show (Reiff and Böhm; Kempa in: Beiträge 1995, 16 – 31 and 152 – 154, figs 3 and 4).

A group of thirteen pits was found in an area of 40m x 60m, with sixty more nearby, at Minot in the Côte d'Or of eastern France. Most of these were 1m x 1.1m, but one was 4m square, probably the result of the collapse of the Jurassic rock forming the roofs of the short galleries joining the shafts. This has not been proved by excavation, but another pit which is bottle-shaped in section (mouth 2.5m diameter, throat 1m diameter) shows evidence of having been enlarged at its base to 4.5m diameter to form the entrance to a gallery of some kind (Peyre 1982, fig. 3). An adit is reported from Combe Velbret (*loc. cit.*, 164, fig 4) and other workings are known from Lavrières et Bouquel (Steck-Hauss *et al.* 1995). It is assumed that all of these were mediaeval or even post-mediaeval workings, though some may be Gallo-Roman. The Cistercian Abbey at Fontenay in Burgundy operated four vertical shafts (3.5 to 13m deep) connected with a gallery 60m long nearby at Les Munières where goethite and some haematite were exploited. Another 7 shafts which were sterile, not having reached the ore, were excavated here, while two pits remained uninvestigated (Benoit 1989; Benoit *et al.* 1992). This site, too, shows a very simple mining technique.

A broad-based survey of the exploitation of oolitic minette ores of the Lorraine (Leroy 1997, 80 – 87) has led to the identification of numerous traces of mining concentrated in two regions — the Plateau de la Haye and the Pays Haut on the border of Luxembourg. These include trenches, pits (*Pingen*), galleries, adits and shafts which have not, however, been systematically investigated. Many of the sites, including Maron, Pont-Saint-Vincent and Rogéville, show fields of pits surrounded by the characteristic crescent-shaped dumps of gangue which regularly occur at mediaeval workings. Their present depths centres on 1.5m and diameters are in the range 7 – 8m. The entrance shafts (1.61m x 1.56m), one of them timbered, to underground mines (unexplored) were found at Hussigny-Godbrange (*op. cit.* 96 – 100, fig. 45). A few of these workings, such as those at Villiers-le-Montagne, are dated to the 13th – 14th centuries by pottery and/or radiocarbon, while some older documents illustrate a high mediaeval sword (*ca.* 13th century) and a Carolingian period vessel which were found in the galleries at Ludres-Poirot (*op. cit.* fig. 37).

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Little information on mediaeval mining techniques can be derived from written sources, although there are hints contained in early Irish literature and in one fragmentary law tract on mining which dates to the later 1st millenium AD. In Irish laws of property, the occurrence of iron ore on land increased its value, while there were penalties stipulated for "claim jumping" (Scott 1990, 177 *ff*).

Iron production in Europe tended to be based on individual communities, though some concentration of activity in specific regions which appear to have been controlled by the early

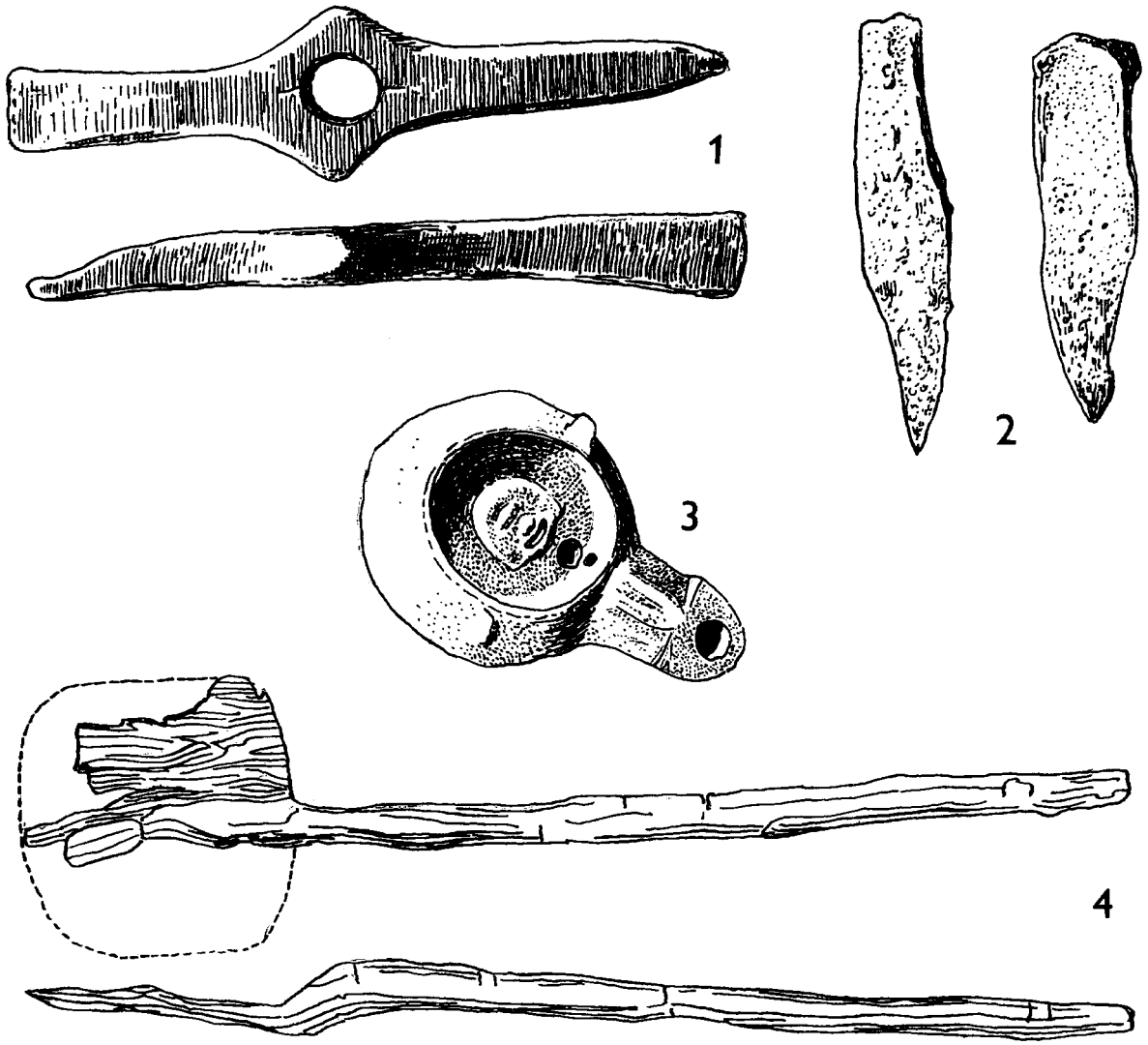


Fig. 27. Ancient mining tools from European iron mines. 1 Lydney Park, England, iron pick from a test mining adit, 3rd century AD; 2 Hüttenberg, Austria, two iron picks from a filled-up gallery, 3rd century AD (lenght about 12cm); 3 Hüttenberg — Knichter Grube, a clay oil lamp; 4 Rudki, Holy-Cross-Mountains area in Poland, wooden shovel from the mine (lenght about 70 cm), 1 and 3: dimensions not given, References: 1 Schubert 1957, 2 – 3 Schmid 1932, 4 Bielenin 1978.

feudal ruling class and later even by the king, is apparent from the 8th century onwards. However, vestiges of the earlier free mining tradition, in the form of *almend*, were preserved, especially in connection with ironmaking, in the organization of the *Mark*, as, for example, in the Lahn-Dill region of western Germany.

Place names provide valuable information about ore mining, both opencast and underground. Names in the eastern Slav lands, in Bohemia, Poland, Slovakia and Slovenia, containing elements such as *rudnici* (ore miners), *železniki* (ironmakers), and *jamnici* (workers in pits), also in various corrupted forms are common in records of the Subalpine region as, for example, at Rudenich (1116), Selesne (891 and 927), and Gaminch (1267), for example. Circumstantial evidence is provided by written documents referring to taxes paid in iron, especially to neigbouring monasteries (Lorsch 780, St. Gallen 9th century, Fulda 912, Gniezno 1136). Iron mining as such is rarely mentioned, though here the Carinthia-Styria region is exceptional. References in several documents to an iron producing 'Mount Gamanara', near Admont (*flatum ferri quod aruzi dicitur, fossa rudensis in monte Gamanara; mons ferrarius 1191*) may refer to the Styrian Erzberg, near Eisenerz.

Notes on iron mining techniques

The mines described in the preceding sections have produced very few examples of the tools used by ancient iron ore miners. Iron picks, gads, mattocks, and hammers are relatively common finds from non-ferrous metal mines and Laurion (Kamareza) and Thasos in Greece, Iglesias in Sardinia, Dacia, and Spain are among the many ancient mines and mining areas that have produced excellent specimens of traditional miners' 'sledge and chisel'. By contrast, iron tools from iron ore mines are rare. There are two picks or gads from the Roman mine at Knicht (Fig. 27: 2) where both were found still embedded in the rock. One was 12.1cm long and 2.5cm thick, while the other was slightly shorter and stouter (Schmid 1932, 178, fig 5). At the bloomery at Ponte di Val Gabbia III, possibly Late Roman, there was found a simple iron pick about 10cm long (Cucini-Tizzoni 1999, 106, Fig. 38b; Fluzin 1999, Pl. 32). An iron pick with a central socket and opposed blades (Fig. 27: 1) came from a Roman hut which sealed the entrance to the adit at Lydney Park in the Forest of Dean (Schubert 1957, 42 – 43, fig. 6). Hammers, scrapers and quern stones are reported by Mangin *et al.* (1992, 97 – 100) from mining sites such as Courcelles Frémoy in the Morvan. The Rudki mine produced a typical set of miner's implements including wooden gads and picks that were sufficiently strong to deal with the soft clay there. Two wooden shovels (Fig 27: 4) came from the same site. One was nearly complete (58cm long with a rectangular blade measuring 10cm x 16cm) and the other in a more fragmentary state, with a broken handle, had an oval blade (Bielenin 1992, 149, fig. 75). Of particular interest is a Roman spade found at the Roman ironmaking establishment at Bardown in the Sussex Weald (Cleere 1970b, 21, fig. 8), even though this was found in a refuse dump on the ironmaking area rather than at one of many large iron ore pits that surround it.

Implements of this kind could have been used in all of the handling processes associated with excavated materials. There is no European archaeological evidence to date for the effective use of fire setting in the iron ore mining and the scant indications from the Far East had been mentioned above. As to the transport of ore, no buckets or baskets, so well known from the Early Iron Age salt mines at Hallstatt, have so far come from iron ore mines, although their use may be inferred. There is some indirect evidence for containers of this kind having been used, in the form of the niches at the Watscher Stollen mine in Noricum, which occurred at regular intervals and must surely have served as resting places for men carrying heavy bags, baskets, or buckets.

Most iron ore mines, even those which penetrated underground, were relatively shallow. Simple ladders or notched timbers would have been required to go in and out of them. There is

no evidence for the use of ropes nor for the use of animals to haul ore to the surface as implied in the mediaeval Irish mining tract *Bla Miand Midchlais* (Scott 1991, 178 – 179).

Some form of lighting would have been essential at the workfaces of underground mines. Clay oil lamps have been found in some Roman mining districts, such as Knicht and Bremsberg, near Hüttenberg (Fig. 27: 3; see Schmid 1932, 179, fig.6) and mediaeval miners also obtained their illumination from shallow pottery oil lamps.

The serious problem of mine ventilation was dealt with in simple pits and short galleries by using natural circulation, but it has not been possible to identify the exact method used from the few, somewhat fragmentary underground mines that have been examined to date. There seems to have been no provision for removing water from these mines, and it appears likely that flooding combined with exhaustion of the ore determined the decision to abandon one pit and open up another nearby, as was typical in the *Duckelbau* system. Sophisticated equipment such as bucket wheels, Archimedes' screws (*cochleae*), and bronze pumps, known from the Roman gold and silver mines in the Iberian peninsula seem not have been employed in early iron mines.

On the basis of the information available at the present time, it can fairly be said that the technological level of iron mining, both opencast and underground, did not go beyond that of prehistoric flint mining until well into the high Middle Ages.

The miners

In prehistoric times, iron ore mining appears to have been the province of specialized ironmaking groups, perhaps based on extended family units. Ethnographic parallels suggest that they may have carried out their ironmaking activities as seasonal expeditions to recognized ore outcrops. Members of the group would extract the requisite amount of iron ore and, if necessary, roast it, prepare their charcoal, construct furnaces, smelt the ore, and return to their communities with the iron in semi-product form, as blooms and bars. Certain members of the group may have been responsible for providing the smelting teams with the ore requested, possibly during certain seasonal periods.

Greek and Roman non-ferrous ore mines often operated using slave-labour and *damnati ad metalla* was a recognized form of punishment for criminals under Roman law. There is, however, no evidence that slave-labour was used in the iron industries of classical times. Many productive regions in the Early Empire seem to have been Imperial estates, for example the Weald of south-eastern England and the provinces of Noricum, Pannonia and Dalmatia. Mining rights were probably leased by Imperial procurators to small tenants (*coloni*) or to entrepreneurs, both individual or corporate (*conductores*). The former were probably the successors of the specialized ironmakers of pre-Roman society, the less successful of whom worked for the *conductores*, having a semi-free status. Sablayrolles (1989a) has studied the situation in Roman Gaul where a special status applied to native iron ore mining (and smelting). In addition to the function of the *procurator* and *conductores*, production was controlled partly by the *iudex arcae ferrariarum Gallicarum.*

In the mediaeval period, European iron mining, for a long time integrated with iron smelting in general, was probably performed by serfs for the benefit of their feudal overlords. In certain regions, however, miners seem to have had a measure of autonomy, though still remaining subject to the suzerainty of feudal masters. The situation of iron ore miners was very different from that of mediaeval gold and silver miners, who were granted many privileges by their rulers and constituted themselves into exclusive and very powerful guilds and fraternities.

Early Irish texts from the later 1st millenium AD make it clear that miners of all forms of metal formed a distinct group, at least as far as the compilers of early Irish law were concerned. The words *clasaige* (derived from the verb *claidid* 'to dig') and *míanaige* (from *mían* 'mineral, ore') invariably refer to miners (Scott 1990, 205). Although the structures presented in the laws must be treated with great caution, since they refer to an idealized situation, rather than to the

small-scale seasonal activity that produced much of the iron in early Ireland, they nevertheless illustrate a recognition of the divisions of labour required.

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In some cases the iron ore was dressed, sorted and selected, close to the mining establishments in order to avoid the necessity of transporting gangue material. However, sometimes the dressing operations were carried out at bloomeries.

Chapter VI

ORE-DRESSING AND ROASTING

In any ore, the metal is bonded chemically and physically to a variety of other compounds, and is also intimately mixed with the non-metallic components of the parent rock, known as *gangue*. The object of the smelter is to separate off as much of the gangue as possible by chemical and physical means and to enrich the metal content of the ore that he feeds to his furnaces. In other words, ores have to be *dressed*.

Ore-dressing

In antiquity, dressing was accomplished principally by mechanical methods, involving hand-picking, crushing (sometimes after heating) and screening, which might involve water-washing (the precursor of modern flotation methods) to separate out the heavier metalliferous fractions from the lighter gangue minerals. It is likely that primary mechanical ore-dressing processes were usually carried out at the mine, but that further dressing was also performed close to the furnaces.

There is very little archaeological evidence for ore-dressing at ancient iron ore mines. The Petley Wood mine in the Weald (Cleere and Crossley 1985, 295) is exceptional. At this 2nd century AD Romano-British site, ore was mined opencast and the overburden and coarse gangue were discarded on large refuse heaps. It was then roasted and screened to remove the fine fractions of roasted ore (see below). The complete absence of bloomery slag anywhere on the site suggests that the roasted and screened ore was then transported for smelting in furnaces at the Cowhurst Park site, some 1.5km away.

Little evidence is available from bloomery ironworks themselves as to the methods of ore-dressing used. The La Tène and Romano-Barbarian bloomery ironworks in central Bohemia very often yielded ferruginous sandstones with haematitic or limonitic cements containing some 10 – 11% Fe_2O_3 which could not be smelted as such. But the smelters might have sorted out the high-grade fractions, leaving the majority behind as waste. Finds of good ore tend to be somewhat rare on ironmaking sites, and the evidence often comes from reject material on slag and refuse heaps. Excavations at Bardown in the Weald (Cleere 1970b, 13) produced a substantial amount of broken fragments of the limonite shells formed around the siderite nodules on which the industry in this region was based. This material was not, of course, charged to the furnace, but its presence indicates that some form of mechanical crushing and picking was probably carried out on the site. Beside the mediaeval bloomery furnace at Minepit Wood, in the Weald, there was a dump of unroasted fragments of siderite nodules prepared for roasting (Money 1971, 90; Cleere in Money 1971, 103 – 104). It would appear that these fragments, which resulted from a primary mechanical crushing, became brittle after roasting and were then further crushed to an appropriate size fraction for charging into the furnace.

At the 9th century AD Slav bloomery ironworks at Želechovice in Moravia (Pleiner 1958, 213), a pit behind furnace XXI contained an accumulation of a rich haematite-magnetite ore (up to 80% Fe_2O_3) in the form of cubes about 3 – 4cm in size, with sharply fractured edges. This is taken to imply the use of a specifically selected ore mixture. Excavations of the mediaeval production sites in the Lahn-Dill Region (Dietzhölztal) have revealed ironstone heaps which had been apparently dressed and sorted out, as Willms (1992) shows in his fraction-size analysis.

There is little evidence for the washing of iron ores in ancient Europe. Sönnecken (1971, 15) suggests that it was used in the Middle Ages in the Sauerland, western Germany, on the strength of a number of place names such as 'Auf der Wäsche' and 'Wäscher Bach' in this area. These place names refer to post mediaeval activities in the Sauerland, for which there is

documentary evidence dating to 1625, but they do raise the question as to whether this may have the continuation of an earlier technological tradition in this region.

There is an early Irish literary reference to the death of the king Conall Cernach who, when fleeing from his enemies, was unable to find a river ford because the water was so disturbed and muddied by the activities of miners upstream who were washing ore. Interestingly, the story is set in an area where sideritic nodules are common in stream and river beds (Scott 1990, 177).

Some authors such as Sprater, in commenting on ironmaking at Eisenberg in the Palatinate, have asserted that iron ores were ground to powder using rotary querns. This view was criticized by Weiershausen (1939, 77 – 78), and is unacceptable so far as ironmaking in ancient Europe is concerned, since ore fractions smaller than pea-size could not have been smelted successfully in forced draught bloomery furnaces. Deep layers of fine fractions of roasted siderite ores are very common finds on the refuse heaps of Romano-British ironworks in the Weald of south-east England as pieces smaller than 0.5cm were usually discarded (Cleere and Crossley 1985, 35 – 36).

It is interesting that rotary querns from ironworks in Gaul have recently been published. There are heavy stones, both bases (*catilli*) and runners (*metae*) of diameters around 40cm, dating to the 1st century BC from Martys, some marked whith Latin letters 'QAL', 'ANT' and 'ND' (Domergue 1993 *et. al.*, 339 – 342, figs. 236 – 239). Pieces of granite of similar dimensions have been noted from the Morvan-Auxois region as having been found close to 'ferriers' at Courcelles-Frémoy and Thoisy (Mangin *et al.* 1992, 97 – 101, figs. 47 – 48). As noted in the literature, there is, in fact, no evidence that such querns were used specifically to grind ore. However, in this context we may note that in the tall natural-draught furnaces of Africa, the ethnographic record shows that it was common for ores to be ground to powder for charging, but these fines are likely to have been made up into some form kind of briquette in order to allow the effective flow of reducing gases through the ore/fuel charge (see Chapter VIII).

Ore roasting

The roasting of iron ore is a special form of ore-dressing that was widely used in antiquity and for which there is considerable archaeological evidence.

The purpose of ore roasting

By roasting we mean the process of heating lumps of ore in a fire at temperatures of 400 – 800°C with free access of air. This was done for two reasons. First, it resulted in the chemical transformation of non-oxide ores into oxides, the most appropriate form for smelting. Secondly, roasting has a beneficial effect on the physical form of oxide ores by making it more porous and thus more amenable to the reduction process. It should be remembered that carbonate and sulphide ores of copper and lead had been subjected to roasting since the Bronze Age. Thus, the use of this technique followed a long technological tradition.

When carbonates, such as siderites of the $FeCO_3$ type, were used for smelting, roasting was unavoidable. They had to be converted to oxides before charging to the furnace, but this did not present any significant difficulties. Ore lumps crushed to a suitable size were spread on an open fire, usually of dry wood rather than charcoal, and exposed to temperatures in the range 200 – 800°C. The oxygen produced released iron (III) oxide according to the equation:

$$2FeCO_3 + O = Fe_2O_3 + 2CO_2$$

The process resulted in a roasted ore which was easily reducible in bloomery furnaces. In those regions where spathic ores of this type were exploited, evidence for roasting may be therefore expected.

Sulphide ores such as pyrites and marcasite have sometimes been claimed as potential resources for early ironmaking and limonitized and weathered nodules do occur in many geological formations. In such cases, desulphurization by weathering would have been incomplete, and so it would have been necessary to expel the remaining sulphur by roasting:

$$2FeS_2 + 5O_2 \rightarrow 2FeO + 4SO_2$$

Recent experiments by Tylecote and Clough (1983) show that weathered sulphide ores required more drastic treatment, involving the use of charcoal for roasting. In spite of such treatment, there would still be some residual sulphur which would enter the slag. However, since it was all confined to the slag inclusions in the metal, it did not have a deleterious effect on the metal, so long as it was forged below 1000°C. Forging at higher temperatures meant that sulphur would not be confined to the slag inclusions but would penetrate the grain boundaries of the iron itself, creating the condition known as 'hot shortness', causing the metal to be brittle and liable to break when hot. Because of that, the use of sulphide ores was not very popular among skilled early ironmakers.

There is no doubt that the majority of the ores used for ironmaking in prehistoric and mediaeval times were oxides, haematites (Fe_2O_3) or various forms of weathered and hydrated limonites ($2Fe_2O_3.H_2O$), bog ores and goethites (FeO.OH). In theory, these ores required no roasting, and there are examples of dried ore being charged to furnaces in the as-mined state. Agricola (1556, XII, IX), when describing ironmaking, makes no mention of roasting, although he does refer to it in connection with non-ferrous ores (*ibid.*, VIII). In practice, roasting also takes place over a limited period in the upper levels of the charge in the shaft furnaces. Nevertheless, many ancient ironmakers recognized the advantages that derived from using well-dried, pre-roasted ores (so long as they were not inhibited by shortage of fuel), and made use of this relatively simple process when smelting oxide ores. The reason for this is understandable because when hydrated ores are roasted, they lose both free and combined water. Thus, for limonite at temperature exceeding 550°C:

$$2Fe_2O_3.3H_2O + \text{heat} \rightarrow 2Fe_2O_3 + 3H_2O$$

For goethite the equation is:

$$2FeO.OH + \text{heat} \rightarrow Fe_2O_3 + H_2O$$

Haematite (Fe_2O_3) undergoes physical changes when roasted. It is softened for subsequent mechanical dressing, such as crushing, and the body of the ore lumps becomes porous, making it more susceptible to the action of hot reducing gases in the furnace. Dense magnetites (Fe_3O_4) benefit even more in this way from roasting and it may be relevant here to draw attention to the blueish-grey magnetic particles which are often found in places where iron ore was roasted. In the hottest zone of the roasting fire, where the access of air is restricted, certain portions of the ore may undergo the first stage of reduction:

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$

Support for the view that oxide ores were roasted regularly comes from Biringuccio (1540, book 6) and Rożdzieński (1612, g 3/17 – 20), in relation to certain ores. Schultze (1732), Swedenborg (1734) and Evenstad (1790) give excellent descriptions of the roasting of bog ores (which are usually thought to have been charged direct to the furnaces, without any treatment), on wooden grids.

It is reported that limonites and siderites were roasted in special furnaces located near the *Stücköfen* at Vordernberg in Styria, Austria (1714). Alternatively, they were roasted, after

having been exposed to the atmosphere to dry for some time, in large heaps consisting of alternate layers of ore, charcoal, and wood, the roasting process lasting three weeks (Beck 1884, 821). The Corsican method of roasting in effect represented the first stage of smelting. Elban haematites which are difficult to reduce were roasted in open hearths. The product, which was sintered together but not slagged, was then crushed and smelted in the same hearth (Beck 1884, 787; Mattioli 1989). This resembles the technique described by Diodorus in the 1st century BCwho wrote (5.13) that the ore was roasted on the island of Elba (Aithalia) using a great fire and forming spongy conglomerates which were transported to the coast of the Etruscan mainland for conversion to iron.

Archaeological evidence for ore roasting

The excavation of certain bloomery sites has produced roasted iron ore but no roasting installations. One of the earliest (about 500 BC) bloomery sites in Europe, Waschenberg in Austria (Pertlwieser 1970), for example, produced roasted bean-limonites and siderites. At the 2nd century AD bloomery at Ashwicken, Norfolk, England, the majority of the ore found was roasted, but there was no unambiguous evidence of roasting hearths. Tylecote (1962a, 221) suggested that the process was often carried out close to the mining areas, at some distance from the smelting sites. This would seem to have been the case at Petley Wood in the Weald, referred to above (Cleere and Crossley 1985, 295, after Lemmon), where the roasted ore was probably destined to supply the Crowhurst bloomery, some 1.5km away. The distinguishing of roasters among other siderurgical structures is a very difficult task, especially what concerns the older excavations, e.g. the Roman features at Tiddington; Schubert (1957, 47 – 48, fig. 7) suggested a horseshoe-shaped roaster coupled to what was presumed to be a smelting furnace base, as he did when interpreting, after May, the installations at Widerspool. However, according to Tylecote's opinion (1962a, 223 – 224; 234 – 235), these features were connected with smithing (or reheating) operations; the 'roaster' from Wroxeter was interpreted in the same way (see Chapter XI).

In the 8th – 9th centuries smelting installation at Ramsbury, Wiltshire, England, roasted siderite nodules were found in an burnt area occupied in the earliest phase of smelting operations, but no other evidence for roasting in the form of features came to light (Haslam *et.al.* 1980). Similarly, at the 9th century bloomery at Millbrook in the Weald, roasted ore of the so called 'boxstone' siderite type was found, but again with no identifiable roasting installation.

Excavations in an iron ore-bearing region of the Great Moravian and later periods (9th – 11th centuries AD) near Blansko in western Moravia, brought to light heaps and layers of material in fractions below 7mm that was subsequently identified, by comparison with that produced in roasting trials, as screened-out gangue waste from roasted haematite or limonite ores (Souchopová 1986). This refuse material has been dated to the latter phase of ironmaking in the region, in the 10th – 11th centuries.

In other cases, however, roasting was carried out at or very close to ironmaking establishments. A very simple form of roasting installation was discovered at the 9th – 11th century bloomery at West Runton, Norfolk, England (Tylecote 1967, fig. 9). An area of yellow and red-baked clay, apparently the site of a roasting pile, was found to the south of the smelting furnace, surrounded by red-roasted fines of goethite ore.

In fact, a roasting pile could be placed on the ground surface near the smelting site without leaving any traces. When it was in use repeatedly, shallow depressions, which may be called roasters, were formed by the evacuation of individual charges.

Circular roasting hearths

The sites of roasting can often be identified in the form of the shallow circular depressions which have been found on many smelting establishments. At Bedford Purlieus, near Peterborough, England, two features were excavated, of which No 2 was the better preserved. This was a circular hollow 2.13m in diameter and 22cm deep, with a fire-reddened base, filled with fragments of lining and small pieces of slag. Tylecote interprets this as a roasting hearth, although no ore fragments are mentioned in the report (Dakin 1968). However, a similar hollow, slightly oval in plan (4m x 3,5m, 35cm deep), found at Łomno in the famous Holy Cross Mountains region of Poland, while showing no evidence on the ground of heating, was covered with magnetic ore particles. Similar roasting features, varying between 2m and 7m in diameter, were found at the sites of Jeleniów 4 and Osiny 1 in the same region. They generally lay from 2 to 7m from the smelting furnace fields (Bielenin 1974, 185 – 187, fig. 90). Oval pits containing magnetic particles of roasted ore were also found at Łysa Góra 7 (Bielenin 1974, 186 – 187, fig. 90), but these were identified as places where roasted ore was stored.

Within the area of the 6th – 7th centuries AD ironworks at Boècourt, in the Swiss Jura, there was an area for roasting in the northern part of the workshop, close to the east of one of a pair of furnaces. In a shallow depression there were 7 circular areas 2 – 7 m in diameter, reddened by heat and covered with three layers of roasted pea-ore (27.48kg), alternating with charcoal beds. These can be called 'roasters' or simply described as places where the ore was calcined repeatedly, immediately before charging to the furnace (Eschenlohr and Serneels 1991, 94, fig. 76).

The bloomery site at Gayvoron, dated to the same period but located far to the east in the Ukraine, contained four features that were completely different in form from the type of bloomery furnace used at that site (Fig. 28: 1). These are claimed to have been roasting hearths (Bidzilya 1963, 125 – 127, Tab. III: bottom) and consisted of shallow, roughly circular hearth-bases measuring 1.36m x 1.18m, which were burnt red and filled with roasted ore. In front of them were shallow pits or working hollows. The spaces between the two depressions were piled over with stones, the purpose of which is uncertain.

Roasting hearths have frequently been recorded by Sönnecken on the 11th – 13th century bloomery complexes of the Sauerland region of western Germany, (1971, 19 – 20, 23, 36, 89 etc.). As at Grossendrescheid-Am Wald 1 and 2, Homert, Sonnenscheid and Linackers Kante (Fig. 21: 4), they were invariably located a few metres from the smelting areas and consisted of shallow, circular or oval pits (*Röstfeuermulden*) 0.6 – 1m in diameter, containing fragments of roasted haematite and charcoal). Sönnecken sees these as the places where freshly mined ore was dried and calcined in order to improve its condition for smelting. They formed part of the standard equipment of a bloomery establishment.

A deeper bowl-shaped roasting pit (1.2m diameter, 90cm deep), thickly lined with clay, was found at Sedgeley, Worcestershire in England and has been dated, somewhat uncertainly, to the mediaeval period (Tylecote 1962a, 285, fig. 70: left). Its filling consisted of ash, charcoal, and calcined ore, indicating that its function was as a roasting hearth.

Stone-lined hearths

A different type of feature was found at another English site, Lindale in north Lancashire (Tylecote 1962a, fig. 70: right), an elongated pit with a horseshoe-shaped plan (1.8 x 1.2m), open on one of its narrower sides and with walls which were reinforced with stone and lined with clay. The absence of any slag or cinder and a similarity to mediaeval lime-roasting kilns led Tylecote to interpret it as an ore roasting hearth. If this interpretation is correct, it resembles

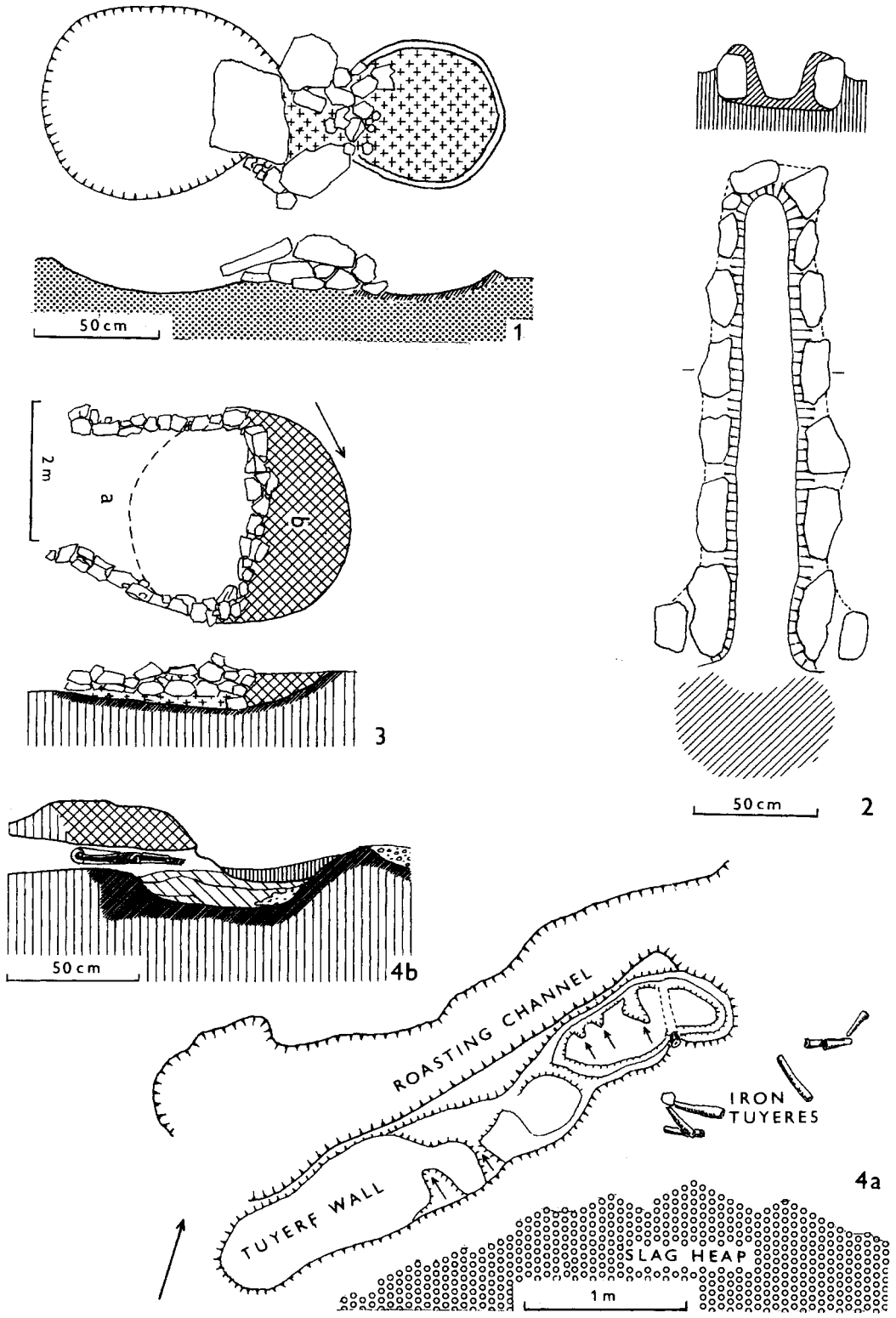


Fig. 28. Roasting hearths. 1 Gayvoron, Ukraine, roasting hearth with burnt-red bottom and some calcined ore (crosses), 7th century AD; 2 Bardown, Weald of Sussex, England, trench-shaped roaster, Roman; 3 Minepit Wood, Weald of Sussex, England, stone-walled roasting stall of the 15th century: a - later stone structure, b - earlier roasting hearth; 4 a – b Radětice, Bohemia, roasting channel of the 13th century: a - plan, b - section of the trench, two phases of the stamped clay-and-sand lining; filled with layers of of dark soil and with charcoal fragments and calcined goethite. References: 1 Bidzilya 1963; 2 based on Cleere 1970a and Tylecote 1987; 3 based on Money 1971; 4 Pleiner 1971a.

very closely the post-mediaeval roasting stalls (*Röststadel*) used for dressing copper and lead ores which are illustrated by Agricola in his sixth book. The elongated shape of this type made it possible to carry out the process over a longer period, since roasted material could gradually be moved forward, as the hearth was charged with fresh supplies of ore. This clearly represents progress in roasting practice by comparison with burning in simple heaps or pits.

This more sophisticated system has also been found in other excavated ironmaking establishments. A good example is provided by the 14th – 15th century site at Minepit Wood, Rotherfield, in the Weald of south eastern England. The usual type of fire-reddened roasting pit containing roasted siderite ore lay alongside the smelting furnace and was used in the earlier phase of operations. This was later superseded by a stone-lined hearth or stall, open at one of its narrower sides, to the south (Fig. 28: 3). Roasted nodules of siderite, analysed by Cleere, were found in the filling, along with charcoal or charred wood (Money 1971, 88 – 89, 92 – 94, 103 – 105, figs 31 – 34). One of the earlier (11th – 13th centuries) ironmaking sites in the Sauerland at Hülsesiepen, produced a roasting pit (1.2m diameter, 50cm deep) within which a stone setting measuring 60cm square was identified. This appears to have facilitated the heaping-up of the ore to be roasted (Sönnecken 1971, 89, fig. 16).

There is a problem of interpretation of these rectangular stone settings or stone-paved features, occurring either within an iron smelting area as at Göhlen and Schöneburg in Germany, or singly or in groups, not associated with any smelting structure as at Waltersdorf near Königswusterhausen in eastern Germany (Leube 1981). At this site, 51 large stone-set hearths surrounded a free-standing post built house. The stones were heavily burnt and among them charcoal and minute non-magnetic slag fragments were collected. Detailed information concerning the form and dimensions of these features is missing and the whole complex remains obscure. On the contrary, the Göhlen stone settings yielded magnetic particles, which are believed to be hammer-scale from smithing operations (Wollschläger 1992). The features, however, are hardly explainable as smith's hearths. On the other hand, roasting of iron ore produces magnetite fractions, and this must also be taken into account. It is well known that stone layers keep the heat longer, which would be advantageous especially in the German lowlands. More analytical work is needed to determine the function of these stone settings.

Ditch roasting hearths

Like the rectangular features just described, a long ditch-type hearth was very suitable for increased output, since the ore could be moved along its axis as it was roasted. This is clear from two Romano-British features excavated at Bardown in the Weald (Cleere 1970b, figs 2 and 3; Cleere and Crossley 1985, 35 – 36, fig. 12). Hearth 2, the more complete of the two, was 2.2m long, 30cm wide, and 30cm deep, lined with square stone blocks, coated heavily with clay and open at one of its shorter ends (Fig. 28: 2). It was flanked on either side by layers of roasted ore fines up to 30cm deep which had been screened out and dumped, prior to deposition, on a large slag bank some 300m away. This feature was associated with the earlier phase of ironmaking on the site (second half of the 2nd century AD), and had gone out of use, to be filled with miscellaneous rubbish and levelled. The filling contained a number of flagon necks, which gave the appearance of having been roughly trimmed. They had been exposed to considerable heat, and were interpreted by the excavator as having served as tuyeres for bellows-blowing. Roasting experiments were carried out on a replica of this hearth (see below).

The use of ditch or channel roasting hearths in the Middle Ages is illustrated by feature XI from the 13th century AD bloomery site at Radětice in southern central Bohemia where a ditch-like hollow, open at each end, had a thick clay wall at its southern side into which iron tubes had been inserted to act as tuyeres. The ditch was 4.08m long, 40 – 55cm across internally, and

20 – 50cm deep. One of the tuyeres was found *in situ* (Fig. 28: 4) and several other fragments, very heavily eroded, were found lying nearby. A section through the wall and its lining showed that there had been several phases of use and reconstruction. Roasted calcite gangue material was found in the filling (Pleiner 1971a, 5, 48 – 49, fig. 4). This feature was associated with a group of destroyed thick-walled smelting furnaces some metres away to the east and north. The positioning of the tuyeres is reminiscent of an older discovery at Döblitsch in Austria, which is not very well documented, but is dated to the Roman period. According to the excavator, the ditch was 11m long and the tuyeres were made of clay (Müllner 1909, 81 – 82, fig. 89).

*

This brief survey ends with the situation found at Dobrzeń Mały, Silesia, Poland (Pawlowski 1979). A group of ten roasting hearths and stores of roasted ore were located to the south-east of a group of smelting furnaces, with reheating hearths grouped on the opposite flank of the installation. The roasting hearths were unfortunately not described in the report and their dimensions and other details are unknown.

Many excavations of early ironmaking sites have produced features which could not have been smelting furnaces, and these have generally been interpreted as reheating or ore-roasting hearths, This was the case at Hüttenberg-Preisenhof in Austria, an old excavation originally published by Münichsdorfer (1871), thereafter notorious for its appearances in archaeometallurgical literature (*e.g.* Schmid 1932, 16, fig. 8; Weiershausen 1939, 157, fig. 42). Hearth 2 was confidently interpreted as a smelting furnace and the larger hearth no.1 which was 58cm diameter and 63cm deep, was considered to be a roasting hearth (Schmid 1932, 16, fig. 8). However, Weiershausen, who refused to acknowledge that ore roasting was used in early ironmaking, identified it as a reheating hearth (1939, 159). There are also the long channel hearths from Wakerley in England, which may be either roasting or reheating hearths.

Roasting experiments

The best indication of how roasting was carried out in relative simple conditions comes from experiments, since more recent accounts, dating from the 18th and 19th centuries, of comparable processes may be misleading. It is clear that ore roasting continued in some regions on a large scale for a long period (Evenstad 1790). There are reports of iron ore being roasted with dry wood in heaps up to 60m long, the process taking from two weeks to several months (Maréchal 1985, 37).

There have been two alternative approaches to ore roasting in smelting experiments. In trials using haematites and limonites, and, above all, bog ores, reports have either omitted any reference to roasting or else it has been explicitly stated that roasting was not used (Zimmermann *et al.* 1985). In other cases, reference is made to roasting having taken place. In testing the Ashwicken furnace, Tylecote (*et. al.* 1971, 29, 40, Table I) reported that Northamptonshire siderite containing 1.31% S was crushed to yield three size fractions (12 – 25, 3 – 12, and < 3mm) and heated in a gas-fired furnace for 6 hours at 800 – 900°C, converting it into soft porous oxide, but without reducing the sulphur content.

The team experimenting in the Holy Cross Mountains roasted cream haematites in heaps with wood in order to reduce the sulphur (1.06 %) and free water contents and succeeded in reducing the sulphur to 0.22 % (Nosek 1985, 167). Voss and Thomsen (Voss 1973, 60) and Hagfeldt (1966, 20) even roasted easily-reducible bog ores, the latter roasting 1 – 5mm fractions for 2 hours at around 200°. Kolchin and Krug (1965, 202) did the same, since they considered this to be very important, but they using a much shorter roasting time of 20 – 30 minutes.

More details are available from the smelting experiments carried out by Pleiner and his co-workers (1969b, 466 – 467, fig. 9). In carrying out experiments on the Želechovice type of

smelting furnace (see Chapter IX), a high-quality haematite (91.20% Fe_2O_3) was used. Roasting was carried out with the ore in an open, square pile on a grid of logs (150kg), surrounded by bricks. Two processes were carried out. In one, when the heap was 80cm square and 70 – 75cm high, 185kg of ore was gradually roasted over a period of 6 hours, to produce 174kg of easily-reducible furnace charge. The other heap burnt for 3 hours, consuming 74kg of ore and 150kg of wood, to produce 70kg of roasted material. Considerable explosive emission of ore particles ('shooting') was observed during the process. The roasted product was magnetic, which indicated that even under the oxidizing conditions which prevail in such a hearth, partial reduction of the ore did take place, especially in the centre of the heap.

It is worth mentioning that the dense Swedish magnetite ore known as Kiruna B, used for smelting experiments with the Scharmbeck furnace, failed completely. In the unroasted state it produced some fayalitic slag at temperatures around 1400°C, but most of the ore passed through the furnace shaft untouched.

Working with siderite, Cleere was obliged to convert the ore into oxides before charging them to his replica shaft furnace (1970a, 7 – 9, figs 2 and 3). He used a model of the ditch or channel furnace found at Bardown in the Weald (see above; Cleere 1970b, 18, fig. 5), 2.4m long, 30cm wide, and 30cm deep, lining the sides with puddled clay but omitting the stone backing that was a feature of the Bardown structures. Charcoal was used as fuel. The large siderite nodules were crushed to coarse lumps measuring 50 – 75mm. The process, carried out on a deep layer of charcoal, proved to be slow and so forced draught was introduced. The operation was controlled by eye, according to colour change. In the range of 300 – 400°C the greyish-green siderite changed first to reddish-brown haematite and then to blue-black magnetite. In many lumps it was found that only the surface skin was converted in this way, which demonstrates that a considerable level of skill and experience in working the process is necessary. The process was carried on throughout a working day of 8 hours. As in the Czech experiments, the smaller-sized ore lumps were observed to disintegrate explosively, as a result of internal pressures created by the free water reaching boiling point and expanding. Roasted ore was raked away from the focus of the burning in the hearth and fresh ore and charcoal were worked in.

There is adequate evidence to support the contention that ironmakers in antiquity usually roasted their ores before charging them to the smelting furnaces. If they were reliant on carbonate ores (as was generally the case in high output regions), this was in any case essential, but there were also many ironmaking centres based on oxide ores — haematites, limonites, and goethites — where roasting was regularly practised. It is still not known, however, to what extent this was the general rule. There have been relatively few excavations of complete bloomery complexes and, in any case, the traces left by ore roasting are not always obvious or easy to recognize.

Chapter VII

CHARCOAL BURNING

Fuel is one of the raw materials essential to ironmaking. It provides the heat needed to drive the reduction process, while at the same time acting as a reductant. In modern blast furnaces, this function is performed by coke, which was first used in England in the early 18th century, and followed the use of charcoal in early blast furnaces and almost all bloomery furnaces.

The function and composition of charcoal

Charcoal represents the final product of the process of thermal decomposition of wood. Wood itself is a polymeric compound of carbohydrates in the form of cellulose $C_6H_12O_7$ (40 – 50 %), which will be transformed to lignin (20 – 30 %) during the ageing of the tree, hemicelluloses (pentosans, hexosans, etc.: 20 – 28 %, depending upon the species), pectins (0.6 – 1.5 %), and ancillary oils, terpenes, alkaloids, and mineral salts. The basic chemical composition comprises around 50% carbon, 44% oxygen, 6% hydrogen (i.e. 35 – 60 % water in green wood or 10 – 20 % in dry wood), and ash 0.3 – 1 %.

When burnt slowly with a very limited access of air, the wood releases water (at 150 – 200°C), gases, essential oils, wood turpentines, alcohol, acetic acids, terpenes, and tars (up to 270°C). Above this temperature and up to about 480°C, the reactions are exothermic and further volatile substances are lost, the residue being charcoal and some tar.

Charcoal contains 78 – 92 % carbon, again according to the species, with wood from broad-leaved trees being richer in tars and containing more carbon than coniferous species. It also contains 7 – 14 % oxygen, 0.6 – 1.8 % hydrogen, and 0.5 – 3 % ash. The ash content, where the mineral content of the wood is concentrated, varies between branches and bark which are very high in ash and core- and sap-wood. Thus, whilst the lime (CaO) contents of wood may be between 0.14 % (pine) and 0.3 % (beech), these rise respectively to 40 % and 26 – 30 % in the charcoal ash made from these woods. Phosporus, expressed as P_2O_5, which is of considerable significance, since it has a potential influence on the quality of the reduced iron, is 0.03% in the wood but may rise to 1 – 7% in charcoal ash. Similarly, potash (K_2O), which varies from 0.04% (pine) to 0.09 % (beech) may increase to 15 – 20 % and up to 40% respectively in the ash, with magnesia (MgO) increasing from 0.03 – 0.06% to 10 – 16%.

Variations can also be observed in the proportions of individual components in the ash, depending upon which part of the tree they come from. The mineral content of charcoal affects its reactivity in terms of the production of carbon monoxide (CO), which is the principal agent in the indirect reduction process taking place inside the furnace shaft:

$$C + O_2 = CO_2 \uparrow$$

$$C + CO_2 = 2CO \uparrow$$

Różański and Słomska (1980, 385) state that CaO, FeO, K_2O, and Na_2O catalyze the reaction producing CO, while SiO_2 and P_2O_5 slow it down.

The same authors carried out experiments to determine the reactivity of charcoal made from different woods. They concluded (1974; 1980) that charcoal from coniferous species, especially *Pinus* (pine) is the most highly reactive in the lower temperature range, 600 – 800°C (i.e. in the upper level of the furnace), but at higher temperatures in the range of 800 – 1000°C, and so closer to the tuyere level, charcoal from broad-leaved species, and especially from *Fagus* (beech), is a more efficient producer of CO. Charcoal mixtures were also used in their experiments. At

600°C the conifers — pine alone and pine combined with fir (*Abies*) — were the most highly reactive. Beech on its own is very efficient at 800°C, but its reactivity is even greater when combined in equal proportions with charcoal from conifers. At about 800 – 1000°C, beech plays a very positive role in CO production, but a mixture with conifer charcoal was shown to be advantageous, since all of the temperature zones in the furnace shaft can thus be adequately supplied with CO.

There are other significant differences between conifer and broad-leaved charcoals. The latter (e.g. beech and oak — *Fagus* and *Quercus*) are dense and strong, and so are suitable for charging into tall furnaces with large internal volumes, such as the *Stuckofen* type, or into blast furnaces, since they do not disintegrate into powder under the weight of the charge. This is an advantage, since fine fractions of charcoal block the airways through the charge. The optimum charcoal size is about 40 – 50 mm, as can be seen from charcoal prints embedded in bloomery slags and the results of numerous smelting trials. Pine charcoal, however, is softer and produces a sharper flame when it is subjected to an air blast. In terms of calorific values, charcoal of all kinds produces over 7000 Kcal/kg, in comparison with green wood (about 3000 Kcal.).

The selection of wood for charcoal burning was always dependent upon the range of trees available in the immediate neighbourhood of the furnace. Smelters and smiths may have had preferences among the trees available to them. Some examples may be found among palaeobotanical data in the published literature, but the value of the evidence is variable. In some cases, the information relates to wide-ranging samples of charcoal derived from a broad smelting area and its charcoal-producing sites, and not too closely dated. Then, there are analysed samples from individual smelting sites, indicating qualitatively the range of woods represented by the charcoal. In rare cases, the composition of the charcoal from individual furnaces is known, providing the most valuable insight into the practices of individual early ironmakers in preparing their furnace charges. The examples that have been selected will be dealt with in roughly chronological order, since available data are not sufficient to allow a purely geographical approach.

Charcoal for early smelters

Palaeobotanical and palynological analyses of survived relics from archaeological excavations provide basic information about wood species used in making of charcoal for ancient and mediaeval bloomeries.

La Tène sites in the Siegerland of western Germany, as represented by that at Obersetzen, indicate that beech and oak charcoal were being used (Gilles 1936, 257). The excavations at Mšec (Pleiner and Princ 1984, 166 – 167) showed that in iron production of the same period in Bohemia, a distinction was made between the charcoal used for smelting – almost exclusively spruce (*Picea excelsa*) and pine (*Pinus silvestris*) – and that for reheating and forging – spruce and pine with relatively small additions of beech and oak. The use of spruce is exceptional, from both the metallurgical and botanical points of view, given the period (2nd century BC) and the topography of the site (the peneplane of western central Bohemia).

The ironworks at Clérimois in France produced iron during the final Celtic and Gallo-Roman periods, when ferriers 1, 2, 3a, and 4 were in operation. The use of different broad-leafed charcoals alternated, with smelting in the earliest phase depending on beech charcoal (78%) which seems to have been produced somewhere in the vicinity. By the time that ferrier 3b was in operation in the last century BC, oak began to replace beech, the charcoal apparently being prepared on site. Minor components were represented by maple, hornbeam and willow (Dunikowski and Cabboi 1995, 134 – 139).

At Les Martys, the bloomeries generally consumed beech charcoal with additions of carbonized hazel, cherry and juniper. There are indications that at the beginning of the smelting activity in the 1st half of the last century BC, charcoal was produced on the site, while it

was later made outside the working area, but stocked in charcoal bunker II which was situated between the furnace batteries (Domergue *et al.* 1993, 359 – 361).

The palaeobotanical research project in the French Pyrenees is directed at study of the development of the mountains forests of Ariège, with particular attention to the needs of ironmaking. For the Roman period, we should note a 1st century AD ferrier at Rivèrenert where the charcoal finds included 35% oak, 20% fir and 17% beech. The 4th century AD ironworks in the forest of Bède de Lercoul consumed 89 – 91 sampling of the modern tree growths shows an overall presence of only 15% beech (Dubois *et al.* 1994).

Roman ironworks in the Weald of south-eastern England used charcoal from the oaks which predominated locally, but charcoals from ash, hornbeam, hazel, birch, and hawthorne have also been identified (Cleere 1970b, 16; Cleere and Crossley 1985, 37).

The ironmakers of the Romano-Barbarian period in the Holy Cross Mountains of Poland used a variety of charcoals (Bielenin 1974, 135 – 142). In the smelting furnaces and slags, pine (63%), followed by fir (*Abies alba* 17 %), beech (*Fagus silvatica* : 11 %), oak (*Quercus sp.*: 10 %) and poplar (*Populus*) predominated, while spruce was very rare. It is interesting that poplar has been identified at the bases of four out of eight heaps (see below) that were sampled at Słupia Stara 4 and 6. At Ambrożów, the charcoal was beech, at Podchełmie 1 pine and unidentified coniferous charcoals, which could have included larch (*Larix sp.*). Orzechowski (1991, 175) states that on the northern slope of the Łysogóry range which constitutes a section of the Holy Cross Mountain area, a large proportion of fir charcoal, as high as 32 %, was used. This is explained by the close proximity to the original forest complex of Łysa Góra. Further to the north, broad-leaf wood species predominate.

Charcoal-production by Germanic ironmakers in Schleswig-Holstein depended apparently on the burning of oak and alder, although individual furnaces were fed exclusively with oak charcoal, as indicated by preliminary data from the Joldelund smelting site (see Backer *et al.* 1992, 105 – 110). A little to the north, at Snorup in Jutland, a large furnace field consumed mainly oak charcoal from branches 5 – 12 cm thick, i.e. from trees about 20 years old. Voss (1993, 208) is inclined to interpret this as indicating the practice of coppicing by this industry.

In the Jura ironmaking region of the Vaud, Switzerland, largely operating in the Roman period, the sites of Bellaires and Romainmôtier consumed principally beech (39%) and oak (30%) charcoals. Smaller quantities of charcoals from ash (*Fraxinus excelsior*) and maple (*Acer sp.*), in the region of 10 – 13.5% were identified, while other woods such as poplar and alder were represented only in traces. It is worth noting that botanical analyses showed that progressively greater use was made of younger trees, up to 40 years old, which is interpreted as being due to the exploitation of surrounding woodlands (Pelet 1973, 184 – 190; 1993, 99 – 103).

In the subsequent Merovingian period, the smelters apparently depended on sources which were available locally. Those who operated the twin furnaces at Frouard in northern France used almost entirely oak charcoal (Leroy 1997, 144 – 145), while at Boécourt exploited beech as the predominant species for making the charcoal for furnace 1 (67%, followed by fir with 19%). Beech (30%), alder (23%), and fir (11%) were used for furnace 2. Beech and fir were also the fuels for the roasting processes (Eschenlohr and Serneels 1991, 19 – 25). At Montcherand 90% of charcoal was made from oak, with only 9.8% being beech, along with some minor additions of maple (Abetel 1992, 42 – 43).

The late Romano-Barbarian (4th century AD) ironworks at Tuchlovice in west-central Bohemia operated exclusively with pine charcoal, both for smelting and for reheating and refining. A similar pattern has been shown to have prevailed at the 12th century refining works at Prague Bethlehem Chapel (Pleiner 1958, 185, 248). No other species were identified among the samples analysed. Pine charcoal was also used in northern Russia, as can be seen from two samples from the early ironmaking sites at Progonnoye pole and Kushmanskoye (Kolchin 1953, 40).

In the 9th century AD ironworks at Želechovice in northern Moravia, however, charcoal from

broad-leaved species was used. This site has produced data from individual furnaces. Furnace XXII produced a mixture of ash and maple in equal quantities, furnace XXI had ash and maple in the proportion of 5 : 3, while furnace XXV contained only maple charcoal (Pleiner 1955, 20 – 22). Both species had to be brought from the slopes of the foothills of the Jeseníky mountains, some 20 – 30km to the north. Contemporary and slightly later ironworks in the heavily wooded region of Blansko in western Moravia used a preponderance of beech charcoal (72 %), with smaller proportions of pine and maple (Opravil 1973).

The mediaeval bloomeries (8th – 11th centuries AD) of the Sauerland in western Germany which lies close to the Ruhrgebiet produced oak and birch charcoal in proportions of 5 : 1 (Sönnecken 1971, 16). However, samples from the bases of charcoal heaps in the mediaeval and post-mediaeval iron-producing region around Isernhagen, near Hannover, dating to the 13th – 16th centuries, produced birch (23 %), alder (20 %), hazel (14 %), beech (12 %), and oak (11 %), the remainder being made up of pine, willow, and ash (Zeidler 1972). Samples taken from the context of furnace 4 at Ramsbury, England (around AD 800) were indetified as oak from mature timbers, with slight admixtures of as, hazel, maple, and willow (Keepax in: Haslam *et al.* 1980, 53).

Charcoal production

In the heavily-forested areas of Europe, the production of charcoal presented no problems for the earliest ironmakers with their relatively limited requirements and small-scale production. But in later periods, consumption eventually came to constitute a positive hindrance to the development of iron production. Limits on the potential for charcoal supplies in the major iron-producing regions sometimes imposed severe limits on the output of the smelting furnaces.

A *stere* (1 m^3) of dry wood, weighing about 600kg, can produce up to 55% by volume of charcoal, in modern retorts, depending on the type of wood being used. In terms of weight, this is equivalent to 16 – 20%. Charcoal for early furnaces would have been crushed to a suitable size, and pieces found embedded in bloomery slag seem to have been from 2 – 5 cm, a size-range that has been used in many smelting experiments.

The consumption of charcoal in early ironmaking was considerable. Taking into account all of the preliminary operations, such as the preheating of the furnace and the need for extra charcoal after the addition of the final ore charge, plus the reheating of the bloom after its extraction from the furnace, it has been calculated that 8 – 10 units by weight, or even more, of charcoal would have been needed to produce 1 unit by weight of iron. Where natural steel was being produced, a process requiring a smelting ratio of greater than 1 part of charcoal to 1 part of ore, charcoal consumption may have been as high as 15 units by weight.

It follows, therefore, that in certain regions where iron was being produced on a large scale, it would have been more advantageous to site the bloomeries close to the fuel source rather than the ore source. Although the ore would have be transported some distance, this was more economical, since the ore to be handled would have been smaller in volume and lighter in weight than the charcoal needed. In cases, where no charcoal burning has been recognized close to a smelting site, it is necessary to envisage the organized transport of this commodity, and sometimes even to postulate the existence of specialized colliers cooperating with the smelters.

Until the introduction of the modern retort method of charcoal burning, two basic methods were in use, although it is not clear which is the more ancient. Free-standing charcoal heaps or piles (which were still in use in recent times in many parts of Europe) and charcoal pits, reported as having been used for producing fuel for smiths (see Vannocio Biringuccio) or for general heating and cooking purposes. The *coleputtes* referred to in English written sources of the 11th century appear to have been charcoal-burning pits, while similar features were in use in Russia until at least the 19th century.

The heap (*kaminos*: kiln) was first described by Theophrastus (373/371 to 288/286 BC) in his *Perí fytón historias* or *Historia plantarum* 5.9 4: 'For charcoal burning they select smooth logs to be stacked densely in a pile; when they coat the pile with clay they ignite it and pierce holes in the coating'.

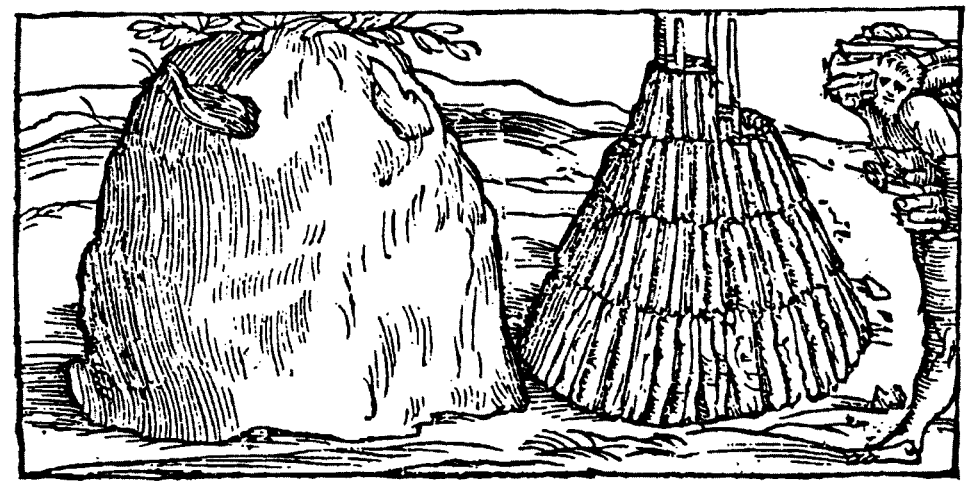
One of the best sources is the *Pirotechnia* of Vanoccio Biringuccio (1540, 3.10), which describes both the heap and pit method of charcoal burning. For the heap, Biringuccio describes how three or four poles were set up in the middle of a levelled area and covered with rings of dry logs or cords, stacked standing on their ends, together with smaller chips and splinters of wood. This was then built up in successive layers to form a pyramid or cone. The whole stack was covered with fern fronds and plastered with a coating of earth or clay about 30cm thick. A hole was left open at the top between the poles, and 10 – 12 vents were pierced in the coating at the bottom. The fire was lit through the hole at the top and left to spread through the whole stack, after which this hole was sealed with clay. The heap was left to burn for 6 – 8 days, after which all of the apertures were closed up. The fire inside died out with the wood having been converted to charcoal. No dimensions are given by Biringuccio since each charcoal burner decided these according to his individual requirements. The wood needed to be dried for six months to a year before being burnt. Judging from the illustration in the *Pirotechnia* (Fig. 29: 1), the heap was about the height of a man.

This illustrates the classical method of burning in a vertical heap which was traditionally used until very recently in areas all over Europe. The levelled bases of hundreds of post-mediaeval charcoal heaps may be seen in many forested areas. This technique was described and illustrated in a number of books in the 18th and 19th centuries (e. g. l'Encyclopédie; Duhamel de Monceau 1761; Percy 1864, 111). These post-mediaeval piles reached 1.5 – 2m in diameter, and could contain more than a hundred steres of wood. Piles 2.5m high and 5 – 7m diameter in 18th century Bohemia consumed 16 cords (i.e. about 133 steres) of wood (Kořan in Dějiny hutnictví železa 1984, 103). They burned for between two and four weeks, depending upon their dimensions and the types of wood being burned. Examples are also known of horizontal piles, long heaps of wood that burned steadily from one end to another. In the forest regions of Europe special craftsmen known as charcoal burners or *colliers* became well-established.

Biringuccio also describes the method of burning charcoal in pits, with particular reference to the craft of the smith. A pit of some 90cm diameter and about the same depth was dug out and filled with small pieces of wood and rubbish. A space was left in the centre which extended right through the filling to enable the fire to be lit, while the upper level was sealed with earth or clay. In this way charcoal could be produced in only 8 – 10 hours. According to Biringuccio, the charcoal produced was not suitable for smelting but only for smithing, and it required a stronger air-blast (Fig. 28: 2).

Charcoal burning in pits for metal production and other purposes was normal practice in Russia until the 17th – 19th centuries, even after 1900 in some areas and is described in Russian ethnographic literature (Uspenskaya 1959, 108 – 109). Two types of pit were operated — circular and elongated (4m x 2m x 1m deep) — both being sealed with green branches, flax, and clay. The burning process took 3 – 4 days. Uncovered pits were also used, these being gradually filled with wood laid onto the burning layer. Wood cut in the spring was charged in the autumn. There are also records of charcoal being produced in open fireplaces, the fire having been damped down.

Archaeological excavations, and especially those of smelting sites, have revealed some evidence of charcoal burning. These should not, however, be confused with layers of charcoal found near the work places, which usually indicate where charcoal was stored immediately before charging to the furnaces. There are unfortunately very few cases where it has been possible to demonstrate a spatial relationship between charcoal-burning facilities and ironmaking and working features. Charcoal burning very close to bloomery furnaces would seem to be indicative of the production of charcoal on a very small scale to meet the immediate needs of the smelters.



1



2

Fig. 29. Charcoal-burning after Biringuccio (1540). 1 Construction of charcoal piles, 2 charcoal-burning in pits.

Traces of charcoal burning some distance from bloomeries and which supplied them on a larger scale have been reported but not fully excavated nor tied to the relevant iron production sites.

Charcoal pits

Three cauldron-shaped pits (features a, b, and d) were excavated to the north of the Late Hallstatt smelting furnaces at Waschenberg in Austria. They were 0.8 – 1m in diameter and 1.1 – 1.4m deep (Fig. 30: 1). The bottom filling of each consisted of fragments of red-burnt clay, ash, and a layer of charcoal some 50cm thick. When compared with the other pyrotechnical features excavated, they could only be interpreted as pits used strictly for local charcoal production (Pertlwieser 1970, 63, fig. 5: 4).

Another typical charcoal pit, unfortunately an isolated find, cylindrical in section and with a fill which contained, large sherds of characteristic late La Tène pottery, was discovered at Prague-Bubeneč (Fig. 30: 2). The pit, the walls of which bore traces of firing (Pleiner 1958, 67, fig. 8: II), was 1m in diameter and 1.45m deep and had a rounded bottom covered by a layer of charcoal 40cm thick and sealed with fragments of fired clay, which showed clear impressions of the logs and wood which made up a grid used to seal the top. The structure may be interpreted in the following way. A charge of wood in the pit was ignited from above and covered with a lid made of plaited branches, plastered with clay, in order to ensure a slow rate of combustion. At the end of the process the lid was broken up, with some traces of charcoal (probably largely fine debris) being left at the bottom. This, incidentally, corresponds exactly with Biringuccio's description and illustration. An identical pit was found in older excavations of bloomery sites in the neighbouring Prague-Podbaba area (Fig. 30: 3; Pleiner 1958, 66 – 67, fig. 8: IV). This was 1m in diameter and 1.6m deep. The charcoal layer in the bottom of the pit was covered with stones, including a rotary quern.

The three pits from the Romano-Barbarian ironmaking site at Kellerberg, near Potsdam in northern Germany, have the same form (Fig. 30: 4). They were cylindrical, 1m in diameter and 1.2m deep, with a 30cm thick layer of charcoal at their bases, and were covered by stones remaining from the original sealing material (Hoffmann 1941). At Leese, near Nienburg in north-western Germany, a cylindrical pit, 85cm in diameter and 90 cm deep, and filled with stones was excavated. The base and part of the walls were fire-reddened into the sandy subsoil. No charcoal was reported but Nowothnig (1965, 262 – 263, fig. 3) points to analogies for its having been used for charcoal burning. There were no associated finds to enable it be dated, although it was covered by a slag heap, presumed to be mediaeval in date.

Peets (1987) reported two relatively large and (by contrast) square charcoal pits from Tindimurru in Estland. Their dimensions in plan were 190cm x 210cm and 220cm x 250cm, with depths exceeding 100cm. They were filled with crossed pieces of wood which were charred, and by red-burnt soil and bloomery slag fragments. In the vicinity, pieces of unconsolidated blooms and iron slag debris were found. The dating comes only from radiocarbon tests (AD 70 ± 70). The author suggests that branches of wood were placed in the pit, covered with earth and then ignited through a vertical channel.

Hillebrecht (1991) investigated charcoal from the Harz. At Pendelbach, charcoal pits associated with slag sites yielded a variety of wood species including maple. They have dated preliminarily to the Middle Ages (after AD 900), being succeeded in the stratigraphy by small post-mediaeval charcoal platforms associated with maple and spruce, and then larger, modern platforms with only spruce. The features are not documented

Englund (1994, 23, fig. 5) excavated a bloomery ironworks in the Tranemo area of Sweden where charcoal pits 3m x 5m in dimension occurred close to a pair of bloomery furnaces. However,

radiocarbon dating has shown that they are about two centuries later than the ironmaking activity and relate to the 11th – 12th century features.
Hundreds of charcoal pits have been reported from early iron-producing districts in Norway, but, as it seems, many of them belong to the category of sunken piles (see below).

Sunken charcoal piles

Some features have been excavated which were evidently connected with charcoal burning but which seem to be hybrid in form. These are pits of large diameter, with sloping sides, the dimensions of which make it difficult to envisage their having had any simple cover over the burning contents. They seem rather to resemble the sunken bases of piles or heaps of wood that had been built up above ground level and then coated with an insulating layer of clay or earth.
Such features are characteristic of the Holy Cross Mountains in Poland, where more than twenty examples have been investigated (Bielenin 1974, 127 – 143, figs 66 – 71). Several sub-types have been identified, the most common of which, seen well at Jeleniów 4, are funnel-shaped depressions, about 3m in diameter and 1m deep (Fig. 31: 1). Others found at Słupia Stara 1 and Podchełmie, are over 2m in diameter, 60 – 80cm deep, with sections which narrow gradually in a series of terraces or steps (Fig. 31: 2). A third type observed at Sarnia Zwola, Ambrożów 1, Podchełmie and Słupia Stara consists of a cylindrical depression, distinguished from the previous types by their larger dimensions of 1.5 – 2.6m in diameter and 0.9 – 1.1m deep (Fig. 31: 3). Several of the pits at Gardzienice 1, Jeleniów 4 and Słupia Nowa 4 were shallower and circular (1.7m diameter) or oval 2.2.m by 2. 61m) in plan and only 40 – 60cm deep. The section of

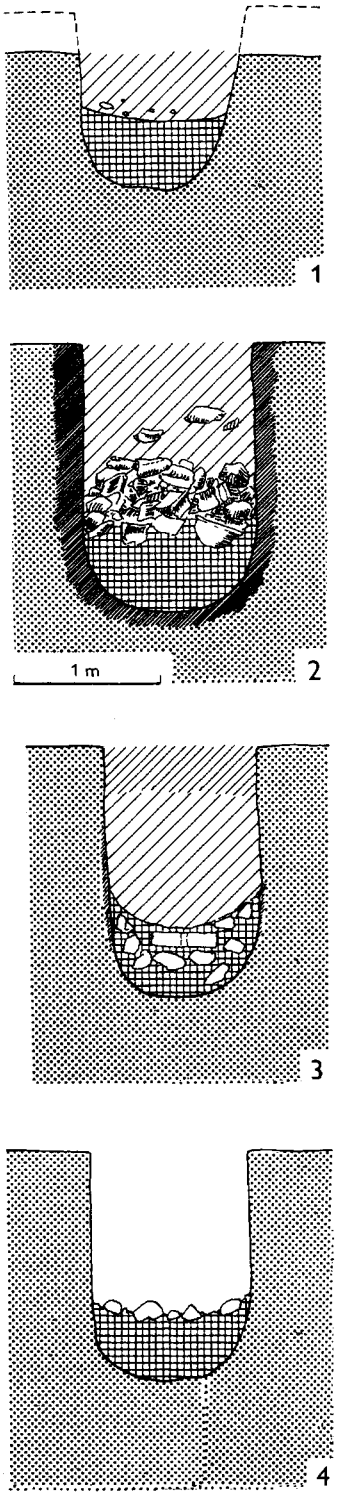


Fig. 30. Charcoal-burning pits. 1 Waschenberg, Austria, late Hallstatt period; 2 Prague-Bubeneč, late La Tène period; 3 Prague-Podbaba, Romano-Barbarian period, a pit found nearby ironmaking plants; 4 Potsdam-Kellerberg, Germany, a pit found within a bloomery site. Crossed layers represent charcoal or charcoal-rich soil, hatching: burnt-red. References: 1 Pertlwieser 1970, 2–4 Pleiner 1958 after Novotný, Jíra, and Hoffmann.

the Podchełmie 1 structure revealed slight reddening of the subsoil and the loess and of the stone paving, at the base of which a thick charcoal layer was observed. The features occurred either in lines as at Słupia Stara 6, or laid out in the form of triangles as at Słupia Stara 1, where the arrangment lay about 5m to the south of the smelting furnaces. In other cases, the charcoal burning structures lay from 10 – 40m from the smelting fields. If it is assumed that the height of the pile above a sunken base of this kind was the same as its depth, then the Holy Cross Mountains features could have processed a stack of about 5 – 10 steres of wood in a single operation, which is ten times greater than the capacity of cylindrical pits. The sunken parts of charcoal piles in the Holy Cross Mountains inspired in the comparison of two pits from Clérimois (130cm x 100cm and 240cm x 160cm, preserved depths 50cm and 90cm respectively) with slightly reddened walls and fillings of charcoal dust and fines related to ferrier 3b, 3rd century AD (Dunikowski and Cabboi 1995, 138, fig. 85).

Silesia is another region which saw extensive iron smelting activity during the Romano-Barbarian period. Excavation of a production site at Izbicko revealed an area with a concentration of 37 sunken bases for charcoal piles (Pazda 1990). They were both square and circular in plan (1m x 1m or 1.5m x 1.5m, 55 – 75 cm deep), filled with charcoal dust and the charred fragments of oak, mixed with beech and other tree species. Recent excavation of the Romano-Barbarian bloomery fields in the Lausitz, at Wolkenberg, revealed some 23 examples of this type of installation, but here, they were squareish in plan with rounded corners and of varying size — 1.6m x 2.6m, 3m x 3m, 4.35m x 5.7m, with depths in the range of 60 – 80cm (Spazier 1996, 1997). There was a layer of charcoal adhering to the sloping walls at the bases of the heaps and charred logs were occasionally found at the bottoms. Site 17 produced 12 charcoal-burning installations set among 165 slag-pit furnaces which were clustered in 7 fields; in contrast, at site 22, there were 11 such installations on the periphery of a field of 144 furnaces.

More to the west, close analogies are to be found in the four circular pits from Westerholz in north-western Germany, which lay about 25m to the east of a group of slag-pit furnaces (Dehnke 1970, 272). These were 3.5 – 4m in diameter and 2m deep, and in the centre of each was another depression, 65cm in diameter and 15cm deep, which can be interpreted as the traces of a supporting structure for the wood stack. Similar open pits for charcoal burning, 3.5m in diameter and 1m deep, found still filled with charcoal to a depth of 50cm, have been reported from early mediaeval Russian sites such as Podmoklove (Uspenskaya 1959, 109), but unfortunately without drawings or further details.

A specific production of charcoal for ironmaking has been reported in southern Norway in Gausdal, Valdres and the Dokkfløy Valley. It would appear from the summary of the thesis by Narmo (1996) that charcoal was made directly in the hearths of the local slag-pit furnaces which are around 1m in diameter (radiocarbon dates range from the 3rd century BC to the 7th/8th centuries AD) before the roasted bog ore was put in. This interpretation should, however, be subjected to detailed analysis. On the other hand, the mediaeval slag-tapping furnaces which have radiocarbon dates of the 12th – 14th centuries AD, were fed with charcoal prepared in large piles with sunken bottoms. These piles had internal diameters of 2 – 3m and were sunk to depths of around 1m and were an integral part of the bloomeries where from 2 to 6 units were observed on four excavated sites. Estimates indicate that such piles would have produced from 2 to 22 steres of charcoal (*op. cit.* figs. 11, 14 – 15, 18).

In addition to these specific examples, other charcoal burning installations with more-or-less sunken floors have been found. It must be borne in mind that there is little hope of finding the remains of genuine flat bottomed charcoal piles as these are likely to have been obliterated.

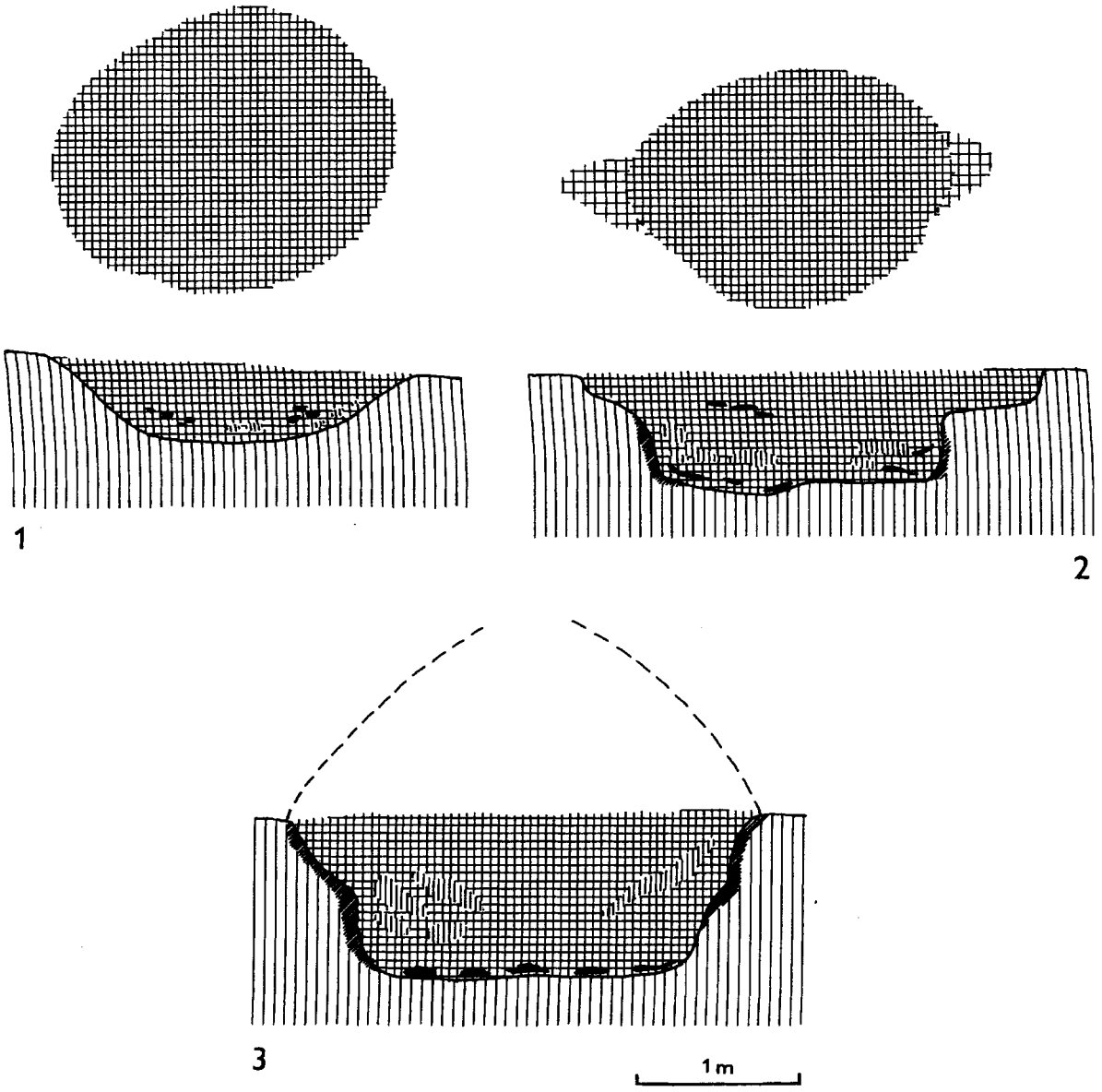


Fig. 31. Various types of sunken bottoms of charcoal piles in the Holy Cross Mountains of Poland, Romano-Barbarian period. 1 Jeleniów 4; 2 Stara Słupia; 3 Sarnia Zwola. After Bielenin 1974.

Charcoal piles

In association with the late La Tène smelting furnaces at Karlskron in the Donaumoos of Bavaria, eleven circular patches of charcoal, 1.2 m in diameter and sunk slightly into the sand, were found. The charcoal had been crushed, but some pieces of pine were identified (Seitz 1937). A comparable and contemporary fragmentary feature was found at Manderbach in the Lahn-Dill region of western Germany. This was a depression in the clay, about 2m in diameter, filled with charcoal (Heymann 1958, 908, fig.7). At Novoklinove in the Carpathians, where a cluster of slag-pit furnaces was discovered, a hollow roughly 2m square and 40cm deep, lined with red-burnt clay and with a layer of charcoal at its base, was investigated (Bidzilya 1970, 41, fig. 6). This was interpreted as the sunken base of a charcoal pile, possibly pyramidal in shape and was also dated to the La Tène period (2nd – 1st centuries BC).

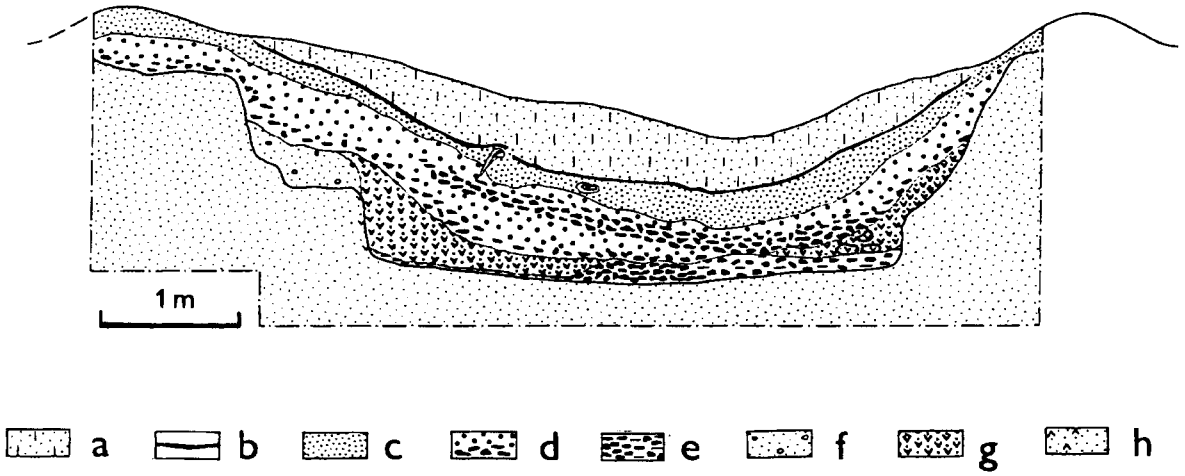


Fig. 32. Kelheim, Germany. Section of an early mediaeval charcoal pile bottom (7th – 9th centuries AD). Symbols: a – quarz sand, b – layers of wood, c – yellowish sand, d – sand and charcoal, e – clay and charcoal, f – grey sand, g – burnt-red sand and charcoal, h – tertiary sand, partly burnt-red. After Schwarz, Tillmann, Treibs 1965/66.

Among mediaeval sites, the shallow sunken charcoal pile from Handewitt in South Jutland is worthy of mention, although unfortunately it has not been described in detail (Hingst 1974, 153). It was found 5m south-west of a contemporary slag heap, containing *Kugeltopf* type pottery. A sunken charcoal pile at Michelsberg, near the Celtic *oppidum*, was sectioned (Schwarz *et al.* 1965/1966, 58 – 61, figs 17 – 19). The pit was dug into the sand, was 5.5m wide in section and only 60cm deep, and was filled with charcoal and had heat-reddened walls (Fig. 32). Two radiocarbon determinations gave dates of AD 610 – 850 and 835 – 1015 respectively, indicating production in the early mediaeval period.

More than 250 charcoal piles of mediaeval date have been recorded in the iron-producing Sauerland region of western Germany (Sönnecken 1971, 15 – 18). Near Hannover, around Isernhagen, no fewer than 375 charcoal piles (also not described) and 359 smelting sites dating from the 13th – 16th centuries have been recorded (Schulz 1972, 312).

Horizontal piles, as known from the 19th century, e.g. in Austria, are not attested in archaeological and other early sources.

Experimental charcoal burning

Smelting experiments carried out in 1964 using replicas of the Želechovice and Scharmbeck furnaces included the production of charcoal from pine in two free-standing piles with flat bases (Pleiner 1969b, 464 – 465, figs 6 – 7; Pleiner 1992). Pile I had a base 2.5m in diameter, in the centre of which three rods of green wood bound together with withies in the form of a triangle, provided a vertical air shaft. Chopped logs were arranged so as to leave three horizontal vents at the bottom. The pile was built up as two horizontal layers of logs 60cm long and weighing 400kg, to a height of 1.4m and with a diameter of 2m. The completed pile was coated with green branches and blocks of turf, the joints being sealed with wet sand. The vents at the base were opened and the pile was lit through the hole at the top. Ignition was confirmed by the appearance of whitish smoke, at which point the lower vents were closed. Charring of the wood began in the morning and continued for 48 hours. When carbonization of the wood began, the smoke changed to a blueish colour. The volume of the pile gradually reduced, which necessitated constant monitoring, so that cracks could be sealed with wet sand and earth in order to prevent complete combustion. By the end of the process, the height of the pile had shrunk to 1m, representing 65% of the original volume. The experiment produced 70kg of excellent charcoal, a yield of 17.5%, which may be considered to be a successful outcome.

Pile II was identical in construction, but slightly larger. It contained 570kg of pine wood, which produced 100kg of charcoal after 68 hours (again 17.5%). In both cases the charcoal output was in the ratio 1 : 5.7 to the original charge of wood.

Wood consumption and deforestation

It is difficult to give any quantitative estimate of charcoal consumption in the early European iron producing regions. Using parameters derived from trials of the Želechovice furnace experiments, it is possible to provide the following data. Smelt II 2 in the underground type of smelting furnace yielded 6kg of crude iron from 44kg of haematite ore (> 70% Fe_2O_3). Including the preheating of the furnace and the reheating of the bloom before forging, 110kg of mixed pine and beech charcoal was consumed in the process (Pleiner 1969b, 471). This gives a weight ratio between charcoal consumed and iron produced of 18 : 1.

Some 16 smelting experiments by Crew (summarized in Crew and Salter 1991, 16 – 17) showed that a far lower blowing rate consumed less charcoal and resulted in a typical, black iron rich slag and a good yield of iron. The most effective smelts consumed 8kg of charcoal (ratio of charcoal to ore of 1 : 1) at a blowing rate of about 230 l/min., and gave 1.25 – 1.7kg of iron in the form of crude blooms. This gives a fuel to bloom ratio of 5 : 1 but does not however take into account the additional charcoal consumption in furnace preheating and heating after the last ore charge, and the actual total fuel bloom ratio is, in fact, around 13 : 1. Assuming that early ironmakers were more skilled and experienced and produced higher yields, charcoal consumption in terms of weight must still have been in order of 10 – 15 times greater than the weight of iron produced.

The 110kg of charcoal consumed in the Želechovice experiments represents about 628kg of wood, or a little over 1 stere. A pine tree 30m high with a diameter of 25cm towards its base would produce 2 steres of wood, sufficient for two smelts in a furnace of this type. It may therefore be concluded that small-scale seasonal operations to meet the limited requirements of local peasant communities would have had no significant effect on the tree cover in the vicinity of a bloomery ironworks.

The situation would have been very different, however, in regions where ironmaking was carried out on a larger scale and over longer periods. Problems of transportation would have obliged the smelters to meet their requirements for wood from over large areas. Let us examine some tentative estimates that have been made in respect of the Weald of south-eastern England, France, the Jura Vaudois of Switzerland, and the Holy Cross Mountains in Poland. All the

figures offered below are, of course, no more than rough approximations and, for the most part, are based on the slag volumes and weights calculated from furnace sites or refuse heaps.

As a general rule, it may be suggested that in order to produce on average 100kg of bloomery slag and 25kg of unworked iron, it was necessary to smelt about 140kg of ore (containing around 60 % Fe) which would have consumed around 140kg of charcoal (using a fuel-to-ore ratio of 1:1). In addition to the actual reduction process, the preheating of the furnace and the heating after addition of the final ore charge must be taken into account. Furthermore, charcoal would also have been consumed in the various reheating and smithing processes involved in the forging of the iron.

According to Dunikowski and Cabboi (1995, 126), the several centuries of activity by the Gallo-Roman 'ferriers' at Clérimois, France, are likely to have seen the consumption of some 15,621 tonnes of wood or about 65,088 steres (including an assumed loss of 70% loss). This would have required the clearance of somewhere in the region of 217 hectares of forest (at an average of 0.45 hectares annually) since their calculations of charcoal consumption do not take into account all of the operations ancillary to smelting. These figures must thus be treated as estimates at the lower end of the scale. There would certainly have been a degree of deforestation of the environment, especially in the early phase of production at the ironworks. Detailed palaeobotanical studies carried out in northern Wales in connection with local ironmaking at the hillfort of Bryn y Castell indicated that a certain decline of trees during the period of iron production there (La Tène and Roman) may be a result of charcoal burning (Mighall and Chambers 1989), although the iron smelting was never more than small-scale and the final environmental effect was not drastic.

There must have been serious deforestation of the landscape in the Roman iron-producing Weald. Cleere (1976, 240 – 241) attempted to estimate the extent of deforestation as a result of intensive iron production there. He assumed a density of some 45 oak trees, in various stages of growth, per hectare for the region, producing around 400 steres of suitable wood (principally in the form of branches), equivalent to 250 tonnes, and representing an annual production of about 35 tonnes of charcoal (taking into account a very low yield). Such an amount would have been sufficient for the production of around 3 tonnes of iron in the shaft furnaces in use at that time. Thus, in the period from 120 – 240 AD during which there was intensive ironworking in the region around Battle, some 300 – 500km^2 of woodland would have been felled to produce 729,000 tonnes of charcoal, at an average rate of 54,000 tonnes per year.

Pelet (1973, 184 – 190; 1993), who excavated 13 – 14 bloomeries over an area about 1km^2 near Bossena, Prins-Bois, and Bellaires in the Jura Vaudois, calculated that iron production in this small area during the La Tène and Roman periods amounted to around 23.5 tonnes and resulted in the deforestation of 40 – 70 hectares of hardwood in the immediate vicinity. The use of young wood, was, in Pelet's view, evidence of the impact of the iron industry on the original forest cover. By contrast, a small bloomery, of slightly later date, at Boécourt with two furnaces can only have had a limited influence on local forests. According to Eschenlohr and Serneels (1991, 19 – 25) about 29 – 173 steres of wood representing 6 – 24 tonnes of charcoal would have been consumed per hectare in the production of one tonne of iron.

How high was the demand for charcoal in the extensive Romano-Barbarian iron production areas of central and northern Europe? Bielenin (1974, 194 – 195) first estimated that some 273,340 slag-pit furnaces (each equivalent to a single smelt) were operated in the Holy Cross Mountains during the La Tène and Roman periods. However, between 1974 and 1992 he was forced to double his estimate of the numbers of furnaces involved (Bielenin 1992). According to his most recent calculations, this industry would have required 83,650 tonnes of ore and more than 84,250 tonnes of charcoal in smelting alone in order to produce 8500 tonnes of unworked iron. It is difficult to estimate what this would have represented in terms of forest clearance, but it must have been massive in this region, where over 6000 ironmaking sites were spread over

some 725km^2.

Orzechowski (1991, 176 – 179) has offered some different calculations for the Łysa Góra area of the southern Holy Cross Mountains. With a total of 90,000 smelts, each consuming 300kg of charcoal, figures based on actual furnace dimensions and the weights of slag blocks, he arrives at a total requirement of 27,000t or 450,000 steres of wood. Taking into account the fact that, based on the archaeological evidence production flourished for only about 100 years (the $B_2 - C_1$ phases of the Romano Barbarian period, AD 150 – 250), his results indicate that 900 smelts would have consumed 4500 steres of wood a year. Thus, during this period some 9 hectares of forest must have been cleared annually. Voss (1995, 208) calculated that the amount of charcoal necessary for fuelling the 170 smelting units at Snorup in Jutland, only a small proportion of the furnace clusters in the area, as high as 43 tonnes, representing 250 steres of wood and deforestation of around 20 hectares. He suggests that the local coppicing must have been practised as part of the organization of charcoal making.

We should also take note of recent research projects in the main iron-production regions of Germany by Smettan in the Schwäbische Alb (1995), by Pott and Speier in Lahn-Dill and by Dörfler and H. Kroll in Joldelund (see Backer *et. al.*, 105 – 110). These include systematic palaeobotanical investigations of the frequencies of pollen preserved in peat on the local moors. These studies demonstrate trends of environmental change and different types of human influence, including the introduction of agriculture, changes in the forest economy and, above all, the exploitation of forests to a greater or lesser degree for charcoal burning linked to iron smelting operations. Such a link would seem to have been made at Dietzhölztal in the Lahn-Dill area where pollen diagrams show the increasing frequency of minute charcoal particles (with a great deal of beech) during the 12th – 13th centuries AD. The analysis of the distribution of individual ironworks in this region suggest a cyclical moving caused by consumption of forest in the close vicinity during several seasons (Willms, personal communication).

By contrast, the results in the Schwäbische Alb area do not provide any unambiguous picture, since forest recovery occurs during the early Middle Ages, just at the time when intensive ironmaking activity is attested for the region (Smettan 1995, 127). In Kempa's evaluation (*ibidem*, 321), individual dating of the minute layers in the peat deposits could play a decisive role in interpretation. Charcoal analyses are planned in all these regions.

Similar investigations have been carried out in the Norwegian Heglesvollen area of Trøndelag and the results produce new problems of interpretation. During the period when iron was being produced (most intensively in the 1st half of the 1st millennium AD) some tree species (pine, birch) seem to have been replaced by spruce, possibly after the destruction of the original tree cover, especially in some micro-regions (Solem 1991). The situation is complicated by the introduction of summer farming in certain areas.

With regard to the estimates of consumption given above, they are all based on inadequate data and really only reflect values at the lower end of the scale. They do, however, illustrate the fact that concentrations of production in certain areas must have had a devastating effect on the natural environment, and in particular on its vegetation, even in earlier times. Recognition of this effect was, in later periods, to result in strict statutory regulation and control of clearance. In the Forest of Dean in south-western England such measures were introduced as early as the 13th century (Schubert 1957, 113; Hart 1968), although, interestingly, the Weald of south-eastern England was largely exempt from such legislation, probably attributable to the fact that coppicing was in use there from an early period.

Indeed, coppicing is a factor that may well have mitigated the impact of ironmaking on ancient woodlands. It is known that as early as the Bronze Age, coppicing was being practised in the Somerset Levels of south-western England, and it is not unlikely that the system was in use in the Weald by Roman times. Certainly, woodland management of a high order was generally practised there by the end of the bloomery period (Cleere and Crossley 1985, 133 –

137). As already mentioned, it is suggested that coppicing mitigated the effects of the extensive iron production around Snorup in Jutland during the 1st half of the 1s millennium AD, and the '*Hauberg Wirtschaft*' survived in western Germany until post-mediaeval times, as in the Veluwe, central Netherlands, as well (van Nie 1995). It is unfortunately difficult to prove from the archaeological record that coppicing was being practised, except in areas such as the Somerset Levels, where evidence in the form of organic materials are perfectly preserved in peat deposits.

The situation in general became acute by the later mediaeval period, when the large charcoal blast furnaces were demanding more than twice as much fuel as bloomeries of the *Stuckofen* type, and it has been suggested (Sprandel 1984, 75) that the introduction of the indirect process may have been delayed owing to the lack of wood/charcoal resources. The short-lived blast furnace industry of the 16th – 18th centuries in Ireland failed in no small degree due to the virtual obliteration of the tree cover by industrial activity, notably charcoal burning (Scott 1985). In 18th century Bohemia, all of the more important iron producing centres were suffering from shortages of wood for charcoal (Kořan in: Pleiner *et. al.* 1984, 207). Indeed, in many countries indigenous iron production was certainly retarded until the advent of a new fuel in the form of coke resolved the problem.

Mineral coal and peat

Other types of fuel were only rarely used for iron production. Theophrastus, whose description of the production of charcoal in piles has already been referred to above, makes an interesting comment in his treatise *On stones* 2.16 on blacksmiths in the Peloponnese who used mineral coals, obtained from the Olympia region, in their forges.

There is evidence for the sporadic occurence of mineral coal on sites in Britain and in the Rhine provinces belonging to the Roman period. Older reports on the Roman bloomeries at Tiddington and Wilderspool in England (Fieldhouse *et al.* 193l; May 1904: see Schubert 1957, 47 – 49, 58) refer to pieces of mineral coal found in slag heaps along with charcoal, and it was assumed that roasting furnaces or smithing hearths were occasionally fed with this fuel. A link has been suggested by several authors (Schubert 1957, 49, 52 – 53; Coghlan 1956, 107) between a block of cast iron and samples of mineral coal from Wilderspool. However this is not evidence of the use of coal for smelting, since the Wilderspool furnaces were operated on the Blackband iron ores of the Coal Measures and may have been naturally contaminated with coal. Tylecote (1962a, 234 – 235) admits the use of candle coal in smithing operations (see e.g. Theophrastus, above), and in that sense he interprets the Tiddington and Wilderspool features. Elsewhere, reference is made to mineral coal found in a furnace in the *via praetoria* of the Roman fortress at Bonn (von Petrikovits 1960, 115, 193).

It is generally accepted that ancient Chinese ironmaking was based on the use of mineral coal from as early as the Han period. According to Barnard and Tamotsu (1975, 61 – 62, 76), the situation was complex. The Han period furnaces at the site of Kung-hsin were fuelled by wood or charcoal, but possibly also by coal. Coal and special briquettes (*mei ping*), made from coal-dust, clay, and quartz, were found near most of the furnaces. Needham (1964, 14, 19) also reports that mineral coal was being used in the crucible process for the production of cast iron in Shansi province as early as the 4th century AD.

Most of the evidence, for antiquity and the Middle Ages alike, points to coal having been used principally in blacksmiths' forges. This is confirmed by written records from Nottingham, England, dating to 1257 (Schubert 1957, 114). Bohemian blacksmiths substituted charcoal for brown mineral coal from the Kladno mines just before World War I (and, as a result, ceased to produce the typical sintered-together PCB slag-cakes).

In Scotland there is evidence of peat having been used to fuel smelting furnaces in the prehistoric and early mediaeval periods. Dried blocks of peat were charred and converted into a form of charcoal (Schubert 1957, 18). The use of peat has frequently been suggested for Irish

sites, although the only juxtaposition of peat charcoal with ironworking activity comes from the later 1st millenium AD monastic site at Reask, Co. Kerry (Scott 1990, 161). Interestingly, in 1865 an Irish patent for the use of peat charcoal in the blast furnace at Creevelea, Co. Sligo was granted to the operating company, and although a report to the Royal Irish Academy commended highly the quality of the iron produced, the venture failed (Scott, pers. comm. 1998). Maréchal (1973) carried out some experiments using peat as a fuel for the reduction of iron ore in order to examine the effect this would have on the nitride content of the iron produced.

Wood

The post-mediaeval evidence shows that the reductant in the smelting process in bloomeries was charcoal, with one exception. Ole Evenstad (1790) described a process practised in some regions of Scandinavia and based on chopped wood which was placed in the funnel-shaped interior of the furnace, kindled and then charred before the first charge of ore was added. During the smelt, a careful manipulation of charcoal followed. The reasons were economic. 'The use of charcoal should ease the work considerably, but, since a lot of charcoal is needed and since burning costs a lot and the furnace will not bear such a heat, it would turn iron to steel, and would have to stand idle to cool. So there is no advantage unless bellows are driven by water power as one man could then turn to the smelting or make the charcoal' (translation by N.L. Jensen). This inspired Espelund (1991a; 1997) who is inclined to believe in a considerably broader use of wood in place of ready-made charcoal in the bloomery practices of the past. A similar view was expressed by Narmo (1996, 197) who suggests that large furnaces of the period AD 200 – 700 in the Dokkfløy area of Norway, claimed to be slag-pit furnaces (documentation is lacking) were fed with wood. Anyway, these are not connected with the post-mediaeval 'Evenstad' technology. The idea of charring wood in slag-pit furnaces found advocates among some Scandinavian archaeometallurgists who conducted practical trials (Nørbach; Gjerløff and Sørensen in: Early Iron Production 1997, 59 – 62 and 67 – 71 respectively). Both experiments produced fayalitic slag with very small amounts of iron embedded as particles in the slag mass. Their verdict that it is possible to operate a slag-pit shaft furnace with chopped and coppiced wood does not seem totally convincing, and more work is required to elucidate the problem.

Chapter VIII

THE SMELTING OF IRON: THE BLOOMERY PROCESS

The metallurgical principle underlying the extraction of iron consists of the chemical reduction of its ores (which are made up of the relevant iron oxide(s) plus other components including non-metallic, mostly siliceous gangue) by carbon or gases formed from it. Chief among the reducing gases, which also include carbon dioxide, is carbon monoxide which combines with oxygen in the ore and releases the metal. As we saw in chapter IV, two methods for achieving this, each named for the way in which malleable iron was obtained, arose during the history of iron metallurgy.

The technology which today supplies industries with all of their requirements for iron, is called the 'indirect process' and consists of the production of liquid, highly carburized pig iron (2 to 4.5 %C) at temperatures in the range 1600 – 2000 °C. The process is 'indirect', because malleable iron and steel are produced in two stages. Apart from the smaller amounts of cast iron used for foundry purposes, the metal has to be transformed in special fining installations into malleable steel, or wrought iron, by secondary re-oxidation in order to lower the high carbon content down to 0.05 – 1.5 %C. The site of the ore reduction is the blast furnace, nowadays a tower up to 30m in height, and up to 1300m^3 in volume, fed with ore, coke and lime fluxes and blown with preheated air. The shaft has a typical biconical profile with a bosh and a narrower hearth, collecting liquid pig iron and glassy slag which is low in iron, with each being tapped out from different levels. The second stage, the production of malleable metal, takes place in special installations. The ancestors of the blast furnaces (*Flossöfen, Massenöfen*) were smaller, from 3m to 12m high and fed with charcoal. The pig iron was converted to malleable iron or steel in different kinds of finery hearths. The origins of the European blast furnace and of the indirect process as such have recently formed the subject of intensive archaeometallurgical research.

The other, older technique which took place at lower temperatures is known as the 'direct' or 'bloomery' process in which the end product of the smelting process was a solid, malleable mass or 'bloom' of iron and iron-rich slag, produced in one stage.

Although the indirect process began to displace bloomery smelting from, perhaps, the 13th – 14th centuries AD, the simpler process survived in various guises to the first half of the 20th century. It was described by metallurgists in Europe and compared with traditional techniques in Asia and Africa, recorded by ethnologists. In the 16th – 19th centuries, such survivals only produced blooms (10 – 150kg of weight), which were removed from the furnace in the solid state. The slag contained as much as 50 % of iron as oxides and was tapped from the furnace as liquid waste. The running of this slag into channels and traps was called in German '*das Rennen*'. Thus, the key German word for the bloomery process derives from the slag removal operation and occurs in such terms as *Rennprozess, Rennofen, Rennverfahren, Rennschlacke, Renneisen.* In English, on the other hand, the product itself lent its name to the process of solid state ironmaking, the bloom — in other languages *die Luppe, la loupe* from *lupus*, the wolf, or *Stuck, kus*, i.e. a piece or lump. Bloomery process, bloomery, bloomery iron and bloomery slag all denote the direct method of ore reduction. Other languages have less precise term for this type of smelting. Thus *dýmačka, dymarka* in Czech and Polish denote, in fact, just the smoking or blown furnace (*casa conflatoria*), while in Russian, the *syrodutnyy* process means simply an operation using a cold blast. As the product was immediately malleable, the bloomery process is known also as the 'direct' method of iron smelting (*méthode directe, direktes Verfahren* and so on). Excavations of early bloomery installations and analyses of iron-rich slags and blooms show that the direct process can be followed deep into the past: it was the original and earliest technology of ironmaking.

The bloomery process: recent views

In spite of the many smelting trials and other research which have enabled us to understand better the principles underlying the basic bloomery process as outlined above, there are many questions which still remain far from being answered and which attract conflicting views.

One group of workers defends the traditional view that throughout the early bloomery process, iron ore was reduced to metallic iron in the solid state, spongy and pasty, low in carbon, penetrated with viscous, iron-rich slag ideally melting at temperatures in the region of 1200 °C. It is argued that although higher temperatures could be achieved, this was not desirable, since too much iron would be reoxidised to ferruginous slag. The iron sponge, sometimes forming a more coherent bloom, was regularly carbon-free, although more carburized areas developed under specific conditions in certain zones of the reduction furnace (Neumann 1954; Schürmann 1956; Osann 1971; Sperl 1979; 1980). The goal was to obtain a softer, easily-malleable metal (Espelund 1996a, b).

Another group considers the bloomery smelt as an integral reduction process, not differing in principle from that taking place in the blast furnace. They suggest that iron particles became heavily carburized in the higher levels of the furnace stack and melted easily to pig iron (Straube, Tarmann and Plöckinger 1964; Straube 1986; 1996; Schuster 1969; Björkenstam 1985; Rehder 1986) and, moreover, that temperatures in the combustion zone at the tuyere mouth were, even in the case of low shafts, always higher than imagined, easily exceeding 1400 °C (Tholander and Blomgren 1985). However, practically all of the molten iron would be secondarily decarburized in the oxidation zone near the tuyere mouth, because the temperature was extremely heterogenously distributed, even in the hearth. Reduced iron and the slag formed constantly received a great deal of unreduced iron ore from higher levels, which had an oxidizing effect and which, within the low shaft, had no chance to react with reducing gases (Blomgren and Tholander 1986; Tholander 1987).

Some authors are inclined to see the main cause of the production of malleable iron in a bloomery as the intermittent style of work, which was not continuous or long-lasting as in the large blast furnace. If charcoal charging ceased soon after the last ore was added, strongly oxidizing conditions developed in the furnace hearth and much of the carbon-containing iron already reduced was not only decarburized but also converted to ferruginous slag, causing considerable losses in yield (Björkenstam 1985). In fact, discharged cast iron particles are regularly found in association with bloomery furnaces in the course of excavation ('gromps', in Polish *grądzie*, groats, see Radwan 1960, Nosek 1977; 1994). Moreover, the metallographically investigated blooms very frequently reveal patches with cast iron structures.

In our view, there is much merit in both sets of arguments. It is easy to envisage that despite the small dimensions of the early bloomery furnace, or perhaps because of them, both types of conditions developed in certain regions, or during different phases, or during changes in the rhythm of the air-flow, caused either temporary carburization, in other words the blast furnace style or, on the other hand, the bloomery character of the smelt. These include the composition and size of the ore fractions, the ore to fuel ratio, the ratio between the diameter and height of the shaft, the intensity of blowing or air induction, the direction of air flow and manipulation of the slag (Pleiner 1969b; Tylecote, Austin and Wraith 1971; Die Versuchschmelzen 1973; Clough 1986; Pelet 1992, Gurin 1996). Indeed, it is no wonder that bloomery waste so often contained highly carburized metal or even pig iron samples.

Reconstructing the bloomery process

Our knowledge of how bloomery smelting worked derives not only from the examination of the remains of furnaces uncovered by archaeological excavation, from chemical, mineralogical and metallographic investigation of slags and iron they produced and evaluation of records, documenting traditional processes, but also from experimental reconstructions. Over some fifty

years, the form of these experiments has undergone a certain development. The goal of the first trials was simply to obtain some metallic iron in the slag produced under primitive conditions and to test reconstructions of some types of furnace. In recent years, since metallurgists have began to participate more systematically, so the experiments tended to diverge along two main lines of approach.

First, there are attempts to keep as close as possible the original conditions, with furnaces built strictly according to remains identified during excavation, using traditional structural materials and bellows worked by hand. These operation have quite often been turned into very succesful public shows, in addition to the original goal of controlled experimentation. The second, metallurgically driven approach stresses examination of the theoretical principles of the process itself, omitting those external parameters such as the structural furnace materials (clays), mode of construction and the location of the trial in the field. Furnace replicas in laboratories and halls, blown by mechanically driven air supplies, are widely applied and chemical and physical measurements including gas analysis and thermocouple readings, levels of ore and charcoal consumption and time recording as the basis for metallurgical evaluation. Combined trials, which are useful when properly documented, are also being carried out.

Another trend in experimental smelting has seen researchers using furnaces of types recovered from excavations with the aim of obtaining slag and product equivalent in appearance and composition to archaeological residues. The goals are a more precise reconstruction of installation and the evaluation of metallurgical results obtained under known conditions.

The literature on smelting experiments, as published since the 1950's, is so voluminous and ever-increasing annually, that its compilation is a task which we have left to others, quoting and citing in the bibliography only those works directly relevant here.

The working of the bloomery furnace

In the light of what has been said above, and being conscious of some uncertainties, it is possible to present in rough outlines the reduction of iron ore in a low bloomery furnace as reflected by the theory of physical metallurgy and the results of experimental smelts conducted in reconstructed installations.

Let us imagine a cylindrical shaft furnace of 100cm height and 35cm – 40cm in diameter, charged with charcoal and preheated several hours under a mild air flow. Oxygen combines at heat with the carbon to form carbon dioxide ($C + O_2 \rightarrow CO_2$) and subsequently, carbon monoxide ($CO_2 + C \rightarrow 2CO$) which is the principal reducing agent. This rises through the charcoal column to the furnace throat where the gas mixture contains only 1 – 4 % of CO_2 (Tylecote et al. 1971, 348). This proportion changes after the addition of the first charges of ore and charcoal which were in varying ratios (expressed by weight — very often 1 : 1). Then, oxygen is removed from the ore so that carbon dioxide is regularly produced:

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2 \uparrow$$

After several charges of ore and fuel, the atmosphere in the upper part of the shaft contains much CO_2 which, at low temperatures around 500°C, acts as a reducing agent (Schürmann 1958, 1300). With the first charges in the furnace, taken into account its dimensions as above, under a forced draught, the intensity of blowing was usually raised to feed the interior with about 200 to 300 litres of air per minute (Tylecote et al. 1971, 340; Crew 1991a; Crew and Salter 1991). We have to bear in mind that during the full process, the temperatures in the furnace are distributed extremely heterogeneously, with the isotherms not being level but in zones shaped like a candle flame, as a result of the flow of the air and gas (Fig. 33). While in the combustion zone at the tuyere mouth, temperatures could reach over 1400°C, indeed as high as around 1600°C (Morton and Windgrove 1970, 6; Tholander and Blomgren 1985, 417;

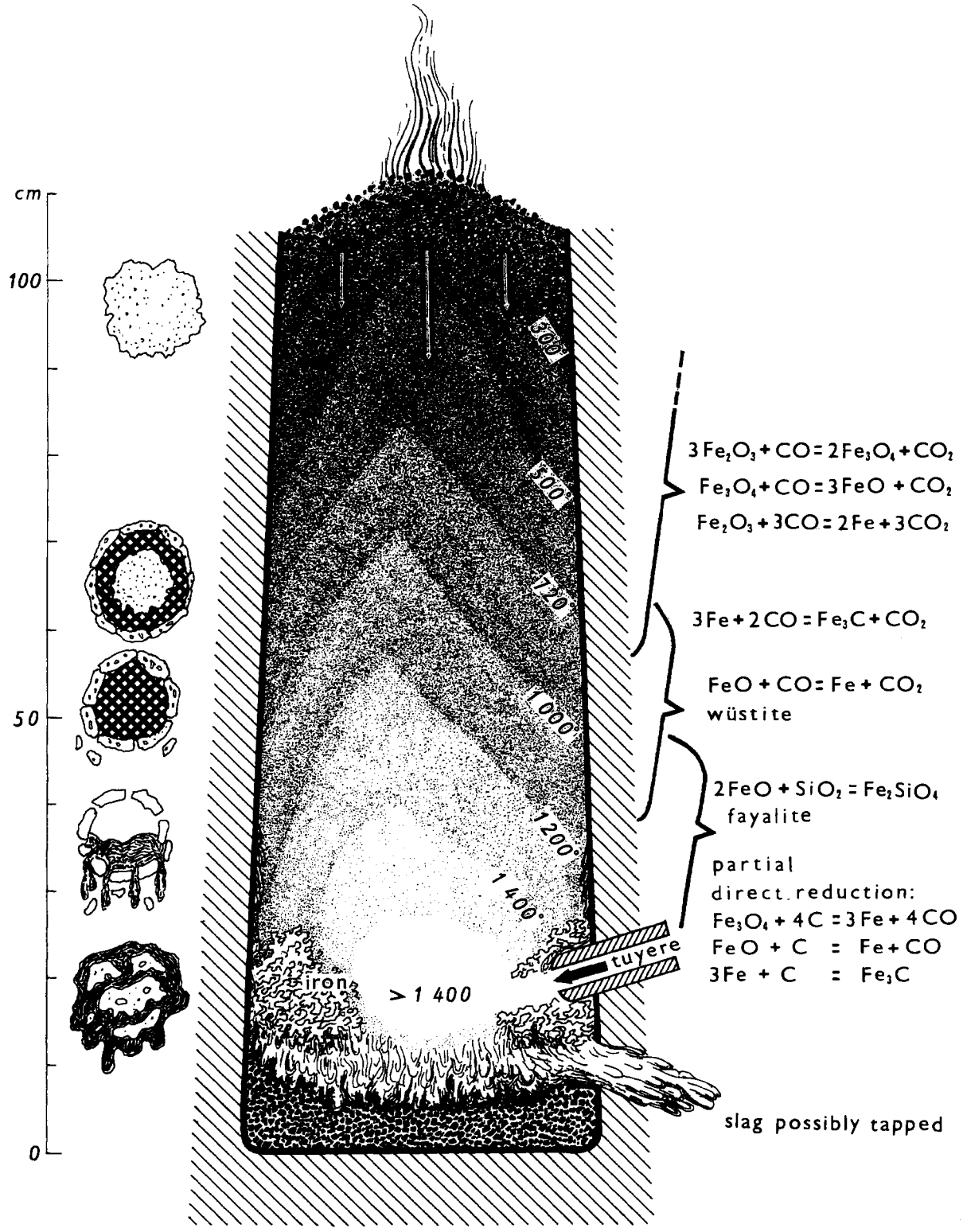


Fig. 33. The principle of the bloomery process. The position of iron sponge in the furnace hearth is marked at the tuyere level. Liquid slag penetrates the pores down and may be tapped. On the left there is schematically sketched the behaviour of individual ore fractions: formation of wüstite, coating with iron shell, slagging, and destruction of the shell (based on Tholander 1987).

Rehder 1986), a few centimeters away, they decreased to around 1200 – 1300°C and higher up the furnace to 1000 – 700°C, falling to around 500 – 350°C in the throat of the shaft.

Let us now follow a grain of a pre-roasted haematite, consisting of the ore mineral and siliceous gangue particles, on its way down the shaft with the charge, against the current of the CO-containing reducing gases. In the upper zone, at 500 – 550 °C, it becomes totally dry and porous, especially when calcined before. Up to ca 700 – 750°C, a great deal of the ore will be reduced to magnetite Fe_3O_4 and partly to the lower oxide FeO, wüstite:

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2 \uparrow$$

$$Fe_3O_4 + CO = 3FeO + CO_2 \uparrow$$

On the surface of the ore grain, an outer layer of wüstite is formed which may be just covered by a thin pellice or skin of metallic iron:

$$FeO + CO = Fe + CO_2 \uparrow$$

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2 \uparrow$$

This metallic skin is visible in many samples of bloomery slag, both from archaeological finds and experimental smelts (Pleiner 1969b, fig. 16: 6 – 7; Morton and Windgrove 1970, figs 1 and 15; Tholander and Blomgren 1985, 418 – 420; Clough 1986, 29; Blomgren and Tholander 1986; Tholander 1987, 153, fig. 8; Leroy 1997, 165, fig 89). Under strongly reducing conditions, after all wüstite having been consumed, it may start to be carburized (Straube 1986, 23; 1996, 52; Morton and Windgrove 1970, 6 – 7), a process which occurs principally in the temperature range over 900°C. The γ-iron absorbs carbon from the gas:

$$3Fe + 2CO = Fe_3C + CO_2 \uparrow$$

Inside the ore grains which contain residual mineral, gangue and wüstite, carbon from the CO ($2CO \rightarrow C + CO_2$) impregnates the fissures and surfaces and the gas pressure developed is powerful enough to perforate the iron envelope, the smallest particles of which can absorb much energy resulting in their being strongly carburized and even melted to pig iron (Tholander and Blomgren 1985, 417 – 418).

Meanwhile, the ore-wüstite-iron conglomerate sinks to lower levels where, at temperatures roughly 1100 – 1200°C, a further reaction takes place. The gangue particles of the ore grains combine with wüstite to form fayalite $2FeO.SiO_2$ or Fe_2SiO_4, the main constituent of slag, which melts and flows out of perforated iron cage. Parts of the iron envelope scatter and sinter together with other iron grains, forming a sort of iron sponge (Pl. XXIV: 2 and 3) adhering to the walls of the hearth, roughly at the level of the tuyere and its mouth, leaving the slag to sink through the pores to the bottom, where it collects and can, in some cases, be tapped out. As the smelt continues, many ore pieces descend still in unreduced state. If they are enveloped by slag, then the reduction by CO-rich gases is interrupted and, for this reason, premature slag formation diminishes the yield.

Nevertheless, in zones with temperatures over 1000°C, another reaction, direct reduction by solid carbon takes place. Ore in contact with charcoal produces further carbon monoxide:

$$Fe_3O_4 + 4C = 3Fe + 4CO \uparrow$$

$$FeO + C = Fe + CO \uparrow$$

Reduced iron particles can be carburized in the same way:

$$3Fe + C = Fe_3C$$

The smelt is rich in antithetic reactions which develop during the movements of the charge, exposing the pieces of iron ore which have passed through various stages of reduction, to different conditions. Slag influences the process in two ways. On the one hand, it tends to decarburize iron which has been already carburized, while on the other, it protects the metal against the strongly oxidizing air stream in the combustion zone. The formation and removal of slag allows the restoration of the reduction of iron oxides and carburization of the reduced metal. However, the direct impact of oxygen at temperatures in the range of 1400 – 1600° despite affecting only a limited space, converts much iron into ferruginous slag. Again, under specific circumstances, it is possible, at high temperatures, for iron to be reduced from fayalite (Hauptmann 1986, 11).

Silicon dioxide SiO_2 is significantly active within the bloomery process, but its role, however, is ambiguous. It not only binds FeO but also other oxides of the gangue and governs the formation of slag. When fayalite is formed too soon, the further access of CO is blocked and the reduction of iron hindered (Tylecote et al. 1971, 360; Osann 1971, 71 – 79). This may happen especially when the ore gangue contains only small amounts of other oxides such as MnO, CaO, MgO, Al_2O_3 and P_2O_5. In cases where the silica content of the ore is too low (2 – 3 %), and there is no sand added and no SiO_2 is available from the furnace lining, the reduction of iron takes place on only a limited scale, with isolated and dispersed iron particles occurring within the cinder mass. Nevertheless, if a high-grade ore with low silica content can be slagged, then the slag will be very viscous and only in small amounts so that there is the possibility of obtaining a significant amount of carburized iron (Osann 1971, I, 71 – 79; Clough 1986, 35).

Molten fayalite-wüstite slag, containing some glass, absorbs MnO, CaO, Al_2O_3, P_2O_5 and other oxides which cristallize as various mineralogical phases (Pl. XXIII; Chapter XIII). However, they lower the melting point of slag only in the limited range of 1150 – 1300°C. Manganese passes into the slag, substituting for some of the iron and combining with SiO_2, thus making the reduction of iron and its carburization easier. Phosphorus pentoxide P_2O_5 (which is found at especially high levels in some bog-ores, and in charcoal ash) plays a positive role in slag formation, but tends, on the other hand, to block the absorbtion of carbon by iron.

Lime is often considered in the archaeological literature to have been added as slag former and limestones and lime kilns discovered in the vicinity of bloomeries are usually explained as being connected with the bloomery technology. In fact, lime content only influences the fusibility of iron-rich bloomery slag to a limited degree, and has a negative effect under the conditions of the direct method. The use of limestone as a flux was usual in the blast furnace process and acted principally in the range of 1300 – 1400°C (Tylecote 1987, 329 – 330). In early fining processes lime played a role in moderating the influence of high phosphorus contents (Horstmann 1996). In any case, CaO contents in the bloomery slags usually vary from 3 to 6 % and higher proportions (16 – 17 %) are exceptional, resulting perhaps from local interaction between the slag and calciferous furnace lining rather than from intentional addition of limestone as flux. Where fluxes were used in the bloomery process, they probably would have consisted of old FeO rich slags.

The particles, sintered-together fibres and nodules of iron finally form an iron-and-slag conglomerate which is concentrated around the tuyere level, leaving the bulk of slag to flow through the pores to the furnace hearth. Under favourable conditions, more compact or consolidated masses (compact blooms) could be created. To prevent unwanted reoxidation of the product in the liquid or viscous slag and to avoid unnecessary losses, the smelter usually removed the iron from the furnace when hot and cooled it rapidly in water (Pl. XXIV).

Most bloomeries produced soft, malleable iron, which was wanted by their customers as an easily workable material for structural parts, sheet and wire. However, a portion of the metal produced could be, as shown, considerably carburized, and used for hard steel cutting-edges and points. Cast or pig iron, if produced by chance in bloomeries, was usually not used for castings but treated as a waste product, possibly being added, together with fresh ore, charcoal and old

slag (as a flux), to new furnace charges.

The making of steel

On the basis of results achieved in reconstructions of primitive bloomery furnaces, the most favourable conditions would seem to be provided by the use of pre-roasted high-grade ore (at least 60% iron oxide), mixing charcoal and ore together in individual charges, more moderate blowing rates (according to the ore properties), a prolonged stay for the bloom in the furnace which is fed at the end only with charcoal and blown after the last charge. Abundant slag, when tapped, promotes the formation of carbon-free or low carbon malleable iron.

In the light of our present knowledge, the manufacture of primary steel requires high-grade iron ore (a high Mn content is especially favourable) with a fuel-to-ore ratio higher than 1:1 (e.g. 1.5:1), while the iron should be protected against secondary re-oxidation by suitable systems of air-ducts (Pleiner 1969a; Pelet 1992). Again, a prolonged residence under the conditions described above is extremely important.

The need for such optimum conditions was known in the past and the extent to which smelters were able to achieve them in their furnaces depended on their experience, working skills within their own traditions. There were individual groups of ironmakers who understood how to make steeled blooms.

Good homogeneous steel was a valuable material, circulating in limited quantities and was an item of trade although at some times and in some places, it was not easily obtainable. On the other hand, hard steel was not always preferred by early smiths. It was good for cutting-edges, but for the bodies of implements, or for making wire and iron sheet, soft and ductile wrought iron was required. Therefore, we may assume that some bloomeries directed their smelting specifically towards the production of malleable iron. Their operators would have accepted that yields would be lower as a result of higher blowing rates, of giving the charges shorter residence times in the furnace shaft and of holding the bloom for longer at high temperatures in the oxidizing zone to obtain an iron-rich, but tappable slag.

The ancient smelter proceeded empirically and the smelting furnace was for him a magical cauldron. As we know from the ethonological record, smelters sought to harness its magic by performing complicated rites throughout their campaigns, incorporating the weight of observations made during successful work. Their criteria of control over the yield were, in the last analysis, the quantity and quality of the product.

Post-mediaeval bloomery survivals

Late examples of the bloomery process were described by authors for several countries in Europe. Thus, in Italy, Vanoccio Biringuccio (1540) devoted brief remarks to iron in books I.6 and III.3 of his *Pirotechnia*, while in Bohemia and Saxony, Georgius Agricola wrote about two models of bloomery furnace, open hearths and shaft furnaces (book IX of the *De re metallica libri XII*, 1556). In 1589, Thomas Payne included in his *Description of Ireland* a reference to what may have been bloomery smelting by smiths using bog ores (Scott 1990, 152). For Poland, a remarkable account of the bloomery ironmaking was given by Rożdzieński in his *Officina ferraria*, published in 1612. Schultze (1732), Swedenborg (1734), Evenstad (1790) and Bush (1851) presented descriptions of stone-walled and timber-clad furnaces of funnel-shaped internal profile, bellows-blown by man power, fed with bog ore and, exceptionally, with wood. Evenstad gives the duration of one smelt as 4 hours and mentions a yield of 8 – 10kg of iron (Espelund 1991a, b).

A very peculiar iron smelting was practised in Corsica from the mid-16th century and ceased in the period around 1830 – 1840. The process took place in an open fireplace with a stone wall pierced by obliquely positioned tuyere and blown by a *trompe* in which the air pressure is supplied by a flow of water falling through a vertical shaft. Heaps of pre-packed fuel and ore

were intensely pre-roasted and the sintered product subsequently smelted to blooms and forged to bars. In four hours, pieces of iron weighing about 50kg were produced and four smelts were performed each day (Mattioli 1989).

A very effective example of the late bloomery process was the Catalan method (*la farga Catalana, Catalan forge*) which spread throughout the western Mediterranean and was especially common on both Catalan and French sides of the Pyrenees. The technique was evaluated metallurgically by the French experts Richard in 1838 and François in 1843 (see Percy 1984; Beck 1884) and involved stone-set open hearths around 60cm x 55cm at the bottom, 80cm x 65cm at the throat and 50 – 90cm deep. The air was supplied by a *trompe*, a vertical tube and water collector producing air-pressure, through a copper tube placed over the lip of the furnace to one side at an angle and directed down towards the bottom of the hearth. The interior was divided by a steel plate into two zones, that at the front, adjacent to the tuyere being filled with charcoal and relatively fine ore, the rear zone containing coarser ore fractions. After this pre-packing of the charge, the sheet barrier was removed. Slag was tapped through a hole toward the base of the furnace and during the final phase of the process, only fuel was charged. At the end of the smelt, which lasted about 6 hours, the iron bloom (100kg to 150kg in weight from ca 900kg of charcoal and iron ore, in ratio of about 4 : 5, thus giving a yield of 30%) was removed from the top (Uriarte Ayo 1995; Cantelaube 1995; experimental studies by Simón 1995). The angle of the tuyere could be varied to meet production requirements. The use of a shallower angle of incidence protected the bloom ofrom the oxidizing blast, making it possible to attain a high carbon content in the final product. A steeper angle led to the production of a softer metal with a lower carbon content. A variant of the Catalan '*farga*' in the north-west of Iberian Penninsula was the '*ferraria*' which consisted of a similar hearth, but with air-supply by water-driven bellows. The method which was practised until the late 18th century is called the 'Basque process' and is known from Navarra, Biscay and Gipuzkoa, although it is less well-represented in contemporary documents. The tradition of both the Catalan and Basque process is claimed to go as far back as the period around AD 1000 (Morral 1995).

We must now turn our attention to post-mediaeval bloomery shaft furnaces. A special development is the Styrian *Stuckofen* or *Stückofen*, the *Stuck* being a lump or bloom of iron. This was a large furnace, the origins of which are to be sought in Alpine regions sometime in or after the 13th century AD when water-driven bellows were introduced for the air-supply of more voluminous shaft installations. It spread northwards to central European countries, where different variants were called *Blauöfen, Blaseöfen, Plaaöfen*, terms which refer, in general, to a bellows-blown furnace. They were operating in Saxony and Thuringia (Schmalkalden) in the 15th and 16th centuries, as well as in Bohemia (Stará Huť, near Beroun, around 1575: Kořan 1946). These furnaces fit with the second model described by Agricola, and were typified by a taller stone-walled shaft. They were later introduced to Upper Hungary (modern Slovakia) where they were denoted as *Windische Feuer* or Slovakian furnaces (*tóthkemence* in Hungarian). The Stückofen was normally 2.5 to 4m high and yielded 250 – 300kg heavy blooms during 24 hours (Vozár in: Pleiner *et.al.* 1984, 209 – 214). These furnaces survived until the 19th century.

This description applies also to Austria, the homeland of the *Stuckofen*. The late Styrian *Stucköfen* appeared as thick-walled stone structures 3m – 4m high, the furnace hearth being 80cm-100cm and throat some 50cm in diameter, 2-4m^3, blown by pairs of water-driven bellows (Köstler 1986, figs 3 – 5). During smelts lasting some 18 hours and performed at relatively high temperature in the hearth, nearing 1500°C, they yielded heavy blooms (*Stucke* or *Stücke*) weighing several hundred kilograms, but simultaneously also minor amounts of liquid pig iron (from about 6 to 40 %). This was originally an unwanted waste product (*Graglach*) to be resmelted with fresh ore and charcoal charges, but was later fined and converted to malleable wrought iron. In the 16th century, some *Stuckofen* plants tried to increase the production of the *Graglach* but due to the unsuitable interior shape of the furnace, this resulted in an enormous

consumption of charcoal. The solution was the bosh and the narrow hearth of the *Flossofen*, the early blast furnace, which began to be adopted (e.g. sporadically in Carinthia) in the 16th and in the early 17th centuries, operating alongside *Stücköfen* (Köstler, *op. cit.* 29 – 30). The removal of the blooms, which at the end of the 18th century reached nearly two quintals in weight, was a tricky technical operation, in the course of which cranes and chains must have been used. The process must have been completely finished and longer time gaps were necessary before a new smelt could be started (*ibidem*, fig. 2, note 10). The blooms were split into pieces to be reheated and worked by water-driven hammers.

Outside of Europe, various methods of bloomery iron production, as survivals, were reported by travellers and ethnologists from different parts of Africa, India, north, south-east and east Asia during the 19th and 20th centuries (up to the 1950's). Different types of furnace (some of which could even be described as picturesque) with different styles of air-supply and modes of operation, different products (from iron sponge embedded in the slag up to more compact blooms) and different organizations of labour were observed and documented, although the evidence of such accounts is of varying value. They do, however, throw light, not only on technology, but also on aspects of the social impact of the traditional metallurgy of iron on everyday life. The bibliography of the pre-industrial ironmaking communities is voluminous and only selected items can be quoted here (e.g. Belck 1907; von Luschan 1909; Klusemann 1924; Rickard 1939; Gardi 1954; Carl and Petit 1955; Cleere 1963b; Tylecote 1965a; Todd and Charles 1977; Eckert 1978; Fuchs 1978, Sunchugashev 1979; van der Merwe and Avery 1988; Rostoker, Bronson and Dvorak 1989; Prakash 1995b). Recently, teams of metallurgists have sought to revive some of the African (and Japanese) processes by mobilizing the successors of ironmaking families to organize smelts in the traditional fashion.

The last outlets for the direct method of ironmaking are represented by industrial attempts to obtain malleable iron in both shaft and crucible furnaces and in rotary kilns, for which about 70 patents were submitted. One of the earliest was the Swedish Höganäss process developed by E. Sieurin, which around 1911, produced 40,000 tonnes of spongy iron annually using a high-grade magnetite concentrate, smelted in crucibles with coal and lime. Other methods applied kilns (Bureau of Mines, Norsk Staal after E. Erdwin, Wiberg process). Practical use on large scale was found in the so-called *Krupp-Rennverfahren* after F. Johannsen. Huge rotary kilns, resembling cement production installations, 50 – 70m long and 3.6 – 4.2m in diameter, inclined 2 – 3° to their horizontal axis, consumed mixtures of iron ore and coke dust (240 – 300kg to one tonne of dry ore with 30 – 40 % Fe), and produced tonnes of small porous bullets of malleable iron, about 2cm in diameter each, and liquid slag at temperatures of about 1250°C. This method was used when only poor ores were accessable in certain countries (for example in Germany and Japan during World War II) and even in some post-war countries before their economies stabilized. Until the 1950's, such rotary kilns were operating in the former Czechoslovakia (at Králův Dvůr and and Mníšek near Prague, with batteries at Ejpovice, near Plzeň). There were also other industrial methods applied (Basset, Flodin-Gustaffson etc.), so much different from the traditional bloomery work. The granulated iron, as a intermediate product, was used in blast or open-hearth steel furnaces.

The problem of cast iron production during the early bloomery period

Before closing this chapter devoted to the long tradition of the bloomery process, it is unavoidable to refer to three ancient texts which have been much-discussed. The first is the 'Treatise on diseases' by Hippocrates, compiled around 400 BC, which in Book I.V.45 appears to characterize the smelting and reheating of iron as ".. Iron separates from stones and earth when heavily heated for the first time and sinters together in the slag (*skória*). When heated for the second and third times, the slag becomes liquid and flows out".

However, the two other texts produce many difficulties in terms of their translations, in deciphering the terminology used and thus understanding their precise meanings. They are explained in different ways in the literature since the Blümner times in the late 19th century (Blümner IV 1886; for different views see Pleiner 1969c, 25 – 27). A century after Hippocrates, Aristotle wrote in Book IV.6 of his Meteorologica a passage which may be read (somewhat paraphrased after the translation H.D.P. Lee) "..Compactly worked iron (*sidéros eirgasménos*) will melt and grow fluid (*hygrón*) and the solidify again, and this is the way in which steel (*stomóma*) is made. For the slag sinks to the bottom and is removed from below, and by repeated subjection to this treatment the metal is purified and steel produced. They do not repeat this process very often, because of the great wastage and loss of weight in the iron that is purified" (cf. the reference in Hesiod's Theogony 861 – 866 which may be also discussed, see Scott 1990, 182 – 183).

Many scholars see in Aristotle's words merely a reference to the reheating of iron blooms (Blümner, *loc. cit.*; Olshausen 1915; Halleux 1974: 193 – 194). However, the expression 'grows fluid' represented by *hygrón* has led other authors to conclude that Aristotle was describing the process of the fining pig iron (Krawczuk and Piaskowski 1958). Photos reached the same conclusion taking into account the peculiar cauldrons depicted on Greek vases as set on the throats of metallurgical furnaces (Photos 1989). In some operations observed in China in the late 19th century, such cauldrons, filled with water, were used to seal finery furnaces in which molten cast iron was bring decarburized. Scott (1990, 181 ff.) reached a similar conclusion based on the above literary evidence and on some Irish terminology and experimental evicence from the work of O'Kelly.

The Aristotelean wording seems to be partly repeated in Book 34. 41 of the 1st century AD Natural History of Pliny the Elder in which he commented upon the making and working of bloomery wrought iron (*nucleus, ferri, strictura*) and added "*Mirumque cum excoquatur vena, aquae modo liquari ferrum, postea in spongeas frangi*" (It is remarkable that when ore is being smelted, iron is liquid like water but later it breaks into spongy pieces). It was argued that liquid slag was confused with iron. Straube (1995, 116 – 118) suggests that Pliny reported on temporary melting of iron during the direct process and that for accidentally survived cast iron was no use.

Should we look for the beginning of the indirect iron smelting in the European classical antiquity? A partial answer may be hidden in the properties of preserved primary products of early smelting processes, the sponges, blooms, and slag, which will be discussed in Chapters XII and XIII.

In spite of all that we may conclude that the bloomery process was the original method of ironmaking applied by mankind, a thesis generally supported by the archaeological record. Except in China (see Chapters I and XII), the majority of iron artefacts dating up to the Middle Ages were made of wrought iron or steel. Excavated furnaces are of many shapes, but not dissimilar to the overall picture derived from historical and ethnological sources for bloomeries.

Chapter IX

THE SMELTING OF IRON: BLOOMERY FURNACES

The bloomery furnace in whifch iron ores were converted to metallic iron and siliceous slags was a metallurgical installation comprising an enclosed space filled with charges of ore and charcoal fuel and with provision for an air supply. The remains of many thousands of such iron smelting furnaces have been uncovered during archaeological excavations, a significant number of which could be reconstructed. A few are fully preserved, so that we have at our disposal data which allow us to build up a fairly clear picture of this basic device which, in many variants, served early ironmakers.

General principles and function

The reduction chamber of a smelting furnace must fulfill a number of basic conditions. It must be made of material capable of resisting temperatures as high as 1100 – 1400°C and be constructed in such a form to permit both air to be supplied to the interior and gases to be exhausted to the atmosphere, so as to ensure that reducing gases can circulate freely through the layers of ore and fuel in the charge. It must also allow for at least the minimum physical separation of slag, either towards its base or to one side, and for the removal of the metallic product, a cake of porous, pasty iron of varying shape with much entrapped slag.

Bloomery furnaces were constructed of clay and/or stone (on rare occasions, even of slag lumps) with, in most cases, a more refractory inner lining of prepared clay containing sand or grog (crushed baked clay) to increase the refractory quality. Linings had different thermal resistances, ranging from those resisting temperatures of around 1300°C and reacting with the molten slag, through to genuinely refractory mortars which could withstand high temperatures in the region of 1600 – 1700 °C (Bartuška and Pleiner 1965).

The air supply was provided either by forced draught by means of bellows positioned on the rim of the reduction chamber or, more frequently, through apertures (one or more in number) in the lower part of the furnace wall, or by induced, natural draught, which could be created if the shaft was made high and narrow enough to produce a chimney effect (Tylecote and Owles 1960, 160 – 161). In some cases furnaces were located on, or at the foot of slopes, where wind pressure was used to increase the natural draught of the furnace shaft (Hamann 1974; 1975). This technique is relatively common among modern primitive societies (Tylecote 1965a) and was certainly applied in antiquity, but is rather difficult to recognize among archaeological remains.

In induced-draught furnaces, the smelting process was slow, with a single smelt consuming large quantities of ore (up to 100kg) and lasting from 10 – 50 hours. The operation of a forced-draught furnace, by contrast, where the services of bellows-operators were required, was much more rapid and a smaller quantity of ore (some 20 – 30kg) could be smelted in a few hours. Tuyeres with internal diameters of 2 – 3 cm can be considered as an indication of forced draught. It must be stressed that the two systems have no chronological relationship. Moreover a single representative of one family could apparently be adapted both for bellows-blowing and for induced draught as seems to be the case, for example, with the very tall slag-pit furnaces of north-west Europe (see below, Chapter X).

As much as possible of the slag produced during smelting had to be physically separated from the iron and this was generally accomplished in one of three ways. The first procedure involved furnace-types in which no provision was made for the evacuation of slag during the smelting process, the slag remaining inside until the operation was complete with separation being carried out after the removal of the entire conglomerate.

The second approach was to allow the slag to move down the shaft in a pasty or viscous form and to rake it out through a furnace arch at the base, or tap it in liquid form through a taphole.

The tapping of molten slag required considerable technological skill in furnace operation, since failure to do so efficiently could result in a loss of heat within the shaft, bringing the whole process to a premature halt. It has been suggested (e.g. Vastagh 1961; Cleere 1972) that in some cases molten slag might have been evacuated continuously throughout the smelting process by means of a 'running taphole', which remained open the whole time. This idea was apparently inspired by post-mediaeval open-hearth charcoal blast furnaces, but its application in the smaller bloomery furnaces seems to be improbable due to the considerable cooling effect. Usually the taphole would have been closed, only being opened at the correct stage of the process to release a flow of accumulated slag.

The third possibility was to allow molten slag to flow, not out of the furnace, but through the pores of the spongy iron, down into a special cauldron-like pit at the base of the furnace, where it solidified, creating a heavy slag-block characteristic of the so-called slag-pit furnace (see below).

Different procedures were also used for the removal of the iron produced by smelting. In open furnaces (bowl hearths), the conglomerate of iron and slag was removed by lifting it bodily from the top. It would often have been necessary to break this product up, and, by a laborious process of crushing and manual separation of iron and slag particles, to build up a pile of discrete pieces for further heating and welding, as African analogies suggest. In furnaces with provision for the separation of slag during the smelting process, the sponge of reduced iron, still containing entrapped slag, could be removed either through an aperture or 'gate' at the base of the furnace also used as the slag outlet and/or for the supply of the air-blast, or by the removal of part of the furnace wall. There is some debate as to whether this would have been done immediately after the end of the smelt when the iron was hot and recognizable by its bright colour, or later when the furnace was cooler, or even when the furnace had cooled down completely. The first possibility seems the most likely when we take into account archaeological finds of slag blocks from slag-pit furnaces which are free from metallic iron, the need to avoid losses of iron by oxidation during any uncontrolled slow cooling and the difficulties of separating metal from slag. In any case, the product required to be refined by reheating and forging in order to expel entrapped slag and weld up the iron sponge into a consolidated bloom.

Archaeological evidence and reconstructions

Chance finds and planned archaeological excavations have recovered the remains of thousands of furnaces. However, the residues are often so fragmentary that the actual appearance of the smelting installation is difficult or even impossible to reconstruct. Indeed, there are frequently problems in distinguishing between bloomery and refining installations. Nonetheless, the aim of any excavator is the reconstruction of furnaces using the evidence available.

Furnace bottoms (slag cakes left in the furnace hearths after the last tap) or slag blocks from slag-pit furnaces may indicate at least the hearth diameter, while solidified slag flows and pools indicate that slag was tapped. But in most cases, it is impossible to reconstruct fully the shape of the furnace. The find of a slagged hearth does not resolve the basic question of whether it represents an open bowl-hearth or a shaft-furnace. Fragments of slagged walls may offer a more reliable guide to reconstruction. When tuyere nozzles or tapped slag runs occur around a destroyed feature they provide further information. However, the recognition of functional details such as the positions of tapholes and air-inlets is very difficult in most cases. Indeed, the circumstances of several excavated bloomery sites has raised suspicions that before they were abandoned, the furnaces were intentionally pulled down, presumably for ritual reasons as some ethnological data from Africa would indicate. Nonetheless, it is sometimes possible to collect enough of the various elements in the debris, so that at least a tentative idea of how the device would have appeared can be derived. However, a critical approach to interpretation of fragmentary remains is necessary in all of these cases.

In spite of such problems, there are a few rare examples of furnaces which have survived complete and intact. This has resulted from their being inserted into the walls of pits, or into natural banks, or having been erected in depressions and pits which were sealed quickly with soil deposits after the ironworks were abandoned. Such examples offer insights which help with the reconstruction of other similar, but more damaged features. What usually remains uncertain is the actual height, even of the best preserved shafts. We only have a very few exceptional cases in which we have full evidence for the shaft, where the fragments could be reconstructed like broken pots (as at Scharmbeck, Pobedim and Vovčansk — see below). For the reconstruction of individual structures, ethnological parallels may be of some help but must be used cautiously and critically. Such reconstructions may be tested on full size models, using them in experimental smelts. Experimental success is not, however, any proof or evidence — it shows merely that the reconstruction is viable. In published reports, reconstructions should be always presented along with all of the plans and profiles of the preserved residues.

The large number of remains found by archaeologists makes it possible to attempt a classification of bloomery furnaces and to establish a typology.

Problems with typological systems for bloomery furnaces

The first attempts to distinguish between different types of iron smelting furnace (Forbes 1950, 122 – 130; Coghlan 1956, 86 – 105) were based principally on the shapes of the structures, taking into account the evidence from post-mediaeval examples. Other classification systems have sought to use functional details of excavated features such as the air-duct system, method of slag removal and the thermal insulation of shaft walls (Tylecote 1962b; Cleere 1972; Pelet 1976; Martens 1978b; Pleiner 1978a; Serning 1978; Tylecote 1987, 151 – 162). But all systems of classification have their weaknesses. For example, the non-tapping slag-pit furnace might have been adapted both for forced and induced draught, while different forms of bowl hearth could have been worked either with slag-tapping or without any slag outlet. Similarly, shafts of identical detail might have been built either free-standing or embanked, according to local conditions and the practices of the smelters.

Naturally, all classifications are linked to the state of our knowledge of excavated furnaces at any particular time and, moreover, to specific geographical areas. No system can be complete, because new discoveries are continually producing new types and variants and, in addition, entire regions of Europe and Asia have yet to produce archaeological evidence regarding the bloomery furnace.

In principle, it would be possible to build up a typology of remains and residues which would be misleading in terms of providing reliable reconstructions. Ideally, a functional typology of 'live' furnaces is needed, since any bloomery furnace has its place geographically and chronologically in human culture. Some distinct forms are seen as typical for certain population groups and in due course have come to be denoted as 'types' as a result of striking similarities in features within certain chronological and geographical limits. Thus, German papers often use the term 'Tuklaty type', after the early Romano-Barbarian period site of Tuklaty in central Bohemia (Pleiner 1958, 141 – 144; 274), to denote those slag-pit furnaces which were built into the walls of sunken ironworks. Slag-pit furnaces represent a large family which dominated *suo tempore* half of continental Europe. During research, several 'sub-types' have emerged, with those with conical sunken hearths originally being labelled as the 'Dřetovice-Klobuky' or 'Slaný type' after finds from central Bohemia (Pleiner 1958, 274 – 275). The huge Romano-Barbarian smelting region in the Holy Cross Mountains in central Poland gave its name to the 'Holy Cross Mountains slag-pit furnace' (*kotlinka świętokryzska*: Bielenin 1973a), while tall furnaces which also have conical slag-pits are sometimes described as belonging to the 'Scharmbeck/Drengsted type' after the fully-preserved specimen from Scharmbeck near Hamburg.

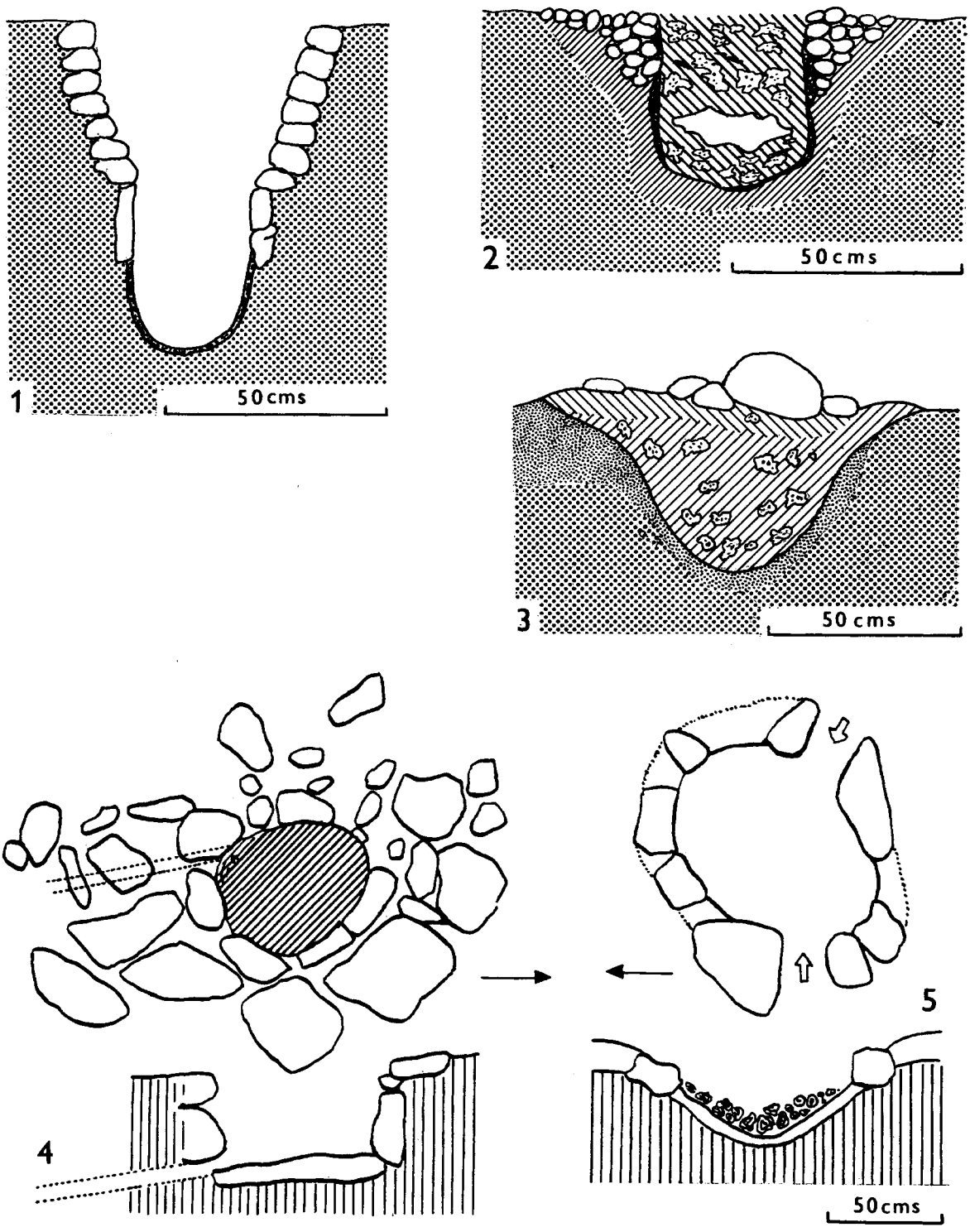


Fig. 34. Exemples of bowl furnaces. 1 Zjikhanzhuri, Colchis, Georgia, stone-lined pit furnace, ca 9th – 7th centuries BC; 2 Waschenberg, Austria, bowl furnace V with slag and slagged iron sponge block (2.7kg), 5th century BC; 3 Kråkbodarna, Dalarna, Sweden – furnace with slag, 8th century AD; 4 Vedby-Lineröd, Sweden, flag-stone-lined bowl furnace, undated; 5 Myrhaugen in Gudbrandsdal, Norway, undated. References: 1 Gzelishvili 1964; 2 Pertlwieser 1970; 3 Serning 1973; 4 Nihlén 1939; 5 Dannevig-Hauge 1946.

The Celtic domed-furnace of the late La Tène and early Roman periods, despite its variants, has been treated as a single 'Burgenland type' (Bielenin 1994) from the region in which modern excavations revealed such features. A distinctive form of furnace appearing on many sites of late antiquity in the region east of Trondheim, Norway is characterized as the 'Heglesvollen type' (Espelund 1987, 1989). The 'Želechovice type' - an embanked Slavic furnace with an unique rear reheating chamber - entered the classification proposed by Tylecote (1987, 158 – 160).

These and other types must be considered as working models (Fig. 73), partially conditioned by the current state of knowledge and which are more useful in the identification of concrete similarities than as components of a general typology, since they have been defined according to differing criteria and suffer from the possibility of modification in the light of new discoveries. Nevertheless, it is useful to present the typical examples of such installations as they appear in archaeological sources, but all the while bearing firmly in mind the *caveats* entered above.

The principal forms of the bloomery furnace

It would be impossible within this survey to deal with all of the tens of thousands of furnaces and furnace remains excavated and published, or even to provide a complete bibliography for them as their number increases steadily. The classes that are described below have to be understood as representing the models of major importance, being arranged according to construction styles and not strictly according their chronology.

Bowl-furnaces

Bowl-furnaces, which are only open hollows in the earth lined with refractory clay, are the simplest and apparently the earliest form of smelting furnace. This does not mean that all such furnaces are necessarily early, as it was brought back into use on a number of occasions in various parts of the world, the most recent examples from as late as the 18th – 19th centuries being the Catalan furnace and certain Scandinavian types.

It was quite possible to smelt iron ore in bowl-furnaces, the essential prerequisite being the production of a forced draught by means of bellows to create a hot reduction zone in a volume surrounding the entry point of the blast. Because the charge effectively does not move in the smaller types of hearth, it has to be assumed that a system was used, similar to the post-mediaeval Catalan forges, in which the ore was packed at the opposite wall behind a charcoal bed to produce a reduction effect. However, no evidence for this has survived from ancient times. The major disadvantage of this type of furnace was its limited internal volume, which restricted the amount of iron that could be produced in one smelt. The reduced iron was distributed throughout the resulting slag mass, especially in the area opposite the tuyere where it became partially sintered together. Separation of the metal from the slag by physical means inevitably resulted in significant losses.

The identification of bowl-furnaces is fraught with difficulties, because of the problem of distinguishing between true bowls and the bases of other types of furnace, the superstructures of which have been destroyed and dispersed. The indicators are an inverted-cone or hemispherical cross-section and the complete absence of wall fragments from any form of superstructure.

The earliest bowl-furnaces known from the archaeological record were found in several groups in Transcaucasia in the 1960's. Four concentrations were located near the Black Sea coast, for example at Charnali, Legva, Zjikhanzhuri, Choga etc. (Fig. 11), with other finds spreading south of modern Tbilisi (Kvemo Bolnisi and Rusas-Ckaro, Gzelishvili 1964, 31 – 38, 57 – 59). As shown in chapters III and IV, some problems have arisen over the dating of these sites and even individual furnaces (radiocarbon, archaeomagnetometry, archaeological associations), although in general, they would seem to belong to the centuries around 1000 BC.

All of the furnaces in the Colchis show practically indentical appearance and dimensions. The Zhikhanzjuri example (Fig. 34: 1), dating by pottery to 8th – 7th centuries BC, is typical:

a pit about 1m deep, the upper part of which was an inverted cone, set round with stones in a square plan. The hearth proper, which was represented by the lowest 25cm of the depth, was 45cm in diameter, clay-lined and hemispherical. There was no provision for the tapping of slag which was apparently removed after the smelt having been finished and deposited on a flat, crescent-shaped spread of debris. Gzelishvili (1964, fig. 34: B) assumed that the blast was supplied through a set of tubes which were inserted into the furnace and ran downwards from the corner of the pit. Khakhutaishvili, who carried out excavations on many other sites, reconstructs the furnaces in a similar way, and was able to illustrate examples of bent clay tuyeres with flared ends into which other tubes could have been fitted (1987, figs 32, 51, 60, 71). The covering of the pits with a dome, as suggested in attempt at reconstruction (*op. cit.*, fig. 68) is hardly justified with regard on the open funnel-shaped throat of the pit and absence of any fragments resembling the walls of a dome. The process must have been performed with carefully pre-packed charges of ore and fuel.

Of the 28 excavated sites on the Black Sea coast, each of which produced 1 – 2 bowl furnaces, the best preserved examples were investigated at Charnali II (Khakhutaishvili 1987, 48 – 52). Two smelting pits were situated side by side, constituting a twin of rectangular pits lined with stones and clay. Both furnaces, 80cm apart, were connected with a 'bridge' of clay (*op. cit*, fig. 3). Because of this, they should be considered, contra Khakhutaishvili (*op. cit.* 55 – 56, as two paired units belonging to the same complex, see Chapter IV). Radiocarbon dates indicate the 9th – 8th centuries BC, being slightly different for each furnace, thus giving rise to the excavator's interpretation. The lining of both features left an internal space ca 80 – 90cm in dia. and over 100cm deep in total, with the site of the smelting process being a cauldron-shaped lagged bottom of diameter about 50cm, depth about 30cm below the stone setting. The filling contained fragments of iron slag and clay tuyeres, charcoal and pottery sherds. On the basis of radiocarbon dates 720±50 for furnace 1 and 770±50 for furnace, the excavator suggested that furnace 1 funcioned earlier than furnace 2. This seems highly improbable as, in effect, the date-ranges overlap significantly, indicating that both furnaces are contemporary.

Other sites in the Colchis have yielded furnaces of the same design, although some (e.g. Mshvidobauri II and IV, and Nagomari I, both from the Supsa-Gubazeul group) were dated by ^{14}C and archaeomagnetometry to 18th–13th centuries BC. This dating has to be treated very cautiously; for example furnace II at Mziani, in the same ironworks concentration, yielded three different radiocarbon dates from indiviual levels inside: 575, 940, 1280 (±50) BC or, in another calibration 628, 1072, 1395 (±100) BC. Furnace Mziani III yielded dates from two levels (80cm and 90cm): 585/640 BC and 900/1020 BC respectively (*op. cit.*, 131 – 132, 135 – 136).

Although very early in date, the Georgian bowl-furnaces seem to be of a somewhat developed and standardized type, showing striking similarities across the whole region. If the location of the air supply in the reconstruction is correct, the stone-lined upper cone-shaped section seems to have acted as a shaft or hopper for the fuel/ore charge.

*

The earliest archaeologically dated bloomery furnaces excavated in mainland Europe date from the Late Hallstatt period (*ca.* 6th – 5th centuries BC). Several bowl-furnaces which displayed no evidence of any form of superstructure were discovered in Upper Austria at Waschenberg, near Wimsbach (Pertlwieser 1970, 53, Figs. 4 and 5: 1 – 3, see chapter IV). Furnace V (Fig. 34: 2) was a cylindrical pit with an internal diameter of 30cm and 32cm deep, although the excavator acknowledges that all of the furnaces of that type on the site were originally deeper. The upper section, which was stone-lined, was coated with slag on the inside and the air-blast would have had to have been introduced over the rim of the furnace. A cake of slag, 18cm in diameter, containing some metallic sponge, was found *in situ*, buried in charcoal and ash.

Similar furnaces are known from Britain. The best preserved example is probably the Iron Age example from Kestor (Devon), a bowl-shaped pit, heavily slagged on one side and equipped at ground level with stone blocks to locate the bellows on the rim of the furnace. It was 30 – 45cm in diameter and about 23cm deep (Fig. 73: 2; Schubert 1957, 29, fig. 3; Tylecote 1962a, fig. 45: B, after Fox). Ore lumps in a bed of charcoal were reduced to a cohesive porous agglomerate of iron that was deeply penetrated by slag, which tended to concentrate in the lower part. The furnace capacity and yield would have been low, as demonstrated by smelting trials in the late 1950's (Wynne and Tylecote 1958), in which the best results were *ca.* 0.33kg iron from 1.7kg of ore.

There is only a comparatively small body of evidence for iron-smelting on sites in Ireland and all of those so far identified have produced open bowl furnaces, the radiocarbon dates of which cover a wide range from the the 2nd – 3rd centuries AD (Clogher, Co. Tyrone and Rathgall, Co. Wicklow); to the 7 – 9th centuries AD (e.g. Ballyvourney, Garannes and Lislea Co. Cork, Reask, Co. Kerry, Knowth, Co. Louth and Kilpatrick, Co. Westmeath) and beyond (Scott 1990, 160 – 161). They are generally simple depressions lined with clay, sometimes having stone linings at their bases. Although very large plano-convex slag blocks have been found on a number of sites (e.g. Lislea, Co. Cork — Scott *op. cit.* 163, Plate 6.5.1), the complete absence to date of any evidence for superstructures indicates that open bowl-furnaces were the sole means of producing iron in the period before the introduction of the blast furnace in the 16th century. Despite the intrusion of Viking settlers in the 9th century AD and Anglo-Normans in the 12th century AD, both groups coming from areas where more advanced types were in use, no evidence of their introduction or use has yet been found in Ireland.

Despite their relative inefficiency, the simple bowl-furnace persisted in various regions of Europe until early modern times, often side-by-side with more advanced types. In some instances, it was even reintroduced. A well known and often-quoted example excavated in the 19th century at Hüttenberg, Austria, and attributed to the Roman period was a large clay-lined and slagged bowl, 1.58m in diameter and 95cm deep, accompanied by a roasting or reheating hearth of similar design (Münichsdorfer 1871, 90 sq., Pl. II. fig. 11; Weiershausen 1939, 157, fig. 42). It is unfortunate that the records of this excavation are no longer available, so that the details and dating cannot be verified, because the large dimensions make the interpretation suspect.

As to early Middle Ages, the late Saxon smelting furnaces at Ramsbury, Wiltshire, England, must be discussed (Haslam *et al.* 1980, see Chapters IV, VI, and XI). The ironworks worked during three successing phases in years around AD 800. A special attention deserves furnace 4, dating from the late phase, called 'developed bowl' installation, because of having been tapped into an oval forepit. The front part was apparently kneaded of clay, so that an arch and a tap hole could be modelled. It is difficult to reconstruct the actual dimensions, since the multiple relining, revealing an open and tulip-shaped bowl, deformed the final width and depth (the space could be about 30cm of internal diameter and 40cm deep). The furnace was five times renewed and at least thirteen times lined with refractory clays (*op. cit.*, figs 14 to 17). The other three furnaces, not tapped, have shown frequently renewed linings as well; they are called 'bowl' installations, although the excavator supposed a domed clay superstructure for furnace 3, because the curvature of relinings in section seemed to be (extremely slightly) inclined towards the interior *op. cit.* 21, 23, fig. 13: section A – B). Traces of stake holes inside are considered as support for this idea. These were observed in the bottom of furnace 2 as well, and in the frontal part of furnace 4. Their role is far from being absolutely clear.

In northern Moravia, where sophisticated smelting furnaces were in use from at least the 9th century AD (see below), shallow pits dating to the 10th century and exemplified by the hearths at Žerotín (Ludikovský 1961; Pleiner 1962a, 187, fig.2) have been found with tube-shaped clay tuyeres and large lumps of slag in their fillings (Pl. XIX: bottom; Fig. 73: 3). These pits, which are identified as bowl-furnaces, had diameters of *ca.* 80cm and their upper rims were clay-lined

and slagged.

Norwegian excavations have brought to light some relatively well-preserved open bowl furnaces (*hellegryte, blester*) from nine sites of the Møsstrond area in Telemark, the time horizon of which (6th – 8th centuries AD, according to radiocarbon dates) precedes the period of local thick-walled shaft furnaces (*skjaktovn*) of the 11th – 13th centuries AD (Martens 1977; 1988, 18 – 26, 74 – 77). The bowl furnaces at Nystaul 7, Erlangsgaard 5 and 6, Hovden 13 etc. are circular (diameter around 45cm, depth preserved usually as 15cm), of a funnel-shaped open profile, lined with flat flag-stones set around (Pl. XX: top). Forced blast was unavoidable, although no direct evidence was announced. The slag produced was deposited to shallow heaps or layers, together with other waste.

The Viking Age type of open bowl-furnace, such as the stone-based structures from Gudbrandsdal in eastern Norway and Swedish examples (Hauge 1946; Hansson 1989; Nihlén 1939; Serning 1973), was used in Scandinavia not only in the early mediaeval period but also in the later mediaeval and early modern periods (Fig. 34: 3 – 5). These later furnaces were modified to allow the slag to be tapped off, and in some cases for operation using water-driven bellows, as at Norre Kvarnbäckskalingen in Värmland (Nihlén 1939, fig. 20).

A number of early mediaeval bowl-furnaces have also been reported from several areas in western Germany, in the Westerwald, in the basin of the Lahn and Dill rivers and in the Sauerland. At Langenbach, a furnace which was 45cm in diameter and 50cm deep and lined with refractory clay, had been blown with forced draught and was equipped for slag tapping (Weiershausen 1941, 170 – 173, figs 7 – 9). The Sauerland has been well surveyed by Sönnecken (1971), who reports that two types of furnace were in use, bowl-furnaces and thick-walled shaft-furnaces. The bowl hearths, operating in the 11th – 13the centuries AD as well, were, in some cases, repeteadly renewed on one and the same spot: at the site 'In schmalen Hagen' near Schlöten a sequence of five hearths was uncovered (*op. cit.*, 66 – 67, fig. 12). Another vertical stratigraphy revealed the excavation at Heimke near Herlsen (*op. cit.*, 56 – 58, fig. 11). The site of Tilges Siepen near Övenscheiderstall yielded the stratigraphical evidence that, sometimes, the bowl hearth was later than a shaft furnace (*op. cit.*, 24 – 25, fig. 5). The bowl hearth dates from the 13th century AD (pottery), the shaft furnace approximately from the 11th – 12th centuries AD. In the case of the bowl furnaces, a low superstructure, no more than 40cm high, is postulated on the basis of evidence provided by one of the three furnaces excavated at Hülsesiepen, near Belkenscheid (Sönnecken 1971, 90 – 91, 145, fig. 17). Furnace R2 is represented by a red burnt ring enclosing a hearth measuring 30 x 35cm by 25cm deep. The base of the hearth contained solidified slag, the bulk of which had run out of the furnace into a flat-based forepit. The slag aperture was reinforced by an unusual device, an arch made of iron sheet, 10cm wide by 21cm long, the thickness varying between 0.7 and 1cm, which distinguished this furnace from the other two in the same workshop and is, in fact, a feature that has not been observed on any other early bloomery furnace. It would appear that this arch reinforcement was intended to be removed when the smelting operation was finished, but in this case was left in place for some unknown reason. No mention is made of the location of the bellows, but the low profile of this furnace, dated to the 11th – 13th centuries AD by the globular pottery (*Kugeltöpfe*) associated with it, would have necessitated the use of forced draught. Recently, a preliminary idea suggests that some of the bowl installations in the region might have served as fineries for cast iron from early *Flossöfen*. The question remains open because no descriptions and mappings of such features have been presented until now.

As discussed in Chapter VIII, open smelting furnaces of this type survived in some parts of Europe until the modern period:. Agricola's open hearths in Bohemia and Saxony and Payne's forges in Ireland, both in the 16th century, and Catalan and Basque hearths in the Pyrenees. Even as late as 19th century, forge-hearths used in conjunction with hammer-mills in southern Bohemia were occasionally converted into bloomeries when scrap metal was not available and

the ironmaster decided to smelt local limonite ores (Pleiner 1995a, 399 – 406). It is interesting to observe this practice, which demonstrates that the two technological processes of smelting and working were still seen as parts of a single technology or craft, even though individual workers and installations had concentrated on one or the other. A similar phenomenon is attested in the late 4th century AD in Britain, at the end of the Roman period. With the cessation of supplies of semi-finished products from major iron-producing regions of the province, smiths in towns or in villa establishments made use of their inherited knowledge of smelting to produce small amounts of metal from local ores to meet the immediate requirements of their communities.

Slag-pit furnaces

In broad terms, there was an upper limit to the capacity of the bowl-furnace. The provision of a circular dam or wall built up on the lip of the bowl made it possible to use larger quantities of ore and fuel, although the initial stimulus towards the use of such a feature probably stemmed from a simple desire to confine the furnace-charge more effectively. This is the hypothetical genesis of the shaft-furnace, which was to have far-reaching consequences in metallurgical terms. The existence of a higher column of furnace charge resulted in the creation of a series of different temperature zones, in all of which the reducing gas could operate on the ore, while the length of time the ore-and-fuel charge spent moving slowly down the shaft could be substantially increased. If the cauldron-shape bowl hearth was retained, another effect arose, namely that with the air inlet at ground level, between the sunken bowl and the shaft, the bowl ceased to play any role in the reduction process, becoming simply a collecting vessel for slag which would pass through the metallic sponge that formed at tuyere level and solidify there. Thus, the sunken bowl became the slag-pit.

The process of creating a block of slag was only possible if one important condition was fulfilled, namely that the slag-pit was kept clear until the slag began to form and flow. On the basis of layers of charcoal found in excavated examples, it had been assumed that the underground volume was first filled with charcoal. Voss has shown (1962, 14 – 15, fig. 8) that this part of the furnace was filled with dry wood or straw bundles at the beginning of the process, an interpretation that has been confirmed subsequently by other workers (e.g. Leineweber 1991, Leineweber *et. al.* 1994 ; Jöns 1992, 1997 etc.). As the slag formed and moved downwards, it ignited the combustible filling, which then slowly burned away to leave a void that could be filled with slag. The prints of bundled straw and brushwood have been observed in many solidified slag blocks (Fig. 35) and hearth bottom pools at the site of Drengsted (Voss 1964) and Snorup (Voss 1995) yielded one important piece of evidence in form of a straw bundle print in the middle of one of the slag blocks found which helped to explain the technique of operating slag-pit furnaces in general. The prints of the straw (and charred grains) of barley and rye provide us, moreover, with information concernin the agriculture of the area (Mikkelsen, Jutland Conference 1999).

The slag-pit furnace was a remarkable device showing great variability of form and construction. It could be built into the walls of sunken-floored huts or workshops, or left free-standing surmounted by a clay shaft. There are even indications that in some cases, the shafts were portable. It could be small, with a slag-pit diameter of 35 – 40cm and a depth of some 40cm, producing some 20 – 25kg of slag, or large, as in the Romano-Barbarian period where the slag-pit diameter could reach around 80cm with a depth of 90cm, the furnaces producing slag blocks of up to 450kg in weight. Especially in the case of the smaller models with their characteristic tuyeres, it could be operated by forced draught by bellows. The larger furnaces could well have been so tall that the necessary chimney effect would have allowed producers to work with natural draught, a strong possibility, particularly in Poland and north-west Germany.

Slag-pit furnaces, both small and large, were able to consume different kinds of iron ore. Rock minerals were the staple in Bohemia and parts of Poland, whilst bog ores were, naturally,

the principal raw material in the lowlands of north-central Germany and eastern Europe. In the light of numerous smelting experiments, as well as metallographic examinations of large numbers of iron objects from areas where these devices were in operation, it is clear that the slag-pit furnace produced a heterogeneously-carburized metal. Where the scale of production was small, the furnace could be refurbished several times, while in some production regions, furnaces were used for one single smelt only. The disadvantage was a limited capacity which could not be increased beyond certain limits, because once the slag-pit was full, the process came to a natural halt.

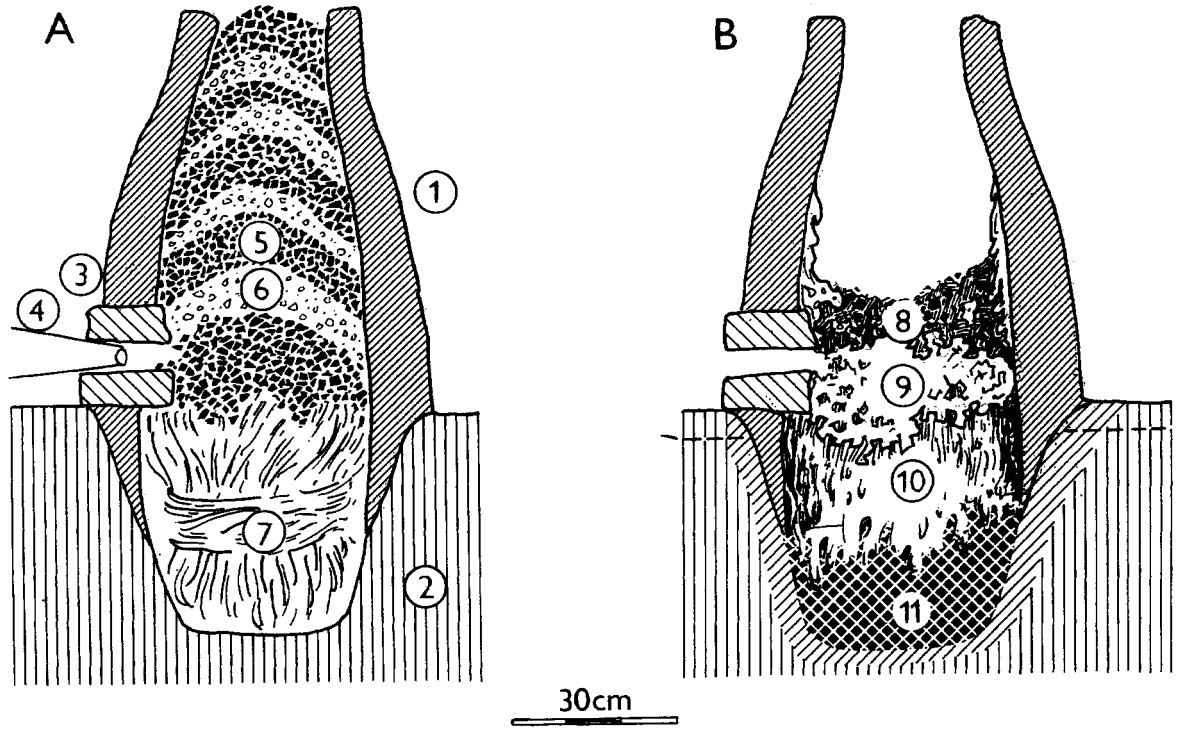


Fig. 35. The working of the slag-pit furnace, based on finds and smelting trials. Left: Before smelting: 1 shaft, 2 virgin soil, 3 tuyere block, 4 bellows, 5 charcoal, 6 iron ore, 7 straw or brush wood. Right: After smelting: 8 furnace slag, ore residues, charcoal, 9 iron sponge, 10 slag bloc in the pit, 11 charcoal and ash. Reference: Pleiner 1980a.

Defining slag-pit furnaces

Slag-pit furnaces or, more correctly, heavy slag blocks from their pits were ploughed out by farmers and occasionally used as building materials from time immemorial, particularly in Poland and Jutland and were first brought to scientific attention in the early 1900's. One of the earliest recorded cases is that of Tarxdorf, now Tarchalice in Silesia where, in 1903 and 1908 thirty seven slag blocks were uncovered as the first known 'cluster' and discussed by Olshausen, Krause, Humperding and Giebeler (Olshausen 1909). The dig failed to respect the stratigraphy, with all of the soil around the 'drums' simply being removed so that some of them tilted over (Fig. 68: 9), with the result that much of the information has been lost. The slag blocks were approximately 60cm in height and diameter. The top surface was a little splayed, creating an effect rather like a slag 'cushion'. On their sides appeared 13 - 16 solidified 'ribs', perhaps the

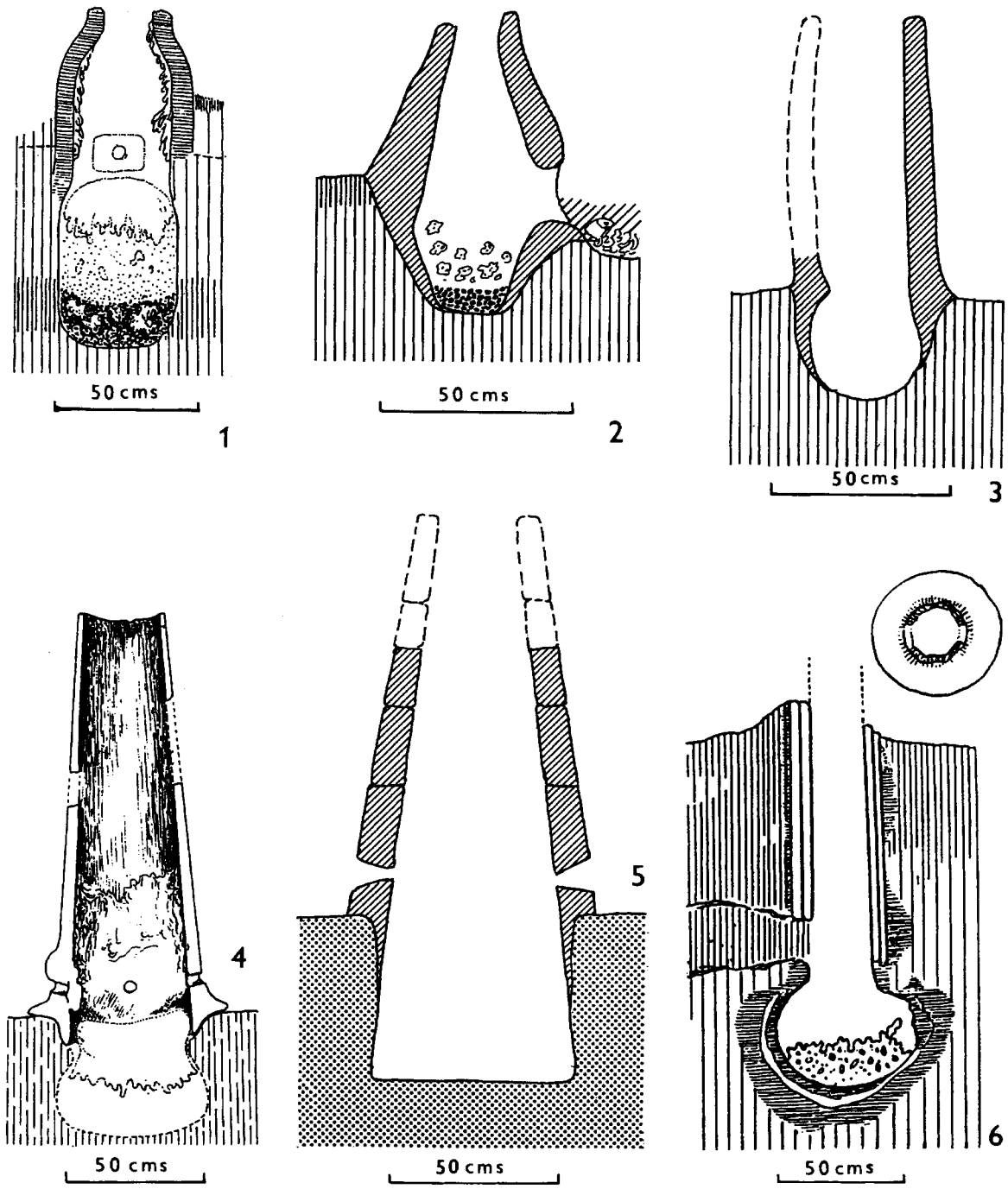


Fig. 36. Slag-pit furnaces. Features with preserved shaft superstructure (except No 5). 1 Podbořany, NW Bohemia, furnace 1, late La Tène period; 2 Gera-Tinz, Germany, furnace 5, early Romano-Barbarian period; 3 Prague-Podbaba, site XI, Romano-Barbarian period; 4 Scharmbeck, NW Germany, transportable shaft, 2nd century AD; 5 Holy-Cross-Mountains, Poland, reconstruction of a typical unit, built of brick-shaped blocks, Romano-Barbarian period; 6 Igołomia, S Poland: furnace embanked in a working-pit wall, 2nd–3rd centuries AD. References: 1, 3 Pleiner 1958; 2 Dušek 1967; 4, 6 Pleiner 1965b (after Wegewitz and Reyman), 5 Bielenin 1983.

prints of burnt-out wooden linings to the slag pits, and there were one or two slag protrusions which implied the existence of slag outlets and/or air-ducts.

The original discussion of interpretation of these blocks resulted in the opinion that they were from primitive smelting furnaces. Despite erroneous conclusions drawn at the time (cast iron production, slag tapping, sinking of the bloom to the bottom), the suggested interpretation by Krause was essentially correct. He concluded that the slag represented the filling of sunken furnace hearths above which had been erected coated structures which enveloped the iron and fuel charges, before the formation of any slag, in other words a form of shaft. Later, this basically sound idea was rejected by Weiershausen (1939, 101 – 104) who interpreted the features as the solidified contents of free-standing shaft-furnaces. The idea of a semi-sunken furnace was forgotten for many years. In the post-war years, Holubowicz (1956) undertook a fresh excavation of the site during which further several units were discovered and correctly identified the existence of clay shafts and sunken hearths. Slag blocks found at roughly the same time in Schleswig in north-western Germany were explained as evidence of unfinished or failed smelts (Hinz 1952).

Between the excavations by Weiershausen and Holubowicz, a rescue dig was conducted in 1942 at Podbořany in north-west Bohemia (Fig. 36: 1) by A. Ratt from the former German Institut für Vorgechichte in Teplice-Teplitz-Schönau. He produced a short internal excavation report which later led to the identification of the slag-pit furnace as a specific type of bloomery furnace. Two features were excavated, standing side by side, with cylindrical sunken hearths (33cm diamter by 50cm deep) and small clay shafts, some 9cm thick, erected as superstructures above the former ground level. Furnace 1 was preserved complete, the shaft being 40 cm high, with an internal diameter of 30cm, narrowing at the top or 'throat' to 20cm. The interiors were not coated with any special refractory lining but were heavily slagged, especially above the sunken hearth, which contained, in a charcoal bed, lumps of iron slag or disintegrated slag block. The same form of slag was found in Furnace 2 which stood some 1.2m away. The shaft was severely damaged, but survived, nevertheless, to a height of 20cm. Both furnaces must have been situated in a depression or working pit which could not be defined due to the conditions of the rescue work and the small area uncovered. A brick-shaped tuyere and some Late La Tène pottery sherds were also recovered. The site was published after the War (Pleiner 1958, 117 – 120).

In the post-war period, further excavation reports on sites in Bohemia became available for study. An important discovery was that of the Late La Tène period sunken-floored ironworks at Chýně, near Prague, which was equipped with furnaces, inclined against the working-pit wall and distinguished by pit-like hearths, often containing buried slag blocks showing that the slag was not tapped out (Pleiner 1958, 113 – 114, pl. I, fig. 22). Absolutely identical furnaces were excavated in 1955 at Kostomlaty in central Bohemia (Pleiner *ibid.* 110 – 117, fig. 23). All of these finds provided clues in the process of establishing the 'sunken-hearth furnace' as it was originally named (Pleiner *op. cit.* 111, 127 – 128, fig. 26) as a 'type'. With more and more examples being recognized in excavation in the following years, the 'slag-pit furnace' entered archaeological systems of classification (e.g. Cleere 1972; Tylecote 1973; 1986, 135 – 136, figs 80 and 81; Pelet 1976, fig. 2). Nowadays, many thousands of excavated slag-pit furnaces are known to represent the iron metallurgy of *Germania Libera* and other non-Roman territories in the period between ca 150 BC and AD 500.

In terms of the reconstruction of such smelting installations, the finds from West Brandon, near Durham in England deserve our attention. They consist of two rock-cut hearths, dated somewhat approximately to the 3rd – 2nd centuries BC, which measured 43cm diameter by 33cm deep and were found on excavation to be filled with charcoal, slag droplets. Fragments of clay lining, vitrified on the inside, sealed the upper levels of the pits. This evidence was used as the basis for a reconstruction (see Tylecote 1976, 42, fig. 32, after Jobey) showing a domed superstructure over a sunken hearth, which would function like a slag-pit furnace with forced

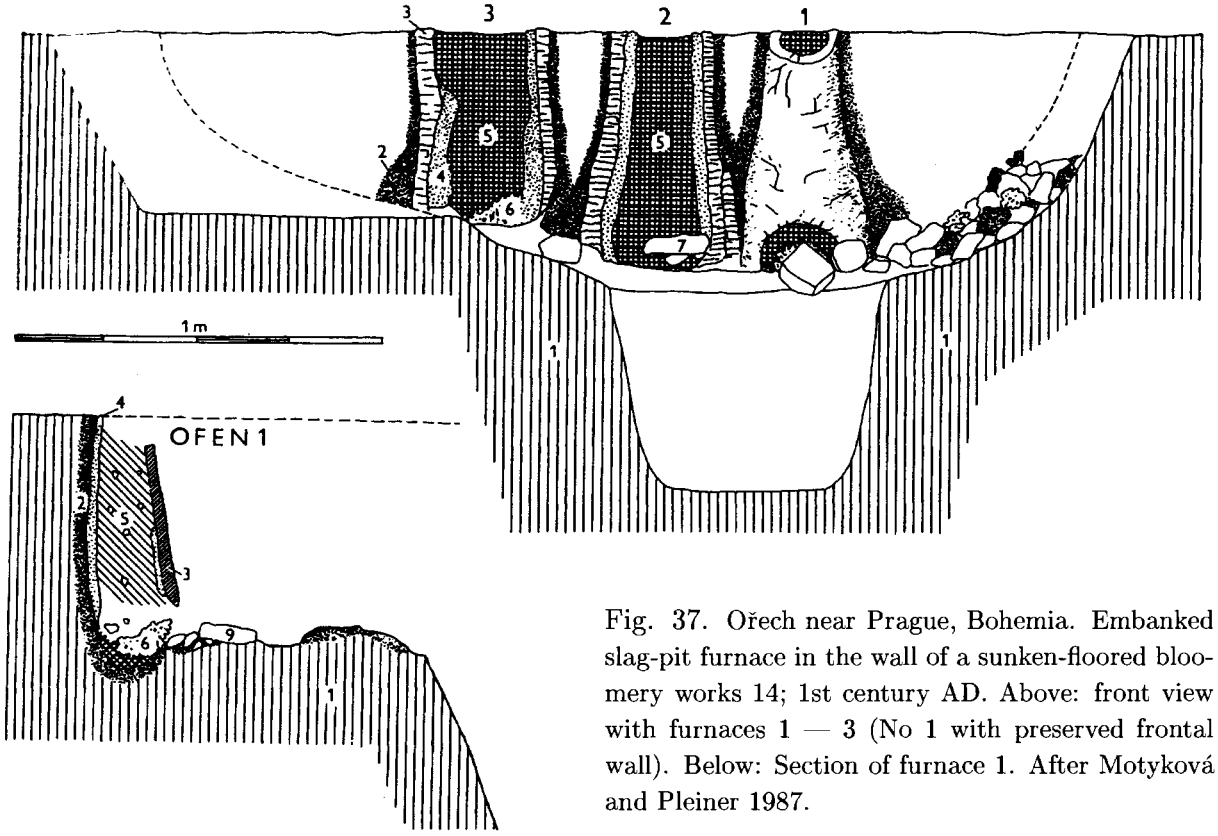


Fig. 37. Ořech near Prague, Bohemia. Embanked slag-pit furnace in the wall of a sunken-floored bloomery works 14; 1st century AD. Above: front view with furnaces 1 — 3 (No 1 with preserved frontal wall). Below: Section of furnace 1. After Motyková and Pleiner 1987.

draught, the blast being introduced through a short groove on the west side of the bowl. It should be stressed that this arrangement is far from typical of the slag-pit furnace, the superstructure of which was unequivocally a cylindrical or conical shaft. However, finds of slag blocks from Aylsham and Mucking in East Anglia (Tylecote 1986, *l. cit.*) show that the true slag-pit furnace of east-Illyrian/Celtic-Germanic form appeared in Britain only in the period of its decline, apparently imported during the invasion of the Angles and Saxons from north-west Germany and Jutland.

The origins of the slag-pit furnace

The origins of the slag-pit furnace remain obscure. There are several finds resembling the type, dating from the second half of the 1st millennium BC, but which are spread over a vast area. At Populonia, Tuscany, a furnace, the radiocarbon dates for which indicate 170±70 BC, was inserted into a large slag heap whose earliest layers were deposited in the 5th century BC. The feature seems to have been a slag-pit furnace with no provision for slag-tapping, originally having supported a shaft (Pl. I: top). It had a cauldron-shaped hearth and the slag-pit, which had been emptied, was 30cm in dia. and 45cm deep (Voss 1988, figs 4 – 5). Its upper part was slagged and a trace of what was called a working floor was observed during the rescue excavation. Not all commentators agree with this classification because of the absence of the characteristic slag blocks among the debris. In any case, it would be premature to claim this as a 'missing link' to finds in central Europe.

Another case is the slag-pit furnace from Taruga, Nigeria (Tylecote 1968; 1975). Several features were excavated showing rock-cut cylindrical or slightly conical hearths, about 50cm diameter by 30cm deep, with traces of clay superstructures on their rims which were heavily

slagged (Fig. 38). Fragments of two opposing tuyeres in hearth 4 may be evidence of the use of two sets of bellows inserted into the shaft at a level slightly higher than that to which the structures survived. These furnaces, as will be apparent, are closely analogous to finds from Europe, but it is difficult to account satisfactorily for their appearance in this region. Radiocarbon produces a date-range of 280 ±120 BC, and the possibility of influences being introduced at that time by trans-Saharan traffic from the Carthaginian sphere in the Mediterranean has been raised.

Returning to the European hinterland, we should note the important find made at Weppersdorf in the Austrian Burgenland. Here, a slag-pit furnace with a classical slag block was found in a stratigraphical layer covered by the remains of a large Celtic domed-furnace of the type that appears on many Late La Tène sites (Bielenin 1977, 55 – 56, figs 4 and 5). On the other hand, the earliest examples of slag-pit furnaces from the regions north of the Danube also date from the Late La Tène period as well as in regions not touched by the presence of the Celtic tribes. This gives rise to the idea that the origin of the central European variety is pre-Celtic. In the relevant geographical area, its roots may have been in the cultures and technical milieu of Illyrian or Venetian smelters, from whom this particular furnace was adopted by eastern Celtic metallurgists on the one hand (there are well dated La Tène finds in Bohemia and Poland) and, on the other, by Germanic tribes directly to the north (Pleiner and Princ 1984, 167 – 170, map fig. 17). But surprises may be expected as, for example, with the announcement by Dunikowski and Cabboi (1995, 41 – 42) of a variant of the slag-pit furnace from eastern Gaul at Clérimois.

Whatever the actual mechanism of its introduction, the fact remains that the slag-pit furnace predominated over the next 600 years outside the Roman world, in the barbarian hinterland, covering vast regions of Bohemia, Austria (the left bank of the Danube river), Moravia, Slovakia, Poland, Germany, Scandinavia, the Carpathians and the Ukraine. With the end of Roman imperial rule, furnaces of this kind appeared for a short time in England, but did not persist there.

Beyond the Roman military border, slag-pit furnaces appear in many variants in construction details and size. Many thousand have so far been excavated and the most typical forms known from better-preserved or reconstructable finds are presented below.

Slag-pit furnaces combined with walls

This is a family of relatively small slag-pit furnaces, which are found particularly in Bohemia, inclined against the walls of sunken-floored bloomeries. They can hardly be classified as embanked, since only the rear of their clay-built shafts was set into a groove in the wall, while the front of the shaft protruded into the interior. Central Bohemia has yielded the best examples, with many preserved furnaces having the fronts of their shafts intact. The majority of furnaces in sunken-floored ironworks date from the early Romano-Barbarian period (ca 0 – AD 50). Their similarities to the Late La Tène examples is so striking that it is possible to suggest that perhaps some Celtic smelters survived and were assimilated among the Teutonic newcomers who colonized the former Gallic territories north of the Danube river.

Workshop I at the Late la Tène ironworks at Chýně produced two furnaces which were very small indeed, with preserved shafts some 60cm high and 4 – 6cm thick, leaning against the walls and facing each other across a pit of some 4m square. The shafts had been erected over slag-pits some 25cm deep, one of which contained a slag block *in situ*. The internal diameter at the tuyere level (which was the floor of the working-pit) was about 40cm. At the fronts of each shaft, an air-duct apperture for inserting the nozzle of a clay tuyere was observed (Pleiner 1958, 110 – 112, pl. 1, fig. 41: 1).

Several examples of such ironworks come from Ořech near Prague (Motyková and Pleiner 1987). Furnace 1 (Fig. 37) was built against the east wall of sunken-floored workshop 14 and

was one of three found in a row (Pl. IV). When found, the shaft was 60cm high, but probably stood originally to a height of 1m before the original surface of the site was ploughed out. It had an internal diameter which tapered from 22cm at the base to 15cm at the top and had been lined to a thickness of 3 - 5cm with refractory clay, the same material being used to build up the front of the furnace in which an arch was left at floor level. The brick-shaped tuyeres found indicate that these had been used to direct the air-blast into the interior of the furnace. The hearth which was sunk below floor-level was relatively shallow, with a depth of 12 – 15cm. It was clear that slag was not tapped from the furnace, since a block of slag, without any iron sponge adhering to it, was found *in situ* in the hearth. The mechanism for removing the iron from the furnace was simple, consisting merely of breaking down the front wall (as was also the case with the neighbouring furnaces 2 and 3). These front walls could be easily rebuilt, although on occasions, the smelters were probably able to remove the raw bloom without serious damage to the main structure (Fig. 68: 4).

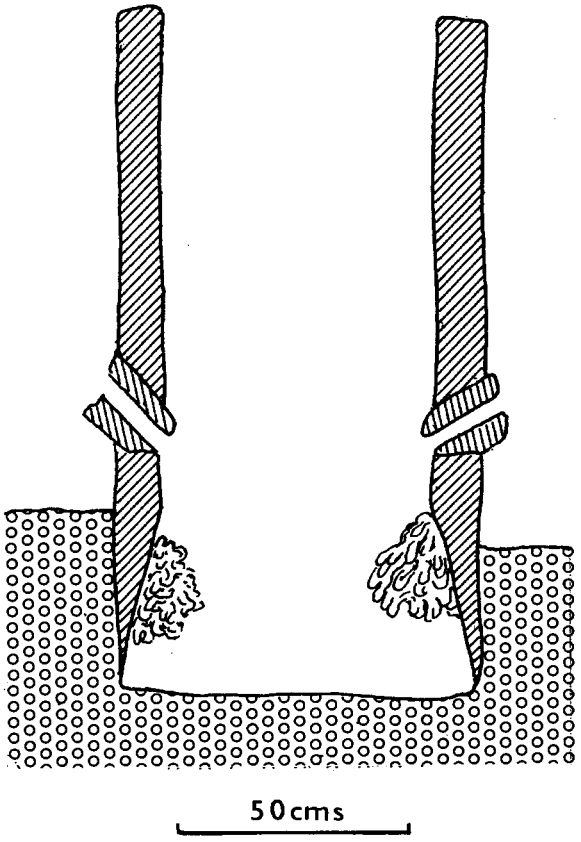


Fig. 38. Ťaruga, Nigeria, Africa. Reconstruction of furnace 2, about 300 BC. Level of preservation: below the tuyeres. After Tylecote 1975.

In Bohemia, many sunken-floored ironworks with well-preserved slag-pit furnaces, dating to the 1st century AD, have been discovered in recent years, in some cases with the front walls of the furnaces still standing. The slag-pits were slightly inclined to the rear forming a sleeve-shaped cavity. Very good examples have been excavated at Říčany near Prague, where the preserved height of the shaft of feature 55 was 50cm, slag-pit depth 25cm and internal shaft diameter 15 – 20cm (Kuna *et al.* 1989) and at Lovosice which revealed three furnaces with surviving shafts (furnace 1, shaft 70cm, slag-pit depth 25cm, throat dia 20 cm — Pleiner and Salač 1987). All of these furnaces represent units with a low capacity per smelt, although they could have been refurbished several times.

A different shape of sunken bloomery housing slag-pit furnaces was observed at Igołomia on the banks of the Vistula river, east of Kraków in Poland. In the early 1950's, on a very slight slope, two depressions were excavated (No 1 about 54m^2, No 10 about 45m^2), depth about 1.2m) in the southern banks of which were slag-pit furnaces with narrow, strictly cylindrical shafts (Fig. 36: 6). They were coated with refractory linings, burnt grey and bearing the imprints of vertical planks. Depression 1 showed two chronological phases with three and two furnaces respectively, whose internal shaft diameters ranged between 14 and 27cm, while depression 2, which yielded pottery of the early Romano-Barbarian Przeworsk culture, contained only one furnace, but the best-preserved of the three. According to a well-documented profile, the shaft of this survived to a height of 80cm (and would have reached originally up to 130cm, when the ploughing-off

of the ground surface is taken into consideration) and was extremely narrow with an internal diameter of only 15cm. There was an opening (10cm) at floor level which had been used as the air-vent. The rear of the furnace wall was surrounded by heavily red-burnt soil. The hearth, which was sunk below the level of the floor, was spherical, almost bulb-shaped, differing from the 'sleeves' of some of its Bohemian counterparts. It was 45cm in diameter and 35cm deep, containing a slag-block, the weight of which is not given (Fig. 36: 6, based on Reyman 1952). The dimensions of the shaft, in particular the height-to-diameter ratio, are such that the use of induced draught cannot be ruled out, particularly since no tuyeres came to light.

Such furnaces, apparently low capacity devices, were roughly contemporary with the much larger slag-pit installations of the Holy Cross Mountains smelting region, situated some 100km to the north-east and their economic hinterland would have been much more modest. It must also be borne in mind that behind the Carpathians to the south, there was another production centre around Varín near Žilina, possibly connected with the iron-smelting tribe of the Cotini (Piaskowski 1981), where exceptionally large shaft-furnaces were probably still in operation at the same time.

Slag-pit furnaces set into sunken working pits were apparently sheltered with a light roofed superstructures.

We must turn now to the site of Gera-Tinz in central Germany (Fig. 36: 2), which yielded 21 furnaces with sub-floor hearths (Dušek 1967), which appeared as groups of two and three, as well as in single units. The shafts of four of the furnaces survived to heights over 50cm (furnace 5 at 66cm and furnace 14 at 80cm). Although we might have expected highly-reliable reconstructions, the circumstances in the field were fraught with many difficulties. In the first instance, the dig was carried out by several excavators under very restricted rescue conditions, after the area had already been bulldozed preparatory to the building of a factory. Moreover, the natural consisted of a dark-coloured layer about 1m thick, followed below by a blackish marshy soil overlying yellow clay. The dark layers showed both furnace refractory lining and reddened marks of heat, so that the furnace bodies must have been partly embanked, although they were, in several cases, entirely exposed during the excavation. Some of the furnaces did not even reach the clay subsoil.

Dušek interprets furnaces 2, 5, 11, 15, and 21 as embanked at the back with separate frontal shaft walls, although the adjacent working-pits could not be documented, except in the case of complex 5. Furnaces 1, 3 – 4, 16, 18, and 19 have been classified as having completely free-standing shafts with sunken hearths. The term 'slag-pit' could be a little misleading here, since all of the hearths had been emptied of slag after smelting, with only a single 21kg heavy slag block coming from the destroyed feature 12. The hearths did contain broken-up fragments of slag and slag also was present in layers surrounding the smelting furnaces and in a number of associated pits. It is thus possible to suggest that all of the furnaces were originally housed in sunken workshops

We must consider the case of the complex comprising units 19, 20, and 21. The documentation shows that furnaces 20 and 21 stood side by side, apparently facing a common working-pit, while the scant remains of a destroyed furnace, no. 19 which was situated in front of them indicate that this unit was pulled down during the life of the bloomery. Other furnaces on the site suffered in the same way, as only the lower parts of the hearths or profiles could be recovered.

Two further examples must be considered. Furnace 1, an isolated feature, had shaft walls preserved to a height of 45cm and a thickness of 15cm at the base and a cylindrical hearth 40cm wide and 50cm deep filled with charcoal and some lumps of slag. An opening was observed, roughly 20cm square at ground level, through which a brick-shaped tuyere was inserted. The tuyere itself was found nearby along with numerous pottery sherds of an earlier phase. This furnace was interpreted as having been free-standing, because the reddened traces of heat were not observed in the adhering dark native soil. It is not out of the question that the furnace was

constructed in such a way that the rear wall of the working pit was not touched. In contrast, Furnace 5, which was the best-preserved on the site, leaned against the dark natural soil, facing an oval fore-pit 180cm x 150cm which contained about 250kg of slag lumps and 12 tuyere nozzles of rectangular, triangular and oval sections. The furnace proper was 66cm high (the original height was estimated to be in the region of 90 – 100cm) and the shaft was conical, the internal diameter narrowing from 40cm at the base to about 15 – 20cm near the throat. The sunken hearth was slightly funnel-shaped, 28cm deep and filled with a charcoal layer and pieces of loose slag pieces (Fig. 36: 2). To the north, an arch (23 x 20cm) faced the working pit.

The Gera-Tinz furnaces were bellows-blown, as the numerous block-like tuyeres with air-duct holes (2–3,5cm) indicate. The site is dated to the period 1st to 2nd-3rd centuries AD (furnace 2 and pit 1 to the earlier period, furnace 1 and pit 4 to the later phase). Taking this time-factor into account, Dušek (1967, 173 – 175) suggests that production was on a small-scale. However, the concentration of 21 furnaces and other features in the relatively small area of about 25m x 12m raises some doubts that the site would have been used by at least 8 – 10 generations of smelters. But despite the uncertainties, the Gera-Tinz site represents an important source for understanding the structural, technological and economic situation in the Romano-Barbarian period.

It was claimed that some of the furnaces at Gera-Tinz were free-standing, erected above underground hearths outside of any sunken shelter although, as already noted, some of the circumstances of the excavation would cast doubt on this interpretation. On the other hand, free-standing slag-pit shaft-furnaces constitute the majority within this category.

Slag-pit furnaces with free-standing shafts

It is exceedingly interesting that free-standing slag-pit furnaces are contemporary with those in sunken-floored workshops, in a relatively restricted geographical area. This can be demonstrated in the case of central Bohemia, where numerous smelting furnaces, dating from the 2nd century BC – 1st century AD, were investigated in the late 1950's and the 1960's. For example, the La Tène period slag-pit furnaces at Mšec (Pleiner and Princ 1984) and Kostomlaty (Pleiner 1958, 114 – 117, fig. 23) were free-standing, while those from Chýně, as noted above, were built against the walls of working-pits.

The situation is similar in the early Romano-Barbarian period. At Dřetovice, a battery of small slag-pit furnaces with typical inclined, sleeve-shaped hearths was uncovered in 1957 (Pleiner 1960, 200 – 201, figs 12 and 13), comparable with those from sunken-floored bloomery sites in the south as that from Stodůlky some 12km away. However, the furnaces in the Dřetovice battery were free-standing. To the east, in the Vltava river valley at a site in Roztoky some kilometres north of Prague and a mere 10km from Stodůlky, another free-standing furnace, of the same period (1st century AD), was found standing in front of a sunken hut which yielded a typical brick-shaped tuyere (Pleiner 1960, 192 – 200, figs 4 – 8). The slag-pit was notable for its hour-glass shape which is typical for other contemporary examples, such as those from Prague-Podbaba site XI (Fig. 36: 2; Pl. V) on the northern periphery of the capital and from Luštěnice near Mladá Boleslav some 45km to the north-east. This 'micro-typology' from a restricted geographical region indicates, without any doubt, the activity of smelters in at least three sub-regions, who were accustomed to build their slag-pit furnaces and ironworks in slightly different ways.

The two furnaces found at Prague-Podbaba site XI had been lined with a refractory clay and are well-preserved representatives of the variant with hour-glass shaped hearth (Pleiner 1958, 159 – 161, fig. 39, pl. VI; 1960, 190 – 192, figs 2 and 3). Furnace 1 (Fig. 36: 3) was a free-standing structure and half of the shaft still stood to a height of 115cm when it was excavated by J. Böhm in 1934, although the front of the furnace had been destroyed. The walls were only

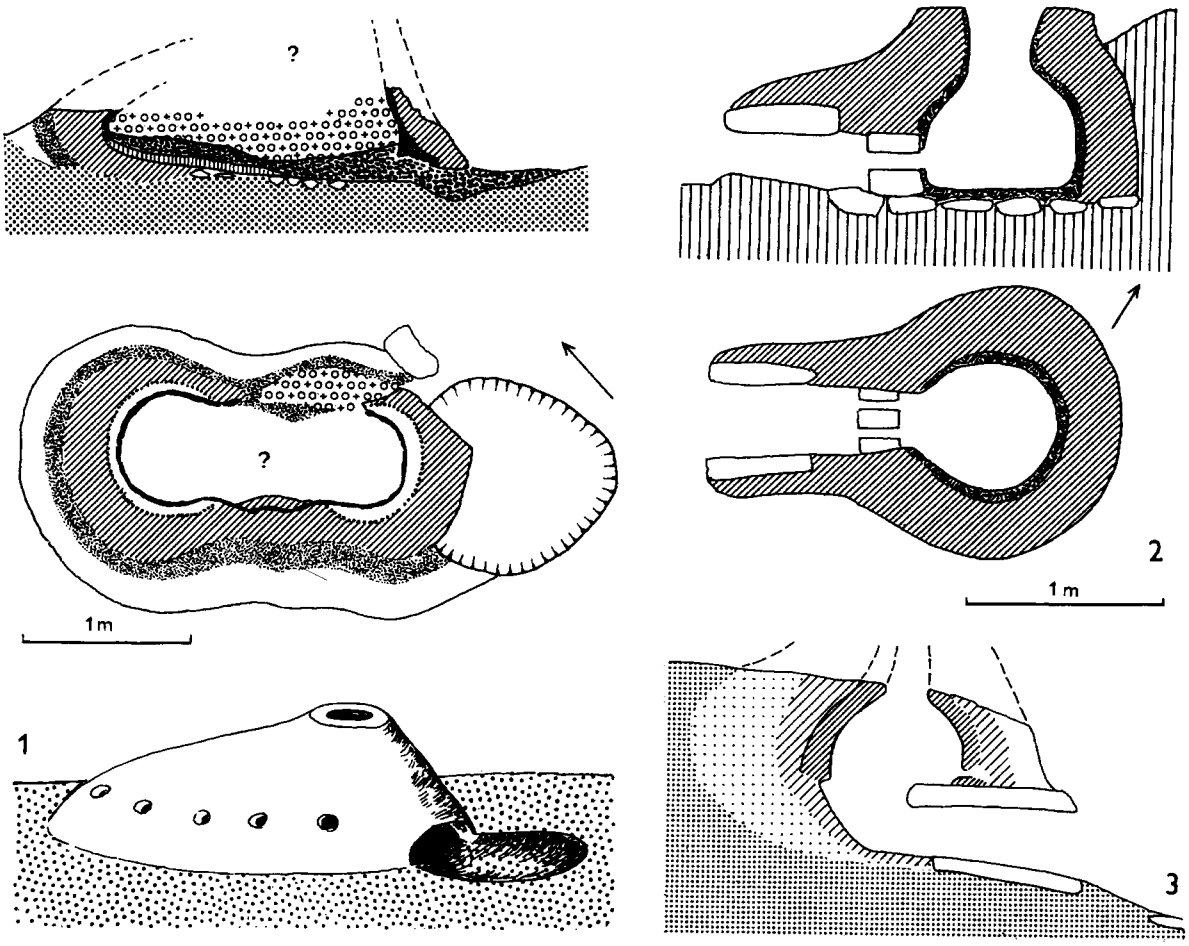


Fig. 39. Domed furnaces in Germany. 1 Kelheim-Michelsberg, Bavaria, ovate domed furnace, late La Téne period; 2 Engsbach, Siegerland, Germany; 3 Minnerbach, Siegerland, both La Téne period. References: 1 Behaghel 1940 (reconstruction: Pleiner); 2 Stieren 1935; 3 Behaghel 1939.

some 5cm thick and the internal diameter above the hearth was 24cm. The slag-pit was 31cm deep, 31cm in diameter and narrowed slightly towards ground level to give the hour-glass profile. Furnace 2, found just beside it, had been more severely damaged, but the free-standing shaft still stood to a height of 45cm. It had a air-blast inlet, 10cm in diameter and blocked with slag, located at ground level, and the slag-pit still contained a block of slag. This furnace had thicker walls (10 – 20cm) at the base of the shaft.

During the middle Romano-Barbarian period (more or less the C_1 in archaeological chronology) the slag-pit furnace underwent a further evolution with its dimensions and capacity per smelt increasing significantly. The diameter of the upper part of the slag-pit regularly reached around 40cm (which may be assumed to be equivalent to the internal shaft diameter) and the depth of the hearth tapered to about 50cm. In many cases the shape of the hearth is conspicuously conical, the bottom diameter being 50 – 90cm. This indicates the size of the slag blocks formed, either left *in situ* compact or disintegrated or crushed, because the slag is brittle. The hearths were frequently equipped with small lateral pits or vents which did not act as blast-inlets but as auxiliary air-ducts to assist when necessary in burning out the filling of straw or brushwood before the liquid slag arrived. Slag would seep into these holes and create a variety

of protruberances on the surface of the slag block as it solidified.

Conical slag-pits or blocks occur frequently among Romano-Barbarian furnace finds over the vast territory of *Germania Libera*. Returning to the evidence from Bohemia, the site of Dřetovice in NW central Bohemia (see above) is of great stratigraphic importance. A sunken-floored hut (No 2) dating from the 2nd century AD, into the filling of which a large slag-pit had been dug, was excavated nearby. In the vicinity, another two hearths of this type came to light, one of them having been damaged by a mediaeval feature. These slag-pit furnaces must have been in operation some time in the 3rd century AD (Pleiner 1960, 200 – 203). Interestingly, they were lined with a distinctive mixture of clay, sand and crushed haematite (Bartuška and Pleiner 1965, 8). This design has been very frequently observed on Romano-Barbarian sites in the area around of the town of Slaný (Fig. 68: 13) and for a short while, such furnaces were referred to as the 'Dřetovice – Slaný type' or 'Schlaner Typus' (Pleiner 1965b, 24). In due course, however, after conical slag-pits had been discovered in many other sites in north-west Bohemia, as well as in Germany, Silesia, and Jutland, the name was abandoned. Perhaps a future detailed study of these slag-pits and blocks will identify many local variants as witnesses to the work of different groups of smelters living within their tribal communities.

One such variant seems to be more instructive than others, on the basis of evidence from numerous finds in north-west Germany and Jutland (Fig. 68: 10, 12, 14). The northernmost occurence of classical furnace slag-pit comes from Hallfrede, island of Gotland, Sweden (Serning in: Iron and Man in Prehistoric Sweden, 83, fig.3). Arkeologi på Gotland, *sine anno*, fig. 3). Then, there is the unusual find reconstructed from Scharmbeck.

The Scharmbeck/Drengsted furnaces

The reconstructed shape of the tall Scharmbeck furnace (Fig. 36: 4), from Hamburg-Harburg in north-west Germany, dated to the 2nd century AD, is based on a number of furnace-wall fragments found in a rubbish pit and fully reconstructed in the laboratory (Wegewitz 1957). This variant had a free-standing shaft and also possessed a striking conical hearth. The shaft, which was heavily-slagged in its lower part, was deliberately made with very thin walls, tapering from 4cm in thickness at the base to 2cm at the throat with an internal diameter of 35cm at the base, tapering to 22.50cm at the top. Three air-inlets of diameter 3cm were situated radially at 90° around the circumference in the lower part, while a fourth would appear to have been located in an area which was damaged. The whole arrangement is evocative of induced draught. Perhaps the most striking feature of the shaft was that the base had pronounced a lip to allow it to be lifted and placed over the slag-pit. Until this discovery, no evidence had come to light for the use of transportable shafts at this time. Conical slag-pits dug in the sandy soil of Drengsted and Snorup, Denmark, produced bizarre shapes of the slag blocks (Pl. IX), sometimes with solidified pools of slag on the very bottom of the hearth (Voss 1995).

Attention should also be paid to a furnace find from Riestedt, Thuringia (Voigt 1961) which was, it must be admitted, compeletly destroyed and reconstructed by sketch from minute fragments. However, a distinct rim may be seen on some of the pieces of the lower shaft. More recently, the remains of an analogous structure found at Huise, Belgium, have been reconstructed (De Laet and van Doorselaer 1969, Figs. 1, 4). Traces of a lip indicating a transportable shaft were observed on the remains of a Romano-Barbarian slag-pit furnace from Dalfsen in Holland, which was later tested by experiment (see IJzersterk 1994, 32–37). It is interesting to note that the film *Noces de feu* made by the French ethnographer Nicole Échard shows a very similar portable shaft being manufactured and used for iron smelting on prepared bases by Hausa tribesmen in Niger in the later 20th century. In summary, the Scharmbeck furnace has provided the model for the reconstruction other slag-pit furnaces from north-west Germany and Jutland, such as those at Westerholz, Hatten, Joldelund and Snorup (Dehnke 1970; Hayen 1968; Jöns

1992; Voss 1993), see Pl. X.

The shape of the Scharmbeck shaft inspired Danish and other archaeologists to set a reconstruction over a conical slag-pit with a narrow throat of a type found in Schleswig-Holstein, Germany, and in the region of Varde on the Danish side of the border, initially by Thomsen (1964) and later by Pleiner (1969b), Barbré and Thomsen (1983), Zimmermann (1985) and Lychatz in IJzersterk 1994, 20–22. In fact, the smelting of iron ore in slag-pit furnaces became very popular among teams of experimenters as, for example, at the performances at Eindhoven 1993 (IJzersterk 1994). In the case of Thomsen's experiments, induced draught was applied resulting in a slow smelting process, with smelts consuming beech charcoal and 20kg of bog iron ore lasting from 15 to more than 24 hours. Temperatures in the reaction zone at the tuyere level attained 1200 – 1300 °C, with 650° recorded just below the top. The reduced iron did not sink down into the hearth but sintered together as a spongy mass around the air-inlets. Molten slag ran through the porous iron into the pit, but heavy slag blocks, of the kind found on excavations, did not form, probably owing to the inexperience of the operators. The metallic yield was low, apparently for the same reason, with iron forming as fibres, nodules, and spongy concretions embedded in a slag matrix. Thomsen (1964) and Voss (1973) succeeded in producing 1.5 - 2kg of iron from 50kg of ore, from which they manufactured a few arrowheads.

The trials by Lychatz (1994), taking advantage of the greater depth of experience gained since Thomsen's work, have achieved better results. The experiments are notable for their efforts to fill the slag-pit with light combustible material before the start of the process. It worked in part, but, again, the resulting slag block was small because slag blocked the air-inlets and halted the smelt prematurely. As before, the cause would seem to have been the lack of practical skill and knowledge of the operational 'tricks of the trade' mastered by ancient smelters. Nevertheless, after 20 hours, a 3kg bloom of mostly ferritic iron was obtained from 46kg of charcoal and 18.9kg of ore (53.3% Fe). The working temperature fluctuated around 1300°C. A small part of the bloom, a piece weighing 510g, was reheated and forged at 1250 °C, resulting in a bar 150g in weight (representing a loss of 70%), still permeated with numerous minute slag inclusions.

Several subtypes of the free-standing slag-pit furnace, varying in size and shape, have been uncovered during the many seasons of research excavations in the famous iron-producing region of the Holy Cross Mountains in central Poland. One particular furnace was used in vast numbers during the *floruit* of the iron-making centre, sometime between the 2nd and 3rd centuries AD. Although the shaft as such has not been recorded, numerous structural elements allow a tentative reconstruction.

Brick-walled slag-pit furnaces

Since the 1950's, the Holy Cross Mountains (Góry Świętokrzyskie) of central Poland have provided abundant finds of slag-pit furnaces, both in 'disorganized' and 'organized' clusters in open-air bloomeries (Bielenin 1973a; 1974; 1992), although among the thousands of excavated remains, no fully-preserved furnace has been found. This is understandable, however, when it is remembered that the area in which they are found has been ploughed for centuries. The main source for the study of the furnaces are the sunken hearths with their slag blocks left *in situ* (Fig. 68: 1 – 4, 12 – 15). Several variants in shape occur, with those pits which are slightly conical with a widened top, or cylindrical in profile being the most frequent. The cylindrical form also varies in size, the smaller being relatively deep (up to 50cm) and narrow (internal dia. 25–35cm). Their slag blocks weigh 8–12kg. Such furnaces are known as the 'Kunów type', and are found in the earliest small clusters. The majority, occuring both in 'unorganized' and 'organized' clusters, are much larger, 30 – 35cm deep with an internal diameter of 45cm, giving slag blocks with an average weight of 100kg (Pl. VII: bottom; Pl. VIII). They are decribed as 'normal', representing what has come to be referred to as the 'Holy Cross Mountains slag-pit'

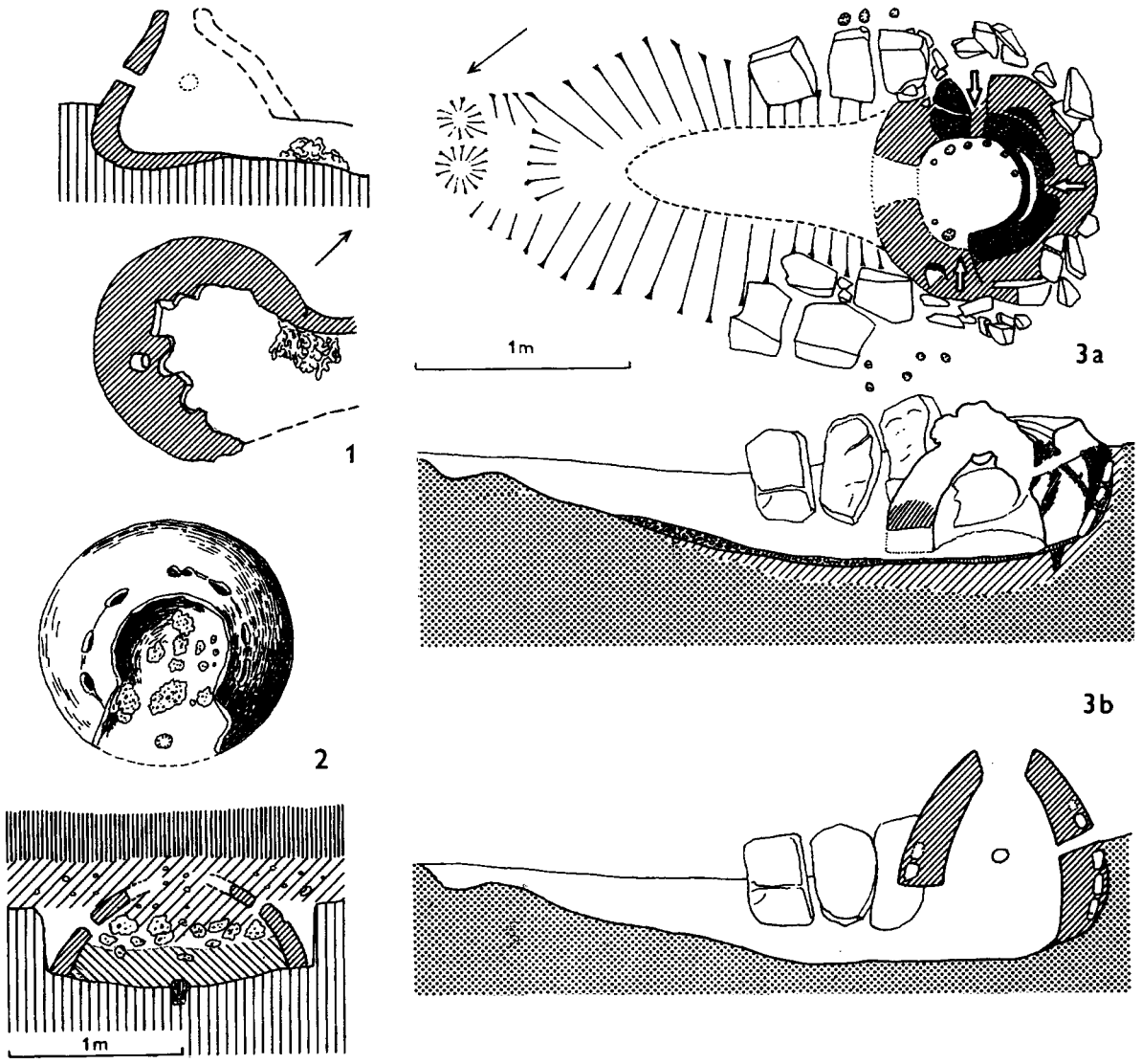


Fig. 40. Domed furnaces in Austria, Poland and Britain. 1 Unterpullendorf, Burgenland, Austria, late La Téne period; 2 Mechlin, Poland, plan and section of a domed furnace with radial air-inlets, early Romano-Barbarian period; 3 a–b Rotherfield — Minepit Wood, Weald of Sussex, England, plan and section of a domed furnace with 3 air-inlets, ca 50 BC — AD 100. References: 1 Pleiner and Princ 1984 (after Bielenin); 2 Kostrzewski 1933; 3a Money 1974, 3b based on Money 1974 (modified).

(kotlinka świętokrzyska). Their massive slag-blocks sometimes show protrusions at one point, mostly at the top, but these are not to be interpreted as evidence for slag tapping. It is rather the case, as suggested by some finds from Denmark and elsewhere, that they represent slag flowing into an auxiliary air-duct, used to burn out the wood or straw that filled the slag-pit before the molten slag mass ran down through the iron sponge. It was critical to keep this clear to enable the slag to separate from the bulk of the charge (Fig. 69).

Discoveries at several sites, particularly Łazy 4, Przełęcz Hucka, Bielnik and Nowa Słupia 5, have made possible attempts to reconstruct the shafts. Slagged and unslagged bricks from different levels of the shafts, made of clay with the addition of chopped straw and husks, and sometimes showing traces of joints, have been found. Their sizes varied from *ca.* 16cm x 8cm

x 5cm to 15 x 12 x 8cm. In several cases, those from the shaft base showed traces of circular air-inlets (external diameter up to 12cm, internal diameter 4cm). These were the true ducts for the air-supply which ensured the success of the metallurgical process taking place above the sunken hearth (Bielenin 1992, 68 - 72). On the basis of these elements, it would appear that the typical Holy Cross Mountains slag-pit furnace was equipped with a slightly conical shaft with walls 6 – 8 cm thick at the base, where the vents were situated (Fig. 36: 5). No tuyeres have been found anywhere in the whole area, which invites the conclusion that the furnaces were operated by induced draught. If this was indeed the case, then the height of the shaft must have reached 100 – 140cm, but the question has not been resolved to date. Below each shaft, a slag-pit was dug out, sometimes with auxiliary inlets of the type referred to above. In passing, similar bricks with duct holes and, in addition, clay stoppers, were found in the furnace clusters of Uman' II, Ukraine (Bidzilya *et al.* 1983, fig. 24; Pan'kov 1993, 91, fig. 14). The slag-pit furnaces of that region must have been of a very similar design. This system of building shafts from bricks would appear to have been very suitable for the style of work *en gross* in the region, where the furnaces were used for one smelt only.

Smelting trials on reconstructions have been in progress since 1957, with the experimental parameters being successively modified in the light of experience gained. They have demonstrated that bellows-blown furnaces ran better, although forced draught was essential for furnaces with shafts 50 – 60cm high and internal diameters of 35cm. In this case, 65 – 81kg of roasted haematite ore (ca 60% Fe) were consumed in smelts lasting 9 – 11h, producing slag blocks weighing about 35kg. In the upper part of the furnace, the iron was partly concentrated as a sponge in a slag matrix and partly distributed as discrete particles which made it difficult to estimate accurately the yield, which in any case lay in the region of 17 – 20%, although there seems no doubt that the ancient smelters were more accomplished. The carburization of the iron was uneven and heterogeneous, the structure of the product ranging from pure ferrite to particles and areas of hard, high-carbon steel. Thorough pre-heating of the furnace before starting the smelting process was observed to be essential. The optimum ore size was a 12 – 15mm cube and the best size of beech and pine charcoal was found to be 25 – 30mm cube. Overall fuel-to-ore ratios of 1 : 1 were generally used (Radwan and Pleiner 1963; Mazur and Nosek 1966; Bielenin 1992, 78 – 82).

Radiocarbon dating introduces some discrepances to the archaeological chronology (see Chapters III and IV). In general, smaller slag-pit furnaces of the Kunów type predominated in the earlier period of iron production in the Holy Cross Mountains. The pottery from Częstocice, Gardzienice, and Kunów indicates a time span between the 1st century BC and AD 100 – 150, Kowalkowice 100 BC up to AD 250, Boleszyn AD 0 – 150. However, radiocarbon dates from Boleszyn, and Częstocice as well, indicate the 3rd century BC. The larger or 'standard' variant of the slag-pit furnace in the region operated in the Romano-Barbarian period (AD 50 to AD 350 according to pottery, including the large-scale made wheel-made grey ware (*ceramika śiwa*). The radiocarbon measurements on charcoal samples from two furnaces at Gregorzewice, four from Łazy 6, and two from Nowa Słupia 11 (all of them within organized clusters) suggest roughly the 2nd century AD with probability of 50% and a range of 1st to 3rd centuries AD with probability 90% (Bielenin 1992, 175 – 179, quoting data taken from Pazdur; on chronology see also Orzechowski 1999).

The slot slag-pits from Hegglesvollen

An unusual variant of slag-pit furnace has been discovered far in the North, on many sites in the region north-east of Trondheim in Norway, the most instructive of which is Heglesvollen (Stenvik 1987; Espelund 1987; 1989). There, an alignment of four large furnaces has been excavated on an edge of a bank, each sunken and lined with stones (Pl. XI: top). The slag-pits,

which had internal diameters of 70 – 80cm and depths of 80cm, were not closed but left open by a slot on the side facing the slope and each contained disintegrated slag blocks (22 to 66kg), thought to have formed around the wood filling of the pit. Slagged and unslagged fragments of the shafts which were erected over the pits have been found loose among the furnace debris. The use of induced draught is suggested on the basis of the absence (except for one clay fragment with an air-hole of 4cm in dia.) of tuyere finds.

Espelund argues that the slot which ran from the slag-pit must have been blocked with clay when the smelt was started. Some circular depressions filled with baked stones, the purpose of which remains unknown, were uncovered around the furnaces (four in the case of furnace C 2,) and are referred to as 'rosettes'. He further suggests that the depressions were fired to elevate the temperature in the lower parts of the furnaces. Radiocarbon dates from the Heglesvollen site are spread over a wide range from about 0 to 600 AD (Stenvik 1987, 6). There is another well-excavated site at Storbekken near Budalen, which has produced five furnaces of the same type as well as the so-called 'rosettes' (Stenvik 1991).

Mediaeval slag-pit furnaces

In her most recent study, Souchopová (1995, 30 – 34) interprets some features in the region around Olomučany in western Moravia, as slag-pit furnaces. In cadasters Nos 591/2 and 3, five empty furnace hearths were uncovered, of which No II was the best preserved. It had dimensions of 45cm x 40cm x 35 – 50cm deep and showed evidence of multiple replacements (a total of eight) of the lining. It is reported that one furnace survived with its conical clay shaft, which was unfortunately destroyed by building workers before the archaeologists arrived (an amateur photograph is, nevertheless, preserved, see Souchopová 1986, pl. VIII, above). As similar hearths appeared in other sites of the region (Padouchov, Olomučany 98/1 etc.), the author is inclined to believe in a temporary episode of local rennaissance of slag-pit furnace practice during the 10th–11th centuries AD, even though this would have been a somewhat retrograde step in view of more advanced practices in the region.

Domed-furnaces

Before dealing with the further development of the shaft-furnace, it is necessary to examine another, distinct form of smelting apparatus. This is a structure resembling a pottery kiln in shape, the reduction chamber being enclosed within a clay dome or cupola. These furnaces are usually oval or circular in plan and are large, exceeding 1–1.2m at ground level. From the point of view of the process, this was not necessarily advantageous in terms of heat concentration or of the circulation of reducing gas and only selected examples will be dealt with here.

Domed-furnaces occur in the archaeological record, however, at a very early date. The oval base of a furnace set in stone, some 1.6m diameter, found at Hillesheim in the Eifel, covered with bloomery slag, is dated to the Hallstatt/Early La Tène period (Haffner 1971). Indeed, domed-furnaces continued in use throughout the La Tène period in western and southern-central Europe, including eastern France and Austria, and appear to be linked to the Celtic ironmaking tradition. A number of the recorded examples were discovered in the 19th or early 20th centuries and so are not very well documented (see Pleiner and Princ 1984, 133 – 135 for bibliography). It should, however, be noted that the *corpus* of European domed-furnaces includes both primitive and fairly sophisticated structures, some of the latter apparently being as efficient as shaft-furnaces.

One of the most primitive forms seems to be the domed-furnace from Kelheim, found in 1939 within the oppidum of the Michelsberg, at the confluence of the rivers Danube and Altmühl in Bavaria. The hearth was oval in plan, 1.1m long by 70 – 80cm wide, with a constricted centre section 45cm wide. The clay walls of the dome, 30cm thick at the base, survived to a height of 30 – 47cm. There was a furnace arch measuring 15cm by 60cm on the south-eastern side, linked

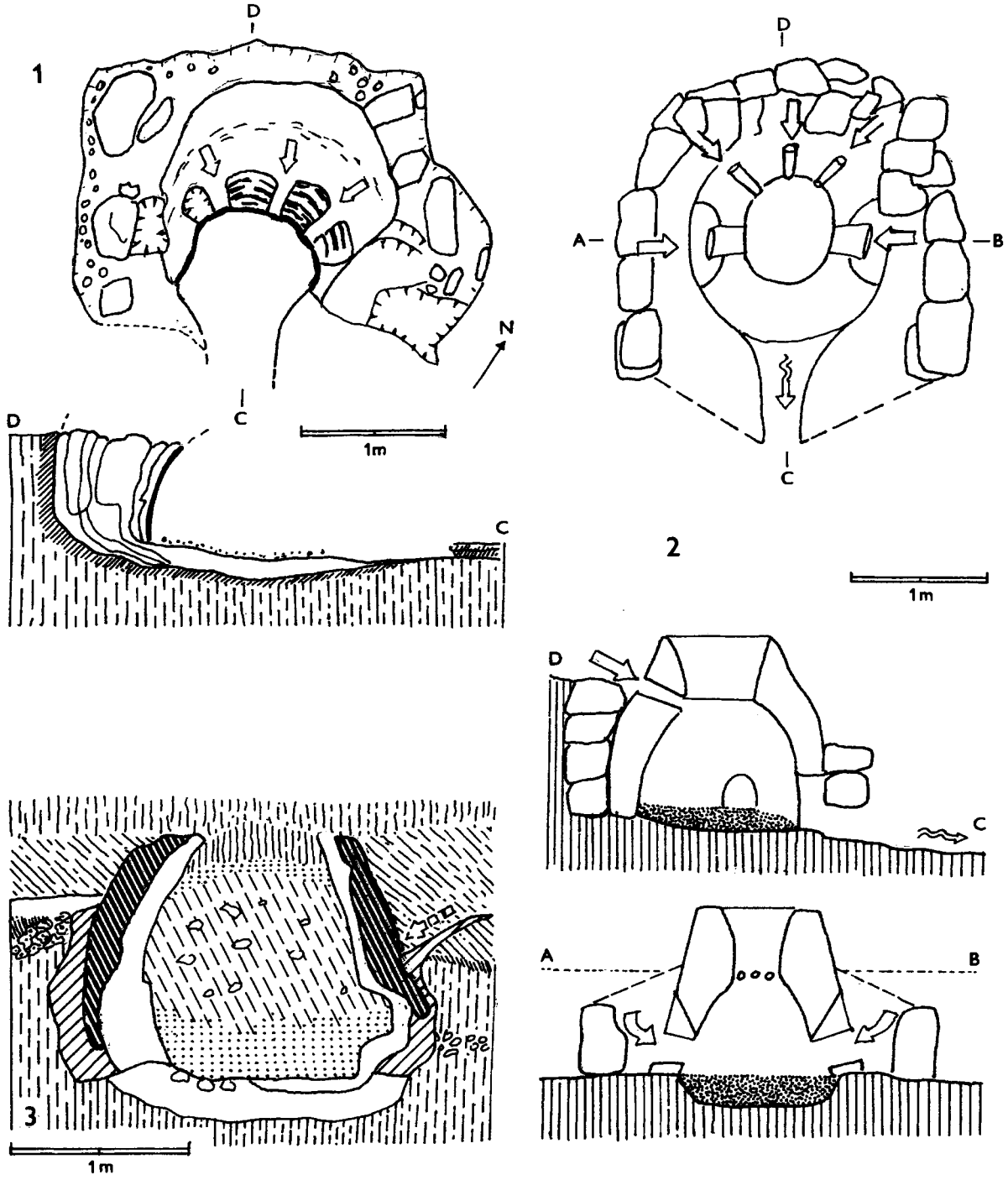


Fig. 41. Gallo-Roman and Norican furnaces. 1 Clérimois, France, furnace F12 with multiple relining, in ferrier 3a, plan and longitudinal section; decline of the La Tène period or early Roman; 2 Reconstruction of domed furnaces at the same site; 3 Möselhof, Görtschitztal, Carinthia, the same period; section of a thick-walled shaft furnace. References: 1–2 Dunikowski and Cabboi 1995; 3 Glaser 1995.

to a shallow depression measuring 1m by 1.2m. No reference is made in the report (Behaghel 1940) to slags from the filling of the furnace, but mention is made of the base of the hearth being covered by a layer of charcoal mixed with the fragments of slagged walls. There was no indication of the method of supplying the air blast, although the report does mention the fact that fragments of lining containing air-inlet holes were found near the furnace, close to two further hearths identified as roasters. Mediaeval shaft-furnaces, equipped with clay tuyeres, were also found in the vicinity. It would appear that high temperatures were achieved in the Kelheim furnace and that it continued in use for a considerable period, as shown by the high degree of firing at the base of the superstructure (fig. 39: 1). The remains of three similar oval domed-furnaces have been found more recently at Altessing-Untertau, some 2km to the west of the Michelsberg *oppidum* (Burger and Geisler 1983, figs 5 – 7).

Attention should also be drawn to a group of domed-furnaces, again of La Tène date, discovered on a number of sites in the Burgenland of eastern Austria in the 1960s and 1970s, including Unterpullendorf (Fig. 40: 1; Pl. III: top), Oberpullendorf, Weppersdorf (where the domed installation overlay slag-pit furnaces), Piringsdorf and Klostermarienberg (Ohrenberger and Bielenin 1969, 88 – 90; Bielenin 1977a). Because of these finds, the term 'Burgenland type' is being promoted by Bielenin (1994) to cover all of the domed-furnaces so far recorded. The furnace from site 2 at Oberpullendorf was set slightly into a bank to a height of 40cm above the hearth level and had a working-pit in front of it. The clay dome, 10cm thick and internally slagged near the base, was well preserved up about 60cm above hearth level. It was apparently blown from three sides, with a circular air-inlet at the back of the furnace and traces of another in one of the much-degraded sides. The hearth measured 95cm by 115cm and had been cleared out after the last smelt, by raking rather than tapping, with slag and charcoal being found in the forepit (Fig. 40: 1). A similar furnace from Klostermarienberg (Pl. III: bottom) exhibited several zones of heavy slagging and slag accumulations on the flat hearth bottom, corresponding to the positions of multiple tuyeres.

The Burgenland lies to the east of the ancient province of Noricum (Carinthia), the traditional homeland of good steel. In comparison with the Burgenland, Carinthia for a long time did not yield any furnace finds of much value as evidence, with the exception of some low hearths at the oppidum of Magdalensberg, recognized later as smithing or reheating installations. However, the recent construction of a pipe-line system in the neighbouring Görtschitz valley finally revelaed a series of important finds comprising large domed or semi-shaft furnaces which have been published in a preliminary report by Glaser (1995). At Möselhof, a robust furnace structure came to light in the profile of the trench, showing a superstructure rather like a somewhat assymetrical cupola, slightly embanked at the rear.

It survived up to 150cm in height, the base or hearth being 120cm wide, with a protruding chamber on one side, 50cm above the hearth level. The interior was heavily slagged and the walls were burnt with the reddening extending into the adhering subsoil (Fig. 41: 3). A massive slag heap was located some 30m to the south and was up to 3m high and 200m long, apparently having served as a central dump for the debris from several neigbouring bloomeries. Similar furnaces, with four air-inlets and identical chamber-like protrusions or niches at their bases, have been uncovered at Kitschdorf, also from the Late La Tène period and at Rattelsdorf where they may be later in date. Fragments of hard steel blooms have been found in the valley (Straube 1996, 108. fig. 39). However, none of these sites have produced traces of a 'Bottich' pressure-blowing system, the use of which has been proposed by several authors in the discussion of Noric iron production (see Horstmann 1995).

Old finds of very well-preserved domed-furnaces, partly set into banks, are known from the northern periphery of the ancient Celtic heartland, in the Siegerland of western Germany, as at Gosenbach, Rötgen-Oberdorf, Oberfischbach and Oberschelden. The best-known examples are probably the domed-furnaces from Engsbachtal, near Achenbach, where Stieren (1935) excavated

around forty examples. Furnace E 25 is that most frequently illustrated by archaeometallurgists. It had a hearth diameter of 0.9 – 1m, the domed superstructure was 1.1m internally, and the oval length of the whole installation, including the tunnel in front of the furnace, was 2.1m. It has been suggested that such furnaces were carefully aligned in order to catch the prevailing wind on exposed slopes, thus operating with induced draught through a 6cm diameter air-inlet in a tuyere block at the end of the tunnel arch in the front end of the furnace (Fig. 39: 2). However, the use of induced draught with a furnace of such volume and shape is a matter of debate (see below).

Behaghel (1939) describes an excellent example of this type of furnace from Minnerbach, in the same region (Fig. 39: 3). The thick-walled dome was set into a bank and was oriented with its mouth facing east, with a stone reinforced wind-tunnel and forepit, partly paved with flat stones. The clay walls, which were baked red and heavily slagged, were up to 73cm thick, leaving a domed inner cavity of about the same diameter at hearth level, while the throat was only 23cm in diameter. When excavated, the dome stood 96cm high. No tuyeres were found *in situ* but a fragment, with a 6cm hole pierced in it, was recovered from among the debris. Four postholes found outside the furnace are considered to have supported a charging ramp (or shed). The furnaces were dated by the excavator to La Tène B-C (*ca.* 400 – 200 BC, on basis of a few pottery sherds, which are preserved in the museum of Siegen and belong, apparently, to the Late La Tène period). After World War II, Gilles (1958a) excavated a similar domed-furnace of the same internal diameter and preserved height at Silberquelle near Siegen (see Pleiner 1980a, 399, fig. 11.9).

Other La Tène period furnaces which have been reconstructed as domed structures are known from a number of sites on Continental Europe, in particular at Donaumoos in Bavaria, Bellaires in Vaud and the earliest phase at Quimper in Brittany. In these cases, however, only the hearths survive, without any evidence for superstructures.

Further to the south, in the heart of the Gallic hinterland, in the valley of the river Yonne, new discoveries have been made in a region known for its ancient iron production. However, the furnace finds, even if any are from the relevant period, have not been sufficiently documented in publication for detailed comment. The situation changed, however, when an iron-smelting area was explored during road construction near Clérimois, a site already referred to in connection with slag-pit furnaces. The bulk of metallurgical operations here was carried out in areas named 'ferrier 1' and 'ferrier 2' by the excavators, which are characterized by large depressions filled with iron slag and other debris. Furnaces of domed type were situated in the northern parts of these depressions (Dunikowski and Cabboi 1995). In all, six furnaces in three pairs were found in ferrier 1 (Nos 106, 112, 125, 141, 150, 151) and two in ferrier 2 (Nos 11 and 12, Fig. 41: 1 – 2). An isolated domed-furnace (No 146) was found within the area of a further focus of smelting, ferrier 3a. Large paired furnaces 62 and 63 in ferrier 4 are interpreted as being of another type (*four à cheval*) but, in the light of the preserved relics, they could form a sub-group of the category.

The furnaces were set into a low bank to the rear, so that their cupola-shaped interiors, preserved to heights of 70 - 80cm, show the curve of the original vaulting of the dome, thus also allowing for estimates of their minimum heights. Furnaces 12 and 41 were the best preserved and, together with the other examples cited, support the reconstruction proposed by Dunikowski and Cabboi (1995, 88 – 93). The embanked bases were reinforced with large stones which formed a horseshoe-shaped setting open to the working area in front of the arch. Within this setting, a clay dome was erected with walls in the region of 40cm thick at the base, the original heights possibly having reached some 160cm. The internal diameters of the flat hearths were about 150cm, assuming a narrowing to 40cm at throat level. A funnel-shaped top can be suggested on the basis of the form of furnace 41, and the volumes of the reduction chambers would have been in the region of 2m cube. There were two large lateral air-ducts on either side of the domes,

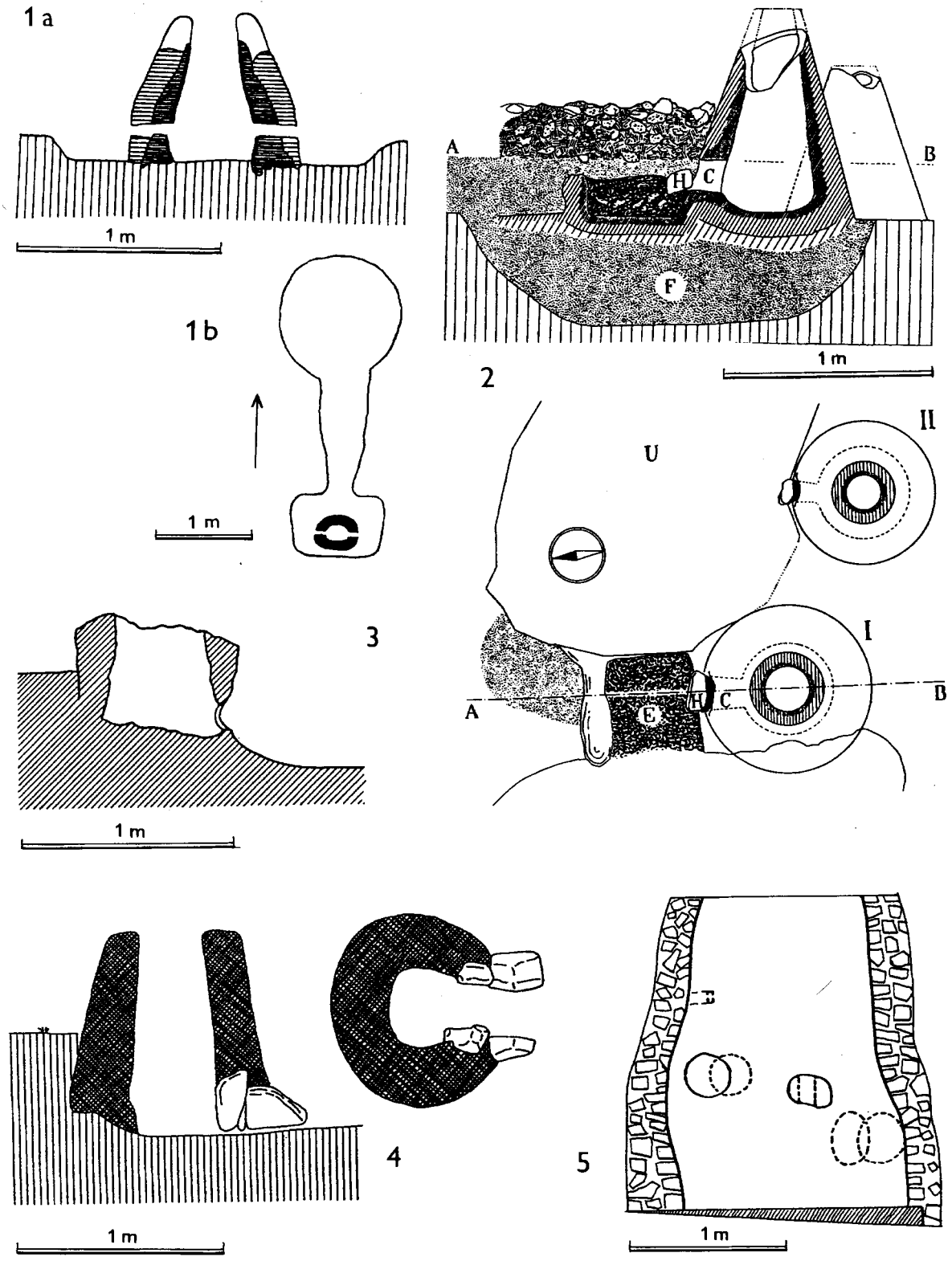


Fig. 42. Free-standing shaft furnaces (features with preserved shaft superstructure). 1 Novaya Pokrovka, Ukraine, early centuries AD — 1a section, 1b plan with the furnace position and shallow working pit; 2 Prague-Podbaba, Bohemia, site VII, Romano-Barbarian period; 3 Salzgitter-Lobmachtersen, W Germany, 2nd century AD; 4 Skovmark, Denmark, a slightly embanked furnace with forepit, 1st–2nd centuries AD; 5 Velikiye Bolgary, Russia, brick-built furnace with multiple air-inlets, 14th century AD. References: 1 Braychevskaya 1956; 2 Pleiner 1958; 3 Pleiner 1965 after Osann; 4 Voss 1989; 5 Efimova 1958.

supplemented by three vents in the upper levels to the rear, set slightly obliquely and pointing downwards (e.g. furnace 12, *op. cit.*, fig. 37). The air supply was provided by bellows, as attested by tuyere blocks with twin conical air-holes of 2.0 – 2.5cm in diameter. Slag fragments in the form of solidified flows show that the slag was tapped or otherwise evacuated in the molten state (Fig. 41: 1 – 2).

The excavators have made calculations of the iron ore and charcoal consumption of the ferriers as well as of the individual furnaces, based on the volume and weight of the slag waste. Each furnace could have been charged with around 300kg of ore and the same amount of charcoal, yielding some 89kg of unworked iron per smelt. As all show multiple repairs to their linings (e.g. furnaces 151, 11, 12, — *op. cit.* 83, Plates K to M), the authors estimate some 50 to 100 operations per furnace, taking into account the 8 tonnes of slag buried within ferriers 1 and 2. The efficiency and productivity of the plant must have been considerable, although it is classified as being of medium size when the huge Gallo-Roman slag heaps of the Yonne valley are taken into account.

The problem of the chronology of the Clérimois furnaces is, as before, that there is a discrepancy which might be misleading in any evaluation of the plant between the dates suggested by pottery and coins and those provided by radiocarbon. While Roman and Gallo-Roman pottery indicates roughly the period from the 1st to the 3rd centuries AD and a Roman coin-hoard, found in pit 147 within the area of ferrier 1, contains pieces dating from AD 23 (Augustus) to AD 161 (Antoninus Pius), the ^{14}C determinations give AD 40 to 180 for battery B (furnaces 106 and 112), 230 BC to AD 30 for battery C (furnaces 124 and 141, just beside the latter pair), 120 BC to 20 BC (or, also, 6th – 7th centuries AD) for furnaces 151 and 150 on the other end of the same ferrier. For ferrier 2, furnaces 11 and 12, the surrounding area of which revealed pottery of the 1st century AD, radiocarbon dating offers a range of 90 BC to AD 50. The pair of large furnaces 62 and 63, ferrier 4, shows radiocarbon dates ranging, however, from 140 to 20 BC, while the isolated furnace 41, is indicated to have been in existence between 30 BC and AD 100. Thus the radiocarbon dating range of these large furnaces of 230 BC to AD 180 would seem to be a little misleading. Despite the authors' attempt to take an average of all of these figures (which calculates as 86 BC to AD 41), something which appears quite unjustified in the light of the coin evidence, it would appear that the furnaces operated during the early and middle Gallo-Roman periods with their beginnings in the Late La Tène, although their sequence and the apparent chronogical gaps must be considered unexplained at present.

It is an inescapable fact that large domed-furnaces survived through to the early Roman period at least, and above all in those western territories settled by the Gallic peoples. Let us turn to southern Britain where the furnace at Minepit Wood, near Rotherfield, in the Weald of south-east England (Fig. 40: 3), the front of which had collapsed, was of large diameter (1.32m) and also slightly below ground level at the rear. The outside of the furnace was reinforced with sandstone blocks and there was a large pit lined with stones and measuring 2.75m by 1.37m in front of it. The walls had been exposed to high temperatures and the clay was burnt red to a depth of 25cm from the interior, while the walls were heavily impregnated with slag. The circumference of the hearth was outlined internally by a circle of small stake holes, which apparently formed the base for the frame of small branches over which the clay dome was moulded. The dome itself still stood to a height of 60cm and it was possible to identify three air inlets 5 – 6cm in internal diameter located at the back and on either side. Tubular clay tuyeres were also found on the site, but these are believed to have been used on a separate forging hearth, although it is possible that one could have been inserted through the blocked furnace arch. There was clear evidence that the furnace had been relined several times. It has been reconstructed as a domed structure, originally standing *ca.* 1m high with walls *ca.* 30cm thick at the base. Postholes around the furnace have been interpreted as the uprights of a light shelter. Dating by pottery and radiocarbon gives a date range between 50 BC and AD 100, but

other factors would favour a date in the first half of the 1st century AD, around the time of the Roman invasion of AD 43 (Cleere 1972; Money 1974).

An unusual find was recorded at Laxton-Lodge in Northamptonshire where an alignment of five large iron-smelting furnaces dating to the 1st – 2nd centuries AD, partly destroyed, especially at the front, was excavated under rescue conditions. Their rear sections were slightly embanked and showed, again, multiple relinings of the furnace walls, which were slightly overhanging at the preserved height of some 60cm above the hearth bottom, indicating a domed superstructure. On the basis of the best-preserved feature 9, the internal diameter would have been in the region of 130 – 140cm and the wall thickness some 30cm (Jackson and Tylecote 1988). The large forepits, which were not well-preserved, were situated on the downhill side. Recently, an additonal furnace has been excavated (No 10) showing 6 air-inlets in the circumference behind the arch (preliminary report by Crew 1998b) A similar feature from Byfield (Jackson and Tylecote 1988, 290 – 295) may also be of Roman date.

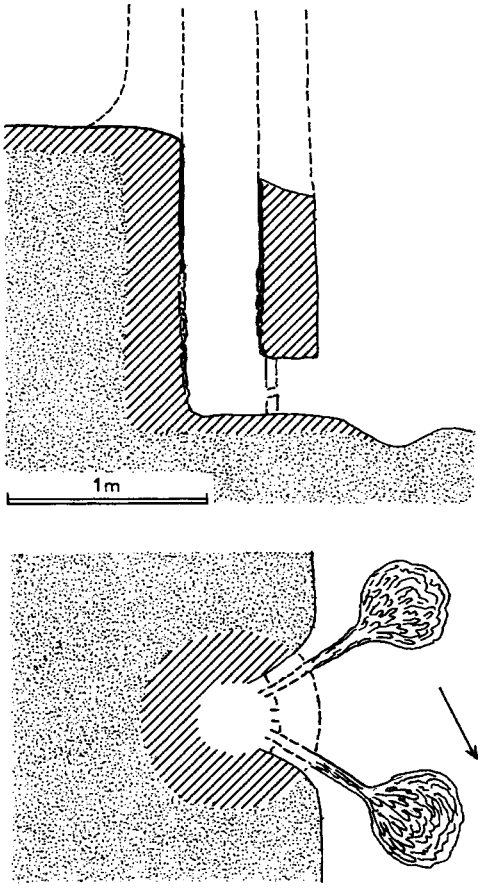


Fig. 43. Ashwicken, England. Slightly reconstructed embanked shaft furnace, 2nd century AD. After Tylecote and Owles 1960.

Excavations at other sites such as Pippingford (Tebbutt and Cleere 1973), Cow Park (Cleere and Crossley 1985, 301), and Broadfields (Gibson-Hill 1975; 1976) have revealed a similar method of furnace construction, with stone used to reinforce the clay superstructures. All of these examples date from the same period in the early 1st century AD. It had been suggested (Cleere and Crossley 1985, 52 – 53) that this represents a Gallo-Belgic influence, which would seem likely in view of the close British contacts with Gaul and the Low Countries at this time.

Iron production in *Germania Libera* was dominated, as shown above, by the slag-pit furnace. Sporadic occurences of dome-like structures have been noted, but are not well documented. The only case which deserves particular attention is the domed-furnace found at Mechlin, near Śrem in western Poland (Kostrzewski 1933). It is technologically anomalous and intrusive, since it is surrounded by many slag-pit furnaces of the same date, which according to reliably-dated pottery finds, belong to the 1st century AD. It would seem to be a technological survival, operated by an independent or immigrant Celtic group, perhaps from the middle or upper Danube river basin. The furnace had a flat circular hearth, *ca.* 1.4m in diameter with a possible posthole in its centre. The domed clay superstructure which was unusually flat, survived to a height of 45 cm, and had probably been no more than 15cm higher in its original form (a clay-covered charge heap would be, perhaps, a better description, than 'domed-furnace'). This superstructure was pierced 25 – 30cm above hearth level by eight air-inlet holes, each 8 – 10cm in diameter, spaced evenly arount the perimeter and directed towards the centre of the combustion chamber. The

superstructure, which did not have a refractory clay lining , was breached on the south-east side, presumably to allow the slag and iron to be removed. It is not conceivable that slag could have been tapped molten from the interior and it is much more likely that it was removed manually at the end of the smelt, along with the raw bloom of iron (Fig. 40: 2).

The origins of the domed-furnace are far from being explained. The principle of smelting with what is, in effect, a large heap of charcoal and ore, certainly does not derive from what may be termed 'the basic metallurgical furnace', blown with single or twin bellows and used initially for the smelting of small quantities, of ore (copper or iron) or for melting non-ferrous metals in crucibles and requiring a concentrated blast toward one point or limited zone. In fact, it is easier to imagine the precursor of the domed-furnace as being a pottery kiln, keeping heat dispersed over a relatively large volume. However, a different situation would have arisen with the more dense volumes of the charcoal and ore charges, when the effective penetration of both heat and reducing gases is imperative and this apparently posed a problem. Some finds indicated, that there was more than one focus of reduction within the dome, each lying adjacent to the mouth of an air-inlet. In their discussion of the furnace from Laxton, Jackson and Tylecote (1988) pointed to those from Klostermarienberg, Burgenland, and suggested the possibility of at least three radial air-ducts, a feature that has been observed several times, an arrangement which would have excluded the central volume of the hearth from the oxygen supply, leaving it as a dead zone. This would mean, that the domed-furnace would have acted as an installation which housed several smelting processes proceeding at the same time, so to say 'under one roof', a curious way in which to try to increase yields. Sperl (1995) counters with the suggestion that there must have been a particularly effective delivery of air which would have brought the whole charge in the furnace interior into the reaction *en masse* resulting in a considerable yield of iron.

In any case, the large domed-furnace is difficult to operate, as several experimental smelts have shown. The first attempt was made as early as the late 1950's, when Gilles (1958b) tested a reconstruction of the Engsbach example which he assumed to have been blown by induced draught. The dome was made 1.9m high, by 1m in diameter. The smelt consumed 152kg of limonite (54% of Fe_2O_3) and 209kg of charcoal, with the yield of metallic iron being 17.34kg (11.2% of the ore), not a particularly significant amount. The furnace operated well, but all of the metallurgical processes took place against the front wall where a single air-inlet had been placed and where a temperature of 1420° was attained. It was found that fanning in front of the tuyere could improve the blast at critical points of the process. The slag produced was liquid or pasty, but solidified rapidly. Gilles found it necessary to break down the front of the furnace and rake out the slag, along with the iron bloom (which had a carbon content of 0.09 average). It is evident that the introduction of the air-blast from several points (from three to eight as identified in various excavations) and the use of bellows, as in the cases of the Burgenland, Burgundy and Weald examples, make good technological sense in the case of such large furnaces.

Other recorded experiments with domed-furnaces do not appear to have been satisfactory to date, but the detailed results, especially in terms of yields have not been presented. The furnaces would seem to have operated well but yields seem to have been poor and in general, most of their volumes filled with ore and fuel charge remained unaffected. A replica of a Burgenland-type domed-furnace was erected at Ameliówka, Poland, in 1989. Over 30kg of haematite ore was smelted over 8 hours, using three bellows as with the find at Unterpullendorf (Pl. III: top), supplying the charge with 750 – 900 l/min. At the end of the smelt, three glowing focuses of semi-molten slag, apparently containing parts of iron sponges were found adhering to the mouths of the air-vents. Despite the fact that no yield calculation has been published (for the operating conditions, see Andrieux 1991) it was obvious that the interior of this large furnace did not act as a whole and that most of the ore remained unreduced.

In 1996, a robust domed-furnace, modelled in shape and dimensions on the Clérimois examples (especially F41), was tested at the Archéodrome at Beaune, Burgundy. The results and

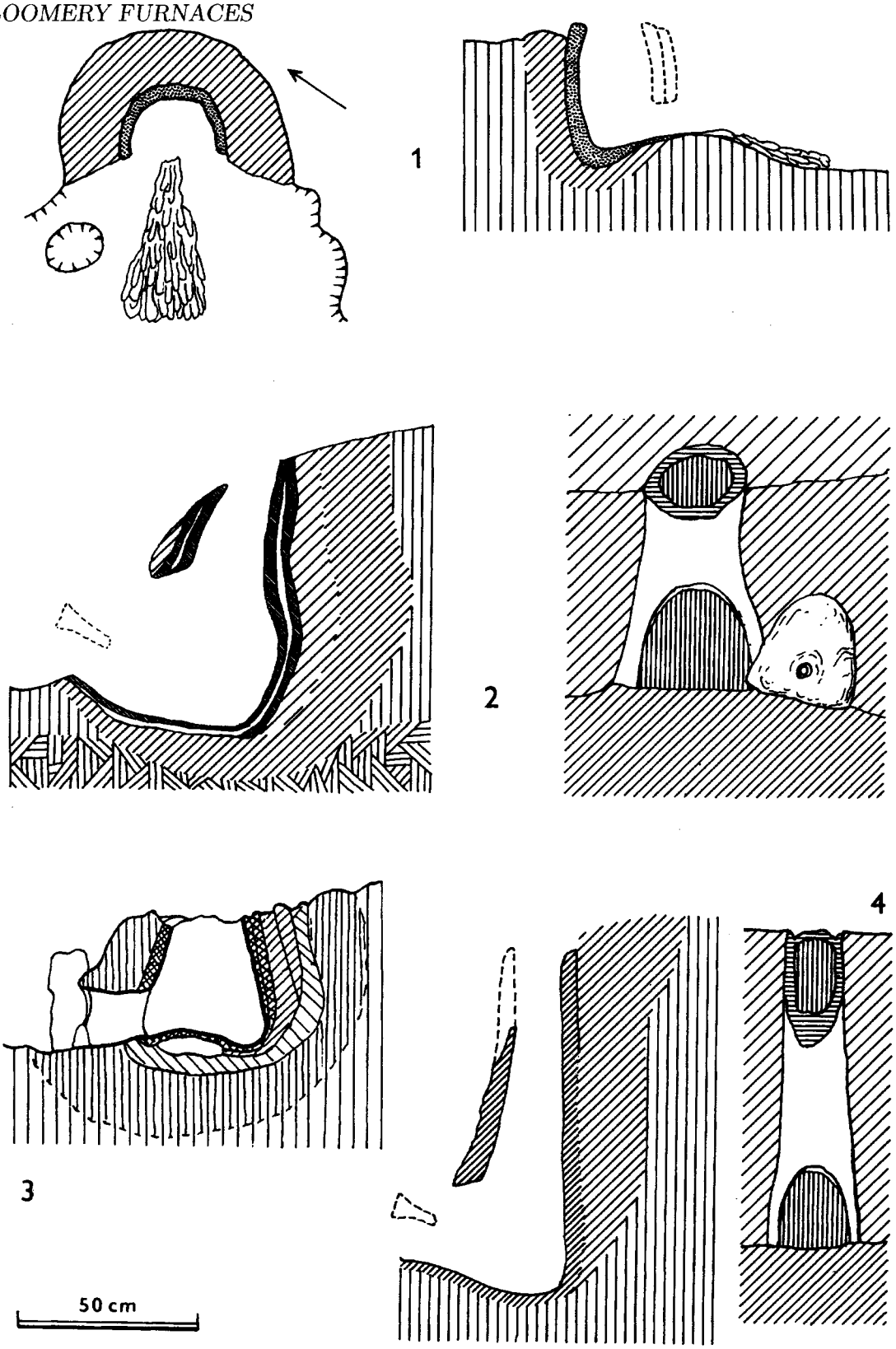


Fig. 44. Early mediaeval embanked shaft furnaces. 1 Tarjánpuszta-Vasasföld, Hungary, 7th century AD, with solidified slag flow, ironworks 1; 2 Olomučany, Moravia, furnace with thin front wall, 9th century AD — right: front view with suiting panel to the arch; 3 Grigorovka, Ukraine, furnace 18, 10th century AD, 4 Imola, N Hungary, 11th–12th centuries AD, right: front view. References: 1 Gömöri 1977/78; 2 Souchopová 1986; 3 Artamonov 1955b; 4 Nováki 1969.

their analysis are not yet published but it was a fact, that despite two large lateral vents and three rear tuyeres, all operated by bellows, the contents of the large rear section of the reduction chamber did not take part in the metallurgical process. It remained as a dead zone and again, it was only at the mouths of the air-ducts that there were adhering isolated balls of iron and slag.

It is evident, that the domed-furnace required a sufficient supply of air, which would reach and keep hot the entire interior, otherwise the reduction would take place in separated smaller areas, but the optimum arrangement has not yet been achieved by modern experimenters. Nevertheless, domed-furnaces must have been stable and effective devices which could withstand multiple refits over long periods. They apparently dominated iron smelting in some Celtic territories, but disappeared in the west during the Gallo-Roman period. It is possible that here they were gradually transformed into and replaced by larger types of shaft-furnaces.

Shaft furnaces

As already noted, the most favourable conditions for the reduction of iron ore exist when the ore can be exposed, when travelling down the high charge column, to hot reducing gases. Such conditions are provided by shaft-furnaces with a cylindrical or conical superstructure and this type represents the most technologically-advanced form of bloomery furnace, since it can be enlarged without loss of efficiency. The monstrous stacks of modern blast furnaces stand in direct line of descent from the early shaft-furnaces which stood only 60 – 80cm high and it was the shaft-furnace which made possible the transition from the direct to the indirect reduction process.

The slag-pit furnaces discussed above were, in principle, a type of shaft-furnace. The distinction between the two lies in the method of separating the iron from the slag. In the shaft-furnace proper, the slag did not settle down into an underground hearth, but was removed from the flat furnace-hearth at ground level, either by tapping in liquid form or by raking it out in pasty form, both operations being performed through an arch in the front wall of the furnace. Tapping was not easy to carry out, but when the technique had been mastered, it had a profound effect on the yield of iron.

The family of shaft-furnaces known from the archaeological record is large and includes types blown both by bellows and operated by induced draught. In terms of structure, several subtypes can be distinguished. First, there are small free-standing thin-walled furnaces which, when damaged, could quickly be replaced by new units. These were equally suitable for small-scale and 'industrial'-scale operations. Then come the thin-walled models, reinforced with frames or wooden stakes or with stones, some of them being wholly built of stone. This method of construction made it possible to increase the height of furnaces considerably, although original heights usually cannot be reliably established, since their walls rarely survive completely. Furthermore, some were free-standing, while others were supported by soil banks or the walls of workshops. Finally, there are thick-walled constructions, again, either free-standing or set into banks, which had the special advantage of good heat insulation, which is an important factor in producing higher yields of iron. Furnaces of this kind had longer lives and, after repairs or relining, could be used intensively over many seasons of ironmaking.

Thin-walled, free-standing shaft furnaces

These are typical for small-scale production as attested, for example, for certain periods of the central European Romano-Barbarian period, especially in its middle or later phases, when they occasionally replaced the slag-pit model. Bohemia has produced some well-preserved examples.

As early as 1908, the Romano-Barbarian settlement at Prague-Podbaba site VII yielded two

conical shaft-furnaces. They were built of clay with hearth diameters of 50cm, throat diameters of 30cm (originally at the top 20cm) and were preserved to heights of 90cm (original height estimated at 1.1m) as documented in a contemporary photograph. The wall thicknesses were 30cm at the base and 10cm at the throat (fig. 42: 2). Reference is made in the original report to there having been channels at the bases of the furnaces some 15cm in diameter, but there is no precise information about the likely method of slag removal. There were no tuyere *in situ*, but a number of fragments of block tuyeres were found in the vicinity. It is assumed that these furnaces worked on forced draught (Pleiner 1958, 156 – 158, fig. 38; references). At site VIII in Za dvorem street, another similar furnace which leaned against the wall of a working pit was reported in 1909, but its date remains uncertain (*op. cit.* 158 – 159, fig. 37).

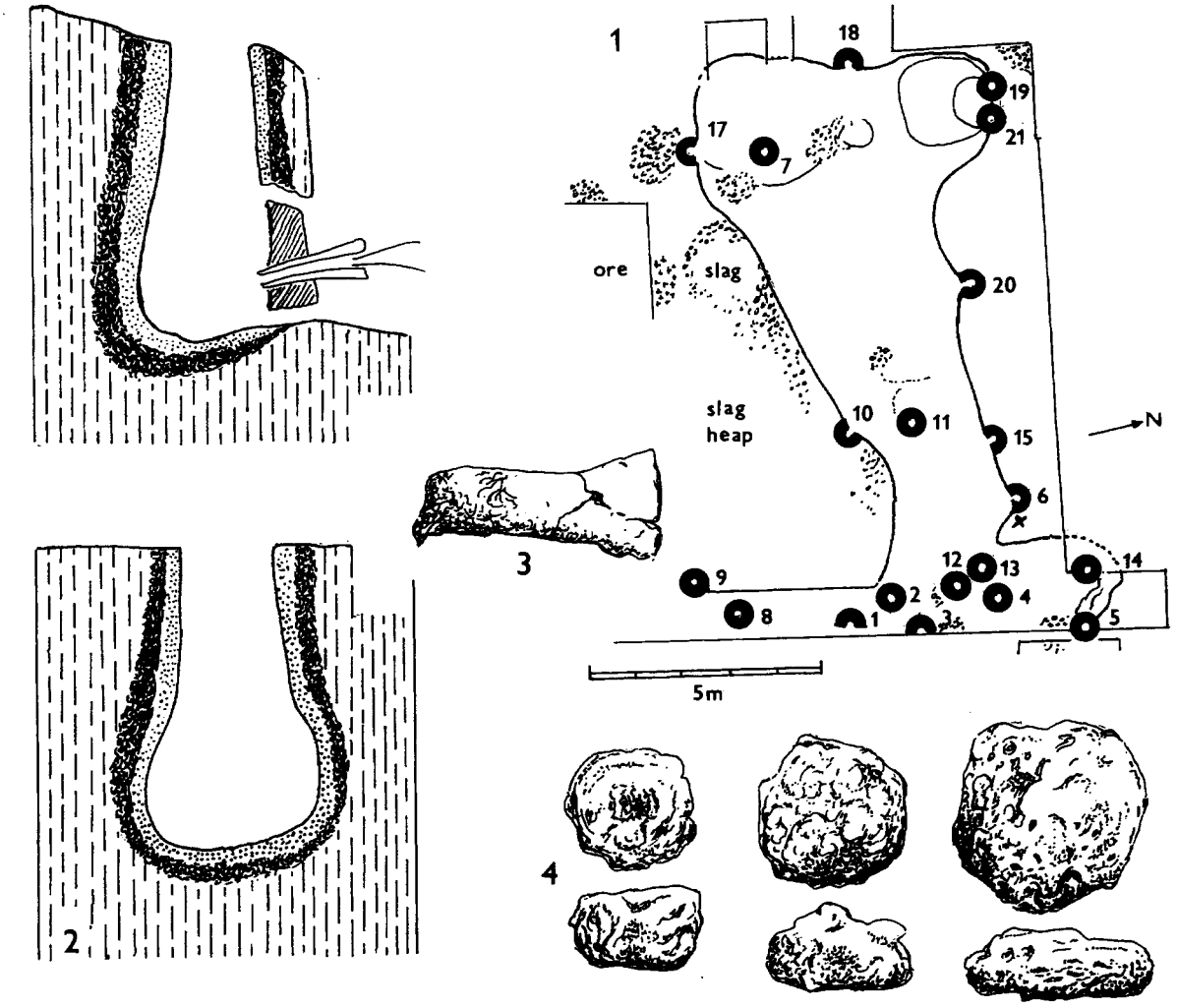


Fig. 45. Somogyfajsz, Hungary, embanked furnaces of the 10th century AD. 1 Schematical plan of the bloomery with 21 furnaces, slag debris and ore storage place, 2 Section of furnace 17; 3 One of hundreds clay tuyeres (length 20.7cm); 4 Iron blooms (1.72 – 2.7kg), one of them having been found at furnace 6. After Gömöri 1996.

In 1941, a well-preserved conical shaft-furnace of Romano-Barbarian date was recorded from Netřeba in eastern Bohemia. It was described as a clay cone 60cm high with a flat hearth of 25cm in diameter and with a throat of 20cm internal diameter. The walls were 10cm thick,

narrowing to some 8cm. The front wall was pierced by two openings, one (7 x 8cm) at the very base which was possibly used as a tapping hole, the other (5cm in diameter) being situated 17cm above and apparently serving as an air-inlet. According to the report, the furnace hearth still housed a furnace bottom which had not been removed. This has not survived so that no information of its composition is available and thus, the furnace and its contents have been interpreted as representing a smelt which had been aborted prematurely (Pleiner, *op. cit.* 166 – 169, fig. 42).

A completely preserved furnace of this type, dating from the late Romano-Barbarian period (3rd - 4th centuries AD) was found at Loděnice, south-west of Prague, in a notable iron-bearing region. It was 70cm high and built of clay using a coiling technique (Pl. XII). The internal cross-section at hearth level was 24 x 27cm. There was an opening at the base of the shaft which had been enlarged to facilitate removal of the raw bloom (Pleiner 1958, 172 -175, pl. XI). A group of six furnace bases of the same period came to light in 1954 at Tuchlovice, some 30km to the north (*op. cit.*, 176 – 188), which were reconstructed in the light of the find from Loděnice. Block- or brick-shaped tuyeres were also found. These furnaces from Bohemia show striking external similarities to the small, traditional shaft-furnaces of eastern India (Orissa) which produced two or three small blooms a day in operations lasting some 6h each (Percy 1864, 254 – 260).

A curious and unique find from 1913, the shaft-furnace from Einzingen, near Sangerhausen, in central Germany deserves our attention. This was found, totally destroyed, in a ploughed field, but 170 fragments were reconstructed, revealing a typical shaft-furnace which had no base. Weiershausen (1939, 134 – 138, figs. 33 – 34) suggested a flat hearth. The fragments show the prints of vertical wooden stakes, twelve in number, which supported a shaft which was 108cm high, oval in plan (24cm x 40cm at the base, 3lcm x 45cm at the throat level) with walls of 4–6cm in thickness. What is unusual is the air-duct system which comprised 6 apertures in the wall, at levels of 13, 32, and 73cm respectively from the base. The two lower ones were interpreted as temporary tapping holes used in different phases of the process because of their slagging, the others as air-inlets. Six red-burnt clay stoppers, suitable to plug the holes in order to regulate the process, including the inflow of natural draught, were found. But questions remain unanswered, with the technological problems revolving around the character of the original hearth, which was interpreted as being flat. However, a photograph (fig. 35) in Weiershausen's publication, upon which no comment is made, shows a heavy hourglass-shaped slag block said also to be from Einzingen, which would make the structure a slag-pit furnace of the Romano-Barbarian period. Although the dating of the feature is unknown, having been variously ascribed to periods from the Bronze Age up to the Middle Ages (as Weiershausen suggests), the dimensions and shape correspond with the thin-walled furnaces described above.

There is a lack of barbarian smelting furnaces in the western parts of *Germania Libera*, an exception being the clay shaft-furnace from a 2nd century AD settlement at Salzgitter-Lobmachtersen in western Germany, beside the region dominated by contemporary Germanic slag-pit furnaces (Fig. 42: 3). The shaft, which had a surviving height of 45cm, still stood to an overall height of 50cm above the flat hearth, with the thickness at the base of the wall being some 15cm. There was an air inlet/tap-hole 12cm in diameter at the front, connected to a shallow pit 1.1 m in diameter (Stelzer 1959). The absence of any tuyere finds suggests that this may have operated on induced draught, but for this to have been effective, the shaft would have needed to be at least 2m high. Particles of iron found embedded in the slag from the furnace were high (1.88%) in phosphorus (Osann 1959) and the metallography shows a P-eutectoid accompanied by ferrite and pearlite phases.

Apart from this central European area there are some interesting examples to the east, in the former territory of Scythia. One of the best preserved is the shaft-furnace from Novaya Pokrovka, in the Kharkov region of Ukraine (Braychevskaya 1956, figs 1 and 2). It had two air inlets, each 3.5 – 4.5cm in diameter, on opposite sides of the base of the shaft. When excavated,

this furnace stood 72cm high, but was probably somewhat higher originally. It was of oval plan (internal 44cm x 24cm, external 75 x 36cm) with the thickness of the walls, which were heavily fired and slagged internally and had at the base been lined with refractory clay, varying at the base between 10 and 30cm. The furnace was surrounded by a squarish sunken platform and was connected by a narrow channel 2.5m long by 50 -70vm wide to a circular fore-pit (Fig. 42: 1). It is believed that the furnace operated on forced draught supplied by bellows. The chronological position of this find has been discussed frequently by many Russian writers, but the few associated sherds of pottery indicate only a wide date-range from the Late Scythian period to around AD 500.

Of definitely later date is another furnace reported from a hillfort at Vovchansk, which belongs to the 8th – 10th centuries AD Saltovo culture (Shramko and Mikheyev 1969, figs 2 and 3). This installation was reconstructed, rather like a broken pot, from 104 clay fragments collected from an area of 2m x 4m. It was of bottle-like shape with a narrow throat, the diameter at the base measuring 70cm, the top level of the throat 45cm. Some 12cm above ground level were two, apparently opposing air-vents with internal diameters of 4.5cm. Some of the fragments show that just below the throat there were three or four small vents of diameter around 1.3 cm. The red-burnt walls which were heavily slagged at the lower levels, were very thin, being some 2.25 to 4.25cm in thickness. At the base there was presumably a tapping hole, the dimensions of which are difficult to reconstruct from the fragments but was perhaps in the region of 15cm x 20cm.

As we have seen, small thin-walled shaft-furnaces survived until the Middle Ages and it is not easy to distinguish them among the remains of the various types of hearth. Other from fragments secondarily composed clay shafts (50cm) are reported from the 9th century AD fortified Slavic site at Pobedim in western Slovakia (Vendtová 1969, 153, 179, fig. 42) and from the contemporary site of Olomučany in Moravia (Souchopová 1986, 26 – 28, pl. III). Among a range of better-preserved examples we should note the so-called Nemeskér type from western Hungary. Excavations at Sopron, Nemeskér, Iván and Tömörd brought to light a type of clay-built shaft which was slightly conical and *ca.* 80cm high, with an oval arch at the bottom which was closed by a clay panel with a perforation for the insertion an obliquely-positioned tuyere (Gömöri 1988, 108, figs 13 and 15; 1989a, 130). It is suggested that the evolution of this type resulted from influences both from Roman Pannonia and from early Avar metallurgy.

During the investigations in the Lahn-Dill area of western Germany, site B88 was excavated near Ewersbach. Surrounded by a crescent-shaped slag heap and an ore storage area was the lower part of a smelting furnace. The walls were badly destroyed so that the thickness could be only estimated approximately at 10 – 15 cm. The height must have exceeded some 70 cm and from the 45cm internal diameter of the hearth, it can be concluded that it must originally have been higher, since several air-inlets at the base indicate that it was operated by natural, induced draught. A stone-set slag channel with a solidified runner (130cm x 45cm, weight 24.5kg) shows that the slag was tapped. Nearby, iron tongs were found, left there by the smelters who operated the furnace sometime in the 13th – 14th centuries according to the associated pottery (Lammers 1995).

It would appear that all of the thin-walled furnaces were suitable either for small-scale smelting or for more intensive production, since they were simple to repair or replace when damaged, or easily constructed when smelters moved to newly-accessible ore sources or settled at a new workshop.

The furnaces from the hillfort of Velikiye Bolgary, near the confluence of the Volga and Kama rivers are peculiar devices (Efimova 1958). One of them, a brick-walled unlined shaft at least 1. 3m high, with an internal hearth diameter of 78cm (furnace 10 – 48, Fig. 42: 5, from Efimova 1958, 302 - 303, fig. 6: II) and dating to the period immediately before AD 1300, is of special interest. The bricks measured 25 x 12 x 4cm, and the walls of the shaft were perforated on all

sides and at three different levels by four air-inlets (18cm x 15cm and 20cm x 18cm respectively). No tuyeres were found on the site and the large dimensions of the air-inlets and their locations indicate that natural draught was used. No information is available about the method of slag removal (Fig. 42: 5). The 1947/53 excavations produced other furnace remains, dated by coins to the 14th century AD and, in addition to iron artefacts of various kinds, cast-iron cauldrons were also being produced on the site at this time.

Thin-walled, embanked shaft furnaces

Like the other types of bloomery furnace, shaft-furnaces with flat or shallow, dish-shaped hearths were also often built into banks or into the walls of workshops. In this case only the front walls were moulded out of clay, with an arch at the base to permit the manipulation of slag and iron. Such furnaces appear in the European archaeological record from the Iron Age and Roman period and some are discussed here by way of illustration.

The classic example comes from the 2nd century AD Romano-British at Ashwicken in Norfolk, England (Tylecote and Owles 1960; Tylecote 1962b). Six furnaces were excavated, built in an ore-pit that had been exhausted and which was subsequently filled, when the furnaces went out of use, with the slag and other smelting refuse from funaces nearby. They were not built into the sides of the pit but into a L-shaped bank of clay constructed in its centre (Fig. 17: 3; Fig. 43). The shafts were cut out of the clay block, their front walls being moulded in clay. The thickness of this wall was around 25cm so that in this case, the term 'thin-walled' is relative. In front of the flat hearths were arches 30cm high by 30cm wide, which spanned the full internal width. During the smelting process the arches were obviously blocked, with a tuyere inserted to provide the air supply. It is possible also that there was a tap hole, although alternatively, the blockage could simply have been removed to allow the molten slag to run out. Two narrow slag runners ran from the arches into two shallow circular depressions. Furnace 6 survived to a height of 1.22m above the hearth and it has been suggested that it originally stood around 15cm higher (Fig. 43: Tylecote and Owles 1960, 148 – 152, figs 2 and 5). The ratio of the hearth-diameter to the shaft-height would suggest that the chimney effect would have been strong enough for the furnace to have operated on induced draught. Smelting trials and detailed metallurgical analyses of the products have been carried out (Tylecote *et al.* 1971), the results of which have thrown much new light on the bloomery process.

This type of shaft-furnace seems to have been the standard iron-smelting device in Britain during the Roman period. A battery of six furnaces of the same type were found in the Weald at Holbeanwood (Cleere 1970; 1971b), and others are known from Pickworth on the Jurassic Ridge and from Cregeen in Yorkshire (Tylecote 1970, figs. 1 –3). It appears to have abruptly replaced the domed-furnaces within a decade after the Roman occupation of Britain in the mid-1st century AD. While the Pickworth furnaces were comparable in height with those at Ashwicken and may well have operated on induced draught, the Holbeanwood examples were probably lower and operated by forced draught, an interpretation reinforced by finds of double tuyeres on an associated site (Cleere 1963a; 1970b). Tylecote is inclined to reckon all of these furnaces among one and the same family; moreover, he takes into account the possibility that the feature bases, uncovered in the lat 1920's at Wilderspool and interpreted as roasters (see Chapter VI) may be counterparts for Ashwicken furnaces (Tylecote 1962a, 24).

With regard to the Germanic hinterland on the Continent, it seems that similar installations arrived at the same time as the free-standing shaft furnace. The case of Prague-Podbaba VIII has been already mentioned, and there are some other examples from eastern Bohemia, as at Církivce and Netřeba. These seem to be of a later Roman date, possibly replacing the older, traditional slag-pit furnaces. Contrary to this scenario, curiously enough, two forms of semi-embanked bloomery furnaces recorded from Denmark, preceded the era of the slag-pit furnace

in that region. Both types were set into soil banks at the rear. The form from Espe, Sealand, which is the smaller of the two (22 – 30cm internal diameter) is represented by two finds, dated by radiocarbon to the 1st century BC to the 1st century AD. The furnace arch was covered by clay panels (as with the mediaeval Nemeskér funaces in Hungary), provided with holes for the tuyere. These plates, which measured some 29cm by 24cm, were slagged on the insides. The form from Skovmark (Fig. 42: 4), of which there are three examples, has an internal diameter of around 40cm. The chronology, as given by Voss (1989) and based on radiocarbon dates is the 1st - 2nd centuries AD.

The other types of thin-walled furnace date to the early Middle Ages. Some problems of interpretation are posed furnaces excavated on an island in the river Bug near Gayvoron in the Ukraine and interpreted as belonging to this group (Bidzilya 1963). The site, which dates to the 6th – 7th centuries AD and provides evidence of early Slavic iron production, produced 21 smelting furnaces and four supposed ore-roasting hearths. Sections through the furnaces imply that they were free-standing shafts with very thin walls and, at the mid-shaft level, air-inlet holes the axes of the which were inclined downwards, towards the hearth. In fact, the high positioning of the holes and their oblique orientation suggests an alternative interpretation, namely, that the furnaces were originally set into alluvial sand banks (see below). Slag fragments were found in shallow depressions around the site.

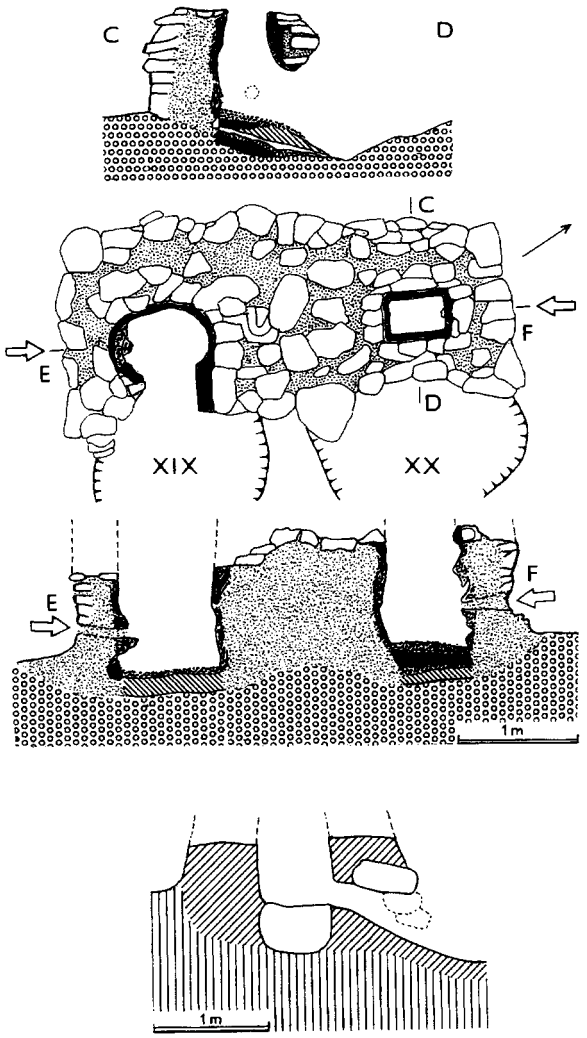


Fig. 46. Thick-walled shaft furnaces. 1 Bellaires III, Switzerland, twin of furnaces XIX and XX in a stone set block and lateral air-ducts (another bellows had been operated throught the arch), 6th century AD: 1a section C-D of furnace XX, 1b section E-F of furnaces XIX an XX; 2 Asote, Latvia, thick-walled furnace with a stone bottom, 8th century AD. References: 1 Pelet 1973; 2 Pleiner 1965a after Shnore.

Other installations have been linked to ethnic movements in central Europe. The remains of furnaces with small, shallow forepits and partially embanked shafts lined with layers of refractory clay 10cm thick were found were discovered at Tarjánpuszta-Vasasföld in Hungary (Gömöri 1977, 88 – 89, figs 8 and 9; 1977/78, 116 – 121, fig. 11). These are dated to the 7th – 9th centuries AD and are taken as providing evidence of Avar ironmaking activities in the Carpathian basin. Although the front walls have unfortunately collapsed, the internal shaft diameters could be determined as *ca.* 30cm, with the shafts only surviving to a height of some 35cm (Fig. 44: 1).

All of the furnaces appear to have been operated using forced draught, as indicated by finds of tubular tuyeres. Solidified slag flows in front of the furnace apertures show that slag was tapped molten into the forepit, which, as with so many furnaces of this type, served as a tapping bay.

As we have seen, the region in which these furnaces appeared was scene of various ethnic interactions, especially between early Slavs and Avars or early Magyars. The thin-walled embanked furnace was common in this area and it is difficult to determine the possible ethnic background of its creators. The chronological position of individual examples may be taken into consideration, but no firm conclusions can be drawn.

Very well preserved embanked installations, denoted specifically as 'furnaces with thin front walls' were investigated at Olomučany in western Moravia, in the Blansko region, once very important for its ore deposits. These are well-dated by the pottery to the Great Moravian period (9th century AD). The Olomučany furnaces were set into a soil slope on the bank of a small stream and are characterized by their shallow dished hearths and very thin clay front walls with oval or domed arches at the base. The arches were closed during smelting with special removable clay panels, quite similar to those from Nemeskér. They were pierced by air-inlet and tapping holes, 4 – 5 cm in diameter. The shafts were lined with a sandy refractory clay that had been baked red and slagged in the lower sections. The hearth diameter was 43cm, with the shaft narrowing to 18cm, while the arch height was 28cm. Some shaft front walls survived to a height of 43cm (Fig. 44: 2, Pl. XVII), with the remainder having been lost, apparently due to the surface erosion which removed the upper layers of the slope.

It is estimated that the original height of the bank step and thus of the furnace shaft was at least 80 - 100cm. The wind coming up the slope would have been useful in the preheating phase but there can be little doubt that the smelting temperature had to be attained using forced draught. This interpretation is borne out by the hundreds of tubular clay tuyeres (Fig 54: 6) found on the site, which are evidence not only of the use of bellows but also of the repeated re-use of the furnaces which were easy to be repaired or rebuild. Slag was tapped molten from the furnaces as shown by the fact that the slag debris on the slope below the working area includes solidified slag runners (Fig. 71: 1, see Souchopová 1986, 24, Fig. 11; 1995).

The furnaces of the Bükk Mountains region, near Miskolc in northern Hungary, at sites such as Imola, Trisz and Borsód are identical in form and construction and the term 'Imola type' is now used to describe them. Furnace 1 from Imola stood to a height of 80cm, being embanked into the wall of a working pit on a plateau shaped terrace. The internal diameter at hearth level was 25cm and at throat level 18.5cm — these were indeed very tall and slim devices. The domed front arch, 22cm high, was similar in shape to the Olomučany examples (Fig. 44: 4). The base of the hearth was flat, and it would appear that the slag was removed through the arch in front wall. Tubular clay tuyeres were found among the furnace debris on the site. Despite the fact that the furnaces so strikingly resemble those at Olomučany, the sites at Imola and other localities in the region are of a somewhat later date, the 10th - 11th centuries AD (Heckenast et. al. 1968, 24 – 28, fig 4: 1; Nováki 1969, 305 – 314, figs. 6, 9, 12). Identical furnaces have been discovered and excavated at two compelete ironworks in the same region, but on the Slovakian side of the border, at Gemerský Sad (Füryová et al 1990). The first shows that the furnaces were situated in the workshop wall in pairs, whilst workshop two was enlarged and some of the older furnace hearths were left in the floor of the working plateau, as mentioned above in chapter IV (Fig. 20: 2). Similar furnaces have also been found in the Burgenland of eastern Austria, as at the site of Unterpullendorf-Sportplatz (Bielenin 1977a, 57 – 59, fig. 5). Recently, a reconstruction of an almost identical type of furnace appeared (Doboşeni in Romania), eqipped with a typical tuyere panel. However, it is said to be Dacian (Ferenczi 1999, 111, 129, fig. 3: 1a-c).

Thin-walled shaft furnaces show a continuity of occurrence in areas inhabited by Hungarian and Slav populations in the early Middle Ages. Inset shaft-furnaces of a more robust type are known from Vasvár, in western Hungary, on which the eponymous 'Vasvár type' was first

identified and where several pairs of furnaces dating from the 11th – 12th centuries AD were found (Nováki 1966, 181 – 189, figs 15 – 22). The pair designated as furnaces 1 and 2 were set side by side into a block of soil. The heavily fired walls show no evidence of of the use of a refractory clay lining. The arches of the two furnaces were directed towards separate tapping bays or forepits. There were depressions to receive bellows on the outer sides of the pair of furnaces, and air-inlet holes (3.5cm in diameter) were directed towards the centres of the shafts about 30cm above hearth level, at right-angles to the axis of the furnace arches. The shafts narrowed considerably towards the top, creating in effect a form of dome or cupola, but these should not be confused with the high-volume Celtic domed-furnaces described in an earlier section. The diameters of the hearths of the two furnaces were 44.5 and 47cm, and they stood to heights of 40 and 58cm respectively. There can be no doubt that these were forced-draught furnaces, or that the local ironmakers were capable of tapping the slag in the molten state. Wide solidified slag runners were found in the forepits of similar furnaces found at Köszegfálva (Fig. 72: left), in the same region (Nováki 1966, 169 – 179, figs 5 – 13; Gömöri 1989a, 129, fig. 2). On this site, the furnaces were also arranged in pairs, but the air supply was through the furnace arch, which was stopped up with a special clay panel to take the tuyere.

Another family of embanked furnaces of early mediaval date has also been excavated in western and south-western Hungary (Gömöri 1988; 1996). On the basis of preliminary reports, it would appear that the embanked shafts were not completed by clay front walls, but were entirely dug out of the soil bank (Pl. XVIII). The front wall appears to have been relatively thin (30 – 35 cm) so that it is not easy to distinguish these furnaces from the so-called 'underground' furnaces discussed below. On the basis of published illustrations, the front walls of the smelting units at Somogyfajsz were apparently constructed out of the loess soil (Gömöri 1996, 277, fig.8), as were those from Szákony. The Somogyfajsz furnaces, 21 in number, were situated in the walls of a large, irregular pit and were very small, a mere 55 – 60cm high. Moreover, their arches are oval and are suggested to have housed a plate with a tuyere inlet as in the types previously described (Fig. 45). At Szákony, the shafts also survived to heights of about 70cm (Pl. XVIII) In terms of the terrains of the sites, the preserved heights of the shafts seem to represent the minimum possible, as seems to have been the case with the furnaces from Prague-Kotlářka which surrounded a circular working pit (Pleiner 1958, 203 – 205, fig. 53).

Thick-walled shaft furnaces

The present state of our knowledge leads to the conclusion that, despite some isolated outliers, this type of furnace is to be found primarily in regions of intensive iron production, since their construction and repair required considerable levels of skill and labour resources. The thick-walled shaft-furnace was a strong structure which could be raised to a considerable height and had much more effective thermal insulation, leading to a greater yield of metal. The shafts were often built entirely of stone, or of clay with substantial stone reinforcement. In addition, they were lined with several layers of refractory clay which, when damaged or heavily slagged, could easily be torn out and replaced. Furnaces of this type were usually blown with bellows and had provision for the tapping of molten slag. They are found in ironmaking centres of the Roman period and in early and high mediaeval contexts. So far as central Europe is concerned, they may reasonably be considered to be the immediate precursors of what used to be called *Stuckofen* in Austria; and of first furnaces of the indirect smelting of iron, the early blast furnaces of the *Flossofen* or *Massenofen* types.

An example of very early Gallo-Roman thick-walled shaft-furnaces were uncovered in one of the leading iron producing regions in the Montagne Noire in southern France, at Martys (Aude). To date, six furnaces have been recorded there in two groups of two (F1 and F2) and three (F10, F11, F12) respectively, with a singleton (F20 with a hearth F20a) units (Domergue *et. al.*

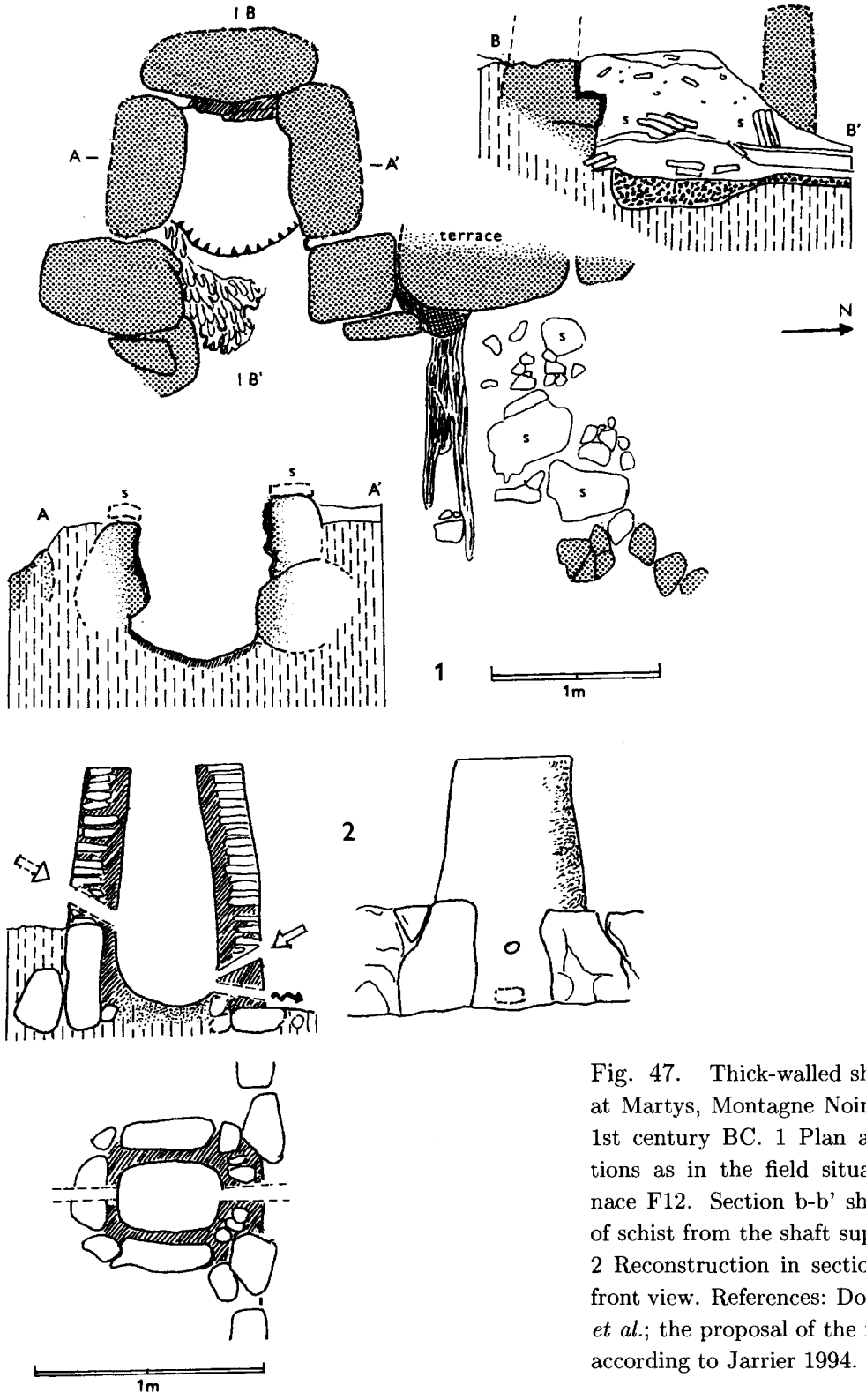


Fig. 47. Thick-walled shaft furnaces at Martys, Montagne Noire, S France, 1st century BC. 1 Plan and two sections as in the field situation of furnace F12. Section b-b' shows bundles of schist from the shaft superstructure; 2 Reconstruction in section, plan and front view. References: Domergue 1993 *et al.*; the proposal of the rear air-duct according to Jarrier 1994.

1993). The arches of the furnaces were all oriented to the east and these structures represent the classical 'floruit' of the site. The superstructures were destroyed but enough details have survived to enable their tentative reconstruction. The base of the typical furnace of the Martys type was built as a horseshoe-shape from large granite blocks (about 1m high and 25cm thick), set into an artificial stone-lined terrace, with a gap left on the eastern side. The shaft was reinforced by flat plates of granite or schist, with the interior being lined with a layer of refractory clay 20cm thick. Some excavated fragments revealed traces of air-inlets and it was originally assumed that there was just one air-inlet in the front arch, an interpretation which is retained in the reconstructions so far published. According to the latest observations (Domergue 1998) however, another inlet existed at the rear and others on both sides, all inset obliquely. This was evident in the case of furnaces labelled as F 101 and 102 (Domergue *et al.* 1999). The shafts with their internal diameters of some 45cm must originally have been some 2m high and their total thicknesses would have been at least 40cm (Fig. 47; Plate I: bottom). A second phase in the use of furnace F2 is visible in its section. Numerous layers of debris gradually filled the hearth, so that it had to be rebuilt at a level some 50cm higher.

All of the features on the site are dated by the numerous pottery fragments recovered, many of Italic origin, to the last decades of the 1st century BC. However, they overlie a layer of slag debris which provides evidence of an earlier phase of metallurgical activity, confirmed by recent excavations which have revealed another group of bloomery furnaces in the northern part of the site. These new furnaces, which are dated to the 1st century BC, have a different orientation, with their arches facing south. Two are of the 'classical' design described above, but one was substantially smaller, with a 30cm diameter hearth. The slag was tapped from this furnace which was operated by a single bellows from the rear (Domergue 1998).

The large furnaces of the Martys model have been tested experimentally in three campaigns (Andrieux *et al.* 1994). Smelt 2, which attained a temperature of 1250 to 1300°C with a supply of 300 litres of air per minute, consumed 112kg of iron ore with an ore-fuel ratio of 1:1 and yielded a bloom of highly carburized steel (0.8 – 1% C) 18kg in weight. This is a good result in view of the fact that the ancient smelters would have been more accomplished. The Martys furnace type was operated, again, in 1999; seven smelts were performed at Lastours in southern France: according to a preliminary note, the last of them was successful, giving, after tapping the slag, a 37kg bloom of unworked iron from 120kg ore (Fabre in Archeol. rozhledy, in press).

Supposedly thick-walled furnaces of Roman date are usually described as having been found at Hüttenberg-Feisterwiese and Lölling in Carinthia, Austria (Schmid 1932, 186 – 188, fig.13). The reconstruction of these furnaces, which has become established in the literature, is based on very scant evidence surviving only at ground level. Furthermore, re-assessment of the pottery from Feisterwiese has shown that the remains date from the 13th – 14th centuries AD (Eibner 1981).

Excavations by Tylecote (1982) identified thick-walled furnaces in Africa, among the slag heaps at Meroë in the Sudan. They were as well-developed as their European counterparts. The stone-built and lined shafts were situated in special workshops or shelters. Estimated to have stood originally some 1.8m high, they were 60cm in diameter, with walls 20 – 30cm thick, and survived to *ca.* 1.2m high. A few centimeters above the hemispherical hearth bottoms, which were filled with charcoal, were slag tapholes which could be enlarged when smelting was concluded, by the removal of some brick blocks to permit the bloom or iron sponge to be withdrawn. Separate niches in the rear wall contained between three and five drum bellows with tuyeres were located ca 30 – 40cm above the taphole and pointed slightly downwards to the hearth. The Meroë furnaces were discovered superimposed one upon the other, demonstrating that production took place at the site over a long period. Dating is difficult, but it is certain that iron production took place somewhen during the first four centuries AD (Tylecote 1977; 1982). Voss (1988) is prepared to see in these Meroitic furnaces the usual model of Roman iron

metallurgy. For Roman Britain, a stone-paved base of what used to be called smelting furnace of Tiddington, 3rd – 4th centuries AD, with atypically elongated hearth (Schubert 1957, 47 – 48, fig. 7), was, together with an adjoint box-like feature, explained by Tylecote as smithing device (1962a, see Chapter XI).

Genuine late-Roman or even post-Roman stone-built furnaces can however, be illustrated by those excavated by Pelet (1973) in the Swiss canton of Vaud, where 23 furnaces, in three chronological phases from the Late La Tène to the 6th century AD, were discovered. It is worth looking here at the rather curious example from Bellaires III, a pair of furnaces (XIX and XX, dating from the latest phase, around AD 500), built as a single unit in a stone-set block (Pl. XIII: bottom) with the shafts lined with refractory clay (Pelet 1973, 98 – 104, 205 – 206, figs 4, 15: D, E, 50, and 51). The blast was supplied from bellows on either side (Fig. 46: 1) and the arrangement is reminiscent of the later furnace pairs described above in chapter IV. What is striking about the Bellaires pair is that one shaft was oval in section (80x50cm) while the other was rectangular (70cm x 50cm). The whole structure survived to a height of 1m, but it may well have been at least 30cm higher, if not more. The front wall of furnace XX was still in place and contained a furnace arch measuring 60cm x 60 cm. The flat hearth was connected with a shallow forepit and the bellows were operated from both sides through clay tuyeres with 4cm diameter apertures. There were also, somewhat surprisingly, auxiliary tuyeres in the furnace arches. The site of Bellaires I also produced two pairs of furnaces (I – II, III – IV), which are dated radiocarbon to around AD 500. One pair is preserved as a technical monument protected by a pavillon at the Bellaires site.

A parallel to the Bellaires furnaces XIX and XX is provided by a pair of stone-walled furnaces, destroyed some centimeters above the hearth bottoms (Fig. 20: top, Pl. XIII: top) from Boécourt, at the

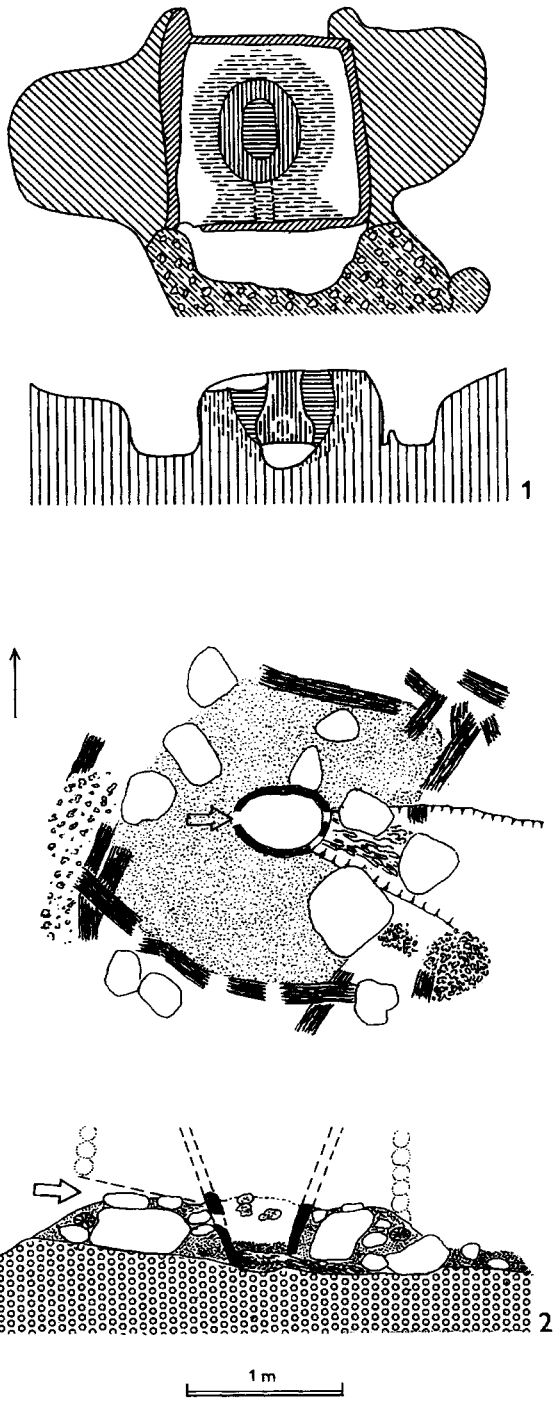


Fig. 48. Timber-clad shaft furnaces. 1 Opole-Pólwieś, Poland, timber-framed furnace in a clay block, 4th – 5th centuries AD (?) or later; 2 Dysdalen, Dalarna of Sweden, timber-framed stone setting with the furnace chamber in the centre, air-inlet and two tap holes, 14th century AD. References: 1 Pleiner 1965b after Fock; 2 Serning 1973.

site of Les Boulies, in the east Jura (Eschenlohr and Serneels 1991). The remains provide many details that are a good guide for a reliable reconstruction. The walls, supported by stones, were lined with re-used Roman tiles arranged radially and covered internally by a refractory layer. The air supply was provided by bellows, through two clay tuyeres, one (internal diameter 2cm) sited laterally roughly at the destruction level, and found *in situ* in furnace 1, and a second, set obliquely into the furnace arch and supported by a clay block constructed from fragments. The internal diameter of both furnaces was about 70cm, and while the original height of shafts is unknown, it is estimated as having been more than 100cm from the hearth bottom. The rear of each furnace was dug a little way into the virgin soil and the front arches were connected with working hollows which served as pools for slag-tapping, a procedure indicated by numerous solidified flows. Furnace 1 (NW) was apparently erected first, after which furnace 2 was built as an attachment to it. Around the stone structures, some 70 slag cakes of PCB type, waste from the reheating process, were found. For a certain time both furnaces operated simultaneously, then furnace 1 was abandoned and furnace 2 continued its function. The authors estimate that each furnace would have been used for around 70 smelts (*cf.* Souchopová 1986, 71), producing some 35kg of slag and more than 7kg of iron per smelt, giving a total production of 5 tons of slag and more than 1 tonne of iron over the working life of the site — a small- or medium-size operation (Eschenlohr and Serneels, *op. cit.* 104–106). The chronology of the Boécourt furnaces has been established by radiocarbon dating as *ca.* AD 550 – 650 (Merovingian period), making them a little later than their counterparts, furnaces XIX – XX at Bellaires. Other furnaces found in north-eastern France (Frouard), near the border with Switzerland raise, in the words of Serneels and Laurent, the possibility of the existence of a distinctive 'Franco-Swiss type' which was characteristic for the late Roman and Merovingian Periods.

Some details observed at Bellaires and Boécourt invite comparisons with another site which has produced a type of furnace worthy of attention. It was discovered within the area of ferrier 3b at Clérimois, Yonne, whose large, domed-furnaces have been discussed above. The new furnaces, designated F50, F60, and F21 are later in date (Dunikowski and Cabboi 1995, 70 – 80, 95 – 100, 103, 106) and the similarities with those from Bellaires and Boécourt include the use of two types of clay tuyeres and their positioning at two different levels of the furnace and, above all, the use of Roman tiles (*imbrices, tegulae*) in the building of the 25cm thick shafts. What is different is the conspicuosly oval plan of the shafts whose original heights are unknown (internal dimensions *ca.* 50cm x 100cm, preserved heights *ca.* 50cm) and the non-existence of pairs. The dating, which is not greatly assisted by the presence of some sherds which could be late Roman Mediaeval, is based on radiocarbon measurements and gives AD 110 – 350 (for F50) and AD 330 – 450 (for F60 and F21). These furnaces may be evidence of a rather small-scale operation on an ancient iron smelting site towards the end of the Roman period.

In 1984, Leroy (1988; 1997) excavated five smelting furnaces at Ludres, in Lorraine. The three smaller units are robust shafts (internal dia. 50 – 70cm, external dia. about 150cm) with stone-supported walls more than 60cm thick. The reconstructed heights of the furnaces might have reached well over 150cm (Fig. 49: 1). A lateral clay tuyere was inserted into the front wall, which was thinner (20 cm), with an inclination of 10 – 15°, pointing down into the hearth. The larger units (labelled 4 and 5) had internal dimensions of some 50 x 60cm, giving a somewhat rectangular section, and the walls, also reinforced by stones, were thicker, being up to 1m in some places. Although the slag outlets were not clearly identified, the form of some of the slag samples indicates tapping. This ironworks apparently smelted limonite from minette-type deposits and isolated fragments of iron, including a piece that could almost be described as pig iron with 2.42% C , indicate the production of a highly-carburized hypereutectoid metal (Forrières *et al.* 1989b, 258). The furnaces, which belong to the 8th–11th centuries AD, have been compared with examples discovered elsewhere in the Jura Vaudois, such as at Bellaires, even though they are somewhat later in date.

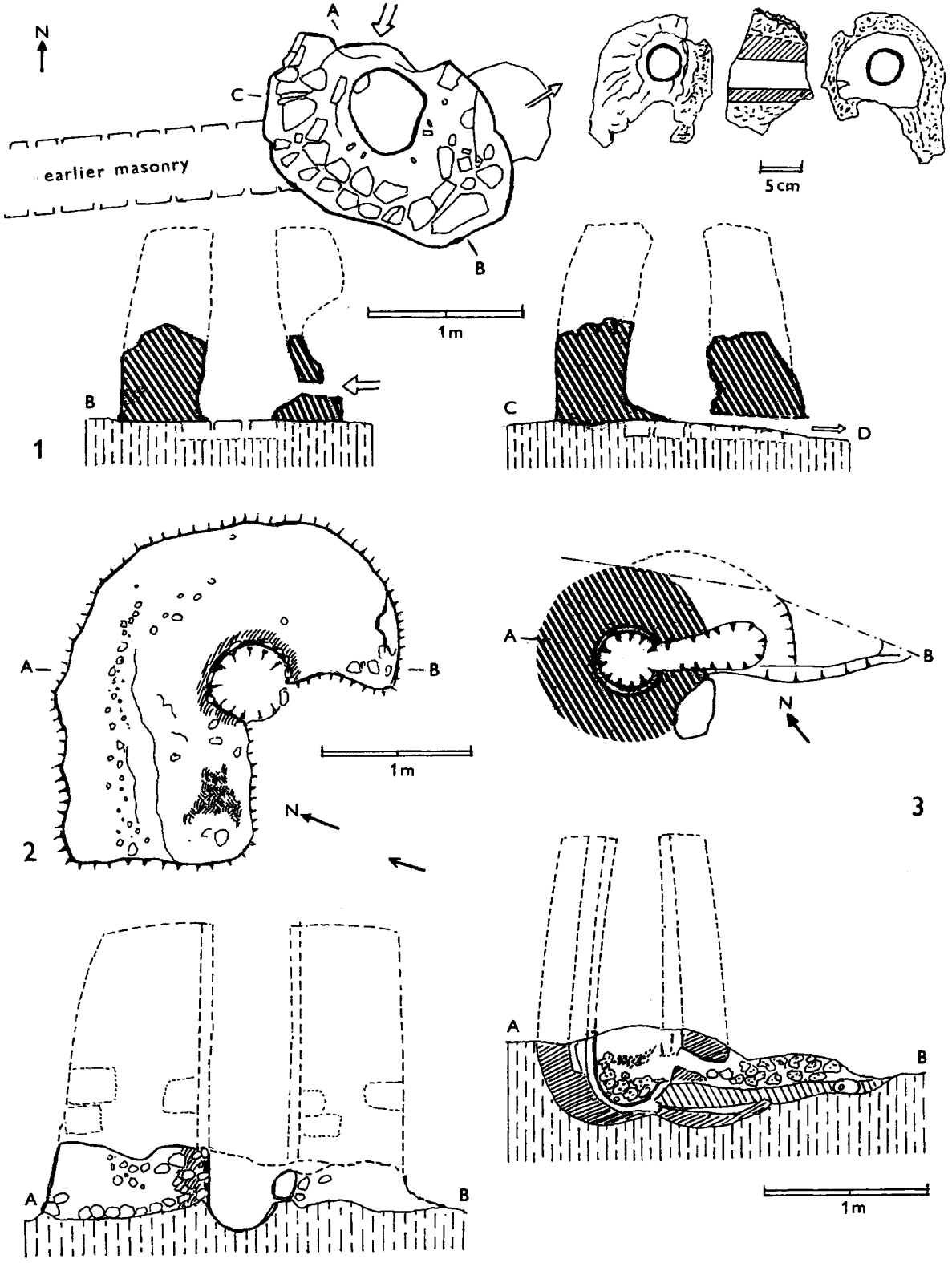


Fig. 49. Mediaeval thick-walled low shaft furnaces. 1 Ludres, furnace 3, 8th–10th ceturies AD; 2 Radětice, Bohemia, furnace feature XIX, 13th century AD; 3 Chýnice near Prague, Bohemia, 13th century AD. References: 1 Leroy 1997; 2 Pleiner 1971; 3 Krajíc and Matoušek 1985.

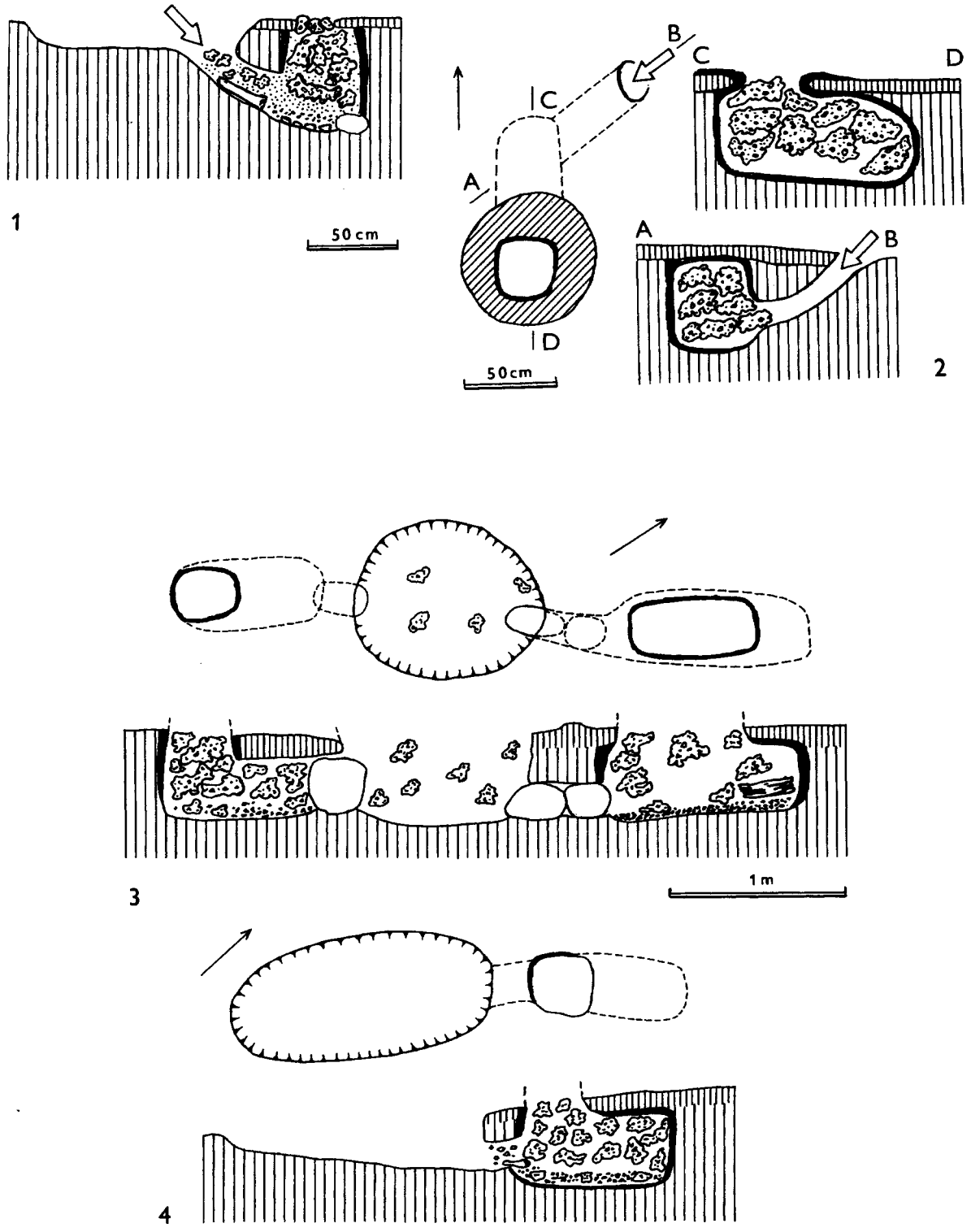


Fig. 50. Underground bloomery furnaces of the Tashtyk period (1st century BC to 4th century AD) in the Minusinsk region of southern Siberia. 1 Akh-Tashtar, furnace 11 with unused tuyeres in the air-duct; 2 Polovinka, furnace 6 with assymetric arrangement of the air-duct and reduction chamber — around the throat is a wide clay-lined collar; 3 Külbüstig, twin of furnace 4 and 6 with arches blocked with stones; 4 Efimenkino, furnace 7. After Sunchugashev 1979.

Many mediaeval thick-walled furnaces located within workshop complexes were excavated and meticuously documented by Sönnecken (1971) in the Sauerland region of western Germany. The best representative is the furnace found at Sonnenscheid, near Lüdenscheid, at a place called 'In den fuhlen Kümpen' and dated to the 11th – 13th centuries AD (Sönnecken 1971, 20 – 23, fig. 3; 196, figs. 25, 26). The shaft had an internal diameter of 45cm and was encased by walls 40 – 45cm thick with an internal lining of refractory clay. It survived to a height of 60cm and the original height is estimated to have been as much as 1.5m. A tapping channel, still containing its solidified slag runner, was sited a few centimeters above the bowl-shaped hearth, connecting it with the forepit. A tuyere was inserted into the shaft at right-angles to the axis of the slag-tapping channel, showing that the furnace was blown with bellows located in a shallow depression

The Sonnenscheid furnace can be taken as the standard model for the average mediaeval European bloomery furnace in the West. Thus, the example from High Bishopley in northern England (Tylecote 1959) is based on the same construction principles and had a slightly conical clay shaft surviving to a height of 63cm, with an internal diameter 50cm and wall thickness of 38cm, red-baked to a distance of 10cm out from the interior. There was a tapping channel on the western side, still blocked by a solidified slag runner, and a tuyere, through which bellows supplied the air-blast, was located at an angle of 90° to the slag channel.

Of the three furnace-bases found between 1889 and 1892 at Erzberg-Feisterwiese in the ancient Noricum (Carinthian) area of modern Austria, furnace 2 is frequently quoted in archaeometallurgical literature. On the basis of some pottery sherds found amongst the slag, Schmid believed (1932, 46 – 48) the bloomery to be of Roman date. Later Eibner (1981), after a review of the finds, suggested that the furnaces were mediaeval, from the 13th – 14th centuries AD. The furnace remains, standing to a height of about 40cm high when found, indicate a robust thick-walled (ca 110cm), stone-set shaft with an internal diameter also of 110cm. Six air-inlets, arranged radially, were observed at the bases, as well as numerous nozzles of clay tuyeres with internal widths of 3.5 to 4.5cm. On the eastern elevations there were arches housing tapping channels (Schmid 1932, 36 – 48, figs. 25 – 35). These features all led Schmid to the conclusion that the furnaces were operated by induced draught. However, the suggested original heights of 2m, set beside the massive internal dimensions, seem to be hardly sufficient to produce sufficient induced draught to produce the heat necessary for the smelting of such a huge stack of ore and fuel.

In the North, the later furnace time horizon (11th – 13th centuries AD) furnaces in Møsstrond, Telemark of Norway, are worth of mention. The term 'thick-walled' has to be understood in the sense that a realtively low clay shaft was backed in three sides by large blocks of unworked stone or stone plates, or, vice versa, this rough stone support or shell was lined with refractory material, so that a furnace of 1m overall diameter and 35 – 50cm internal dia. was erected presumably to a height of less than 1m. The slag was tapped. Although no air-inlets could be observed in the preserved level, some finds of clay tuere block indicate the use of bellows. Among 17 furnaces of this type having been excavated the best preserved remains are represented by finds at Velurhagen (Pl. XX: bottom), Erlangsgaarden 2 and 3, Hovden 5, Homvassbekken, Nystaul 4 and 5, Martinvika etc. (Martens 1988, 26 – 74, 75 – 77). These shaft furnaces operated within wooden houses or shelters. The mediaeval furnaces from the valley of Dokkfløy, as to published plans of DR 1 and DR 63, were practically of the same design (Narmo 1996, 69 – 79, figs 20 – 22).

At Llwyn Du in Coed y Brennin, North Wales, there were recently excavated furnaces, one of which measured 2m x 1.5m overall, with external stone casing and clay lining (internal diameter 40cm), heavily vitrified. At Gelli Goch the survived D-shaped furnace base which revealed stoke-holes at the outer circumference and in the rear: the latter may possibly indicate the bellows arangement. Documentary sources concerning these two sites seem to date this ironmaking to

the 14th century AD (P. and S. Crew 1998). Excavations will continue, so that only preliminary data are available.

It is helpful at this point to make reference to the site of Dysdalen, far to the north in Dalarna in Sweden (Serning 1973, 102 – 109: Fig. 48: 2), because it introduces a new structural element, namely a timber-clad shaft. During excavations in 1963, a squarish stone setting came to light, framed with wooden timbering, the residues of which were found *in situ*. At the centre was a smelting hearth lined with burnt-red clay. It measured 65cm x 45cm and was preserved to a height of 50cm, with the original height estimated to have been at least 1m. In the western elevation, an air-inlet 5cm in diameter was situated 25cm above the hearth bottom and there were two slag-tapping holes at the foot of the opposite side with tapped slag being found in a shallow channel running to the east. The radiocarbon dates span the period 1245 – 1460 AD, possibly centring on the 14th century. The furnace seems to belong among the predecessors of installations which survived in Scandinavia until the 18th century and were described by Schultze, Swedenborg and Evenstad.

Let us turn now to the lands of central and eastern Europe, where robust, thick-walled shaft-furnaces also appeared and apparently became very common over the course of time. Bearing in mind the Dalarna example, another thick-walled furnace is worth studying, namely that from Opole-Pólwieś (formerly published under its German name Oppeln-Halbendorf by Fock 1941; see Rauhut 1957, 240 – 241, fig. 35) which was encased in a framework of wooden logs. It consisted of a block of natural clay 1.4m in the centre of which, a shaft measuring 20cm x 30cm was apparently excavated. The shaft widened out at the base and the hearth bottom consisted of a large flat stone (Fig 48: 1). It is assumed that the blast was supplied by two bellows operating on opposite sides of the furnace and located in two adjoining pits. Two air-inlet holes connecting these shallow pits with the interior of the shaft are mentioned in the report but are not illustrated, nor is the reported taphole in the front wall, supposedly linked to a forepit. The walls had been exposed to intense heat. The Opole furnace is dated to the 4th – 5th centuries AD solely on the basis of finds in some nearby occupation pits. It appears as an oddity in the world of late Roman period slag-pit furnaces and a later date cannot be not excluded.

Attention should also be drawn to a form of true thick-walled shaft-furnace used by the early mediaeval Baltic peoples, as illustrated by the examples from Spietini and Asote in Lithuania. The two furnaces there, which were very similar in construction and form, had relatively small internal diameters (30cm), but the thick walls produced an overall external diameter of 0.65 to 1m. Front arches or tunnels connected the flat hearths, formed of flat stones, with forepits. In the Asote furnace, the flat hearth stone formed a step down to the arch (Fig. 46: 2). Slag appears to have been removed by tapping in the molten state. Nothing is known about the method of supplying the air blast, although the furnaces were in a good state of preservation when excavated. Although the furnaces are very similar, they have been dated to different periods, the 7th – 8th centuries AD for Spietini (Daiga 1964, 23 – 37, fig. 6) and the 10th century for Asote (Šnore 1957, 20).

The thick-walled furnace has been accepted as characteristic of eastern Slav metallurgy and was used as the model for smelting trials carried out by Kolchin in 1960 (see Radwan and Pleiner 1963, 68 – 71, figs 23 – 25; Kolchin and Krug 1965). The experimental furnaces were built to work on forced draught and the trials were remarkable in that a perfect tapping of molten slag was achieved, with the product being a low-carbon iron sponge containing some highly-carburized areas.

After an interlude in which sunken, underground and embanked furnaces predominated in the south-east and centre of Europe from the 9th century up to somewhere around the 12th century, it seems that during the 13th century the effective thick-walled shaft model came to prominence, at least in Bohemia and we must examine two examples here.

At Radětice, near Příbram in south-central Bohemia, a bloomery site of the 13th century

was excavated (Pleiner 1971a), which yielded the bases of thick-walled smelting furnaces, the shafts of which were erected from worked blocks of Cambrian rock. One furnace, designated feature XIX (*op. cit.*, fig. 5), had an internal hearth-diameter of 25cm at the preserved level and the surrounding shaft walls were more than 30cm thick (Fig. 49: 2). The wall-section was open to the southern side, where an fan-shaped arch, apparently housing a slag-tapping hole as well as the air-inlet, was situated. No clay tuyeres were found on this site, and the ditch-shaped roaster in the north-west section of the site was operated by bellows through a set of iron tuyere nozzles (cf. above, Fig. 55: 15). The bloomery consumed goethite ore, an outcrop of which ended some meters to one side and the tapped slag deposited in several heaps was manganiferous and low in phosphorus.

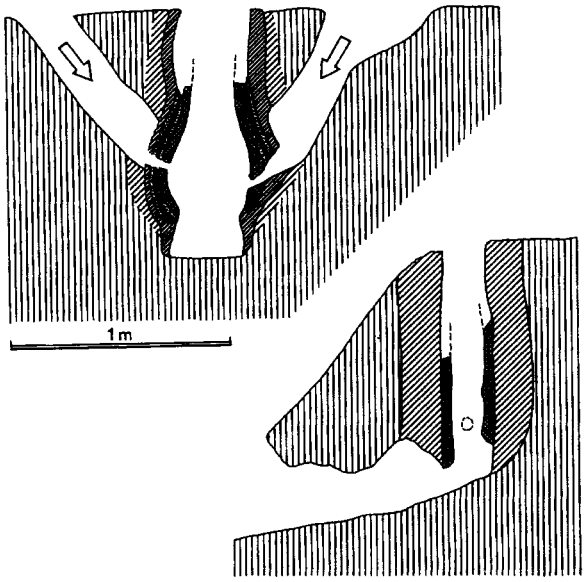


Fig. 51. Yutanovka, Ukraine. Underground furnace of the Saltovo culture, 9th century AD in front and longitudinal sections. The reduction chamber is modelled of clay and insulated by sand-mass layers and sand-grogged clay lining. Two lateral air-ducts point steeply to the furnace hearth. After Afanasyev and Nikolayenko 1982.

Two thick-walled furnaces were found during rescue digs at Chýnice south-west of Prague, in an ore-bearing region of the Barrandian facies. The internal diameters of the hearths were 35cm and the burnt-red clay walls, lined with a grey refractory coating, were 30 – 40cm thick (Fig. 49: 3). Both furnaces were connected to oval forepits and their arches were arranged differently from those at Radětice, in the case of furnace 1, facing south-west, in the case of furnace 2, south-east. The associated slag heaps could not be investigated because the area was covered by buildings. However, it is known that the slag was tapped and contained up to 1.43% P. A clay tuyere nozzle indicates the use of bellows to provide the air suuply (Krajíc and Matoušek 1985).

There is no doubt that by High Middle Ages at the latest, central Europe had adopted this most progressive type of furnace, culminating in the development of robust *Stucköfen* of Styria. In the Rhineland and in Sweden, it was developed into the predecessor of the blast furnace, mostly stone-walled and lined to form a funnel-shaped 'bosh', pointing in the narrow hearth: this was one of very important trick in the construction, influencing the temperature regime of the furnace (Pl. XXI and XXII). But much of Europe was, meanwhile, influenced by another, completely different concept in bloomery smelting furnace design, the 'underground' furnace, which apparently came from the east.

Underground smelting furnaces

This is a form that is strikingly different from the other furnaces so far discussed. These furnaces were fully excavated underground smelting installations, the shafts of which were set entirely into soil banks and which were extremely well-insulated. Other advantages, at least in

terms of the central European examples, were that they were mechanically stable, were suited to taking multiple repairs which prolonged production life, and allowed the use of different kinds of refractory material which could be shaped so as to modify the spaces where the blooms resided after smelting. The disadvantage of these installations, some of which were of a very sophisticated design, was the limit to which production capacity could be increased, particularly at a time when yields from shaft-furnaces were steadily improving. Because of this, it represents a *cul-de-sac* in the history of the development of European iron metallurgy.

It is difficult to trace the genesis of the principle of this furnace, although its perfect insulation may indicate that hard climatic conditions were among the factors contributing to its appearance. In fact, relatively early examples are known from Siberia. Near Minusinsk on the Upper Yenisey river, many furnaces have been excavated which fall into a wide date-range from the 1st century BC to the 5th century AD, the period of the local Tashtyk culture (Sunchugashev 1979). Furnace 6 from Polovinka consisted of box-like lined chamber 117cm x 50cm x 50cm deep, excavated into the soil and accessed via a rectangular throat section measuring 40cm by 40cm, which was also lined. A long sloping air-duct, 60cm long and 20cm x 30cm in cross-section, led into the combustion chamber from the surface (Fig. 50: 2). When excavated, the chamber itself was found to be filled with charcoal and pieces of slag. Any detailed evaluation raises practical questions concerning the operation, air-supply and blowing of these furnaces, as well as of how the bloom and slag were removed. The Polovinka 6 example rather resembles a fox's lair, but the burnt-red linings and bloomery slags found in them show that such furnaces worked. Many similar installations, often arranged in pairs, have been found in the region between Abakan and Ouzhur, as, for example at Külbüstig (Fig. 50: 3), Efimenkino (Fig. 50: 4), Akh-Tastar and Maliy Topanov. Furnace 11 from Akh-Tastar with its unused tube-shaped tuyere in its air-duct shows some similarity with underground bloomery furnaces from central Europe (Fig. 50: 1).

In Tuva (Altay and the Upper Yenisey river basin) excavations revealed low underground shaft-furnaces with tunnels of various lengths excavated into the subsoil and similar to those from the Minusinsk region. The dating indicates a wide chronological range, from the 3rd century BC up to the 1st century AD for the sites at Turlug, Tardam and Chinge Aksy (Sunchugashev 1969, 103 – 130).

It is difficult to answer the question of where the idea of building subterranean furnaces originated due to the very uneven investigation of areas in the East. Nonetheless, there are further finds from distant regions of Siberia which reveal some similarities. In the area of Kom-Agach excavations uncovered eight sunken furnaces with shafts elongated in plan (50cm x 125cm), lined with large stone plates and refractory clay, their hearths facing a tunnel connected to a working pit (Zinyakov 1981). They date to the period AD 500 – 1000, corresponding with the period of the Chagan-Uzun culture. What is striking is the presence of multiple air-vents fringing the throat and pointing down into the shaft at angles of 45 – 50°.

As noted above, it is possible that the inception of the well-insulated underground furnace was stimulated by climatic conditions. Gömöri (1988) has suggested a connection between the European examples and their eastern counterparts resulting from the westwards movement of the various steppe-peoples. However, the eastern models are distant and geographically isolated and any links with historical events must be considered speculative.

We may refer, in passing, to the large, box-like Japanese Tartara furnaces used in steel production, known from post-mediaeval sources. These furnaces are operated using two rows of tuyeres, again obliquely inclined into a groove-shaped hearth with air supplied by box-bellows. The technology is, however beyond the scope of studies of early European iron metallurgy of iron and the reader is referred to the extensive bibliography relating to the Tartara forges (e.g. Rostoker *et al.* 1989).

As has been pointed out, to look for any genetic connection between Far Eastern and European finds is difficult at the present time because of the huge geographical gap, an area some

4000km across, from which there are no analogous finds. The first underground furnaces, in fact of different design, appear in the Ukraine, at Yutanovka, near Belgorod. It belongs to the Saltovo culture and dates from the 9th century AD (Afanas'yev and Nikolayenko 1982, fig. 1: 3, 6). Typically, a bottle-shaped shaft, oval in cross-section, with a throat section measuring 22cm by 15cm, had been dug into the soil. The centre section of this shaft, measuring 25cm by 40cm, still retained an intact red-baked clay lining which was surrounded by three layers of refractory sand backing. The inner chamber survived to a height of 60cm, but it is assumed that it was higher before the upper section collapsed. The total height of the shaft above the small hearth was 1m. Two air-ducts, inclined at an angle of 45° and measuring 30cm in diameter and 85cm long, were directed towards the centre of of the reduction chamber on either side, implying that two independent sets of bellows, located on the surface, were used. The front wall of the furnace was thick and formed from the natural soil, having in its lower part an arch which connected to the working area and doubtless served as a slag-tapping hole (Fig. 51).

The Yutanovka furnaces are no longer unique, since, eleven years on, other furnaces of the same date (2nd half of the 9th century AD), found at Roganino in the Kharkov area and also attributed to the Saltovo culture, have been published (Koloda 1996). Unfortunately, they were damaged by deep ploughing, so that they survived only 40cm above the levels of their bases. However, the furnaces designated G and D show very similar common features, having been set deep into a soil bank. They also have flat, oval hearths of 14cm x 45cm lined with two kinds of sandy refractory materials, interiors bi-conical in shape and, in the case of furnace D, clear traces of two lateral air-vents pointing from the surface downwards at a steep angle. Arches connected the hearths with elongated, tongue-shaped forepits 2m long and 50cm wide at their outer ends.

The Želechovice underground furnace

The use of a steeply inclined air-duct from the rear ground surface to the interior of the subterranean chamber appears to have been a specific design of early mediaeval bloomery furnaces from central Europe. In the realm of Great Moravia, the territory of the western Slavs who rapidly developed their material culture during the 8th and 9th centuries AD, very sophisticated installations emerged. A well-known example is that of Želechovice in northern Moravia, discovered before the war and excavated completely in 1950/51 (Pleiner 1955; 1958, 208 – 224, pl. XVI – XX; 1962, 181 – 185; 1992a, 545, fig. 10; Tylecote 1987, 161). Here, the furnaces were arranged in batteries, laid out in a straight line and set into a bank of earth, consisting of 25 furnaces in total (see chapter IV). The funnel-shaped and slightly inclined shafts, which were excavated into the loess subsoil, were short, only some 55cm high. They were 25cm in diameter at the throat and 16cm at the lower shaft mouth and lined with three layers of different kinds of refractory clay, the innermost of which (a siliceous mixture) was resistant to a temperature of 1690°.

At the base of the shafts was a horizontal tunnel, 77cm long by 36cm high, in the case of furnace XXV, connected to a foreditch which linked the tunnel openings of the entire line of furnaces. The overall heights of the furnaces from hearth to throat was that of the loess bank, *ca.* 80cm. The tuyeres were located at the back of the throat, pointing downwards to the hearth at an angle of 40°; it was 3 – 4cm in diameter and serving for the insertion of bellows of unknown type. Behind the air-duct, where it entered the combustion zone, there was a distinctive cavity, a reheating chamber into which the reduced bloom could be pushed to keep it out of the oxidizing air stream (Fig. 52: 1; Pl. XIV – XV). An identical furnace was excavated at Dolní Sukolom before war, some 2km to the north, on the same loess stream terrace (Pleiner 1955, 40, fig. 11, after Schirmeiesen).

An experimental smelt (Pleiner 1969b) demonstrated that pushing or sliding the bloom

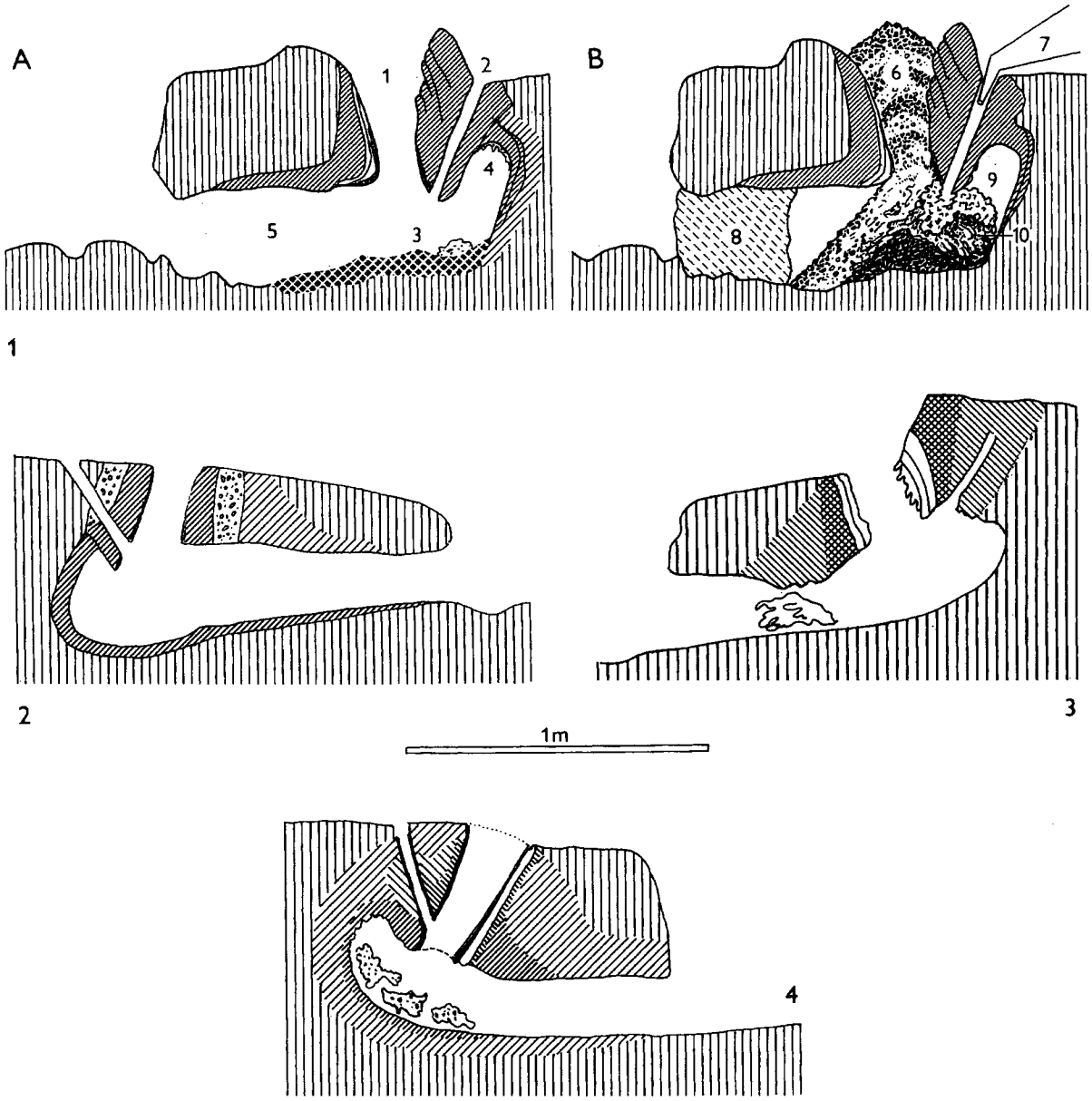


Fig. 52. Underground furnaces of the Želechovice type in Moravia, Czech Republic. 1 Želechovice, furnace XXV, about AD 800 – A: As found: 1 throat and shaft, 2 tuyere, 3 hearth with charcoal and slag, 4 reheating chamber, 5 tunnel-shaped manipulation arch. B: functional reconstruction based on experimental smelts: 6 ore and fuel charge, 7 bellows, 8 blocked arch tunnel, 9 iron bloom near the tuyere mouth and in the rear chamber, 10 slag. 2–3 Olomučany, bloomery works 98/2, 8th century AD: 2 furnace 2, 3 furnace 1; 4 Senička. References: 1 Pleiner 1955, 1958; 2 Souchopová 1986; 3 Pleiner, personal field drawing; 4 Dohnal 1982.

into the rear reheating chamber resulted in the reheating of the iron within the furnace, a better separation from slag and — this should be stressed — in protection against secondary decarburization by the air-flow at the tuyere or air-duct mouth. The product was a hard, homogeneous carbon steel of nearly eutectoid composition. Only the tip of the bloom, nearest to the tuyere opening, was decarburized to a structure of ferrite and ferrite-and-pearlite. During the experiment all slag shifted below the bloom onto a charcoal cone in the rear chamber and could not be tapped. After the addition of the last ore/fuel fraction, the charging of charcoal continued for about one hour under normal bellows blowing. This contributed to the separation of the slag from the sponge, resulting in a more compact bloom. The whole mass was raked out, still glowing, when the smelting process thought to be finished and the red-hot bloom was cut off. The wind tunnel acted as an air-duct during the ignition and preheating of the furnace and had to be sealed before bellows-blowing commenced.

Furnaces of this design were subsequently investigated near Blansko, western Moravia, at the site of Olomučany (Souchopová 1986, 15 – 19, figs 4 – 9; 1995 19 – 20, pl. 7). Two batteries of 7 and 8 furnaces respectively, were excavated in forest districts 98/2 and 3 (Pl. XVI). They date from before AD 800 and are earlier, than the inset furnaces with thin front walls referred to above. The furnaces were dug into a loess bank on the slope of the same stream valley. Their internal arrangement was exactly the same as those from Želechovice, although the dimensions are slightly smaller (Fig. 52: 2 – 3). To the north, another battery of four identical furnaces lying side-by-side was excavated at Senička (Fig. 52: 4) during a rescue dig (Dohnal 1982). There is, however, a problem in respect of the dating of these furnaces. A few sherds recovered from a destroyed pit nearby belong to the later mediaeval period which is at complete variance with the furnace type, suggesting that this pit is unconnected with the bloomery. However, the rescue nature of the excavation gave no opportunity to examine the whole area of the site in its wider context.

The sophisticated Želechovice model constitutes a family known, to date, from four Moravian sites. The question arises whether there are analogous finds from a broader area. While no exact counterparts are known until now, it is possible at least to speculate on potentional relationships with finds from three sites.

We can return to the 7th century AD furnaces at Gayvoron, on a sandy island in the river Bug in Ukraine. As noted above, these appeared in excavation as thin-walled burnt-red shafts. The high position of the rear air-inlet holes (inner dia. 2cm, outer dia. 5cm), i.e. 25 – 45cm above the hearths of shafts which stood to 60 – 75cm, suggests that the bellows, pointing down to the combustion zones, must have been situated at a much higher level, something indicated on the simplified profile sketch of furnace 2. Similar position is indicated in the case of furnaces 8, 17, 20, and 21 (Bidzilya 1963, 130 – 133, pl. I–III). An alternative interpretation is that when the furnaces were in operation, they were, in fact, set into sandy banks and lined with refractory clay. Subsequent erosion, coupled with the inadvertent removal of the loose sandy sub-soil during excavation would have left only the slagged and hard-fired linings. If this was, in fact, the case, then we see the Želechovice scheme emerging, especially in case of furnace 2 which seems to be equipped with the front tunnel, giving the typical L-shaped profile (*op. cit.*, pl. I). However, no trace of any rear cavity can be seen.

Another example, seemingly preserved in the same way, is a smelting furnace found at Mönchmotschelnitz (now Moczydlnica Klasztorna) in Silesia, seen in a copied museum photograph taken in pre-war times (Weiershausen 1939, 109 – 110, fig. 25). It was excavated in late 1890's and described by Wedding (1896) as a *Renntopf* (literally 'bloomery smelting-pot'). The preserved picture shows an L-shaped clay structure, the shaft of which was some 60cm high, with an estimated internal diameter of 40cm and wall thickness of 8cm. There is a protruding clay tunnel on one side and two lateral air-inlet holes seem to be inclined downwards into the shaft. It is, again, the high position of these air-ducts that excites suspicion of the ground level having

been originally significantly higher. In other words, the furnace represents an underground installation, the slagged and fired-red lining having been preserved after erosion of the overlying soil. Should this indeed have been the case, then the L-shaped profile of the interior suggests the Želechovice scheme with its tunnel on one hand, and the lateral tuyere holes the Yutanovka design with its downwards-inclined air-ducts on the other. Unfortunately, the original situation in the field can no longer be reconstructed. Wedding (*op. cit.*, figs 1 – 3) worked from a second-hand description by Grempler, who provided him with schematic longitudinal and transverse sections which contradict the description and fig. 1 as to the positions of the air-inlets. The cross-section (fig. 2) definitely supports our interpretation of this as an underground furnace, as does the longitudinal section (fig. 3), although it shows only one air-duct at the rear. According to Grempler, the feature is mediaeval, dating from the 10th century AD.

The third possible parallel may be noted for the Želechovice bloomery from Hirschwang 1 in Austria, although this ironworks is ascribed to a later date, the 11th century AD, on the basis of associated pottery (Mayrhofer and Hampl 1958, 13 – 19). A certain similarity is rooted not so much in the construction details, the documentation of which is presented only in schematic form (*op. cit.* fig. 14 and 15), but in the arrangement of a battery of four smelting furnaces, situated side-by-side at distances of some 80cm each from the other. The red-burnt and slagged shafts were set into a clay bank and their shape, insofar as it can be made out from the published photographs, was rather box-like (preserved height or depth 39cm, length 55cm, width 21 – 25cm). What is worth of mentioning is the rear position of the air-inlet which was 8cm in diameter and furnished with clay tuyeres, some one hundred fragments of which were found among the debris. The air-inlet was connected with a stone-paved rectangular channel 70cm long, 20 – 21cm wide and 24cm deep, which, during smelting, operations, apparently housed a blowing device of unknown type. Slag was removed from the front of the battery, while charcoal pits lay to the rear. In spite of differences in detail, the overall lay-out resembles that of the Moravian batteries which were operating some three centuries earlier.

The underground furnaces represent an early mediaeval episode which enriched the pattern-book of European bloomeries and reflects the impact of immigrating populations (Slavs, Avars, and, subsequently, Magyars or early Hungarians). They were efficient enough to supply such groups with good quality iron from local ores. Among them, pride of place is taken by the sophisticated Želechovice furnaces, allowing the production of hard steel, the result of the metallurgical thinking of western Slav smelters. However, it was nevertheless only an interlude, since the design did not allow for increases either in dimensions or the production capacity. Instead, the palm of victory went to the simple free-standing shaft-furnace, opening the way to the development of the earlies blast furnaces some two to three centuries later.

*

It has only been possible in this short survey to describe and discuss the forms of early bloomery furnace through selected examples. Naturally, a lot of early ironmaking installations are badly preserved, which makes it difficult not only to classify them but also to reconstruct their shape and method of operation. Nonetheless, they contribute to our knowledge of geographical distribution of iron production sites and they provide laboratories with samples of slag, metal, structural material, and fuel. Furthermore, recent research projects have been provided us annually with more and more new features. Some of these are well-preserved, but have so far only been referred to in conferences and symposia, remaining to be fully published and evaluated. In the late 1990's discoveries have been made, for example, in the Le Mans and Indre regions of France, in the Schwarzwald of south-west Germany, in Sweden and elsewhere but we cannot deal with them in this work as only preliminary data are so far available.

*

Before closing this survey, it is appropriate to mention briefly some non-European discoveries. African furnace finds from earlier periods, the Taruga slag-pit furnaces and the Meroë shaft-furnaces, have been quoted as *comparanda* for some European sites. It is interesting that in recent years, the archaeological remains of traditional post-mediaeval African furnaces have been subjected to excavation, showing them to be the predecessors of many bizarre designs, air-induced or bellows-blown, which survived up to early the decades of the twentieth century. Their analysis and bibliographic survey is worthy of its own special study, but we can here only refer the interested reader to the published literature (e.g. von Luschan 1909; Olshausen 1909, 1915; Klusemann 19243; Crawhall 1933; Rickard 1939; Gardi 1954; Carl and Petit 1955; Tylecote 1965a; Todd and Charles 1978; Fuchs, Eckert, Gardi in: Eisen + Archäologie 1978; Métallurgies Africaines 1983; Avery, van der Merwe, Saitowitz 1988; Kiethega, Bocoum, Yandia in: Paléometallurgie du fer et cultures 1995, 131 – 158; Hahn in: Traditionelles Eisenhandwerk in Afrika 1997 etc.). In India and south-east Asia many survivals have been documented from similar ethnological contexts (e.g. Tylecote 1965a; Cleere 1963b; Prakash in Paléometallurgie du fer et cultures 1995, 33 – 40), but well-preserved examples from archaeological contexts are lacking. And special attention will have to be paid to the important multi-tuyere steel-producing installations dating broadly to the period 200 BC – AD 300, recently discovered at Dehigaha-äla-kanda in Srí Lanka (Juleff 1995; Forenius and Solengaarachchi 1996, 95 – 102).

In ancient China, iron production began much later than in south-west Asia and Europe, in the 6th – 5th centuries BC, not becoming common until the 3rd century BC. But here, from earliest times cast iron was produced (Needham 1964; Wagner 1993). Wagner is inclined to see the effect of large copper-smelting installations in the development of cast iron production. The Han period (202 BC to AD 220) saw the mass-production of cast iron and archaeological evidence of smelting furnaces has been reported to date from 100 BC onwards. As regards to the source materials and documentation for furnaces, the situation is, at present, not very clear. Apart from pictorial representations of iron smelting, there is, unfortunately, a marked dearth of available reports of excavated features. A drawing, without explanatory text, depicts a reverberatory furnace with box-shaped smelting chamber from T'ieh-shang-kou, near Kung-hsien (Han period), which is claimed to have produced blooms of iron (Barnard and Tamotsu 1975, 34, fig. 15: 8), and a blast furnace is described from Kushing, but without illustration (Cheng Shih-Po 1978; see reconstruction by Tylecote 1983, 437, fig. 4). There is a pressing need for a new supply of primary information about early iron smelting installations in China.

Furnace finds as sources of evidence

The value of furnace finds (Fig. 73) as the most common source of evidence for the early history of iron smelting, may be examined at several technological, historical, and social levels. First, when adequately preserved, they tell us something about their methods and techniques of operation (air-supply, handling of slag and iron etc.). Second, furnaces encapsulated a bloomery technology which, although bound by specific rules of chemistry and thermodynamics, allowed for considerable variations in their design and construction, something which inevitably leaves any grand 'unified' typology incomplete. Furthermore, such variety influenced both the quality and quantity of iron and wastes produced and sometimes, the ingenuity and sophistication of individual forms admirably illustrate the skill and experience of those who built and operated them.

Third, all of this, combined with measurements of the sizes and capacities off different furnaces, provides data allowing for a degree of economical evaluation of production operations. Most of the furnaces described in this survey are relatively small in terms of the enclosed volumes available for production when we consider that they would have operated only discontinuously. The range was from 20 – 70 litres in the case of early bowl or small shaft-furnaces, 90 – 100 litres or so for the larger shaft-furnaces and around 500 for the La Tène period domed-furnaces.

Their iron production can be measured in only kilograms, or, at best, in tens of kilograms of unworked iron.

Fourth, smelting furnaces are archaeological artefacts which reflect not only existing conventions, but also innovations which were slowly introduced by smelters who, themselves, were members of small population groups in different regions and time periods, and who built their devices according to inherited practices. Viewed in this way we may approach the idea of strictly local typologies which may well be more historically-accurate reflections than any one macro-typology. It seems clear that there were 'schools' of ironmakers who met the requirements of ancient and mediaeval societies for iron.

'Et fornacium magna differentia est' wrote Pliny the Elder in the 1st century AD (Hist. nat. 34.41). This would be a convenient phrase with which to close this chapter. Nevertheless the remark itself invites a brief comment. Pliny compiled his work, containing so much technological information, by collecting the comments of other writers, mostly now lost, and from many reporters who provided him with information. In this way he gathered that the furnaces for making iron in his time differed apparently in construction, shape, capacity and mode of operating (cf. Vetters 1966). Unfortunately, however, he left no description. Writers in the Roman world seemed faintly conscious of the use of large, bellows-blown devices (Vergil, Aen. 8. 420: *vasta fornace*; 664; Curtius Rufus 39: *cum fornacibus quod ferrum excudi opportebat, impositum esset admotisque follibus igne flatu accenderant*; Phylargyrius ad Aen. IV 172: *folles taurini habent cum liquescant petrae ubi ferrum fit*). But how such a *'fornax'* or, rarely, *'caminus'* (Rutilius Namatianus, De reditu suo, 5.351–356) might have appeared remains veiled.

As has been shown in this chapter, the Roman world saw at least five basic furnace models, from which a minimum of ten variants have been identified through archaeological research. If we add what we know from the barbarian lands at around the same period, the number of furnace types and variants reaches more than fifteen. The same can be said about the European Middle Ages but, with the appearance of the first blast furnaces and introduction of indirect process in the major production regions, the situation began to change, with the variability in furnace form reducing. Bloomery installations retained their variability, but were gradually pushed into the background and, by the end of the 19th century, had been relegated to survivals. The early charcoal blast furnaces which definitely dominated the 16th and 17th centuries, centred on two main systems, the Brescia, and the Walloon. In the 20th century, bloomery production revived to a limited degree as a result of specific economic demands, but was practiced in installations very different from traditional forms and utterly subordinate to the indirect process. The Höganäss process produced sintered iron concentrates in crucible furnaces, but mostly, rotary kilns yielding spongy iron granulates were used (Bureau of Mines, Norsk Staal, Krupp-Rennverfahren). Except for some electric-arc furnaces in Sweden, the coke-fed towers of blast furnaces with their upper bells and Cowper air regenerators dominate the production of iron. Their number decreases, their capacity increases immensely. *Et fornacium magna differentia erat!*

Chapter X

TUYERES AND BELLOWS

In the discussion of smelting furnaces in various European regions in chapter IX, frequent reference was made to tuyeres (French *tuyères*). These represent a special category of archaeological find and as such require more detailed treatment. They constitute a significant technological component of the air-supply systems of furnaces and hearths and, moreover, in certain instances show distnctive features related regionally and chronologically to cultural groups.

The function of the tuyere

A tuyere is a nozzle into which the outlet tube of a blowing device (in the case of early furnaces, the bellows) was inserted, to permit a blast of air to be delivered to the interior of a smelting furnace or forging hearth. Its roles were to protect the bellows tube from the effect of the hot furnace charge and to dampen down the vibrations from the bellows and prevent them from being transmitted to the furnace wall. Such nozzles could be easily replaced when they became blocked with molten slag, something which would result in loss of temperature inside the furnace and the interruption of the smelting process. Tuyeres were almost always made of specially-prepared refractory clays and were usually used dry. During smelting, the inner tips became fired and because of this these tips survive more frequently among archaeological assemblages than the rest of the tuyere. Examples of tuyeres made from other materials, such as iron or brass, are very rare. Clay tuyeres date back to before the introduction of iron technology, since various types of tuyere were used in the Bronze Age for non-ferrous metallurgical operations, such as copper smelting and the heating up of crucibles and include the 'bent-knee' shaped nozzles of skin bellows and the clay tips of blow pipes (Tylecote 1981).

In iron production, tuyeres were used both in smelting furnaces and in forging hearths. There was often no differentiation in the type of tuyere used for these purposes, and so they cannot be distinguished except from the contexts in which they are found. Furthermore, the bellows of smithing hearths were sometimes protected against heat and sparks with special perforated clay or stone blocks. This chapter will deal, above all, with tuyeres found on smelting sites or *in situ* in bloomery furnaces or reheating installations. Analogies may be found among ethnological sources for Africa, India, and the Far East.

Air-inlet systems for induced draught and wind-blown furnaces

Numerous ethnological examples from West Africa, eastern India and Burma testify to the fact that many types of traditional smelting furnace worked with natural or induced draught. In the same way, some of the excavated remains of early European furnaces have been interpreted as being those of induced-draught or wind-blown furnaces. This assumption has usually been based on the siting of furnaces on slopes and other places exposed to prevailing winds or on fragments of furnace walls with traces of air-inlet holes with internal diameters exceeding 5cm (Pelet 1973, 28 – 29, fig. 11). The problem in the latter case is that it is never certain whether these large apertures were not used to receive normal-sized tuyeres which have been removed. In fact, it is not out of the question that the nozzles of bellows could have been inserted directly into larger air-ducts without the use of tuyeres.

Experiments have shown that an effective natural draught, sufficient to penetrate the resistant column of ore and fuel, can be induced when the internal diameter of the furnace is about 30cm with a minimum shaft height of 1.5m (Tylecote and Owles 1960, 216 – 217). With such dimensions, temperatures in the region of 1200°C can be achieved as a result of the chimney effect. Tests carried out by Hamann (1974; 1975; 1976) showed that a wind speed of 18km/h

will create favourable temperature conditions in furnaces of the Scharmbeck type (height 1m, internal diameter 35cm) where the three or four 3cm-diameter air-inlet holes at the base of the shaft allowed air to enter very effectively, without creating turbulence inside the shaft. The effect of the wind passing across the throat of the furnace, moreover, had an additional suction effect, creating sub-atmospheric pressures at this level and increasing the upward draught.

Unfortunately, few European furnaces survive to their original heights or can be reconstructed with certainty, and so it remains a problem to distinguish natural-draught or wind-blown furnaces. Several shaft models have, however, been classified as being of this type, notably the 2nd century AD examples from Ashwicken in England (Tylecote and Owles 1960), and those from Salzgitter-Lobmachtersen in Germany, also of the 2nd century AD, the original heights of which are unknown, but which had internal diameters of 50cm and air-inlet diameters of 12cm (Osann 1959, 1206 – 1207).

The curious find from Einzingen in central Germany (Weiershausen 1939, 134–138, fig. 33 – 34), unique up to now, was described in chapter IX. A free-standing clay shaft, 1m high, was reconstructed from fragments. Six conical holes (14cm dia.) perforated the walls at four levels. The two lower ones, 13cm and 32.5cm above the base, were slagged. The first was apparently used as slag outlet, the second one perhaps originally as an air-vent which could be sealed with a clay stopper. When this second aperture became blocked with slag as well, the role of air-vent shifted to the upper holes, which were at opposite sides to the lower ones. These too were also equipped with clay stoppers. What is difficult to understand is their high positioning, 74 cm above the base and only 26cm and 23cm below the throat. Possibly they acted as regulatory auxiliary air suppliers for the remaining charge in the upper levels of the furnace and were intended to provide a means of subjecting this area to the action of reducing gases. Nobody has yet experimented with this unique system which was based apparently on induced draught.

Large air-inlet holes (10 – 27cm diameter) in the tall brick walls of the mediaeval furnace shafts at Velikiye Bolgary on the upper Volga, Russia (Fig. 42: 5), which were at least 1.3m high (Efimova 1958), also indicate the use of induced draught. These holes were arranged radially at various levels of the shaft. It is reported that, in the mid-19th century, a 14th century induced-draught furnace was excavated at Sarai Berke, in the same region, with 79 tuyeres (also quoted by Efimova 1958, 306), but no details of this find have survived.

How the Romano-Barbarian slag-pit furnaces of the Holy Cross Mountains in Poland were supplied with air remains an unsolved mystery. These were constructed of clay bricks, none surviving *in situ* which, on a number of sites including Łysa Góra-Bielnik, Przełęcz Hucka, Słupia Nowa 4 and Kunów (Bielenin 1974, 72 – 73, figs 33: 6 and 9; figs 34 and 35); 1992, 71, fig. 32: 11, and 16), were found to have holes in them, tapering from 12cm diameter on the outside to 4cm in the interior. Some new interpretations see these furnaces as having been operated using induced draught (Orzechowski 1991). Shaft brick fragments with holes of about 4cm of dia. appeared in the Ukrainian slag-pit furnace field of Uman' II (Bidzilya *et. al*, fig. 24). Whatever the truth is, these large slag-pit furnaces and their analogues in *Germania Libera* were rather complicated. Some of the sunken hearths, or maybe even individual smelts, required auxiliary air vents to allow for the burning of the filling of brushwood or straw in the slag-pit before the incandescent mass of liquid slag descended into it. In any case, it would seem that the air introduced through these channels, which slope steeply or even perpendicularily down into the hearth, must have been supplied by bellows.

The form of air-supply was the subject of experiments, carried out on a Romano-Barbarian furnace design modelled on furnaces found at Zethlingen (Leineweber 1991). Two smelts, carried out over 43 and 43 hours in a tall clay shaft (internal diameter hearth 30cm, throat 25cm, height 170m), were conducted entirely using natural draught. The auxiliary air-duct leading into the brushwood-filled hearth was opened after the first slag began to flow down and was not blown by bellows. It must be added, however, that, contrary to the Holy Cross Mountains evidence, this

air-duct, which was connected to the working forepit of the furnace, was not steeply inclined, but ran at a very shallow angle. The results of the experiments were slag blocks in the hearth which contained sintered-together particles of iron, so that the approach worked, but unfortunately, no yield calculations were included in the published report. The technique had, nonetheless, not been fully mastered, as in further experiments carried out at Eindhoven, in which, during a 20h smelt the system worked, but was temporarily delayed by the descent of the slag which reduced the yield of iron to 3kg from 18.2kg of ore (Leineweber et al. in: IJzersterk 1993, 20–22). More practice is obviously needed.

The air-supply and the use of tuyeres on the large Celtic domed furnaces discussed in Chapter IX remains an enigma and we may look at some examples. One supposedly natural-draught furnace with special tuyere blocks is furnace E 25 from Engsbachtal in the Siegerland, Germany (Stieren 1935, 15, fig. 2). The clay block found there measured about 30cm x 40cm and was pierced by three holes, 6 – 7cm in diamater. It was positioned inside the wind tunnel, which also served as the front access to the furnace. This tuyere block would have been removed to permit the outflow of slag and the removal of the bloom. Experimental smelts conducted by Gilles (1958a) showed that the air stream influenced only the front internal surface, leaving the rear practically unaffected. It is possible that other air-ducts, positioned to the rear of the furnace but not recognized during the excavation, would have existed. This would seem to be the case with other furnaces of this family, where air-inlets were positioned in more than one location and, moreover, at different levels.

The air-ducts of the large domed-furnaces from Clérimois in France, were relatively complex (Fig. 41: 2). While the arch, and possibly the wide lateral air-ducts of 20cm diameter (Dunikowski and Cabboi 1995, 89 – 92, figs 62 and 63) could have served to induce a natural draught at least in the initial preheating phase of the process, the narrower air-ducts positioned at higher levels at the rear (up to three in number) must have been connected to bellows. No tuyeres were found *in situ* but many fragments, some with twin holes (3cm dia.) and some very large (15cm dia.), would indicate that a combination of types of air-supply was used, possibly in different phases of the smelt.

The domed furnace of the so-called 'Burgenland type' exemplified by those from Klostermarienberg, Unterpullendorf and Weppersdorf (Bielenin 1977, 53; 1995)) worked on a similar principle to that from Clérimois. Whilst the frontal arch or tunnel might have secured an air-supply by natural draught, for example during the first phase of the operation, the rear or rear-and-lateral air-inlet holes were 25 cm wide, inclined slightly downwards from the surface and into the lower combustion chamber (Fig. 40: 1). No tuyeres were found, but in this case artificial blowing seems self-evident, particularly in the case of furnace 2 at Unterpullendorf. At Minepit Wood near Rotherfield, Sussex (Fig: 40: 3), a tuyere fragment is mentioned as having been found in the refuse dump associated with the domed furnaces. Here again, three sets of bellows would have provided a strong blast over a greater volume, possibly after any natural wind supply through the arch tunnel had ceased.

The domed furnace at Mechlin (Kostrzewski 1933) had eight large (8 – 10cm diameter) holes located about 30 – 40cm above the hearth bottom and arranged radially (Fig. 40: 2). This is also thought to have been an induced-draught furnace, despite its large diameter (1.4m) and low height as reconstructed (60cm). It does not, however, conform to the conditions for regular blowing and it may be that we must think in terms of individual foci of smelting, adjacent to to the air-inlets as seems to be the case in some of the Burgenland furnaces. Unfortunately it is no longer possible to carry out more detailed studies of this 1932 find.

The positioning of tuyeres in forced-draught furnaces

Most tuyeres with small bores (internal diameters) of 15 – 30mm are interpreted as being nozzles for receiving the ends of bellows-tubes which were probably made of organic materials

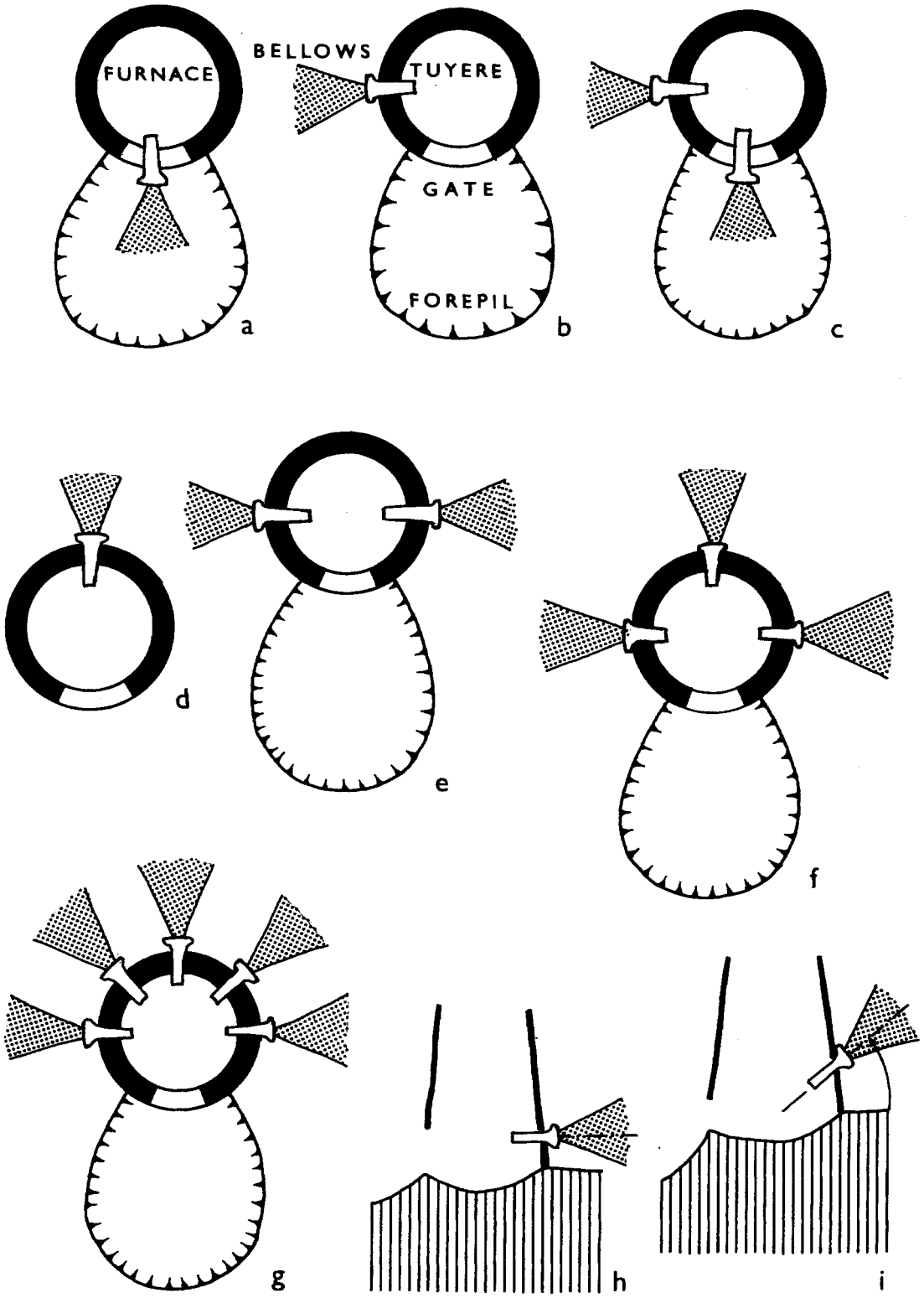


Fig. 53. Positions of tuyeres and bellows as revealed during excavations of bloomery furnaces. In plan: a – arch position, b – lateral position, c – side-and-arch position, d – rear position, e – bi-lateral position, f – three point position. g – radial arrangement. In vertical section: h – tuyere horizontal, i – tuyere sloping.

(wood, horn, bone, etc.). Those ends of tuyeres which came into direct contact with the metallurgical process, and were therefore exposed to great heat, are frequently found to be heavily slagged or even blocked by solidified slag. In such cases, the tuyeres would have been withdrawn and replaced. Among the slag debris found on some bloomery sites, the numbers of tuyere fragments may reach hundreds and even thousands.

In the simple bowl hearth, the tuyeres could have been directed at the smelting zone from the surface or ground level, over the lip of the hearth and at any position. In the case of the much-discussed example from Kestor, Devon, England, a stone setting may have been used on which to set the bellows on one side (Tylecote 1962a, 195, fig. 45B). Although tuyeres of various forms occur on Irish sites, none have been found *in situ* and there is no archaeological evidence for the bellows/tuyere arrangement (Scott 1990, 166 – 167). The last, well documented examples are the Catalan hearths in the Pyrenees of the 19th century, blown by trompes through copper tuyeres, the angles of which could be altered to produce the required quality of bloom.

The plans of many more sophisticated furnaces demonstrate different arrangements of bellows in the horizontal plane. They were usually positioned at some distance above the level of the hearth bottom, so as to leave space for ash and slag to collect at the base of the furnace. Tuyere holes in furnace walls may be horizontal or inclined downwards towards the hearth (Fig. 53: h, i). Furnaces with single tuyere holes, capable of taking one or two pairs of bellows, have these either directly through the furnace arch or at right angles to it, or even placed in the rear, so as to leave the arch free for the manipulation of the slag and bloom.

There are several examples known where tuyere was inserted through the furnace arch, meaning that the bellows had to be removed when operations such as slag-tapping or emptying the hearth at the end of the process (Fig. 53: a) were carried out. This is assumed to have been the normal arrangement among the family of Romano-Barbarian slag-pit furnaces, in the earlier period of their operation and there are some unambiguous examples which confirm this. In front of the arches of the 1st century AD furnaces 1 and 2 at Lovosice, northern Bohemia, which were built into the wall of a working pit, block tuyeres were found in the positions in which they had been left at the end of the final smelt (Pleiner and Salač 1987, figs 2 and 3). This arrangement was apparently the norm for all furnaces in the sunken-floored huts of the period and was also observed in the forepit of the 2nd century AD furnace at Gera-Tinz in central Germany (Dušek 1967, fig. 3).

Single tuyeres passing through the arch into the furnace have been reported from many mediaeval sites where embanked installations with clay arch-panels were found, including at Olomučany in Moravia (Souchopová 1978, 10 – 16), Nemeskér, Somogyfajsz (Fig. 56: 4 – 5) and other sites in western and northern Hungary and southern Slovakia of the 10th – 12th centuries (Nováki 1966; 1969; Heckenast *et al.* 1968; Gömöri 1977; 1995; Füryová et al. 1991). A similar arrangement has been observed in a number of thick-walled, free-standing shaft furnaces, for example in Bohemia at Radětice and Chýnice, both of which date to the 13th century (Pleiner 1971a; Krajíc and Matoušek 1985, fig. 4, cf. here Fig. 49: 2 – 3). In all of these and in many other cases, observations in the field show that the furnaces were operated using one or two sets of bellows. The 10th century AD site of Grigorovka in the Podol region of Ukraine (Artamonov 1955a, 109, fig. 45) revealed a pair of long tubular tuyeres inserted into the arch of furnace 3 (Fig. 54: 3 left), which suggests that blowing was performed with two pairs of bellows. However, another furnace was excavated which had four tuyeres remaining in the arch (Fig. 54: 3 right, see Pleiner 1966, 146, fig. 7, after Artamonov). It is difficult to imagine how four bellows could have been operated simultaneously on this furnace, and so another explanation must be found. In this connection, the find at Dehigaha-äla-Kanda in Srí Lanka (Forenius and Solegaarachchi 1996) must be noted. Here, eight tuyeres were found *in situ* in the front arch of a tall shaft furnace (at least 162cm high) at a level 25 – 40 from the bottom. Multiple tuyeres in front arches, will always arouse suspicions of the use of induced draught. The Grigorovka furnaces,

though generally dated to the 10th century AD, might have been the result of the building activities of different smelter groups, learning over the course of several generations different methods of furnace operation.

The second method of arranging the air-blast was to locate the bellows laterally, almost at right angles to the axis of the furnace arch (Fig. 53: b). This was probably seen to be advantageous by allowing the operation of the bellows to continue unimpeded by other work at the arch. One of the typical examples comes from Sulzbach in the Saarland of Western Germany, where a furnace which is undated, but seemingly Roman or Mediaeval, has been reconstructed as a rather domed device (Kolling 1973, 57, figs 2 and 3). A key-shaped tuyere led obliquely to the axis of the furnace arch through the wall on the south side, the arch being on the east.

It would seem that this system is the norm for the thick-walled shaft furnaces of the Middle Ages, which were operated in intensive production regimes. A laterally-positioned air-inlet system was demonstrated to have existed in furnaces investigated in N France, namely furnace 2 at Frouard, of the 5th – 6th centuries and furnace 3 at Ludres, of the 8th – 10th centuries (Leroy 1997, 125–134, figs 53, 590), both of which sites produced a variety of tuyere fragments. An analogous arrangement predominated in the Sauerland of western Germany, from where Sönnecken (1971, 89, fig. 4) reports an identical configuration from the 10th – 13th century furnace R, at Uhlenstein near Homert. Here, the arch was located on the east and the bellows bay to the south. The positioning of the bellows was indicated by two fan-shaped stone settings and three postholes, which possibly denote their bedding. Other sites in the same region, such as those at Linacker Siepen near Altena, and An den fuhlen Kümpen near Sonnenscheid (Sönnecken 1971, 21 – 22, 35, figs 3, and 35), have their bellows at an angle of 60° to the axis of the furnace arch, although the orientations are not given. However, other furnaces in the region had their air-blast supplied through the arch and tuyeres with internal diameters of 2.5 – 4cm have occasionally been found in the forepits of these furnaces, although none remained *in situ.* Apparently, in course of several generations the builders of smelting furnaces in the region used different practices and styles of construction.

The 13th century furnace at High Bishopley, England (Tylecote 1959, 30, fig. 4) was also equipped with a lateral air-inlet, the arch being on the east and the air-inlet hole to the north, although no tuyere was found.

It is worth mentioning that the right-angled positioning of the tuyere, in relation to the arch, appeared as a classical feature in charcoal blast furnaces from their very beginning, as for example at the Jubach valley sites and others in the Bergisches Land of western Germany and at Lapphyttan in Sweden.

The third possibility was to put the bellows to the rear, opposite the furnace arch (Fig. 53: d), which presumably was sealed during blowing. The earliest examples are furnaces of Slavic or, in general, eastern origin, which appeared in Europe between the 6th and 11th centuries AD. From among the furnaces discussed in Chapter IX, we may draw attention, once more, to the 6th – 7th centuries AD furnaces found at Gayvoron in Ukraine (Bidzilya 1963) and to those from Hirschwang 1, all of which date to the 11th century AD. The Hirschwang 1 battery of four embanked furnaces was supplied with its air-blast from the rear, with the bellows being directed to the reduction chamber by clay tuyeres, fragments of which were found in large number in the debris (Mayrhofer and Hampl 1958, 18 – 19, figs 14 and 15). Other typical examples are represented by the iron smelting plants at Želechovice, Sukolom, Olomučany and Senička, Moravia, where the individual furnaces were furnished with steeply inclined air-ducts (3 – 4cm diameter), located to the rear, behind the shaft throat. It is difficult to describe these air-ducts as tuyeres since they were modelled of good refractory clay, and, in fact, constituted the entire back part of each furnace (Fig. 52: 2; 53: i). Here, the arrangement served to protect the reduced iron, which had been pushed backwards, behind the air stream, against decarburization. The arches, shaped like prolonged wind-tunnels, are not to be considered as having induced the

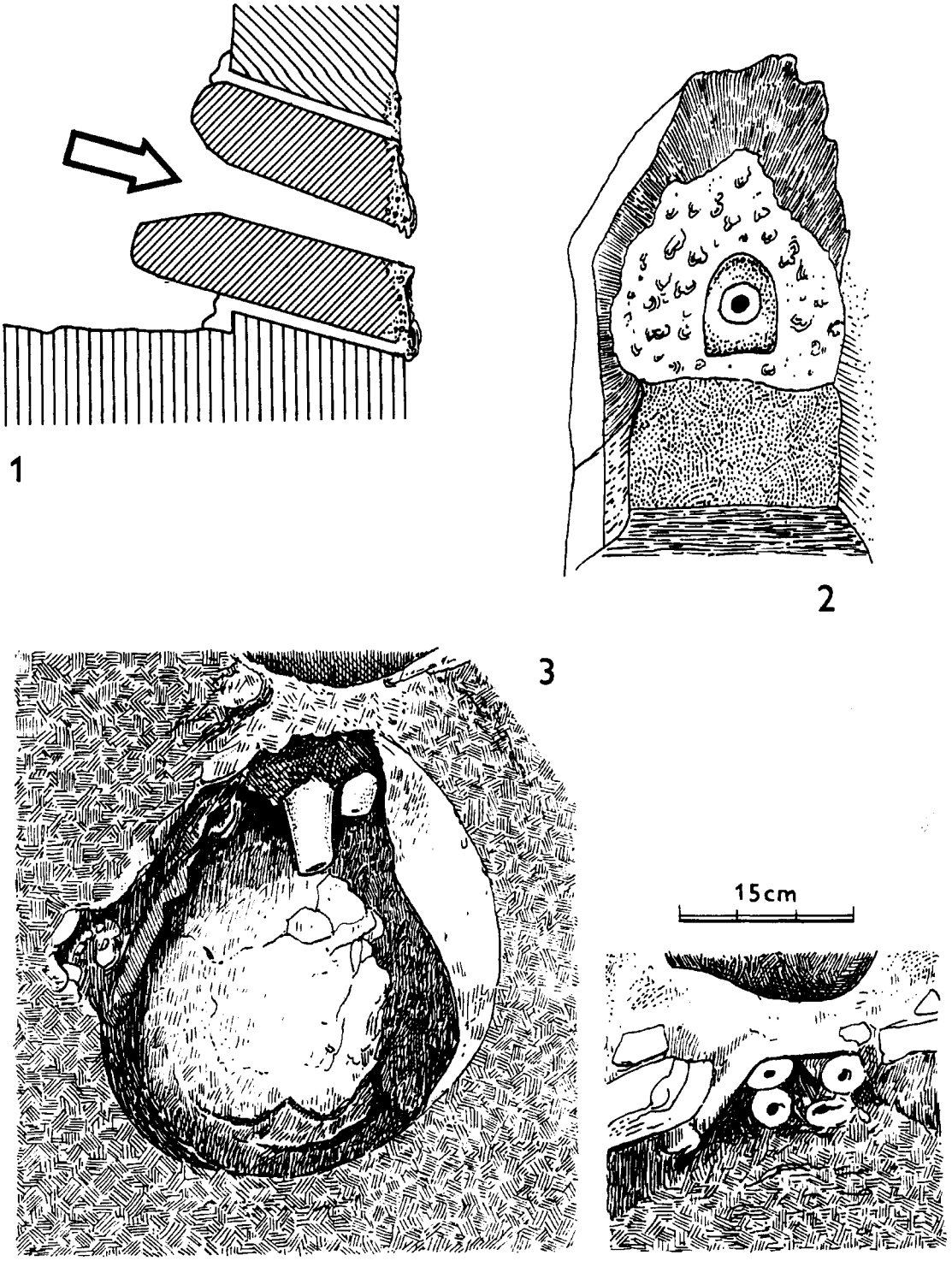


Fig. 54. Examples of tuyere installation in bloomery furnaces. 1 Lovosice, N Bohemia, 1st century AD, inclined position of a block tuyere from furnace 1; 2 Bellaires III, Vaud, Switzerland, post-Roman, block tuyere A in furnace XIX from interior; 3 Grigorovka, Ukraine, 10th century AD – right: tuyeres protruding into the hearth of a cleaned furnace (bird's view); left: Arch with four tuyeres in another furnace (front view, both after photograph). References: 1 Pleiner and Salač 1987; 2 Pelet 1973; 3 Artamonov 1955b.

air-flow, since, as experiments have shown, they could not have functioned as a supplement to the bellows blowing during the smelt. In fact, they were used solely during the preheating of furnace and were then sealed.

The rear positioning of bellows, however, did form a part of systems which reflect the need for an improved air supply, provided from several positions. The arrangement might possibly have been combined with that for natural draught as discussed when dealing with the large Celtic domed furnaces the form of air supply for which remains a puzzle. The robust 1st century BC Roman shaft furnaces from Martys in southern France were originally reconstructed as having been blown through the arch (Domergue 1993, 353, Fig. 251). However, subsequent analyses by Jarrier (1995) discovered the presence of magnetite in the slagging of the rear of the internal furnace wall, implying the possibility of another bellows, acting from the rear through what appears to have been a sloped air-inlet. This suggests the simultaneous use of two bellows, driving the air stream from different positions (Fig. 47: 2). No tuyeres were found *in situ*, but numerous clay fragments, some with twin holes, were collected from among the layers of debris (Domergue, *op. cit.*, fig. 243) and, in addition, fired clay 'packings' of tuyeres and air-ducts were identified (*ibid.*, 344 – 346, figs 181, 242 – 244). Domergue (1998) suggests that this furnace design was equipped with three air-inlets, two lateral, and one from the rear (Fig. 53f).

Another combination was observed on each of the late Roman or Migration period furnaces at Bellaires in the Vaud, (units XIX – XX) and at nearby Boécourt (Pelet 1973, 100 – 103, figs 50 and 51; Eschenlohr and Serneels 1991, 63 – 65) which not only had tuyeres located laterally, on the north and south sides, but also tuyeres set into the arches from the east. It is not clear whether both sets of bellows would have been used simultaneously, or were operated separately at different stages of the process (Fig. 53: c; Fig. 54: 2). The positioning of tuyeres in relation to the volume of the furnace could have had a considerable influence on the process of decarburization of the smelted iron as shown by the Želechovice experiments (Pleiner 1969b). Pelet (1992) has suggested that the arrangement of two tuyeres, placed at different levels and pointing in different directions was a possible solution to the problem of obtaining steel blooms in the assymetrical furnaces found in the Vaud.

There were also furnaces with laterally-opposing air-vents which might be termed the 'bilateral arrangement' (Fig. 53: e). Furnace XXII from Bossena I, Vaud, Switzerland, which is dated to the period around AD 600, had horizontally-mounted tuyeres set into its north and south stone-built walls, the former still *in situ*. The south wall was missing and the aperture had been sealed with clay, although it is not clear if this was deliberate (Pelet 1973, 106, figs 54 and XIX; 1993, 58, fig. 105 and 107). The excavator of the timbered furnace at Opole-Pólwieś in Silesia, Poland, the dating of which to the Migration period is only indirect (Fock 1941), assumed that the same system was used with two bellows located on the west and east sides of the furnace in special depressions (Fig. 48: 1). Unfortunately, no reference is made in the publication to any tuyeres having been found and the air-inlet holes are only referred to, not illustrated. The arch and forepit are assumed to have been on the south side. The walls of the free-standing furnace of the 1st half of the 1st millennium AD at Novaya Pokrovka in the Kharkov region of Ukraine (Braychevskaya 1956) were pierced by two opposing air-inlet holes (Fig. 42: 1), which are suggested as having accommodated the nozzles of bellows, but are not described in detail.

Apart from this horizontal arrangement, there is a bilateral, but steeply-inclined system, characteristic of the 9th century AD underground furnaces of 'Yutanovka type' from Belgorod, Ukraine (Fig. 51: Afanas'yev and Nikolayenko 1982, fig. 15) which subsequently appears on the furnaces from Roganino in the Kharkhov region, also in Ukraine (Koloda 1996, fig. 2).

Multiple bellows set radially at the rear of the furnace (Fig. 53: g) are rarely encountered. However there is an example from furnace F5 excavated at Meroë in the Sudan and dating from the first few centuries AD (Tylecote 1977, fig. 8). A group of six pot-bellows were used, installed in special niches in the furnace wall and fixed to it by means of clay tuyeres, set at a slight angle,

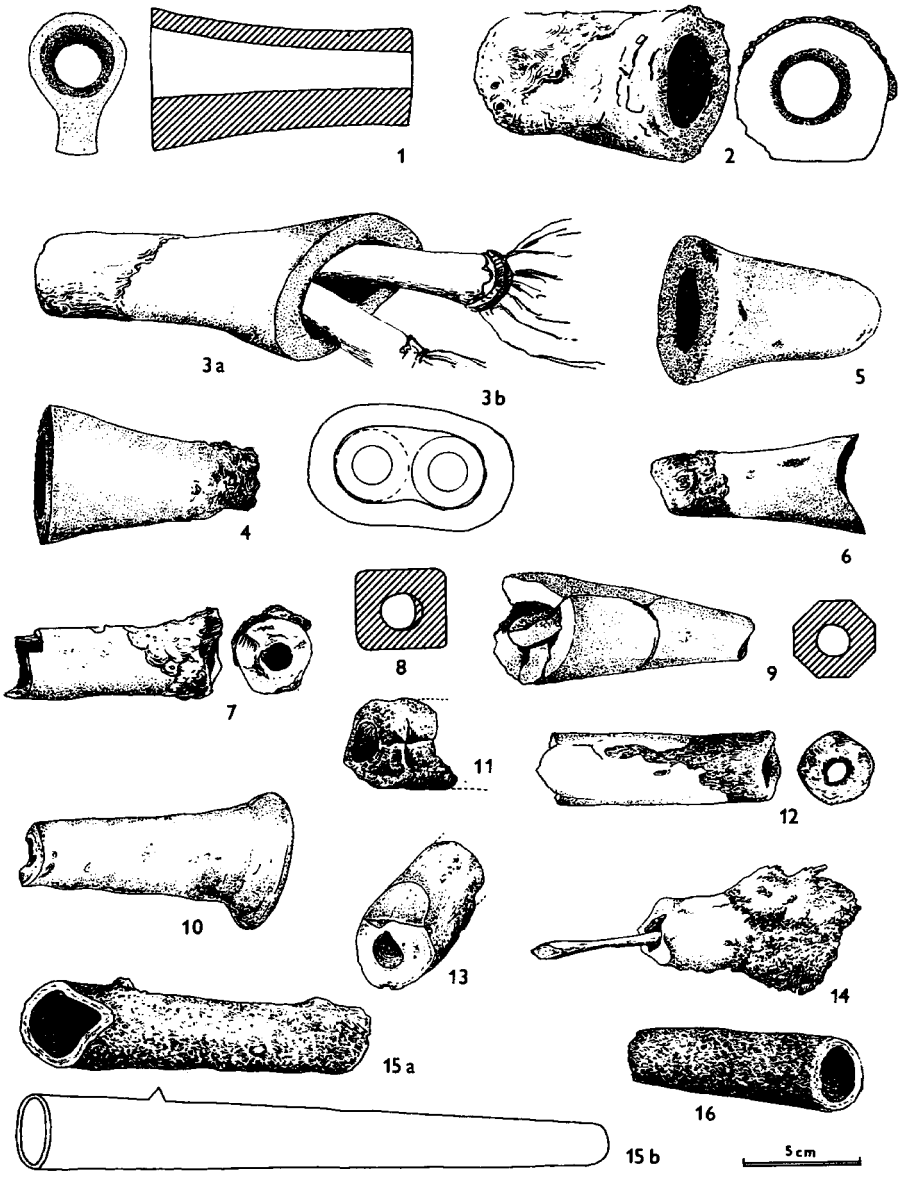


Fig. 55. Tubular tuyeres from European bloomeries. Clay: 1 Sulzbach, Germany, tuyere from an undated furnace; 2 Bellaires I, Switzerland, No B 365, early 5th century AD; 3 a–b Tarjánpuszta-Vasasföld, Hungary, 8th century AD, tuyere adapted presumably for housing two bellows nozzles; 4 Imola 1, N Hungary, 10th–11th centuries AD; 5 Arnbathie, Scotland, mediaeval; 6 Olomučany, Moravia, 9th century AD; 7 Braneshti I, Moldavia, 8th–9th centuries AD; 8 Early Russia, section of a prismatic tuyere; 9 Staraya Ryazan', Russia, early mediaeval clay tuyere with slightly hexagonal section; 10 Žerotín, Moravia, 10th century AD; 11 Prague, Chapel Bethlehem, Bohemia, 12th century AD — cross marked tuyere mouth from a reheating plant; 12 Piotronowice, Poland, 11th–12th centuries AD, from a reheating plant; 13 Adamov, near Blansko, Moravia, 10th–12th centuries AD; 14 Obora, near Blansko, 10th–12th centuries AD — an iron rod sticks in the slag blocking; Iron: 15 Radětice, Bohemia, 13th century AD, from a roaster — a as found, b reconstruction; 16 Öneking, Germany, 8th–9th centuries AD. References: 1 Kolling 1973; 2 Pelet 1973, 3 Gömöri 1977/78; 4 Nováki 1969; 5 Tylecote 1986; 6 Souchopová 1986; 7 Fedorov 1960; 8–9 Kolchin 1953; 10 Ludikovský 1961; 13–14 Pleiner 1958; 12 Pazda 1976; 15 Pleiner 1971a; 16 Sönnecken 1975.

which reached the interior of the furnace about 75cm above the base. According to Tylecote, the bellows were capable of supplying the relatively tall furnace with about 960 litres of air per minute. He empasizes the affinity of this system to that used in Egypt and in recent ethnological contexts in Africa. Apropos, six tuyere vents were found at a recently uncovered domed furnace at Laxton (Crew 1998).

To make the things more complex, atypical arrangements are invariably encountered. At Bellaires III, the Roman period furnace XX housed a lateral tuyere block with a second one having been inserted into the clay stopping of the arch and it is possible that the twin furnace XIX was arranged in a similar way (Pelet 1993, 54–55). And at Boécourt, Jura, Switzerland, it is reported that slightly-inclined tuyeres were located at the arch, but placed asymmetrically (furnace 1: left margin, furnace 2: right margin of the arch). Moreover, furnace 1 was equipped with another tuyere, lateral and horizontally positioned, an arrangement also indicated by the slagging of numerous discharged fragments in the debris in the forepit (Eschenlohr and Serneels 1991, 58 – 66, figs. 45 and 46).

Types of tuyere

The shape of tuyeres vary greatly. Again, two opposing trends seem to have developed, based on the use of tuyeres and may have been influenced not only by the differing methods of supplying the air-blast but also by differences in furnace construction. For example, clay-block tuyeres are characteristic of the late La Tène and Romano-Barbarian metallurgy of central Europe, linked to the Boii, Marcomani, and Hermunduri in Bohemia, Saxony, and Thuringia respectively, but different systems of air-supply and types of tuyere were used with the family of related slag-pit furnaces which prevailed in the first half of the 1st millennium AD in large areas to the north of the Roman military *limes*. Moreover, different types of tuyere could be used in a single smelting district or site, as in the Vaud in Switzerland (Pelet 1973; 1993, 27 – 28, fig. 40).

Some of the best-preserved examples of tuyeres from bloomery contexts found on excavations are described below, but it should be stressed that this is not intended to be a strict typology. Basic types of tuyere can be identified from the archaeological record, despite the fact that many were broken when deposited on waste heaps. They were often not fired but merely air-dried, with firing of the parts exposed to heat from the furnace having occured during use. This means that the parts of tuyeres nearest to the bellows will have disintegrated over time. Completely preserved specimens are rare but do exist.

Tubular tuyeres

This is the most common form, which appeared early on over a wide area and survived until the Middle Ages. In Europe, they were typical for 10th – 13th centuries. It is also the simplest form, being designed as a tubular sleeve for the cylindrical nozzle of a set of bellows. In length they range from 15 to 20cm, the bore being between 9 and 25mm an the diameter of the trumpet-shaped outer end between 7 and 10cm (Fig. 55).

The earliest examples, from the centuries around 1000 BC, come from bloomeries in ancient Colchis (western Georgia), where they are attested among all cultural groups and at many sites (Khakhutaishvili 1987, figs 14, 26, 28 – 29, 32, 34, 38, 42, 43, 45, 51, 54, 60, 71). Published illustrations depict fragments of narrow clay tubes, some of them slightly bent, with others perforated by a small hole and some having trumpet-shaped ends. A combination of the bent form and the recorded use of bowl-furnaces in this region, has led to the assumption that the air-input comprised several tubes which brought the blast to bear on the furnace over its rim and the remains of inserted tuyeres have actually been found (*op. cit.*, fig. 60: 1). This idea is reminiscent of a much later and geographically-removed installation for air blowing, made up

of a number of elbow-shaped pipes in the Gu-Xing (Kushing) and Nan Yang ironworks of Han China (Tylecote 1983, 437 – 438, fig. 5).

Another example of non-European tubular tuyeres of this type is provided by fragments found at Taruga in Nigeria, with internal diameters of 3–5cm, and in one example as long as 25cm (Tylecote 1975, 52, fig. 4). Tylecote also described fired fragments of tubular tuyeres (internal diameter 22mm) found at the Meroë iron-producing centre in the Sudan (Tylecote 1977, fig. 2A) where furnace F5 shows that they were connected to pottery drum bellows.

There are many tubular tuyeres from European contexts, dating from periods from the la Tène to the Middle Ages, when they predominate. At Mšec in western central Bohemia, middle La Tène, a fragment of a thick, trumpet-shaped tuyere was found in the layer of slag and debris (Pleiner and Princ 1984, 145, figs 8: C, and 10: 8). This is an unusual form to have been found with a slag-pit furnace. The contemporary or just slightly later finds from Martys in southern France show that robust tubular tuyeres were used in air-duct systems of these developed shaft furnaces (Domergue *et. al.* 1993, 346, fig. 242), although other forms, some facetted, others double-bored were also found among the debris.

Three main types of tuyere are known from Roman ironworks in the Swiss Vaud, one being the tubular form, mostly found as fragments in the waste heaps. These specimens were up to 25cm long and 25 – 30mm in internal diameter and were slightly flattened at the bottom (Fig. 55: 2) and were the main form found in the western and eastern sectors of Bellaires I (Pelet 1973, fig. VII; 1993, 18 – 22). The other two types, ogee and block tuyeres, are described below.

Cylindrical tuyeres, heavily slagged at one end, were found on a 3rd – 4th centuries AD bloomery site of the Przeworsk culture at Sinica in the basin of the river Bug, outside Roman Imperial territory. They were 15 – 20cm long, with a 30 – 45mm bore, a trumpet mouth of 4 – 9cm diameter, and walls 1.5 – 3cm thick. Two tuyeres were found in the hearth of furnace 2, facing in opposite directions (Kropotkin and Nakhopetyan 1976, 319, figs 1: 4 – 5).

Most of the European clay tuyeres known belong to the early and late mediaeval periods (7th – 12th centuries AD). They appear predominantly in central and eastern Europe, where they represent a distinct technical horizon, especially in the 9th – 12th centuries. Almost identical forms of tuyere were in use on blacksmiths' forges (Fig. 55; 11 – 14), but those cited here relate exclusively to bloomery furnaces. The eastern examples should be introduced by those from the site of Lopatna, near Alchedar, SW of Russia, which yielded some fifty fragments of tubular tuyeres (bore 16 – 20mm, diameter of trumpet mouth 4 – 6cm, length 5 – 12cm), some of these having been found within destroyed furnaces (Fedorov 1960, 206, fig. 57: 2 – 4). At Braneshti, in the same area of south-east Europe, similar finds were made, with some of the tuyeres being blocked by solidified slag (*ibid.* 260, pl. 70). In this connection, the site of Grigorovka, more to the north in the Podol (see chapter IX), is very important, since tubular tuyeres were found *in situ* here, inserted into the furnace arch and projecting into the interior (Fig. 54: 3; Artamonov 1955a, 109, fig. 45). The complete specimens were about 23cm long, with bores of around 10mm. These tubular, or, better, trumpet-shaped tuyeres are the norm for early mediaeval Russian ironmaking sites such as Gorodsk and Staraya Ryazan' (Kolchin 1953, 33, figs 8 – 10). Their upper surfaces may be facetted and they are rectangular or polygonal in section (Fig. 55: 8 – 9). A tubular tuyere with a longitudinal projection on the lower site, hidnering the torsion, comes from an undated furnace at Sulzbach, W. Germany (Kolling 1973); with its key-shaped cross-sectioned remains unique so far (Fig. 55:1).

Tubular tuyeres were widely distributed in the area spreading from Moravia to the south of Austria, the Burgenland, western and northern Hungary and southern Slovakia. Two types have been found on bloomery sites such as Olomučany in western Moravia, one thin-walled and well fired (Fig. 55: 6), the other more robust and presumably inserted into the furnace to receive the thinner tubes which constituted the protection for the bellows nozzles proper (Souchopová 1986, fig. XII: 1 – 2). The debris of one furnace could produce up to 140 tuyeres (*op. cit.* , 71).

There are also stray finds, some two centuries later in date, from unexcavated sites in the same region around Blansko, as at Adamov (Fig. 55: 13) and Obora. The Obora find is of special interest, since it is a slagged tubular tuyere with an iron rod still embedded in it (Fig. 55: 14), stuck there when the smelter failed to clear the blockage of solidified slag. Some specimens have bevelled ends which are also slagged, indicating that they were positioned in an inclined plane down towards the furnace hearth (Pleiner 1958, figs 59, 64, 65).

Another Moravian bloomery site, Žerotín in the north of Moravia, dated to the 10th century (Ludikovský 1960) yielded some undamaged trumpet-shaped tuyeres (Fig. 55: 10) which were up to 15cm long with 10 – 16cm bores and 7 – 7.5cm diameter trumpet ends. They were positioned over the rim of a flat open smelting hearth found during a rescue excavation. Bohemia, to the west of Moravia, shows a similar picture. Tubular tuyeres of the 11th, 12th or 13th centuries are known from smelting sites at Lysá nad Labem and from Prague-Chapel Bethlehem, where they were used for blowing into reheating hearths (Fig. 55: 11; Pleiner 1958, 240 – 250, pl. XXII). A tubular tuyere nozzle comes from the forepit of furnace 2 at Chýnice, SW of Prague, which is said to have had a bore of 23 – 25mm (Krajíc and Matoušek 1985, 174, fig. 4).

Tubular and trumpet-shaped tuyeres of the type discussed have been found on almost every early ironmaking site in Hungary, including the the adajacent border regions of Slovakia in the north and of the Burgenland and Upper Austria in the west. The northern ironworks province operating in the 11th – 12th centuries, includes sites such as Felsökelecsény, Imola (Fig. 55:) and Trisz (Nováki 1966, Heckenast *et al.* 1968, fig. 20) and Gemerský Sad (Füryová *et. al.* 1990), while the western area includes Tarjánpuszta-Vasasföld, the earliest site from the 8th century AD, which yielded a remarkable specimen with a wide trumpet end (Fig. 55: 3a – b: Gömöri 1977/78) and the sites of Veszprém, Köszegfálva, Vasvár and Nemeskér (Heckenast *et. al.* 1968, fig. 40: Gömöri 1977). In the furnace debris of the 10th century Somogyfajsz ironworks, hundreds of trumpet-shaped tuyeres and their fragments were found (Fig. 45: 3; Gömöri 1995, fig. 4), a similar situation to Dörfl in the Burgenland which produced more than 100 nozzles (Ohrenberger and Bielenin 1969, 91 – 92; Bielenin 1977, 55 – 60, fig. 7, pl. 2: 11). With regard to the sites at Olomučany, Nemeskér, Somogyfajsz, Sopron, and Dörfl it must be noted that tubular tuyeres were inserted into special removable clay panels which sealed the furnace arches. Classic examples are the tuyere panel from Olomučany (Fig. 56: 4: Souchopová 1986, fig XI: 1) and those from among the 11th – 12th centuries finds at Nemeskér and Sopron-Magazhíd (Fig. 56: 5: Gömöri 1977/78; the panel from Dörfl is depicted in Bielenin 1977, fig. 7). These panels were of the same thickness, around 10 – 12cm, as the front walls of the furnaces they served. The ogee-shaped arches of the embanked furnaces of the Imola type from northern Hungary, indicate the use of similar panels, which must have been removed, along with the bellows, before the bloom could be extracted.

These tuyeres were mostly designed to receive the mouth of a single bellows, regardless of the number of units blowing the furnace. Rare examples of flattened-trumpet outer ends suggest the use of two sets of bellows through a single tuyere, which would permit an uninterrupted air blast when the bellows were operated alternately. The tuyeres from Glastonbury Lake Village in England, dating from the 1st century BC to the 1st century AD, were 10cm long with a 8cm wide trumpet mouth (Tylecote 1986, 141 – 143, fig 87: a) and, as with those from the early mediaeval sites at Tarjánpuszta-Vasasföld I (42cm long, trumpet mouth 4cm x 8cm: Fig. 55: 3) and Nemeskér, both in Hungary (Gömöri 1977/98, 128, figs 19: 1–2, and fig. 35) are assumed to have been used in this way. All of the tuyeres described so far were made of clay, but rare examples of iron tuyeres exist, such as the 8th – 9th centuries AD example from Öneking, near Lüdenscheid, in the Sauerland of western Germany (Sönnecken 1974/75, 169), which was made from an iron sheet 2.5mm thick, 12cm long and with an internal diameter of 20mm (Fig. 55: 16). Iron tubes, positioned horizontally, were found in the side wall of the 13th century roasting hearth at Radětice in south-central Bohemia (Pleiner 1971, 48, figs 3, 4, 6: 39–42) and seem

to have projections on their surfaces, presumably to prevent them from turning in hearth wall (Fig. 55: 15).

Tubular tuyeres show close affinities with the bellows mouth proper, which has to be protected and are presumably descended from the ceramic blow pipe covers of Bronze Age metallurgy. They were easy to replace when necessary during the process and their consumption might have been considerable on some smelting sites.

Conical tuyeres

Short conical tuyeres have so far only been found at two sites, both in the Roman ironmaking district of the Vaud, Switzerland (Pelet 1973, 31 – 32, figs 2 and 3; 1993, 18 – 19, fig. 11). Complete and broken specimens were scattered throughout the waste material over all three sectors of the Bellaires I site and indeed were the only type of tuyere present in the northern sector. They are typically short, around 10.5cm long, with a 30 – 40mm bore and a rear aperture 5 – 10 cm in diameter (Fig. 56: 1). The rim of the rear aperture was circled with shallow depressions, imprinted in the clay when it was still wet. The purpose of these depressions is not clear, although similar features have been observed on the rear sides of the local block tuyeres (below). Some tuyeres had been inserted into the furnace wall at an angle of 45° to the horizontal, according to the excavator, although none was found *in situ*. Among the remains of ferrier 3b at Clérimois in France, around the later furnace 50, there are fragments of tuyeres which are also conical in shape, of preserved lengths around 16cm with bores of 5cm expanding 11cm for the outer end (Dunikowski and Cabboi 1995, 91, fig. 63: 4).

Block tuyeres

This kind of tuyere should be regarded as a removable element of the furnace wall or arch blocking. It is difficult to understand why these were preferred to tubular tuyeres in some ironworks, although it may be that they absorbed a considerable proportion of the vibrations produced by the operation of the bellows, especially when protruding through the furnace arch, which is where they seem largely to have been positioned. However, they were also considerably resistant to damage.

In general, two principal sub-types have been recognized. One resembles a perforated brick, while the other is a clay block, semi-circular or ogival in section the bore of which is often situated eccentrically in the upper part.

The great majority of tuyeres of the first sub-type come from the La Tène and Romano-Barbarian periods, and in their classic form they may justifiably be held to be products of eastern Celtic ironmaking practice, later adopted by some Germanic tribes. It must be borne in mind, however, that comparable block tuyeres were in use on blacksmith's forges far beyond this area - in Gaul, in Scandinavia and the northern part of the British Isles (Fig. 57: 4). The earliest finds of brick-shaped block tuyeres were made before World War II in the La Tène ironmaking region of the Siegerland in western Germany. In addition to the large block with three air-inlet holes from the Engsbachtal, this region has provided examples of tuyeres with single 15 – 28mm bore ducts, which are slightly tapered internally, as is the case with the finds from Oberdielfen, Trupbach and Alchen (Fig. 57: 1–3).

In central Europe, in Bohemia and Saxony, brick-shaped tuyeres constitute a distinct archaeological horizon. The smaller blocks, usually 10 – 12cm by 8.5 – 10cm in section, are dated to the La Tène period, whilst the larger ones (14 – 15cm by 11 – 13cm) date from the Romano-Barbarian period. It is rarely possible to state their lengths, since their rear parts, which received the nozzle of the bellows, does not survive, except in some very rare cases, such as the 10cm long specimen from Ořech near Prague (Motyková and Pleiner 1987, 307, 392, figs 11 and 16), one from Lovosice, 12cm in length (Pleiner and Salač 1987, pl. II and III), and an

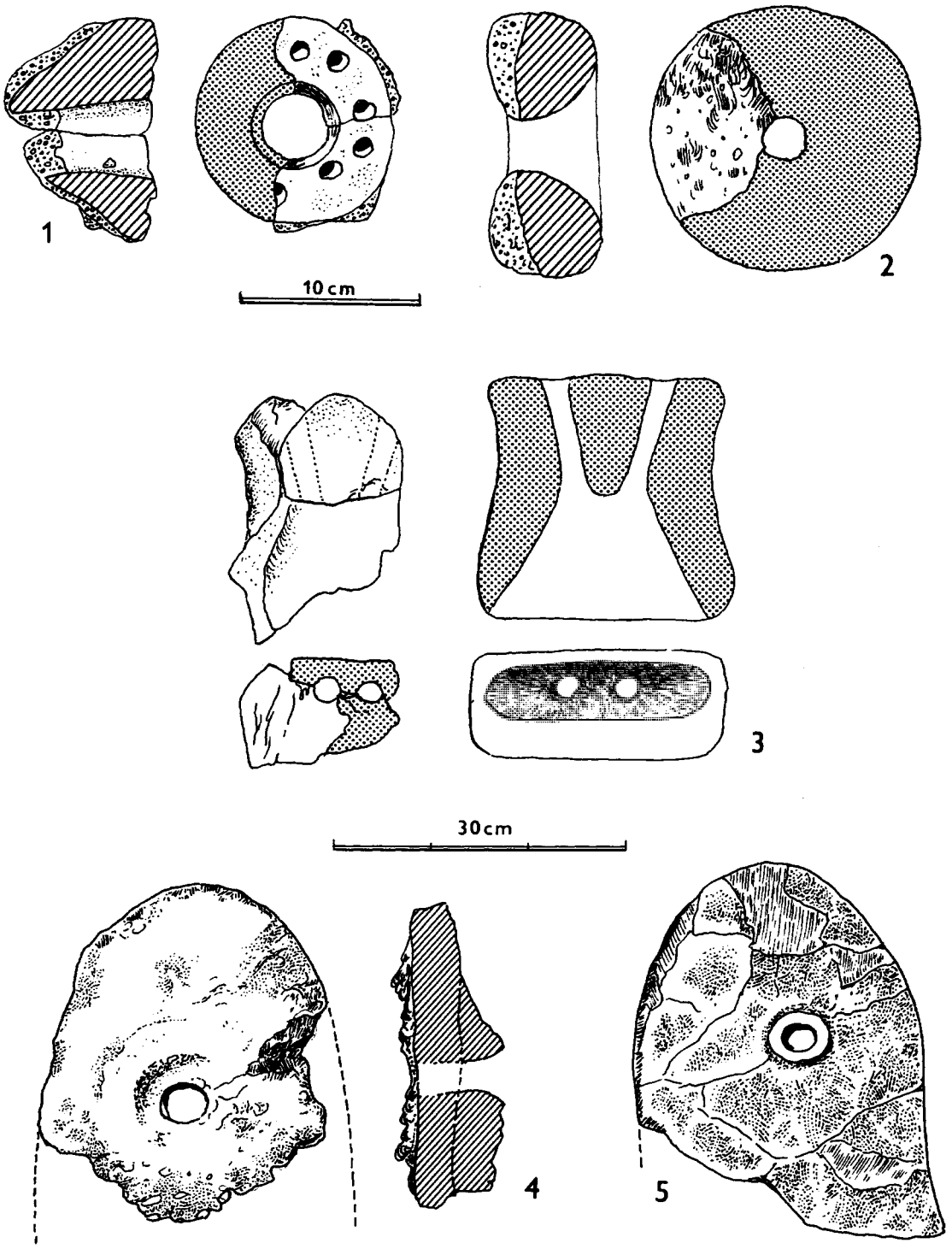


Fig. 56. Other kinds of tuyere and tuyere panels. Conical: 1 Bellaires I, Roman. Disc: 2 Ballyvourney, Ireland, mediaeval. Block tuyere with diverging air flow: 3 Bardown, England (left: as found, right: reconstruction). Tuyere panels from furnace arches: 4 Olomučany, Moravia, 9th century AD; 5 Nemeskér, Hungary, 11th–12th centuries AD. References: 1 Pelet 1973; 2 Tylecote 1986; 3 Cleere 1963a; 4 Souchopová 1986; 5 Gömöri 1977/78.

example from Gera-Tinz in central Germany, which was at least 36cm long (Dušek 1967, pl. XXXIV to XLVIII). The outer apertures were funnel-shaped, while the slightly protruding front ends of these blocks, which were in contact with the hot interior of the furnace, are usually heavily slagged and in some cases their mouth have become blocked by slag. When this happened, the tuyere would have been replaced, to avoid interruption to the process. They were often inclined slightly downwards, so that their mouths could be protected to some degree against the slag running down them.

There are examples of this type being made from high-quality refractory materials. Mineralogical analysis of a block tuyere from furnace 2 at Tuchlovice, Bohemia (Romano-Barbarian period, 4th century AD, Fig. 57: 7, see Pleiner 1958, pl. XV: I), showed that it was composed of clay containing mullite needles which had been heavily grogged with quartz sand that was a little coarser (0.2 – 0. 5mm) than that used for the furnace structure. The slag which had solidified over the end had several distinct layers in it, showing that the tuyere had been inserted into the furnace on several occasions, possibly after slag had been tapped off. The clay body was obviously capable of withstanding temperatures well up to 1540°C (Bartuška and Pleiner 1965, 10).

The finds from the Siegerland referred to above were isolated examples from bloomery waste tips, and it was not possible to reconstruct the furnaces on which they were used with any certainty. In the late La Tène and early Romano-Barbarian cultures of central Europe (Bohemia, Saxony, Thuringia) however, there is no doubt that they were used on slag-pit furnaces. Many come from working pits, as at Chýně, near Prague, of La Tène D date, Ořech, near Prague, of the 1st century AD and Kyjice, north-west Bohemia, dating to the 1st century AD. As already noted, some have been found immediately in front of the furnace arches, as was the case at the 1st century AD site at Lovosice in northern Bohemia (Pleiner and Salač 1987, figs 2 and 3). At Lovosice and also at Chýně, Ořech and Alchen, the front part of the block sloped, as it apparently was the axis of the entire air-inlet (Fig. 54: 1; Fig. 57: 3 and 6). At the 2nd century AD ironworks at Gera-Tinz in central Germany, 26 fragments of block tuyeres (Fig. 57: 6) were found in the forepits of both slag-pit and apparently free-standing furnaces from different phases. They varied slightly in shape and, in addition to the more usual rectangular form, some were triangular or oval in section (Dušek *op. cit.*, 144, fig 3, pl. XLI, XLIII). The tuyere from Tuchlovice, referred to above shows that similar examples were also used in low shaft-furnaces with flat hearths, dating from the end of the Romano-Barbarian period (Fig. 57: 8).

Of different appearance are the semi-cylindrical or ogee-shaped blocks from regions within the Imperial military border, in Switzerland, France and Belgium, which date from the period of decline of Roman power through to the Middle Ages. These are typical for medium size ironworks using shaft-furnaces and were often installed laterally and/or frontally. Examples include those from the sites at Bellaires II and III and at Bossena in the Vaud which had an ogee-shaped cross-section, 10 – 13cm wide by 25 – 16cm high, with a hole of about 25mm diameter located eccentrically in the top part (Fig 57: 5: Pelet 1973, 39 – 45; 1993, 22 – 25, figs 20 – 35). These also had at the rear a halo of shallow indentations, like those already noted on the conical tuyeres from Bellaires I. They date to the later phase of operation of the Vaud ironmaking region, in the late Roman or even post-Roman phases (4th – 6th centuries AD). Of even later date, the 7th century AD, are the tuyere blocks used with the furnaces at Boécourt (Eschenlohr and Serneels 1991, 58 – 65, figs 41 – 43, pl. 2 and 3).

There are fragments of the ogee-type of tuyeres from eastern France, from Clérimois, apparently connected with furnaces of the later Roman phases (Dunikowski and Cabboi 1995, figs 52 and 72). The site of Frouard in France, 5th – 6th centuries AD, yielded similar examples, and the type emerged also in the much later ironworks of the 8th – 10th centuries, discovered at Ludres (Leroy 1997, figs 60, 61, and 65). A relatively large block tuyere was found at Serrig in the Saarland of western Germany. Measuring 13 x 13cm in section, with a 30mm duct, it was a

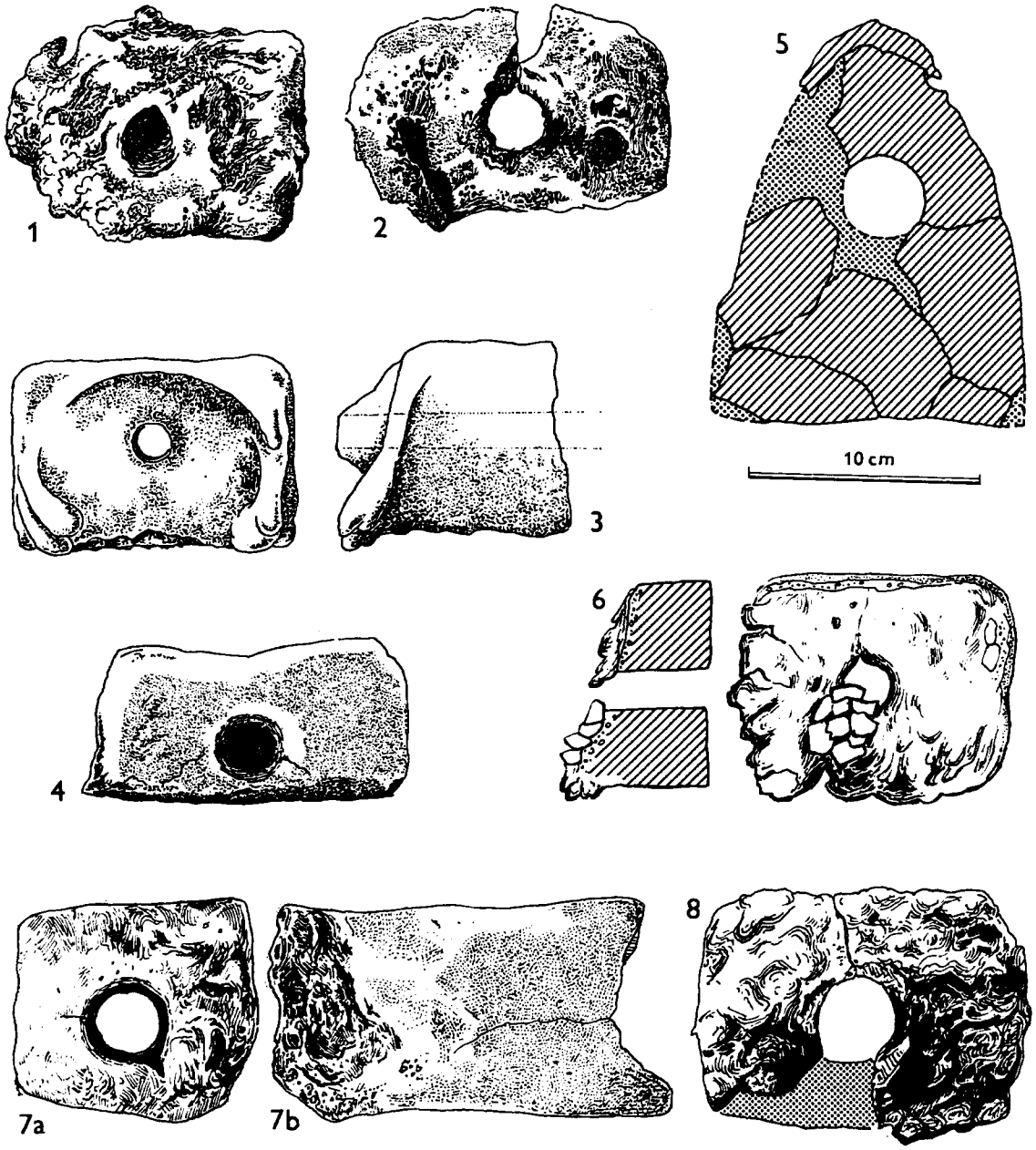


Fig. 57. Block tuyeres. Brick-shaped: 1 Oberdielfen, Germany, La Tène period; 2 Trupbach, W Germany, La Tène period; 3 Alchen, W. Germany, La Tène period; 4 Bibracte – Mont Beuvray, France, La Tène period; 6 Ořech near Prague, bloomery 37, 1st century AD; 7 a – b Gera-Tinz, Germany, pit 3, early Romano-Barbarian period; 8 Tuchlovice, Bohemia, late Romano-Barbarian period, 3rd–4th centuries AD. Ogival type: 5 Bellaires II, Switzerland, Migration period, both ends broken, preserved length 41cm. References: 1 – 4 Pleiner 1958 after Weiershausen and Bulliot; 5 Pelet 1973; 7 Dušek 1967; 8 Pleiner, Archives Archaeol. Inst. Prague.

stray find from the iron-smelting debris on the site (Schindler 1976, 56, fig 5: left).

Of especial interest are two block tuyeres of different design, from the 2nd – 3rd centuries AD Roman ironmaking site at Bardown in Sussex, England (Fig. 56: 3). These are oval-section clay blocks, surviving to 12.5 and 20cm in length respectively, with two air-holes of 20 – 25mm diameter, which diverge, rather than converge, towards the interior of the furnaces (as shown by the slagged ends), and in this way spread the air blast from the bellows over the whole active zone of the furnace rather than concentrating it on a single point (Cleere 1963). Comparable specimens are known from elsewhere in the Weald from this period, at Cranbrook, Chitcombe and others and it is possible that they may have received the blast from twin sets of bellows.

Later phases of the Continental mediaeval period of bloomery production saw block tuyeres only rarely. A clay block 10cm high in section with a 20mm duct was found in the later of the two furnaces at Krummenscheid, near Altena, in the Sauerland region of western Germany (Sönnecken 1981, fig. 2). It was inserted into the left side of a shaft furnace, embedded in a very thick furnace lining.

Disc tuyeres

Only a few examples of so-called disc tuyeres are known, and these come primarily from Ireland. Those from Ballyvourney, County Cork, Ireland, included intact specimens 13cm in diameter and 6cm thick (Fig. 56: 2) The aperture on the heavily slagged inner face was 30mm, tapering down from an external aperture 7.5cm (O'Kelly 1952, 33, fig 3. nos. 1 – 3: Tylecote 1986, 142 – 143, fig. 87: d). Others have come from excavations at Garryduff I and Lislea, both in Co. Cork, Cathedral Hill, Armagh, Co. Armagh, and Reask, Co. Kerry (Scott 1990, 163 and 166, Figs. 6.5.7). Another, and larger, example comes from the Östergötland region of Sweden and was 24cm in diameter by 6cm thick, although no other details having been reported (Serning 1979, 85 – 87, fig. 32). While these were not tuyeres in the classic sense, in other words inserted into the furnace wall, they did act as the protectors for the nozzles of bellows and, in Ireland at least, on the basis of literary evidence, were more likely to have been used with smithing hearths rather than smelting furnaces (Scott *op. cit.* 167 and 193 – 194).

Bellows

There is no evidence in the archaeological record of Europe for the type of bellows used in prehistoric and mediaeval bloomery furnaces to supply the air blast. Only from the Roman period ironworks at Meroë in the Sudan is evidence advanced to justify the claim that furnace 5 was operated using drum bellows (Tylecote 1977, 168 – 169) in a tradition that is spread over the African continent and the Near East since the Copper and Bronze Ages. Pot-bellows consist of a pottery or wooden vessel into which air is drawn, to be expelled via a tube in the base into the tuyere and thence into the furnace or hearth, by pushing down upon a leather cap or membrane stretched across its top. A pair of drum bellows is usually operated by one man, blowing each alternately, the leather membrane being pulled back into place by a tensioned rope or strap (Fig. 58: top left). This type of bellows was in use still in the 1950s at the bizzare smelting furnaces of the Matakam tribe in North Cameroon, Africa (Gardi 1954). In this particular case the pair of bellows set on a platform to the rear concentrated the blast in a huge clay tuyere, over 150cm long, which led from the throat down to the furnace hearth — a system absolutly unknown in Europe. The so-called 'bellows pot' from the Roman site at the Little Farningham Farm, Sussex (Cleere and Crossley 1985, 43, 45, fig. 15) is not easy to be explained as a blowing device; unfortunately it has no counterparts until the present days.

Consideration must also be given in all regions to the possibility of simple bag or skin bellows being used for blowing bloomery furnaces. Pairs of animal skins (goat or sheep), with the legs sewn up and fitted with outlet tubes, would be alternately pushed and pulled. A slot at the

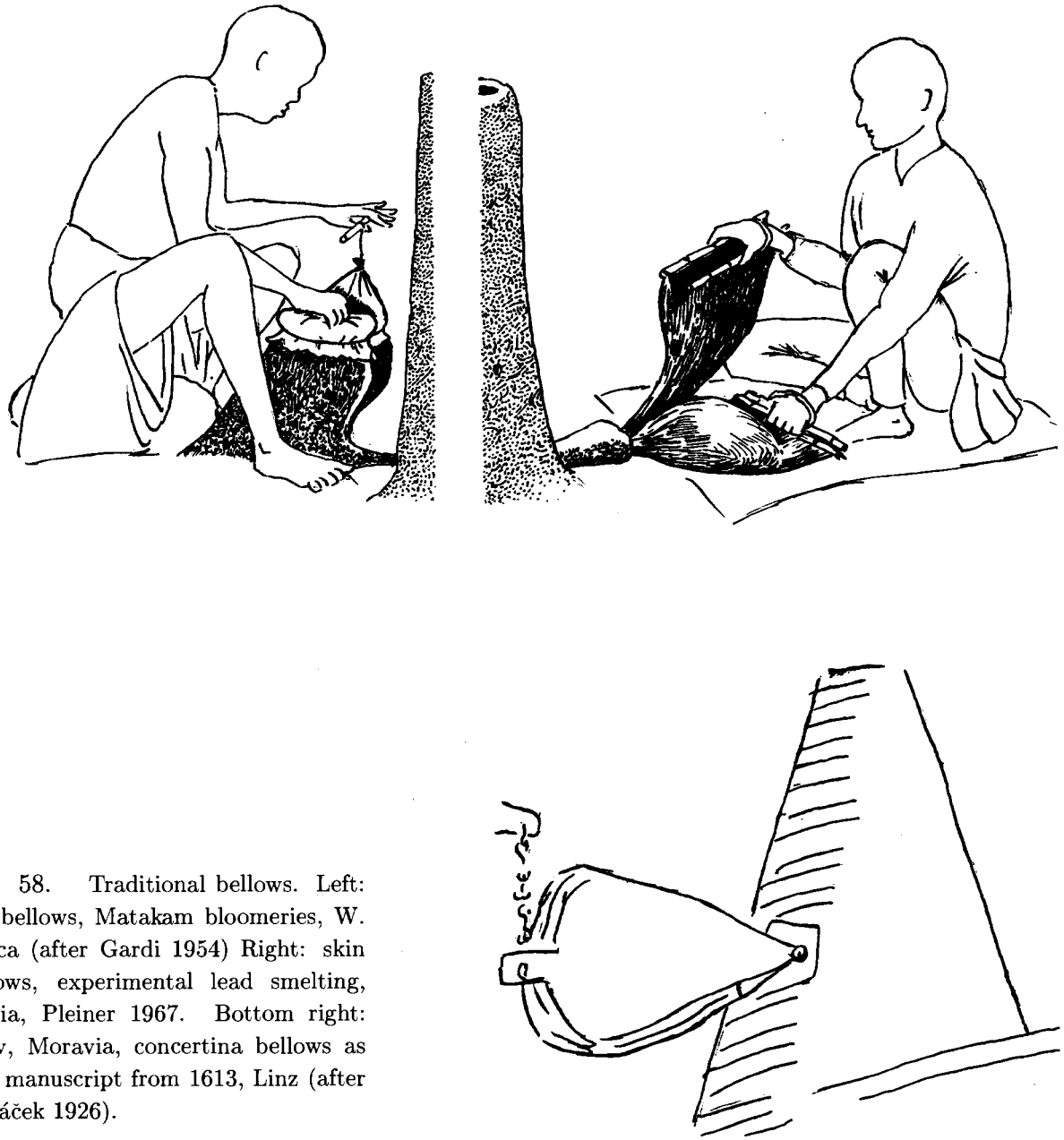


Fig. 58. Traditional bellows. Left: pot bellows, Matakam bloomeries, W. Africa (after Gardi 1954) Right: skin bellows, experimental lead smelting, Persia, Pleiner 1967. Bottom right: Úsov, Moravia, concertina bellows as in a manuscript from 1613, Linz (after Pilnáček 1926).

back would be covered by the operator's hand when pushing, so as to expel air, and left uncovered when being raised, allowing air to be sucked into the skin (Fig. 58: top right). A skilled operator would work in this way for as long as two hours and it is known from ethnographic sources that operators could change over without interrupting the air blast. According to iconography, simple skin bellows were widely used by Roman smiths (Weisgerber and Roden 1985). There is also considerable literary and linguistic evidence for this, and indeed, the words for 'bellows' across the spectrum of the Indo-European language families is usually cognate with words for 'skin' or 'bag' or 'belly' (Scott 1990, 174).

The valved concertina bellows was introduced into Europe some time during the Roman period, as shown by contemporary iconography, although this depicts only the blacksmith's work. A rare archaeological find comes from a 10th century AD smithy at Sarkel-Belaya Vezha (Pleiner 1962, 181, fig 28: B: after Sorokin, recently treated by Pletneva, 1996, fig. 6). At a forge there, a roughly-triangular wooden 'desk', apparently a support for a leather bellows, possibly of concertina type, was found. It may be postulated that this type of bellows was also used for blowing smelting furnaces. Unfortunately a relevant passage by the late Roman author Phylargyrius (*Ad Aeneidem*, see Chapter IX) refers only to the material from which bellows were made (ox hides) and not their construction: '*folles taurini habent cum liquescunt petrae ubi ferrum fit*'. Concertina bellows could be operated in either the horizontal or vertical plane and illustrations show that both orientations were used (Fig. 58: bottom right) An application of the latter is to be seen in a rare illustration of an early 17th century (1613) *Stuckofen* from Moravian Úsov from the Liechtenstein archives in Vienna (*sub item* Aussee 2, quoted by Pilnáček 1928, 26, fig.). This was the time which saw the use of bellows driven by water wheels more than five centuries, both in bloomery and first blast furnace plants.

There is no firm archaeological evidence for the use of the '*trompe*', known in post-Mediaeval Italy, Corsica, and the Pyrenees. This was a vertical tube directing a stream of falling water and air down to a closed tank in which air-pressure was developed and directed through a tuyere with adjustable inclination into the furnace or hearth. Nonetheless, a rudimental system, known as '*Bottichgebläse, Trommelgebläse*' has been proposed in a reconstruction of the system supplying the air-blast to Noric steel-producing furnaces and the idea has been acctepted by Horstman (1995) in his interpretation of Noric steel-making. Unfortunately, no reliable archaeological evidence has been presented. The '*Bottichgebläse*' also works on the air-pressure principle using membranes or wooden vessels which collect the bubbles of running water and direct the air through pipes to the forge. It is known from the ethnography of the Alpine region where the device used to be installed in smithies sited beside fast-flowing mountain streams (Zeilinger 1965).

The very efficient cylinder and box piston bellows were hardly used in Europe before post-Mediaeval times. They are known from the ancient Far East, and were in use in China as early as the 3rd century AD (Needham 1964, 47; Barnard and Tamotsu 1975, 62, 64 – 65, fig 37). It is claimed that water-driven bellows were also introduced in the Far East as early as the 1st century AD (Needham 1964, 19). However, water wheels for driving bellows in ironmaking did not reach Europe until the 11th – 12th centuries at the earliest.

During the many smelting experiments carried out in various parts of Europe the need arose to supply air blasts to the different reconstructed furnaces, and experimenters have been obliged to use various types of blowing equippment to deliver, according the type and dimensions of furnaces in use, 200 – 300 or even over 900 litres of air per minute. Various types of electric compressors have been pressed into service (the so-called 'vacuum-cleaner metallurgy') or even electrically driven old blacksmith's bellows. In recent years, hand-driven concertina bellows of varying size were successfully applied in experimental set-ups, giving the crews the possibility to train their muscles. In his experiments, Crew (1991a, 25 – 27) used a variety of blowing apparatus, from hand devices to electrically driven piston bellows. The latter, capable of delivering 180 – 350 litres per minute, proved to be the most effective because of the practical difficulty of delivering precisely measured air-rates using concertina bellows.

Chapter XI

REHEATING HEARTHS

In the majority of cases, the primary product of the smelting process consisted of a porous conglomerate of fibres, sheets, and globules of iron which, having been reduced in the solid state, were roughly sintered together and permeated with slag and charcoal residues. In this form it could not be used immediately for the production of iron artefacts and the first task of the ironmaker was therefore to remove as much slag as possible from the iron and to weld together the particles of metal.

The principles of reheating

According to some accounts of bloomery ironmaking in its latest phase, in the 16th to 19th centuries, the raw bloom was extracted from the furnace and, when still hot, hammered with wooden mallets to free it from adhering and entrapped slag. This was, however, only a preliminary treatment and of limited efficiency. It was also very difficult, since the slag cooled very rapidly and the conglomerate was often crushed and fractured and would disintegrate, so that it was necessary that for the mallet to be applied gently. There is ethnographic evidence from many regions in Africa among, for example, the Baels in Chad, the Senufo on the Ivory Coast and the Matakam and Mafa in Cameroon (cf. articles by Fuchs, Eckert, Gardi in: Eisen + Archäologie 1978, 87 – 123: Gardi 1954: David *et al.* 1989, 199 – 200) that the iron-slag conglomerate was mechanically separated from the superficial slag while still hot with the help of water being poured over it. The cold remainder was worked later, not just at the site, but at other locations such as villages far removed from the smelting operation, by shattering it with stone hammers and on stone anvils. The heavier and more ductile fragments of metallic iron were separated out, cold-hammered flat and then heated in clay envelopes to be welded together.

Something closer to a more compact piece of metal could be expected from the operation of a slag-tapping furnace, but even here, the product contained so much slag entrapped in cavities that further treatment was essential to make it suitable for the smithing of artefacts. There was only one effective way to ensure the adequate removal of slag and this was to reheat the conglomerate or raw bloom to temperatures at which the metallic iron was in the austenitic state (above 900°C) and the associated fayalitic slag became molten (1200 – 1300°C). By so doing, it became possible to weld together the discrete fibres and more compact nodules of metal within the spongy mass by hammering and to expel the viscous or liquid slag from the surface and, most important, from internal pores. It must be borne in mind that under these circumstances, some of the reheated iron was oxidized to hammer-scale which had also to be removed. The working of the smelted product thus consisted of two successive stages: first, the raw bloom was reheated in a fire, furnace or hearth, and, second, it was forged up immediately by hammering it on the anvil. This procedure might be performed several times to ensure the maximum possible consolidation of the metal and expulsion of slag.

Both processes are mentioned in ancient as well as later written sources. The treatise on *On diseases* by Hippocrates (5th century BC), already quoted in Chapter VIII, contains an interesting comment on iron smelting (IV.45): iron 'having been heated for the second and third times, will be left by the visibly-molten slag' (Halleux 1974, 190 – 191). The reheating and hammering of blooms is referred to in a number of later works on the art of mining and metallurgy, most notably by Biringuccio (1540, chapter 6 of book I), Georgius Agricola (1556, XII, IX), and Rożdzieński (1612, K, 2/5), although, unfortunately, all lack descriptions of the installations used. Special reheating furnaces or hearths, either as regular components of the most up-to-date bloomeries or as installations in ironmaking centres, are referred to by writers

such as Swedenborg, Lampadius, Evenstad, Osiński, and others in the 18th and early 19th centuries.

Archaeological excavations of ironmaking sites of almost every period often produce features that have usually been interpreted as reheating hearths, on the basis that they differ fundametally in form from the smelting furnaces. Such features are rather flat, open hearths or hollows that would not have been suitable for the creation of a reducing atmosphere and which have little or no slagging of their walls. They are usually larger than the smelting furnaces and their fills contain charcoal and small particles or lumps of slag. It is very difficult to verify these interpretations, especially those in older excavation reports. In cases where these features are found within the smelting complex, there is a greater likelihood that they were indeed reheating hearths. But where they occur isolated, or in groups consisting solely of features of this kind, there is a considerable degree of uncertainty over this description.

Strictly speaking, no special provision was necessary for the reheating of raw blooms and a heap of charcoal blown with bellows could have produced the necessary conditions, leaving little or no evidence in the archaeological record. Only the repeated use and cleaning up of the same spot would result in the creation of a depression or shallow pit with red-firing of the subsoil. In sandy soil this burning layer will often have disappeared completely. To keep the fuel gathered together and the heat concentrated, some metalworkers deliberately used depressions. In clay soils, they can be recognized as pits that might be round, oval or irregular in plan, often lined with reddened clay or flat stones, or adapted especially for reheating purposes some other way. They vary greatly in size which gives rise to the suggestion that two kinds of reheating hearths might have been used at different stages of the reheating process. The reheating of large and heavily slagged blooms, possibly several in one operation, required larger hearths which would have been of use only in the first stage of reheating which involved, above all, the remelting of the smelting slag adhering to the product. Thus, the slag waste found in the fills of such hearths would comprise amorphous lumps of solidified bloomery slag and hammer-scale deriving from the hot metal.

The reheating of the remaining, smaller pieces of iron-slag conglomerate led to the production of a more compact bloom or billet and required a device, suitable for a blacksmith's work, in fact, more or less a blacksmith's hearth, of some 40cm in diameter. The heating of the iron resulted in the creation of a different slag, consisting to a great degree of molten hammer-scale from the metal and possibly sandy and lime fluxes, with only a minor fraction of the original bloomery slag. This waste product solidified in the form of dish-shaped cakes (PCB's which are planoconvex bottoms, called SHB's or smithing-hearth bottoms as well — *scories en forme de calotte, Schlackenkalotten*). In addition, non-molten hammer-scale and particles of iron, both of which are magnetic, can occur among this waste. These are the typical residues of forging which are found at any place where blacksmiths worked with any regularity. In terms of their compositions, however, they are unlikely to include elements from the ore which are difficult to reduce at temperatures below around 1300°C. Instead, such slags were contaminated with components of the charcoal ash surrounding the developing cakes and it would seem that study of the chemical and mineralogical compositions of slags can contribute to the identification of reheating hearths.

Slags from reheating processes

The waste produced by secondary reheating operations represents, in most cases, a problem for the metallurgists and mineralogists who analyse it. In some cases, analyses have produced contradictory results but, recently, researchers have acknowledged the differences between some slags which were recognized in the past on the basis of shape (PCB's — plano-convex blocks some 15cm in diameter) and were interpreted as the result of post-smelting operations which produced a different metallurgical waste (see Chapter XIII). Such waste is now generally described as

post-reduction slag (*scorie de travail post-réduction*), because it is, in most cases, very difficult to distinguish reheating slags, *scorie de raffinage, épuration, Ausheizschlacke* from the usual smithing waste, *scorie de forge, Schmiedeschlacke.* Both types contain high proportions of iron oxides (wüstite, fayalite and sometimes magnetite) and glass (Bachmann 1982; Keesmann *et al.* 1983; Keesmann 1985; Dunikowski *et. al.* 1996; *iidem* 1998; Fluzin 1998).

Much analytical work has been carried out in recent years (Eschenlohr and Serneels 1991; Serneels 1993; Serneels in: La sidérurgie de l'Est de la France etc. 1994; Serneels 1997; Fluzin and Leclére 1998). With regard to chemical composition, the generally-prevailing opinion is that the PCB cakes from reheating may contain residues of the smelting slag revealed by the presence of elements derived from the smelted ore, albeit in reduced proportions. Thus, manganese, vanadium, chromium which, for all practical purposes, would be absent from normal smithing slags, occur as a result of the hammer-scale formed by oxidation of the metallic iron. This would have been liquefied through interaction with sand flux and would have absorbed more components from the charcoal ash (Leroy 1997, 185 – 205; Dunikowski *et. al.* 1996; 1998). More comparative work is needed, as individual analyses are of limited value.

To make matters worse, the rough products might be traded over wide areas, with reheating operations being carried out in distant rural and urban forges. A case in point is the bloomery at Boécourt in Switzerland, where SHB's were found among the construction material of furnace 2, but where no reheating installations were identified within the area excavated. They must have been transported from elsewhere, possibly from a nearby refining site (Eschenlohr and Serneels 1991, 107 – 115).

Reheating hearths from excavations

The selective survey that follows covers a number of features, mostly from post-war excavations, that have been interpreted as reheating installations. Some of them were found within smelting sites, even directly beside bloomery furnaces, from which they differ considerably in shape and dimension, thus making their identification more plausible. Others have been discovered isolated from any smelting complex (sometimes in groups) and in these cases the verdict must be open. Nevertheless their existence and operation is not out of the question, since the possibility of the post-reduction treatment of blooms imported from afar can be taken into account. There were several models of reheater which were used according to the practices and convention of different smelting masters, groups or clans.

Open reheating sites

In theory at least, the reheating or preliminary treatment of raw furnace products could have been carried out in any open space near a smelting furnace. There is little chance of archaeological field work being able to register and identify such locations on their own. Nevertheless, some evidence, or at least indications, exists.

The bloomeries of what is, to date, the earliest-investigated iron-producing region in ancient Colchis in Georgia, operating in the centuries around 1000 BC, were equipped with special paved platforms ranging from around 90cm x 100cm to 200cm x 190cm, which were regularly situated behind furnaces or pairs of furnaces (cf. Fig. 11) and show evidence of having been exposed to high temperatures. They were sometimes paved with flat stones as at Charnali I and II, Mziani III and Nagomari I, or are represented only by heavily-reddened elongated patches in the ground, as was the case at Askana I, Mziani II and IV and Mshvidobauri II. They have been described as 'tables' or 'anvils' and explained as being the places where iron from the furnaces was worked. Unfortunately only a few indicators are described, except for fragments of baked-red clay (Khakhutaishvili 1987), but in the author's summarizing chapter there is a note of 'iron powder' having been found among the stones of these 'anvil' platforms (*ibidem*, 211).

Excavation of the 2th century AD Romano-British bloomery at Ashwicken (Norfolk, England) revealed a small area of 70cm x 90cm in the centre of a working hollow which housed six shaft furnaces. This area was covered with hammer-scale composed of magnetite cemented together with fayalite, and is interpreted by the excavators as being connected with the reheating and consolidating of blooms (Tylecote and Owles 1960).

The large Romano-Barbarian iron-producing district of the Holy Cross Mountains in Poland, with its thousands of slag-pit furnaces, has yielded relatively little evidence for post-smelting practices. The reason would seem to be that the iron conglomerates were heated and roughly worked at the smelting sites using, in the majority of cases, no special hearths. Due to deep ploughing, many of them have gone. Reddened areas were reported at the corners of the so-called 'organized' furnace clusters from sites such as Łomno 23 and Jeleniów 1 and 4 (Fig. 14: 8) where magnetic fractions, hammer-scale and some metallic particles were found. At Skoszyn 3, a fired circular patch, 70cm in diameter, slightly depressed and consisting of charcoal and the sintered-together iron nodules known as *'grądzie'* ('gromps'), was uncovered (Bielenin 1987; 1992, 132 – 133). Circular and oblong depressions around 120cm x 180cm and 40cm deep, containing solidified slag flows, different from the slag blocks from furnaces have been reported from sites at Starachowice 1, Słupia Stara 3 and Gregorzewice 1. These features are interpreted as waste, which was re-melted during the separation of the iron sponge (Bielenin 1992, 132, fig. 66). It seems apparent that traces of the different stages of post-reduction work may be expected to occur, a view which seems to be confirmed by the discovery of a late 3rd century AD settlement at Pokrzywnica, where numerous pits have been recently excavated. In the middle of trench 4, three circular reheating hearths (see below) which contained plano-covex slags came to light (Bielenin, Mangin and Orzechowski 1996, 356 – 365). In other words, it would also appear that some of the final stages of refining the bloom were conducted away from the bloomeries. In general, all surface traces of the treatment of smelted iron may be interpreted as representing the initial stages of the process. Further work in hearths apparently followed, either in the smithy or elsewhere.

Circular reheating hearths

The circular fire-places used for reheating the furnace product several times seem to represent the simplest and most logical shape for a hearth, one which could be worked at from any position. It is interesting to observe that facilities of this kind, ranging in diameter from 0.6m to 1.5m and in depth from 20cm to 50cm, are most often found on mediaeval ironmaking sites, although earlier examples have also come to light. The function of a reheater was attributed to a stone-built construction with a circular clay-lined hearth space, with a specific additional depression, which came to light at Wilderspool, England, dating from the 2nd century AD (Schubert 1957, 49, fig. 8); this was some 65cm in diameter and equipped with an air-durvt at the bottom. Unspent charcoal and traces of mineral coal were found in front of this feature, and some iron objects and scarp as well. Tylecote (1962a, 235, fig. 61: B) classfied as smithing furnace. At Wilderspool, another hearth, of an elongated shape, was found (see below). A circular stone-built and clay-lined hearth and a large flat-topped boulder found beside three bowl-furnaces of the 4th – 7th centuries AD at Clogher in Co. Tyrone (Scott 1990, 160 and 165, Plate 6.5.3) may have been used in the treatment of the raw furnace products.

A number of clay-lined circular flat hearths (60 – 70cm diameter, 25cm deep) discovered in the earlier levels of the Celtic *oppidum* at the Magdalensberg, near Klagenfurt (Austria), were originally thought to have been bloomery bowl furnaces (Egger 1959, 40, fig. 50) and were reported to have been associated with charcoal, slags and tuyeres. According to a new interpretation (Sperl 1985, 414; Straube 1996, and Dolenz in: *op. cit.* 149 – 151, fig.10), however, similar installations functioned in an urban context as reheating hearths (R1 – R4, ca

100cm in dia., 20cm deep). The Late Iron Age/Romano-Barbarian period site at Padenstedt in north-west Germany produced a circular pit with fire-reddened walls in the gravel subsoil which Hingst (1959, 200, fig. 7, No 1/66) saw as being a reheating.

As mentioned above, the recent discoveries in the Holy Cross Mountains, Poland, include the site of Pokrzywnica, near Pawlów, where roughly circular hearths not associated with any slag-pit furnace cluster have been uncovered. These three large hearths (nos. 11, 12 and 27) have dimensions of 95cm in diameter, 115cm x 85cm, and 120c, x 100cm respectively, and range in depth from 15 – 45cm. All three were located side by side, so that it is not out of the question that they represent a chronological sequence. Hearth 11 was lined with slagged clay, as were the other two, which also produced charcoal and a number of PCB's. The examples in hearth 12 ranged from 5 – 7cm to about 10cm in diameter and weighed up to 0.5kg, while the total weight of PCB's and their fragments in hearth 27 was around 26kg. PCB's also were scattered among the fills of surrounding pits (nos. 9b, 9d, 9e, 35, and 37) and included pieces of up to 23cm in diameter and 3kg in weight. These reheating features belong to a chronological horizon which is dated by the associated archaeology to the second half of the 3rd century AD (Bielenin, Mangin and Orzechowski 1996, 357 – 359, figs 12 – 15).

With regard to the circular hearths of the Middle Ages, we cannot avoid discussion of some of the many examples of the type from sites in the Sauerland of western Germany, an early mediaeval iron-producing region of the 11th – 13th centuries AD. These hearths are usually located in front of the smelting furnaces, a short distance from their fore-pits, as was the case, for example, at Grossendrescheid, sites Am Walde 1 and 2 (Sönnecken 1971, 18 – 20). In some cases the hearths were lined or flagged with stones and the hearth at Wixberg 2, near Altena, was noteworthy for the crust of hammer-scale on its base (*ibidem* 33, fig 6: top). The same feature was also observed in the hearth at Linackers Siepen, which, in addition, had a slag furnace bottom sitting in its fill (*op. cit.* 35 – 36). The siting of the reheating hearth at Linackers Kante is unusual as it lies close to the left of the furnace arch, linking up with a roasting hearth (see chapters IV and VI).

The circular plan of several mediaeval reheaters was interrupted by an extension which would have allowed for the placing of the bellows. Bellows must have been used to achieve the high temperatures required but their locations usually escape recognition. The air-blast would appear to have been supplied to a sunken reheater from the edge of the bed of charcoal or over its edge. Some examples have been found, however, of hearths with depressions in their sides that may be explained as mountings for bellows.

Staré Město in central Moravia was one of the important political and economic centres of the Great Moravian kingdom in the 9th century, and produced considerable evidence of post-reduction iron working but, naturally, no smelting sites survived in the civil and ecclesiastic built-up areas. Some burnt-red features were excavated which resembled the reheaters found on other sites (Hrubý 1965, 312 – 324, fig. 100). Hearth 43 was a clay-lined and dish-shaped pit, 70cm in diameter (Fig. 61: 1), located off-centre in a shallow depression, which was extended on one side into a form of of forepit. Two further hearths, placed side by side (nos. 44a and 44b) were of similar size and 28cm deep. These were set into an L-shaped hollow only 18cm deep, and one of them would have been suitable for the setting for a blowing device. Unanalysed slags are reported to have been found in their fills. One of the two heavily clay-lined hearths found at Piotronowice in Silesia (Pazda 1976, 56 – 92, figs 4 – 8), was similar in appearance, with a shallow side extension and a preserved air-duct (Fig. 61: 2). Tubular tuyere nozzles were found close by, along with a stone anvil. So-called bellows-beds appear to have been formed accidentally as a result of the more prolonged operation of certain hearths, and they do not justify identification of a separate type. Other hearths on the same site show no trace of them as, for example, at Piotronowice 2 and elsewhere the 12th century Bethlehem Chapel site in Prague-Staré Město (Pleiner 1958, 245 – 250).

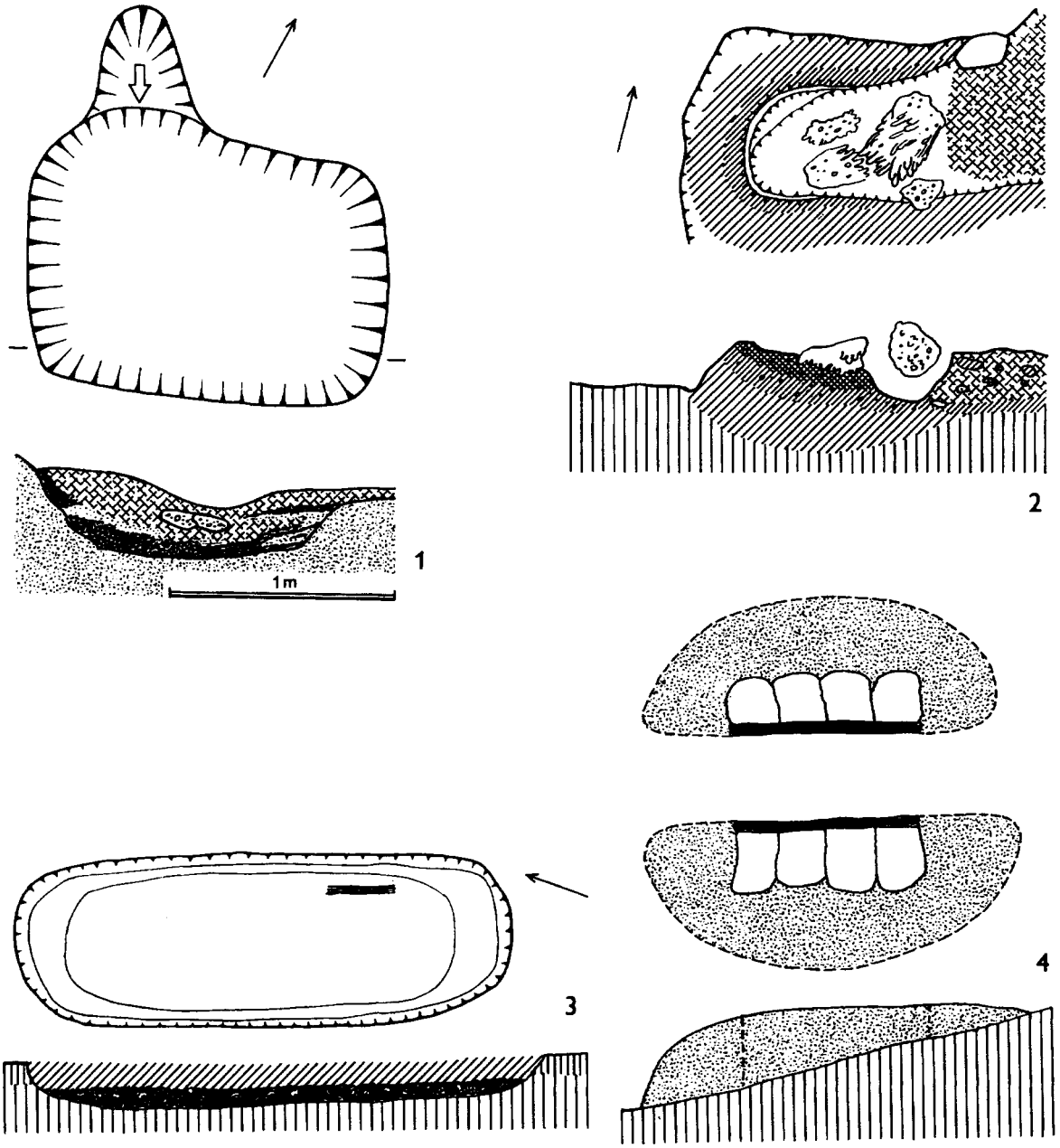


Fig. 59. Features explained as reheating hearths. 1 Hatten, NW Germany, squarish hearth 45 from a slag-pit furnace field (see fig. 14: 7); with a bellows bed, filled with charcoal layers and a sintered-together slag cake, 1st century AD; 2 Mšec, Bohemia, reheating hearth on the edge of a slag-pit furnace field (see Fig. 14: 3) — molten-together slag block as fill, 2nd century BC; 3 Tuchlovice, Bohemia, oblong reheating hearth 1, one of the five similar features surrounding a bloomery furnace group, 4th century AD; 4 Wroxeter, England, reheating channel, Roman, 4th century AD. References: 1 Hayen 1968, 2 Pleiner and Princ 1984, 3 Pleiner 1958, 4 Tylecote 1962a).

Four reheating hearths were found in a small excavated area on the Bethlehem Chapel site. Three were circular in plan and funnel-shaped in section, whilst hearth IV had an extension to one side, forming a shallow bed measuring 60cm x 40cm and 15cm deep. The features had all been dug into the sandy alluvial subsoil of the Vltava river and were lined with clay which been subsequently burnt red. Hearth IV had been relined several times, as shown by the thin layers of charcoal between the different clay linings (Fig. 61: 3). A layer of industrial debris produced many tubular clay tuyeres and fragments of iron slag in the form of furnace bottoms. More industrial workshops equipped with reheating hearths of the same period have been found within settlements of the early Principality of Bohemia on the right bank of the river Vltava, suggesting that iron ore or, more plausibly, raw iron blooms were shipped down the Berounka and Vltava rivers to Prague from a nearby iron bearing region to the south-west for further processing in the pre-urban settlement there.

Horseshoe-shaped and box-like reheaters

During the late Iron Age special features appear on some of excavated bloomery sites, depressions which are open to one side, and bordered by clay walls on the opposite, having what it best described as a horseshoe shape. In some cases, a stone-setting replaces the clay walls, so that the devices resemble a flagstone box. They are distributed over Roman and Barbarian Europe over a small number of sites which will be described below.

A complete 2nd century BC bloomery plant of the La Tène period was excavated in west-central Bohemia at Mšec (Pleiner and Princ 1984), and consisted of nineteen bases of slag-pit furnaces in a small cluster, covering several phases. A fixed reheating hearth was found at the western end of this area which operated throughout the whole life of the site. It was an elongated shallow depression in the subsoil which was burnt to a depth of 20cm, and measured 1m x 0.8m. An opening at its eastern end faced towards the smelting furnaces. The western rims were slightly elevated and created a horseshoe-shaped enclosure. On excavation it was found to contain a massive conglomerate of slag, resulting from the fusion together of two or three slag blocks from the furnaces (Fig. 59: 2). It appears to have been used for remelting these blocks in order to obtain more iron from their upper surfaces. The iron was worked in a smithy alongside, a sunken house containing much magnetic hammer-scale and SHB's in one corner (Fig. 14: 3).

The horseshoe-shaped reheater from Mšec is a dwarf in comparison with the large Romano-Barbarian feature from Milanówek, Masovia in Poland, published in preliminary form by Woyda (in: Eisen + Archäologie 1978, 52, fig. 61). Masovia was an extensive iron-production centre of the time, the second largest after the Holy Cross Mountains, and has yielded thousands of slag-pit furnaces on a large number of sites. The Milanówek feature has also been claimed as a reheating device and comprised a large elongated furnace or hearth (200m x 0.5m internal dimensions) with burnt-red clay walls 30 – 40cm thick still standing up to 70cm, leaving an open space in the east and forming a horseshoe shape. It was sited in the middle of a field of slag-pit furnaces, comprising more than 90 furnaces within an excavated area of only ca. 280m^2, within a free-standing post-built house (11m x 4m) the floor of which was covered with fragments of baked clay. This house is explained as a smithy and the hearth as a reheating furnace. Unfortunately no details of the finds and fills are given, so that the interpretation remains open.

In Roman western Europe, what can be called reheaters of elongated shape have been discovered on some important smelting sites. They have stone settings closing off one end, producing a rectangular box-like shape for which the term 'horseshoe shape' seems a little inappropriate.

Excavations of the large shaft furnaces operating at Martys, in the Montagne Noire of southern France revealed an interesting complex comprising a smelting furnace (F20) in the vicinity of which at a distance of 1m to the west, lay an oblong or rectangular stone setting (F20A) of

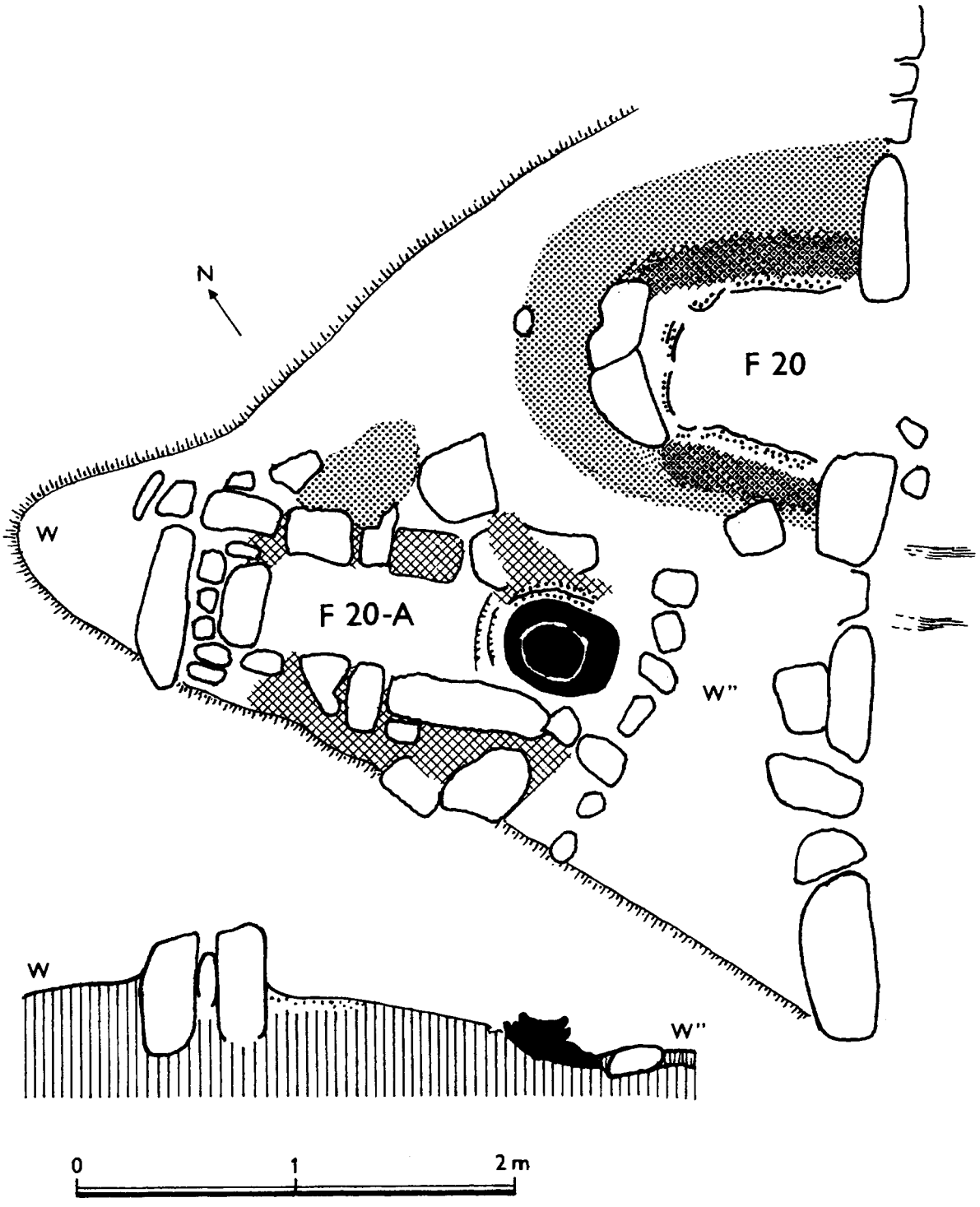


Fig. 60. Martys, S France. Feature F 20-A, explained as stone-set reheating forge with sintered-together slag cakes (black). Ironworks of the 1st century BC (Domergue *et al.* 1993).

internal dimensions 100cm x 50cm, bearing traces of heat and containing charcoal and iron nodules. In its eastern section there was a clay-lined circular depression containing as well as charcoal, a slag conglomerate of two or more calottes or PCBs which had fused together (93kg in total, Fig. 60). This has been described as 'forge' or refining hearth (Domergue *et. al.* 1993, 312 – 321, figs 217, 221 – 222) and in the light of the detailed stratigraphy, it seems that this hearth was independent of furnace F20, being slightly earlier, possibly only in the order of a few years in the 1st century BC. No other similar feature was excavated at Martys.

A rectangular box-like feature, in the preliminary report denoted as smithing hearth (Dieudonné-Glad 1997), was excavated aside furnace 1 in the Gallo-Roman bloomery at Oulches. It is later, dating from the mid-4th century AD. It was built in stone and clay and measured 50cm x 50cm and involved a lined and vitrified bowl (40cm x 30cm). This hearth was in the western end of a rectangular pit (210cm x 50cm, 50cm deep). Three air-inlets were mentioned (two piercing the walls at sides, the third at the bottom) but their exact positions are not legible in the general plan. A metallic plate should be found outsiude the walls, supposingly as a bellows support. The ground between furnace one and the smithing hearth was covered with flat hammer-scale.

As to some installations from Roman Britain, Tylecote (1962a) considers as smithing hearths the coupled stone-lined feature base found at Tiddington: one would be an elongated hearth for heating long bars, the other, rather box-shaped, was destined for working smaller pieces (*op. cit.* 234 – 235). Formerly, this complex was held for a smelting furnace with its ore roaster (Schubert 1957, 49, fig.8, after May).

Investigations undertaken by Pelet (1973) in the Roman iron smelting region near Bellaires in the Jura Vaudois, Switzerland, brought to light two stone-built hearths, designated XV and XVI, which were situated on the left side of the manipulation arches of furnaces XI and XII (4th – 5th centuries AD, Pelet 1993, 88, fig 144). They had internal dimensions of 70cm x 50 – 60cm and both show stratigraphical evidence for superimposition. They are open towards the working spaces in front of both smelting furnaces and Pelet's interpretation of them as reheating hearths is very plausible in view of their configurations. The smelters would have been able to remove the the iron conglomerate through the smelting arch and put it directly onto the stone-set hearths to their left. Some charcoal and slags were found in these features, but Serneels (1993, 103) feels that the slags cannot confirm his interpretation.

Complex excavations at the mediaeval site of Bargen, near Schaffhausen in northern Switzerland, revealed a 15th century bloomery and hammer-mill (Guyan 1965). Some four meters from the remains of a smelting furnace three reheating hearths from different subphases of the site were discovered. Hearth II (*op. cit.* 177 – 178, Plan II, squares 117 and 109) was the best preserved and was built of basalt blocks cemented together in the form of a horseshoe and lined with clay. It was open on the north-west side, facing a forepit. Plano-convex cakes around 21cm in diameter were found *in situ* in the remains of hearth III.

There is little doubt that the hearths found at Mšec, Martys, and Bargen actually served in the reheating of the products of smelting furnaces. The function and mode of operation of the large installation at Milanówek remain uncertain.

Elongated hearths

The archaeological evidence offers a number of other features, fired-red and containing iron slags, which are elongated but without any overt traces of partial enclosure with walls. As to the reasons for working style, two possible reasons may be offered for this style of working, first it provided free access to the blooms and iron-and-slag conglomerates in one operation, and second allowed for the easy manipulation of fuel and ash from the sides. These relatively large features may have been used during the first phase of the reheating process, when the task was to free as much of metallic mass as possible before its heating in smaller hearths and forging on wooden

or stone blocks. The earliest example comes from the late La Tène period, with the majority dating from the Roman period being spread over both Roman and Barbarian territories, while several sites are of mediaeval date. A significant number of these hearths were discovered in smelting sites where they were obviously intergral parts of the complex. Some of the mediaeval examples were discovered as working areas apparently unassociated with smelting.

We should note a small, flat and footprint-shaped hearth at a bloomery at Kostomlaty in central Bohemia, which is dated to the 1st century BC (Pleiner and Sakař 1955; Pleiner 1958, 116). To one side of a group of three small slag-pit furnaces was found an elongated burnt-red hearth (46cm x 20cm, 24cm deep) with slightly burnt-red bottom, the fill of which was permeated with charcoal and contained fragments of baked clay and slag. We may interpret it as having been used for secondary work with iron.

Larger elongated hearths appeared subsequently, in the later Romano-Barbarian period, which covers the 3rd – 4th centuries AD. One of the most striking examples of the time comes from a bloomery at Tuchlovice in west-central Bohemia. A battery of free-standing shaft furnaces was flanked on one side by three long hearths and on the other by a further two, all of which averaged 2m long by 0.7 – 1m wide and 25cm deep (fig. 59: 3). The walls of all of the hearths were red-baked and their fills were a mixture of charcoal and slag (Pleiner 1958, 181, figs. 46 – 47). The idea arose that two, three or even more blooms or slag-and-iron conglomerates could be heated in hearths of this kind, which were set in in a row and blown with bellows, possibly from both sides. At Velké Žernoseky in northern Bohemia, three slag-pit furnace bases were found arranged in a triangular formation. An oblong flat hearth was located in the centre of the triangle, and was apparently used for reheating (Pleiner 1958, 148, fig 32).

In connection with these features, it should be noted that reference has been made in the literature to other hearths, differing in form from slag-pit furnaces, which are interpreted as having been used for working smelted iron, but these have not usually been reported in any detail. At Westerholz in north-west Germany, for example, seventeen flat hearths, described as reheaters, are reported as having been found among scattered groups of slag-pit furnaces (Dehnke 1970, 272). A more complex situation was revealed at Hatten, also in north-west Germany, where more than twenty oblong, square or irregularly shaped hearths, described also as reheating devices, were, again, scattered among the slag-pit furnaces found. Exacavation at the southern tip of the industrial area revealed a large rectangular hearth 1.5 m square and 50cm deep, with a groove extending out from one corner, possibly a bellows bed, and containing a slag cake in the charcoal fill (Hayen 1968, fig. 12; Fig. 59: 1).

Returning to the specifically oblong features, it is worth noting the large hearth from Drvalovice-Vanovice, western Moravia, 4.6m x 1.9m and 20cm deep, which was filled with charcoal and iron slags (Ludikovský 1980). No further details are available, and dating is not possible although it probably belongs in the Romano-Barbarian period. At Dobrzeń Mały in Silesia, Poland, groups of alleged hearths both on the western and eastern edges of a furnace complex, with groups of roasters in the east have been reported (Pawlowski 1979, 199). These reheating hearths, 20 in number, seem to be oval in shape with dimensions in the ranges 60 – 120 cm x 110cm – 150cm and 25 – 56cm deep. They contained small pieces of iron slag of a 'porous and cast' texture. Unfortunately, no detailed documentation of the hearths was given.

If we turn our attention to the west, across the Roman military border, some finds of elongated iron working hearths attract our attention. Some 20 rectangular, oblong or square features of the 2nd–3rd centuries AD, which ranged from 150 – 200cm x 50 – 100cm, and were very shallow (10 – 20cm in depth), were excavated at Rémilly-Petit Fin in NW France. They were reddened by heat and their fills contained charcoal and, in two cases, accummulations of PCB-cakes (the total weight of which is given as several tens of kilogrammes), as well as small slag droplets and some particles of highly carburized iron. This slag debris has been interpreted as secondary waste dumped from the site. No smelting furnaces were found within this 'reheating'

area (Leroy 1997, 195 – 199, figs 112 – 114).

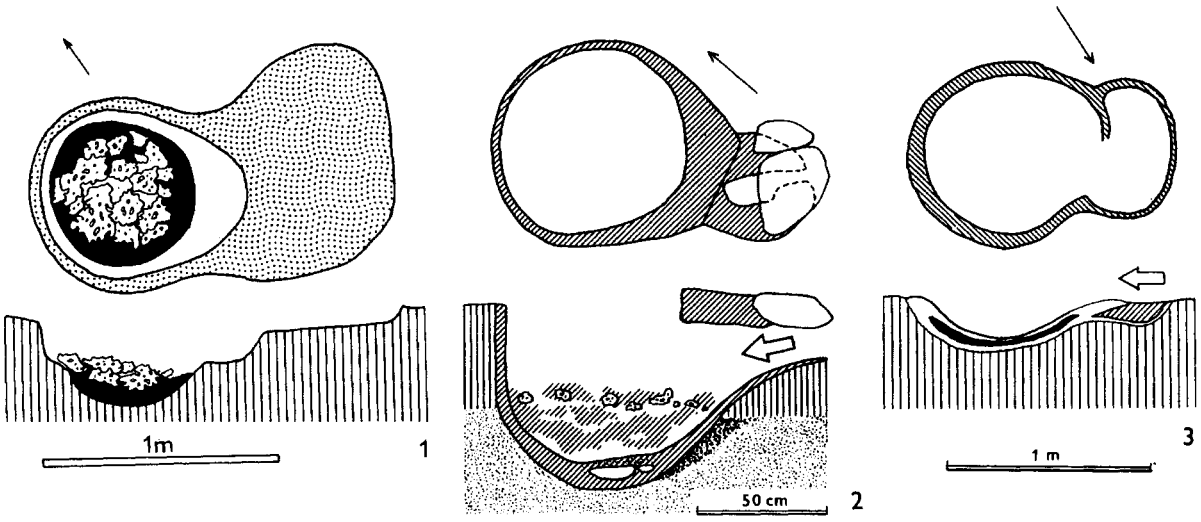


Fig. 61. Mediaeval reheating hearths. 1 Staré Město, Moravia - reheating hearth 43 filled with charcoal and slag, 9th century AD; 2 Piotronowice, Poland, cauldron-shaped reheating hearth 1 with an air-duct, 12th century AD; 3 Prague-Chapel Bethlehem, reheating hearth with a bellows bed, layers of the 12th century AD. References: 1 Hrubý 1965, 2 Pazda 1976, 2 Pleiner 1958.

It is also not easy to explain the very long so-called 'channel hearths' of 2nd century AD date found in Northamptonshire in England, in the iron-ore mining region around Wakerley, sites 2 and 3 (Jackson et. al. 1978, 152, 163, fig. 24). These are narrow (50 – 70cm) features, but vary in length from 2.5m to 4.6m, and are 15cm deep. The walls are baked red to a depth of 2cm. In the final phase, before the site was abandoned, they had been cleaned out and no magnetic fractions could be detected. The authors of the report hesitate to ascribe them to roasting, reheating, or smithing.

Tylecote (1962a) explains, as a reheater, the late Roman channel-shaped and stone-lined feature from Wroxeter (Fig. 59: 4). The same author (*op.* cit., 35 – 36, fig. 61: A) discusses an elongated hearth from Wilderspool which was of a figure-of-eight shape in plan, lined with burnt-red clay, being nearby 2m long and 30cm to 30cm wide. The maximal depth was about 15cm. An air vent pointed from one side to the deepest end. The hearth should serve as a smithing installation work working both large and small objecs; with regard on dimensions it could operate rather as a reheater.

Within a Late Saxon bloomery at Ramsbury (dating from the late 8th to the early 9th centuries AD, see Haslam *et al.* 1980, 12 – 13, figs 5 and 9) elongated shallow depressions 99 and 117 were interpreted as smithing hearths. The former was equipped with a slight clay lining, burnt-red in patches, containing what is called small smithing waste and charcoal fragments in its filling (dimensions about 95cm x 70cm, depth about 30cm); the latter was unlined, showing traces of firing and revealing smithing waste and charcoal (70cm x 45cm). In fact, these smithing hearths might have served as reheaters for blooms from nearby bowl furnaces (see Chapter IX).

As in the case of the circular hearths discussed above, there are a few mediaeval features which also show elongated plans and charcoal and some slag in their fills. They appear in settlement contexts or as isolated installations on sites which have not yielded any traces of the smelting activity. The excavator of the 9th century AD site at Jazbine in the former Yugoslavia claims that several of the pits investigated (XXXIII, XXXIX) were reheating hearths (Čremošnik 1977, 246). These were very large (6.2m x 2.5m, 35 – 90cm deep) and resemble sunken-floored

huts rather than hearths. It would seem likely that pieces of slag would have found their way into the interiors of these structures from the industrial waste materials widely scattered around this settlement, where iron smelting or working appears to have been taking place. More to the north, in the 9th century realm of Great Moravia the princely fortified site of Břeclav-Pohansko in southern Moravia was excavated. No iron-smelting activity has been attested on this site, but some evidence for ironworking came to light beside the ruler's residence in the form of a rectangular pit with red-baked lining some 1.7m x 0.75m by 35cm deep (Dostál 1967, 119, fig. 11: 6). The feature compares with hearths of similar shape which have been claimed to be reheating installations.

Such features are known in later centuries as well. The suburb of Libice in central Bohemia, an important ducal centre of the 10th century, produced two oblong reheating hearths with slags in their fills, which measured 2m x 1m (Pleiner 1958, 198 – 199, fig. 59: B and C). From Jenišův Újezd, a village in north-west Bohemia destroyed by opencast coal mining, a large oval pit 266cm x 144cm, filled with clay and charcoal layers and permeated with minute fragments of iron slag should be noted. The aim of the first discussion of this pit (cf. Pleiner 1958, 236 – 237, fig. 62) was to disprove its function as a smelting furnace. The hearth was relatively shallow, some 46cm in its centre, and rose up on both its northern and southern narrower ends to 10cm. The facing half was shallow and unlined, and could have served as the base of a blowing device and there was a trace of clay walling on the northern side, standing to a height of some 36cm, so that it could be considered as a horseshoe-shaped hearth, although no strict typology of such features is possible in our present state of knowledge.

Less distinctive in shape were features 5, 28, and 29 at Kamionka Nadbuźna in SE Poland, a site which, to date, has yielded no smelting furnaces, but only furnace slag-bottoms against walls of a rectangular house, marking its ground-plan. The features said to be reheating hearths were relatively large (200cm x 100cm, No 28 was sub-circular 110cm x 120cm) and both shallow (feature 28: 20 – 25cm) and deep (feature 29: 115cm). They were filled with debris after they went out of use, as shown by the fact that they contained not only the usual charcoal and slag but also dumped tuyere nozzles (of tubular type) and pottery sherds of the 12th century (Rauhut 1956, figs 2 – 8). The unresolved question is whether post-reduction operations were performed in conjunction with bloomery activities close to the site, or whether the blooms to be worked were brought from elsewhere.

Other possible reheaters

There are a number of bloomery works excavated in the past which revealed no open hearths which could be explained as reheaters. At Chýně, near Prague, a late La Tène sunken-floored bloomery plant II-1 (Pleiner 1958, 110 – 114, figs. 21 and 22) produced another type of furnace, facing four slag-pit furnaces, belonging apparently to two or three of the phases of activity there. This was built into the southern wall of the workshop pit and is distinguished from the normal slag-pit furnaces by its wide throat and frontal lower section which sloped down to the hearth. Such an arrangement would have been suited to taking hot raw blooms for further heating and was thus classified as a reheating furnace. However, it is clear that more evidence would be needed to confirm this. An identical situation appeared in the case of bloomery works II-2, found nearby which was, unfortunately very badly damaged. The 'reheating' furnace which was in an identical setting, was also practically destroyed.

A hypothesis has been put forward that damaged smelting furnaces might have been used, after demolition of their shafts, as reheaters. In the ironworks at Olomučany in Moravia (9th century) were found two forged and split blooms in a burnt-red pit in front of smelting furnaces VI and VII (Souchopová 1986, 25, fig. 10) which were interpreted as having been used in such a way (Souchopová and Stránský, in press). This idea may be considered, indeed, but more direct

evidence is needed, especially from those smelting sites which have not yielded any reheating or other open hearths.

The peculiar rear cavities behind the air-ducts of the Želechovice type furnaces (about 800 AD) may have acted as reheating chambers for the blooms from the previous smelt during the subsequent, continual process. This idea proved to have a sound basis, as the results of experiments showed that more compact blooms could have been produced immediately during the smelting process (see Pleiner 1958, 221, fig. 58; 1969b).

*

The interpretation of archaeological features which are claimed to represent reheating hearths is hedged round with many unsolved problems, rooted, to a great degree, in a lack knowledge, especially when field work was conducted in earlier years. Large hearths with burnt-red linings, charcoal beds or layers, and scattered slags which are usually no longer available for study, when found with actual smelting furnaces, show striking differences in comparison to the latter and automatically raise suggestions of some kind of post-reduction operations. Possibly, they operated during the initial phases of this work when the task of which was the removal of the bulk of the solidified slag, still adhering to the iron-and-slag blocks. Old records are usually unhelpful in important details and samples rarely, if ever, survive.

Such features cannot be identified as parts of smithies, because these were equipped with smaller hearths used for the repeated reheating of blooms and forging to expel most of the internal slag and to produce a workable product. If they had been, both phases would have produced slag wastes with differing proportions of the original smelting slag and of molten iron oxides (hammer-scale) and siliceous components. This would be indicated by minute variations in chemical compositions, even taking into account the extreme heterogeneity of materials of that kind. Thus, the true explanation of a number of excavated 'reheating' hearths remains uncertain. Possibly, during future excavations, attention should be paid to magnetic hammer-scale and metal particles (gromps) which are to be expected in installations acting in the final phase of reheating. Calcined ore from roasting could also produce magnetic fractions, but it would be possible to recognize them during careful excavation. Any old records are, unfortunately, hardly eloquent, when no samples were preserved.

Experimental reheating

Whilst the smelting of ore has been the subject of hundreds of experimental operations in many countries, reheating tests on the products has only been carried out very rarely until now. The reason for this is, on the one hand the small number of raw blooms available for working; and, on the other, that such work is, in itself, a special project requiring to be well-documented and evaluated.

During the experimental smelts in the Želechovice furnaces in 1964, a portion of the 2.5kg bloom, which underwent preliminary consolidation in the special rear chamber of the furnace, was successfully reheated in an everyday forge, using borax as flux, and four good steel knives were manufactured from the metal. The other portion of the bloom was left preserved. Similar forging of a knife from experimentally smelted iron was carried out by Mazur and Nosek (1966), but in neither case were quantitative measurements were undertaken.

The first project designed to examine the reheating of experimental blooms, under precisely-controlled and measured conditions, has been carried out by Crew in Wales who has reheated over 40 blooms (unconsolidated iron sponges) and forged them first to billets (more consolidated blooms) and then to fully consolidated iron bars (Crew 1991a; Crew and Salter 1991). His pioneering work throws new light on the reheating process in terms both of economy of the bloomery process. He used a simple hearth (ca 30cm in dia.), blown by bellows (200 – 350 litres

of air/min.) and from unconsolidated blooms weighing from 1.7 to 3.1kg he obtained, after 3.5 – 5 hours and 12 – 59 heats more compact iron blocks (billets) of 0.8 – 1.3kg weight. This represents, for this first stage, losses of 19 – 71 % and for a typical bloom, losses are usually in the region of 50%. The reheating of an 11kg iron sponge from Bielenin's experiments in the Holy Cross Mountains, which was also undertaken by Crew, produced after cold cleaning of adherent bloomery slag a 6.5kg bloom. After 25 heats over 2.5 hours, a billet of 3kg was forged (Crew and Salter 1991, 21). Losses of about 58 % of weight were recorded after the the reheating (13 heats in about 2 hours of work) of a part of bloom, having been yielded in an 18th century model of a Basque hearth at Agorregi, Gipuzkoa (Dillmann *et al.* 1997, see below Chapter XII).

The process of bloom-smithing is not easy, especially during the initial phase of heating and forging, when the slag-iron conglomerate shatters easily, because the slag cools much more quickly than the iron. In the later stages, the work can be more vigorous, but the bloom, still containing a good deal of entrapped slag, requires careful handling before it can be converted into bars and artefacts. The waste produced in this work was in the form of different kinds of slag and hammer-scale. A plano-convex cake formed from molten slag and cinder at the tuyere mouth but, to date, the production of genuine PCB's, as found among the archaeological record, has not been achieved by the above team.

Useful information was obtained during experimental smelts in a furnace of slag-pit furnace type by Faivre (1994) at Saintes, France, in 1992. The products were reheated in a rectangular clay-built hearth in two trial operations (*op. cit.* 168 – 169). The first required 15 heats, beginning with the first three, during which glowing slag on the sides of the conglomerate was carefully removed. Continuing the work, the experimenters reached the point at which the iron sponge began to take shape. It was observed that slag being expelled from the pores, was gradually replaced by hammer-scale (0.2 – 1cm dia). After the fifteenth heat, the product was forged into a rod. In the forge, both a solidified slag flow and a slag calotte (PCB) were found at the tuyere mouth. This waste represents, in fact, the two principal phases of reheating carried out in the one hearth. The primary products of Faivre's smelts are discussed in chapter XII on blooms and sponges. Two other reheating experiments, also discussed in chapter XII, were carried out during the performances of Japanese traditional master smiths at Nancy-Jarville in 1989, who used brick-built box hearths (60cm x 20cm), and during another traditional smelt in Mali, Africa, documented by E. Huysecom (see Serneels *et al.* in: Early Ironworking in Europe, Abstracts Plas Tan y Bwlch 1997, 104 – 110).

Interesting data were published recently by Rozanova and Terekhova (1997, 7 – 14) on the reheating of original archaeological blooms of 14th century date from Novgorod Velikiy in Russia, the diameters of which were 13 – 14cm, thickness 5 – 6cm and weight 2.7 –3kg. Metallographic examination of the loaf-shaped blooms which had already been already forged in the Middle Ages, revealed large cavities in the low-carbon metal, up to 1 – 1.5cm, partially filled with slag and charcoal fragments (Fig. 63). A bloom of 2.9kg was heated seven times during 90 minutes, with individual heats lasting 20 – 30 minutes followed by short periods of forging of 1 – 4 minutes each. The work resulted in a more compact product, weighing 1.1kg (a loss of 62%) after the expulsion of the slag and removal the oxidized hammer-scale. Another bloom (2.7kg) was heated several times and forged at over 1200 °C for 60 minutes, using river sand as a flux. After 2 – 3 heats molten slag flew from the pores in a 'golden rain'. The result was a billet weighing 1.7kg (a loss of 37%). One of the blooms shattered at white heat under the strokes of hammer, but it proved possible to rework the splinters into bars. The final products were knives, constructed according to the different methods of blade composition known from archaeometallurgical research.

It is possible that skillful masters smelters in antiquity were able to work with more compact sponges, producing blooms and billets with fewer losses. However, we are probably not far from the truth in considering that about a half of the smelted iron was lost during reheating.

Without any doubt, more experiments and more analytical work will provide us with new and useful data.

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We have presented some of the archaeological evidence for the post-reduction processes which were essential for delivering workable iron. There is, in fact, on the one hand a great mass of evidence which may be interpreted but which, on the other is perhaps the most intractable. Our current inability to properly evaluate it represents the most severe lacuna in our knowledge and understanding of the archaeometallurgical remains surviving from the early production of iron. It seems that these processes were very complex in many regions and times and comprised different phases of operation before a solid bar of iron could be placed in the hands of the blacksmiths who transformed them into tools, weapons and utensils of every kind. It should be appreciated that every such operation or even every heat consumed a significant portion of the iron smelted. Because of that iron remained a valuable material even during the fully-fledged Iron Age, and scrap economy was extremely important until the 19th century, especially for small smithies and hammer-mills, which were, for all practical purposes, fully dependent on supplies of iron which could be recycled.

Chapter XII

IRON BLOOMS

The metallic products of the direct process, either consisting of solid spongy iron from smelting furnaces or as more consolidated masses following the reheating processes described in the previous chapter, occur among archaeological assemblages from a wide variety of contexts. The English term for such objects is 'bloom', from Old English *blóma*, which means 'a lump of metal', as a rule iron. In other languages the term used can derive from local terms (*Stück, kus, kęs*) or from Latin *massa* or *massa ferri*, giving rise to words such as *masella, massiot, Mass*, all of which also also mean, quite simply, 'piece' or 'lump'. The Latin word *lupus* (wolf) gave rise to another group of terms, such as *Luppe, loupe de fer, lupa, lupka, vlk.* There are also examples of other words not connected with either of these concepts, such as derivatives from Germanic languages such as *Deul, dejl, plik*, Russian *kritsa*, Hungarian *buca* and Irish *cáer.*

The blooms which were extracted at the end of the smelt from the smaller furnaces of the prehistoric, classical, and early mediaeval periods were spongy lumps or iron, permeated with slag. In contrast, the larger post-mediaeval installations blown by water-powered bellows produced more compact and less vesicular blooms, according to surviving contemporary accounts (Agricola 1556, chapter IX, Biringuccio 1540, chapter 6; Rożdieński 1612; Schlutze 1732; Evenstad 1790; Busch 1851). Some of those which come to light on archaeological excavations have partly been left in the unworked state, while others have been subjected to some degree to at least the first stages of the forging process.

More than three hundred early blooms are known from some 90 sites, including bloomeries, settlement areas and, occasionally, hoards. These vary in form and are at different stages of reheating or forging, some being almost unconsolidated, containing over 50% of slag by volume, both adhering to the surface and trapped in the interior. Others have been partially forged and also are flattened on one or two sides, or even shaped into regular, somewhat prismatic forms. The dimensions and weights of the blooms in current use changed over time (e.g. Tylecote 1986, 211, fig. 150).

The normal weights of prehistoric and early mediaeval blooms (Hallstatt period to early Middle Ages), produced in low shaft furnaces, is regularly no more than 1 – 3kg, although heavier blooms, weighing between 4kg and 13.5kg, do occasionally occur on Roman or Mediaeval sites. Blooms from the late Styrian *Stucköfen* weighed 100 – 500kg or even more (Köstler 1986) and were removed from the furnace hearths in the form of hot blocks using cranes or derricks. The Scandinavian forges with hand-driven bellows produced much smaller blooms, weighing 8 – 9kg (Busch), whereas those from the contemporary 18th – 19th century contemporary water-powered bloomeries (including the so-called Catalan hearths) ranged in weight from 80 to 150kg. The date of blooms from several Hungarian sites which weigh around 50kg is still under discussion because of lack of local stratigraphical evidence, with opinions variously ascribing them as Roman or post-mediaeval.

The information on iron blooms to be derived from the archaeological literature of earlier years is of very variable quality and there are often references to blooms without any further detail relating to their shapes or weights. In a number of cases, in fact, it is highly likely that plano-convex smithing hearth bottoms have been confused with iron blooms. However, smithing slag may also include minute particles of metallic iron, so that the problem of precise indentification is complex when no metallographic or chemical examination has been carried out or when no details at least of weight are given. There is, however, a corpus of finds which have been properly described and illustrated, with details of dimensions and weights, and in addition, a number of blooms (or fragments of blooms) have been examined metallographically

and/or chemically analysed. These latter are of particular value, since they throw light on the metallurgical processes involved and can be compared with other objective data and the number of examined and dated blooms has increased by more than 70% in recent years.

Due to the fact that information on early iron blooms is scattered throughout numerous publications, we cannot claim this survey to be absolutely complete. Nevertheless, it offers a picture of the character of blooms in their chronological and geographical contexts, presented in broad chronological order.

Prehistoric and Late Iron Age blooms

Iron blooms are known from as early as the Late Bronze Age. A pit of the Kyjatice culture (Halstatt B_3 period, *ca.* 8th century BC) at Šafárikovo (Fig. 62: 1) in southern Slovakia produced a round, loaf-shaped bloom (12cm x 10.5cm x 6cm, 2.43kg, see Pleiner 1981) at present under study (Furmánek 1988). It is remarkable that this should be equivalent in size to the average blooms of much later periods. Given the extreme scarcity of iron at that time, it represents a considerable quantity of metal, equivalent, for example, to three long swords, six to eight axeheads, or several hundred small knives.

Three further iron blooms from the Slovakian Hallstatt period, each weighing around 2kg, were found at Krásná Hôrka, near Orava (Pleiner 1962, pl.I: 1 – 3), together with two large socketed iron axes which can be hardly thought of as commonplace tools in this context, but should rather be seen as representing precise quantities of this highly-prized metal. A bloom of similar dimensions and date, again accompanied by two large socketed axes, was found in front of the cave at Jasov-Fajka in southern Slovakia (Fig. 62: 4). The Hallstatt C (7th–6th centuries BC) hillfort at Smolenice-Molpír, on the south-west foothills of the Carpathians, produced three blooms from what can be considered as a smithing complex. They weighed 1 – 1.5kg and had been roughly shaped, with quasi rectangular edges to measure some 10cm x 10cm x 5cm (Fig. 62: 2). Metallographic examination (Pleiner, unpublished) showed that they had extremely heterogeneous structures, ranging from zones of pure ferrite to areas of pearlite, with local ferritic cells and Widmannstätten textures. The carbon contents ranged from 0.02% to 0.7%, and the iron was low in phosphorus. An iron bloom of the same date comes from Berezan', far to the south-east, near Olbia in Ukraine, although no details of weight or dimensions were published *cf.* Fomin 1974). It was an irregular ovoid in shape (Fig. 62: 5), and though it was heavily corroded and had apparently been badly forged, was found to consist of ferritic iron.

Returning to Slovakia, a region which has yielded a considerable number of very early iron blooms, we must not overlook the group of thirteen small blooms from Nový Smokovec in the north of the country, found at the end of the 19th century in dumps of bloomery slag of the Púchov culture (late La Tène) in an iron-bearing region at the foot of the High Tatra Mountains. They were loaf-shaped, about 10cm in diameter and 4cm thick (Fig. 62: 3). No analytical results are so far available but a cross-section of one shows a spongy texture with much entrapped slag (Pleiner 1962b, 67, pl. 1: below; fig. 11: 5, with references). The La Tène period settlement of Radovesice, in north-west Bohemia, yielded some features which can be connected with iron working, namely hearths, PCB slags and what can be described as an unconsolidated bloom (Pleiner 1993 in: Waldhauser 1993 I, 240 – 249). The site yielded no evidence for smelting so that the bloom must have been imported from elsewhere in the locality.

Two finds of blooms, one dating to the 1st century BC, the other to the 1st century AD, are known from territories with more advanced proto-urban civilizations. The first group comes from Magdalensberg in Carinthia, Austria, a well-known trading post for Noric steel, the other from Sarmizegetusa, the capital of ancient Dacia. The Dacian blooms were in an enormous hoard weighing 887kg, found unassociated with any remains of smelting but within a smithing area. Their *terminus ante quem* is given as the 1st century AD, meaning that they are pre-Roman and were abandoned before Trajan conquered the Dacian capital in AD 106 (Glodariu 1975, fig.

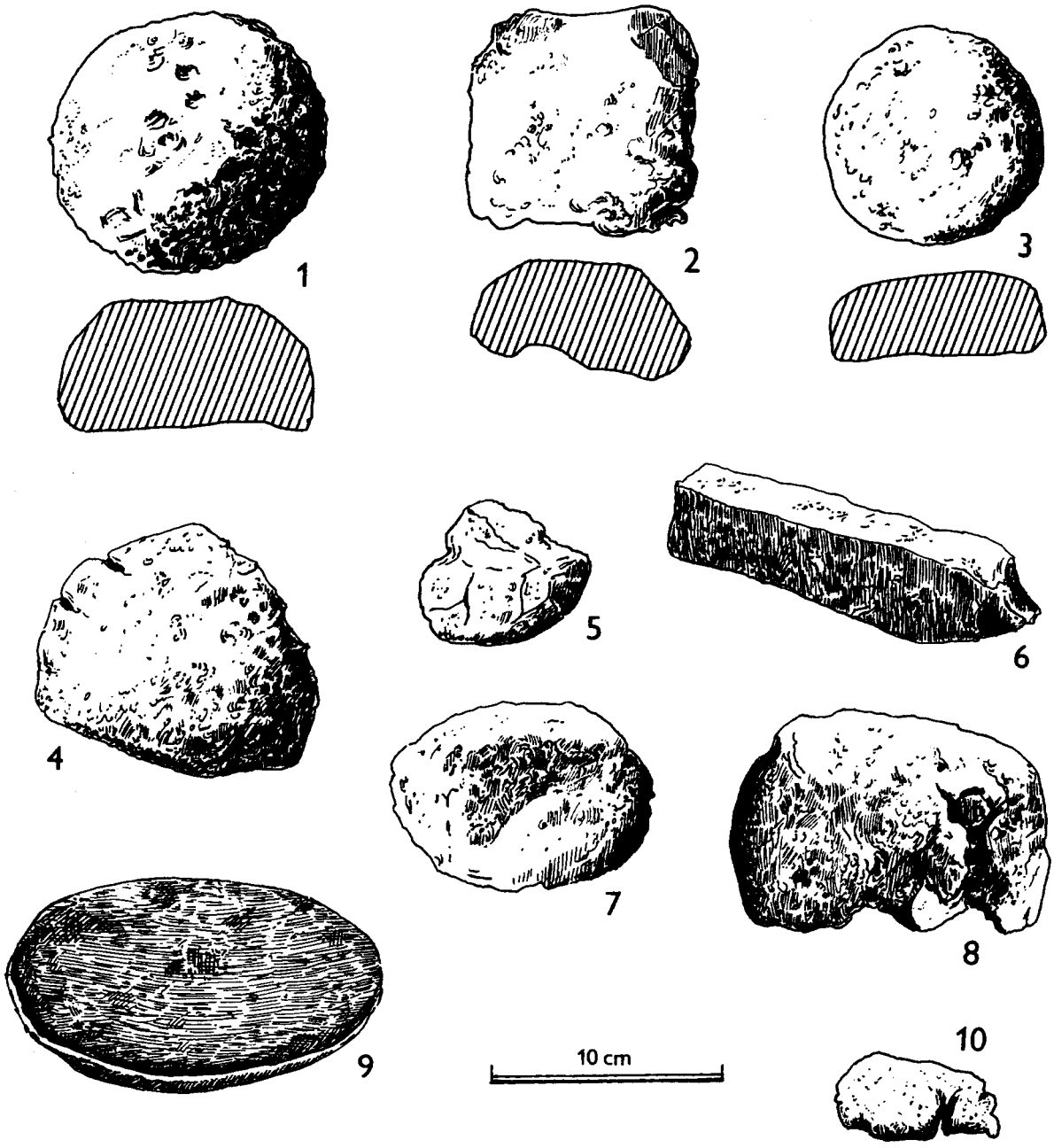


Fig. 62. Loaf-shaped and prismatic iron blooms. 1 Šafárikovo, S Slovakia, 8th century BC (2.41kg); 2 Smolenice-Molpír, SW Slovakia, 7th century BC (Nr 410, from a smithy); 3 Nový Smokovec, N Slovakia, La Tène period; 4 Jasov, S. Slovakia, Hallstatt period, from a hoard (2kg); 5 Berezan' near Olbia, Ukraine, 6th – 4th centuries BC; 6 Little Franingham Farm, England, prismatic bloom (2kg); 7 Knyazha Gora, near Kiyev, Ukraine, early mediaeval (2.05kg); 8 Olomučany, W Moravia, 10th–11th centuries AD (3.15kg); 9 Vasilievskiy district, Ukraine, early mediaeval flat disc (1.75kg); 10 Tervete, Latvia, 13th century AD (0.73kg). References: Pleiner 1981 (excavation by V. Furmánek), 2 Pleiner, unpublished, archives of the Arch. Inst. Prague; 3 – 4 Pleiner 1962a; 5 Fomin 1974; 6 Cleere and Crossley 1985, 7 Kolchin 1953; 8 Souchopová 1986, 9 Kolchin 1953; 10 Anteins 1960.

6; 1980, 85, fig.5). The blooms are notched on one side and thus belong to the category of split blooms and will be discussed below as the earliest representatives of this group.

Three of the Magdalensberg blooms (labelled B, C, and D) came to light in stratified positions within the later temple area, where orginally smithing or reheating activities took place, while a further five were found scattered over a wider area. All were metallographically investigated by Straube (1996, 97 – 107, figs. 33 – 35). The three stratified finds (weights not given), which range in diameter from 10 – 12cm and in thickness from 2 to 5cm, are high-carbon steels with pearlitic or even hypereutectoid structures (0.8 – 1,2% C). They are unconsolidated with much adherent and entrapped slag. The scattered blooms from the 1977 season which weigh from 0.2 to 1.93kg are also highly-carburized metal with their carbon contents locally reaching that of white cast iron, showing ledeburite, pearlite, cementite, and, in two cases, martensite. Schaaber (1963) described other blooms from Magdalensberg, one of them weighing 18.4kg, the carbon contents of which reached around 2% C, although no ledeburite appeared due to the thermal regime suggested, with the structural components instead being pearlite and cementite in form of thick plates. Straube deduced that the majority of the iron in these blooms passed through a liquid consistency and were much decarburized partly at the furnace tuyere mouth, partly during further heating processes. They had apparently not been worked and some of the smaller pieces in fact may be considered to be discarded refuse.

The artisans' area of Magdalenberg yielded no smelting furnaces and these were found instead at several nearby sites in the Görtschitz valley. Furthermore, a bloom fragment (0.107kg) with similar structure phases of pearlite and cementite and a carbon content of 1.5 – 1.8%C was found at Gracarca (Straube, *op. cit.* 107 – 108, fig. 39). While conclusions from the Magdalensberg evidence are far from definite, the notion is strongly supported that the urban workshops received unworked, extremely highly-carburized blooms from outlying ironworks and that some workers used quick cooling or even quenching as part of the subsequent processing.

From the far west of the ancient Celtic world, two blooms have been recorded from England. A highly oxidized iron lump is known from Wookey Hole, Somerset, which with its dimensions of 20cm x 9xm x 6 – 4cm is claimed to be the largest known from the pre-Roman period. In its present state, oxides make make up 87% of its volume, but the original weight has been calculated to have been 3. 12kg. According to Tylecote (1986, 144), it seems to have been made of fairly pure steel (0.48 – 0.7% C). The date of the bloom from Crowhurst, Sussex, is uncertain and it may be Early Iron Age or Roman. It has been suggested that it is only a fragment (1.25kg) of a larger complete bloom, the metal of which contains up to 0.3% C (Tylecote *ibid.*).

Roman blooms

Compared with the high number of reported prehistoric and, in particular, protohistoric blooms (the total weight of which cannot be calculated because of the unspecified number of the Sarmizegetusa finds), Roman blooms are relatively few in number and only three come from iron-producing sites. The barbarian smelting areas lying outside Roman territory have yielded neither blooms nor iron-sponge-blocks. The few examples come from sites without any metallurgical context. The reason is unknown, but may be related to the notorious incompleteness of archaeological record or, presumably, to the fact of economics that the more iron was demanded and produced, the less likely it would be for any important amount of iron to be left on a site.

An unstratified iron comglomerate was found in Gaul, in the Roman production district in the Montagne Noire at Martys-Mountrouch 1 site, situated close to the ironworks Martys-Domaine des Forges (Domergue *et al.* 1993, 247 – 249, figs 158 – 159, 166). Designated M 105, this is a ball (measuring 30cm in dia. and was 12cm thick) of slag with dispersed iron particles, hiding a compact and heterogeneously-carburized iron core estimated at 6 – 7kg in weight, measuring 12cm in diameter by 5cm thick and with a coarse ferritic-and-pearlitic structure. The slag inclusions in the iron nucleus consisted of wüstite, fayalite, and leucite. The object had

not been worked or reheated and would appear to represent an unfinished bloom. A furnace bottom believed to be of the 3rd century AD date, measuring 30 – 40cm x 6 – 15cm, is reported from Saint Denis in the same iron-smelting region in the Montagne Noire (Lavielle *et al.*1991). It is, in fact, also a mass of slag containing a ferritic iron sponge and with solid iron at the centre. The complete lump, an unconsolidated slag-and-iron conglomerate, was presumably thrown out as a waste.

A considerable body of information on the debris from smithies at the Gallo-Roman site of Alésia (Auxois) and at 38 contemporary rural workshops in its environment has been prepared for final publication (Mangin *et al.* 1998, II, 136–199, preprint). In about a half of the 28 investigated smithing and/or reheating slags (mostly smaller pieces and fragments of 5 – 6cm diameter and weights averaging *ca.* 0.16kg) varying amounts of metallic iron have been observed, from around 20% to 60 – 70% of volume, in the form of fibres, isolated particles, grains and nodules or more compact pieces. The majority of the metal was ferritic or, as is common, heterogeneously carburized, with levels locally reaching up to 0.6 – 0.7% C, although the sample from forge 104 at Blessey-Salmais (No 104/13) contained grey cast iron with graphite lamellae. These pieces are interpreted as representing different stages in the reheating of raw blooms.

A rather flat object from Blessey (forge H603) weighing 0.136kg with dimensions of 9.5cm x 7.5cm x 1 – 1.5cm, contains up to 70% of unconsolidated steel of carbon content 0.4–0.7% C, decarburized at the surface to 0.2 – 0.3% C. It is very easy to believe that the samples from Alésia, Blessey, Sombernon, Flavigny, Darcey, Vic-de-Chassenay and other sites represent fragments and discarded waste originating in working processes on the blooms imported from elsewhere. In this survey, the only complete bloom or, better, forged billet, the porosity of which does not exceed 1%, is reported from Coulmier-le-Sec (*op. cit.* 196 – 199, fig. 77). This is an ovoid object 16.3cm long and 7.5cm in diameter, weighing 4.465kg with some fissures at either end which may be ascribed to the forging process. The metal is a 0.6 – 0.7% carbon steel, with the higher levels concentrated especially near the surface. Unfortunately it is not precisely dated as it was found together with other disparate iron-working debris, and is suggested to be antique (the site lies on the Roman road network) or mediaeval.

Apart from slags, the Gallo-Roman settlement site of 'La Bure' at Saint Dié in the Lorraine produced five lumps of iron weighing from 3.7 to 13.5kg. One of the smaller pieces, which had a ferritic structure, was partially forged and chiselled-off. These objects are interpreted as billets, ready for trade and further smithing (Leroy 1997, 201 – 202, fig. 115). Similar products have been found in smithies (and smaller ironworks) at Bliesbruck (Moselle), near the French-German border, a Gallo-Roman *vicus* dating to the 2nd – 3rd centuries AD. In front of stone-walled buildings 2 and 3, fragments of blooms in various stages of forging were discovered. One was a small block of iron (0.5kg) separated from slag, the second a more completely-forged bloom with a flattened bottom (0.75kg) and heavily carburized. Structures observed include cementite, bainite and P-eutectoids, with carbon contents over 1% C, the pieces having been rapidly cooled. The site was also used for manufacture of ingots and domestic iron work which were not analysed (Forrières *et al.* 1989).

Of particular interest is the 2nd century AD semi-forged rectangular bar (Fig. 62: 6) found in a stone structure and accompanied by a clay tuyere at Little Farningham Farm, Cranbrook, Kent (Brown 1964; Cleere and Crossley 1985, 47 – 48, 297, fig. 16). It contains areas which are highly carburized (1.46% C, 0.2% Si, 0.014 – 0.025% P) and had been martquenched. The crystalline phases identified were martensite, troostite, ledeburite, cementite, pearlite, and ferrite, heterogeneously distributed.

The object from Lower Slaughter, Gloucestershire, is interpreted as a part of a structural beam from a bath-house rather than as a bloom (Tylecote 1986, 167-168). It is flattened on one side and weighs 10. 81kg (20cm x 9.9cm) and shows a heterogeneous distribution of carbon content which varies from 0.0 – 0.8%. In fact, the large structural beams which have been found

in England for example, at Catterick and Corbridge, and their metallography belong to the sphere of the early blacksmith's work, which cannot be included in this volume. Nevertheless, worth of mention are four iron lumps from Strageath in Scotland, 2nd century AD, which interpreted as billets or bars, rather than as blooms. Their weights are 5.7kg, 6.9kg, 7.3kg and 7.9kg respectively, but no further details are available (Tylecote 1986, 167 – 168, 178). The fragment from Nanny's Croft, near Arundel, Sussex, dated to the late Roman period (4th century AD) is a roundish block of hard steel containing 1.6% C and weighing 0.33kg (Tylecote 1986, 168, 211, tables 82 and 103).

Up to the present time, only three blooms have been published from those distant regions never conquered by Romans, but none, however, are directly connected with iron smelting sites. There is a rather irregular, unconsolidated bloom found at Kowel in Poland (Mazur and Nosek 1965) measuring 25cm x 28cm x 10cm (Fig. 66: 1) and weighing 1.5kg (though it should be borne in mind that there is a great deal of entrapped slag). Metallographic examination revealed a very heterogeneous structure of pure ferrite, ferrite-pearlite, cementite, and ledeburite — i.e. wrought iron grading into areas of hard steel, with some areas of cast iron. The phosphorus content also varies, reaching 1.85% P in places, and showing a clear phosphorus eutectic. It would appear that this bloom was subjected to preliminary reheating, but was not forged. It is probably a typical example of an unworked product of a small bloomery furnace.

Stankus (1996) reported blooms from Lithuania in the Baltic population sphere. One from Pietrasiunai, which is said to date to the 2nd – 3rd centuries AD, measures 5cm x 9cm x 10cm and weighs 1.2kg. The carbon content was found to be extremely heterogeneously distributed, varying from 0.1 to 1% C. A fragment of bloom from Gardlösa, Skåne in Sweden, in the Germanic cultural milieu and dating from the Romano-Barbarian period or later, was examined metallographically (Stjernqvist 1971, 169 – 173) and shows phases ranging from ferrite-pearlite (0.1% C) to eutectoid pearlitic steel (0.8% C).

The preserved blooms or fragments of this period show similar diversities in consistency and qualities (carbon content). The complete Roman blooms seem to be heavier (5 – 6kg) in comparison with their 'barbarian' counterparts which average just over 1kg. Billets, bars or even 'beams' may have been welded together from two or more blooms (Baatz *et al.* 1991), as the Celtic bi-pointed ingots (*Doppelspitzbarren*) definitely were.

Mediaeval blooms

There are several blooms, bloom fragments and unworked products known from early post-Roman contexts, following the local smelting traditions in the territories of the former Roman provinces. In slags from ironworks at Frouard (Lorraine, France), dating from the 5th – 6th centuries AD, many pieces were found which contained unconsolidated parts of amorphous iron sponges, eight of which were submitted to metallographic examination. The metallic fibres, as well as some sintered-together porous clusters are mostly ferritic. In five samples, structures of ferrite-and-pearlite or pearlite up to hypereutectoid levels with cementite cells could be observed (Leroy 1997, 159 – 161, figs 82-84). The three white cast iron blocks will be treated in the relevant section below. At the slightly later iron-smelting site of Boécourt in Switzerland, part of an unconsolidated and unforged bloom weighing 0.78kg and measuring 10cm x 9cm x 4cm, was found. It was heavily permeated with slag, the crystalline phases of which are, at the time of writing, unpublished (Eschenlohr and Serneels 1991, 71).

A different form, found in 1936 in an area 200km north of Trondheim in Norway, has been presented in a preliminary report by Espelund (1996a, 53). Dating to the 5th – 6th centuries AD (AD 390–545, according to ^{14}C), this is a part cut off from a consolidated bloom. It weighs 9.3kg and is a homogeneous steel with 0.7% C, showing decaburization of the surface. There are voids without slag in the interior and only small slag inclusions in the metal matrix.

Four blooms are known from early Ireland, apparently of the later 1st millennium AD, but their precise chronology has not been established because of the lack of archaeological contexts. The Carrigmuirish, Co. Waterford bloom (Tylecote 1986, 191 – 193) weighs 3.34kg and has a carbon content of 0.0 – 0.7% C. Scott (1990, 162, 165, pl. 6.5.4 and 6.5.5) published two microphotographs of blooms, one from the Brothers' Cave, Co. Waterford, the other from Ballyhenry, Co. Antrim, a settlement site which also produced unspecified amounts of slag. The Ballyhenry example comprised two fragments of unconsolidated ferritic iron with much entrapped slag weighing 250g, while the Brothers' Cave specimen is a more consolidated steel with an acicular Widmannstätten structure of ferrite and pearlite. There is no detailed information surviving on the allegedly-consolidated bloom reported to have been found on a crannog in Lough Faugham in Co. Down bloom (Scott *loc. cit.*).

Far from Ireland, at the Lithuanian site of Lieporiai, two interesting lumps of iron, dating from the 5th – 6th centuries AD were found (Stankus 1996). One was a relatively heavily-carburized (0.7% C) fragment weighing 0.118kg and measuring 2cm x 3cm x 4cm, while the second was an iron casting (see below).

*

Other finds are designated in archaeological terminology as mediaeval in the west of the Continent, or early mediaeval in central and eastern Europe. It has to be noted here that in the period after the 9th century AD, blooms with deep cuts or notches on one side, known as 'split' or 'semi-split' blooms occur more frequently and will be discussed below in a separate section. We shall turn our attention now to the bun- or loaf-shaped blooms which occur among archaeological assemblages of the Middle Ages.

Four well-formed, bun-shaped blooms come from the south Hungarian smelting site of Somogyfajsz (Fig. 45), which is known as an ironworks of the 10th century AD (Gömöri 1996, 274, 276, figs 5, and 7). One weighing 3.20kg was found directly at the throat of furnace 6 (0.16% C, 0.71% Mn, 0.40% P), while the weights of the others ranged from 2.45 to 2.75kg, their contents of carbon, manganese and phosphorous being respectively 0.03%–0.74% C (bloom 2), 0.01% – 0.92% Mn and 0.64% – 1.2% P. The exceptional levels of Mn and P result from the application of bulk analyses and reflect the influence of entrapped slag derived from the local bog iron ores.

Another rounded bun- or loaf-shaped bloom weighing 3.10kg came from Olomučany site 951/3 in western Moravia (Fig. 62: 8), from an ironworks of the 10th – 11th centuries. Its texture was extremely porous, containing about 50% of entrapped slag in some areas, while the metal structure was mainly ferritic, with localized Widmannstätten structures. Two other fragments of triangular iron plates from the same locality were subjected to metallographic examination, with interesting results (Pleiner 1980). One was a ferritic sponge embedded in a matrix of slag, while the other proved to be a compact piece of hard steel (0.5 – 0.8% C), containing pearlite and ferrite cells (Pleiner 1978b). It is possible that they were artefacts, representing different phases of trials of how to consolidate parts of blooms by forging them flat.

Further finds of loaf-shaped iron blooms belong to the high Middle Ages, i.e. the 12th–14th centuries. Apart from a 13th century unforged example from Downpatrick, Ireland, which is exceptionally large, weighing 6.4kg and contains much slag in its porous interior (Tylecote 1986, 191, 193, fig. 133) and an undated piece from Backebo, Sweden also said to weigh over 6kg (Nihlén 1939, 81 – 82, fig. 39)), the other specimens all come from eastern Europe.

Four bloom fragments, from Gdańsk in northern Poland, the shapes and weights of which are not given, have been studied. In two cases, dating from the 12th century, the metal was only ferritic, with numerous slag inclusions. One of these was exceptionally rich in sulphur with a content of 1.06% S, with sulphides occuring on the ferrite grain boundaries and it is considered to have been discarded waste. The other two, which date to the later 13th century, were steels with carbon contents around 0.75% C and as high as 0.9% C in places, with structures of pearlite and

pearlite with cementite (Piaskowski 1960, 72 – 73, figs 35 – 43). Three flat, sub-triangular pieces of bloom weighing from 0.4 – 0.5kg, formed like the sectors of a circle, have also been found in northern Poland at Kołobrzeg and appear to have come from blooms that were originally about 25cm in diameter. It is reported by Łosiński (1959, 19, 25 – 28, figs. 6 – 8) that the metal was spongy and mostly ferritic (0.19% C, 0.10% P, 0.25% Si).

Examination of a very flat 12th – 13th century bloom from Jurgaiciai in Lithuania (6.5cm x 8.5cm x 1cm) revealed a homogeneous structure of ferrite with pearlite with an average carbon content of 0.24% C (*cf.* Stankus 1996). A similar picture is provided by a small bloom or part of a bloom from Tervete in Latvia, weighing 0.732kg (Anteins 1960, 30 – 31, figs 90 – 91), where, in some areas, the ferrite grades into to spots of pearlite with a cementite network. The carbon content is estimated to have varied from 0.0 – 1.2 % and there were many slag inclusions and voids in the interior (Fig. 62: 10; Fig. 66: 2). Reference is made to ferritic or ferrite-pearlite structures in some early or later mediaeval Latvian blooms such as those from Kente and Turaida (Anteins 1960, 18 – 19, 47, figs 43 – 44).

Then, there is an important collection of Russian loaf-shaped blooms described by Kolchin (1953, 28, 42 – 45), which were found, mostly during the pre-war period, in several fortified sites dating from the 10th to 13th centuries. Presumably, these finds can be ascribed to the 'catastrophe horizon' of the 13th century which is linked to the destructive Mongolian raids and occupation which brought these flourishing centres to an end and left many valuable metal objects in their deposits. The hillfort of Gorodsk yielded several items, one of which was a lump of iron (2.65kg) covered with slag and scale (*op. cit.* 42 – 44, fig. 13: 1). Tens of blooms are said to have been found at the fortified site of Knyazha Gora, near Kiyev (Fig. 62: 7), one of which weighed 2.05kg and measured 14cm in diameter by 4.5cm thick and had been cut in two. The published photograph shows a very large number of pores and large cavities. It can be described as a relatively well-shaped but unconsolidated product although, unfortunately, there is no description of microstructures. Some 47 heavier blooms weighing from 5 to 5.6kg are reported to have been found in the eastern part of the rampart system of the fort of Raykovetskoye along with a destroyed smelting furnace (*op. cit.* 28 – 29, 45). Mongayt (1955, 99) has also discussed two blooms from the ancient town of Staraya Ryazan'.

Many iron blooms came to light at Novgorod Velikiy in northern Russia, an important urban centre and Hanseatic trading post. Six examples were found in layers of the 13th century. Three loaf-shaped blooms (Fig. 63) weighing 2.05, 2.92, and 2.76kg respectively, about 14cm in dia. and 6cm thick were described by Kolchin (1959, 12, fig. 2), the remaining three by Rozanova and Terekhova (Terekhova *et al.* 1997, 7 – 8) who also refer, after Kolchin and Yanin, to an interesting hoard of iron blooms, dating from the 14th century, some of which were the subject of reheating experiments (see chapter XI). This exceptional assemblage consisted of 31 well-formed loaf-shaped blooms (Terekhova *et al.* 1997, 9, fig. 1: top) measuring 13 – 14cm diameter by 5 – 6cm thick and weighing

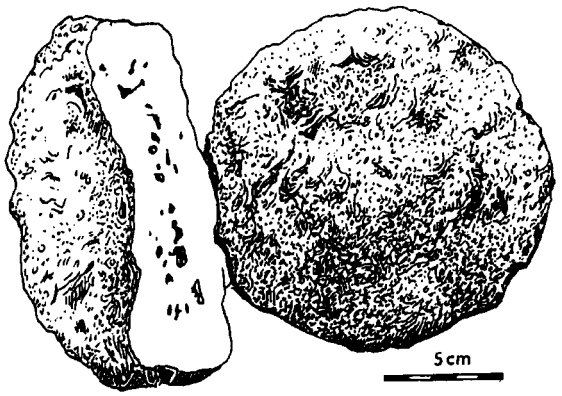


Fig. 63. Novgorod Velikiy, N Russia. Iron blooms from the hoard of the 14th century AD (after Terekhova *et al.* 1997).

from 2.7 – 3kg, the total weight being 85kg. The picture derived from metallographic examination shows that despite their pleasing shapes, the metal was not fully consolidated and still contained numerous cavities partly filled with slag in the mainly ferritic matrix (Fig. 66: 3). The carbon contents of the surface layers reached higher values, 0.1 – 0.25% and even 0.4 – to 0.5% C, giving a structure of ferrite and pearlite, with a P-eutectoid being visible in the ferritic grains.

A very curious object was discovered in 1912 on an unknown fortified site in the Vasiliyevskiy region of Russia. This was a dished iron disc 17cm in diameter and only 1.6cm thick, weighing 1.75kg (Kolchin 1953, 45, fig. 15). It must be a shaped forging rather than a bloom, possibly a commercial ingot or the final form of the average loaf-shaped bloom after it had been compeletely forged flat. Unfortunately the piece has not been subjected to scientific examination (Fig. 62: 9).

In the Russian Far East, at the hillfort of Shaigin in the Amur region, numerous traces of iron-making and working were discovered during excavations conducted between 1962 and 1972. In layers of the 12th – 13th centuries, more or less amorphous and slaggy lumps of unconsolidated iron, some 14cm in diameter and with heterogeneous ferrite and pearlite structures came to light. These proved to be unworkable and were instead divided into smaller pieces which could be reheated and forged to the compact billets, some 15cm long, which were found in the same contexts (Len'kov 1974, 98 – 99, figs. 19 – 20).

Split blooms

In addition to rounded loaf-shaped blooms in early Russia as well as in other regions of Europe, we must now turn to objects of similar dimensions and weights which have been deeply notched on one side by cutting with an axe while still hot. They belong to the curious family of split or semi-split blooms which stand out among other archaeological finds. Their occurence must result from specific techno-economic conditions, since there are localities where both types appear together as on the site of Velikiye Bolgary on the Volga river, where numerous blooms were found. The loaf-shaped examples were the larger (19 – 20cm in diameter) and heavier (about 4kg), while split blooms (Fig. 64: 5) from the same site weighed around 2.5kg (diameter 12 – 14cm, thickness 4.5 – 8cm). The divided halves of a semi-circular form weighed about 1.2kg. These almost-standardized variants were apparently destined to be traded to the urban markets of the 13th – 14th centuries AD in the region (Efimova 1958, 299, fig. 4). What is of particular interest is that all of these blooms and fragments are said to have been found in the fill of a pit in a considerable, but unspecified, number.

Other split blooms are extremely variable in size and weight (from 0.4 to 50kg), distinguished by a deep V-shaped notch from which the term derives. It was believed at one time, in the early days of the archaeometallurgy of iron, that these notches were made by a sharp stream of cold air which attacked the bloom when still inside the furnace (Zbierski 1955, 310) but this is impossible under the conditions of bloomery smelting. Moreover, closer examination brought much evidence that these blooms were notched while still hot with a heavy blow from an axe. The reason was obvious. Such a deep cut allowed workers to see to what extent the iron was consolidated and thus to judge its value. Furthermore, it facilitated the subsequent division of the bloom into halves, either for further working or for trade.

In the light of present evidence, the geographical distribution of split blooms covers the Middle East (e.g. Almatu in Kazakhstan), spreading down to Bulgaria (e.g. Preslav) and Romania (e.g. Dealul Gradiştei, the ancient Sarmizegetusa), then westwards into central Europe (with sporadic finds) and Scandinavia where there is a concentration of finds in Norway and Sweden. The most distant examples come from Ireland and the northern Spanish coast. The chronological range is puzzling, since the earliest examples, from Sarmizegetusa, are said to be of the 1st century AD date, so early as to be so far absolutely unique, while the bulk of dated

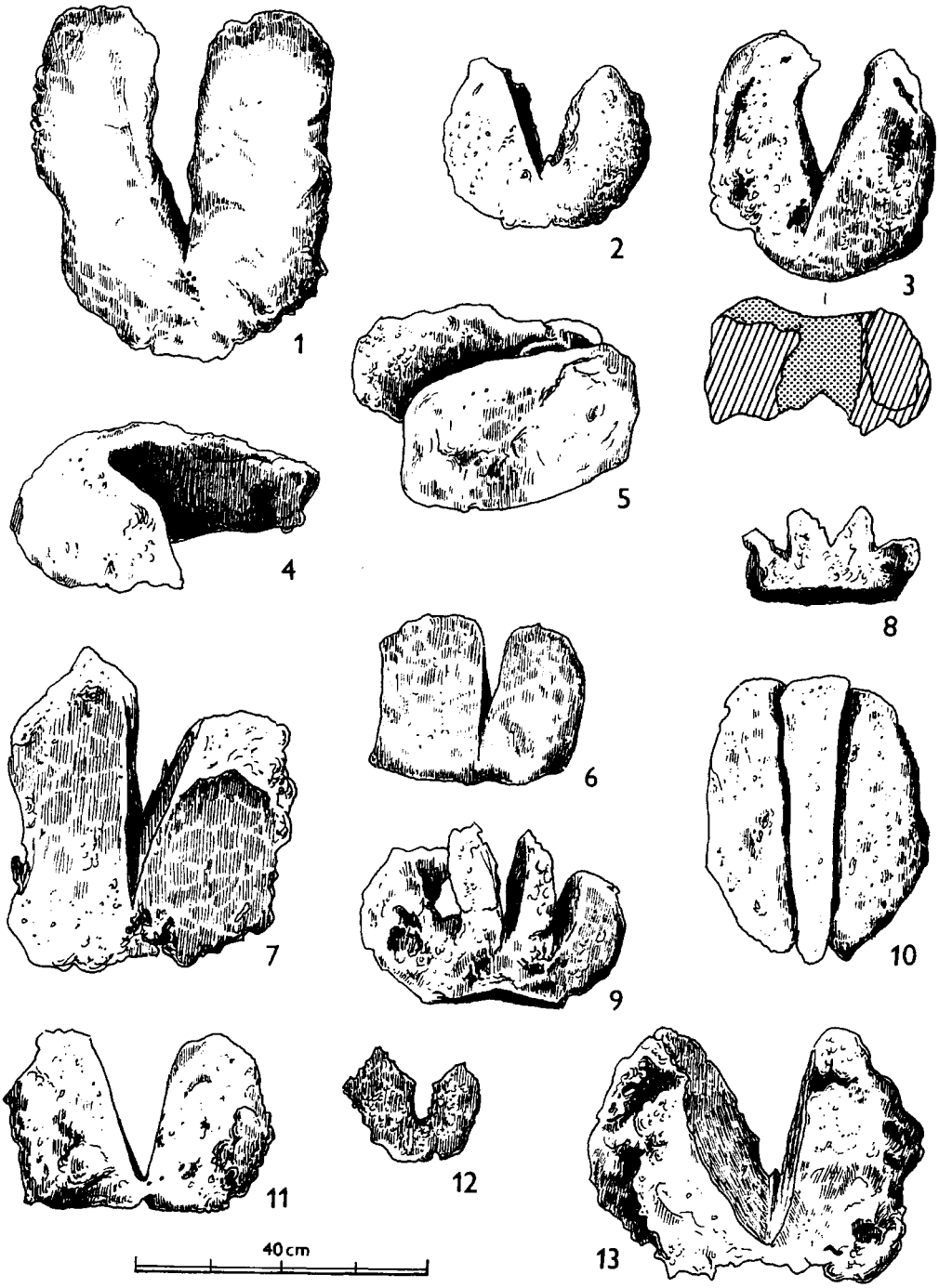


Fig. 64. Split blooms from Europe and Asia. 1 Dealul Grădiştea-Sarmizegetusa, Romania, 1st century AD (ca 9kg); 2 Olomučany, W Moravia (9th century AD, 2.45kg), from a bloomery); 3 Lęczyca, Poland, 12th–13th centuries AD (2.2kg); 4 Vyshgorod, Ukraine; early mediaeval (4.9kg); 5 Velikiye Bolgary, Russia, 13th century AD (ca 4kg); 6 Almatu, Kazakhstan, 13th century AD. Scandinavian blooms: 7 Hardingbukti, Norway, early mediaeval (12.45kg); 8 Lamøya, Norway, 9th century AD ('fingers', from a boat grave, 0.6kg); 9 Ålems, Sweden, early mediaeval (5.22 kg); 10 Våxtorp-Bölinge, Sweden, early mediaeval (from a hoard containing cut-off pieces); 11 Li (Egge), Norway (2.9kg); 12 Vadstena, Sweden, 14th–15th centuries AD (0.4kg); 13 Edland, Norway, early mediaeval (from a hoard with six similar pieces, ca 10kg). References: 1 Glodariu 1975; 2 Souchopová 1986, 3 Zbierski 1955, 4 Kolchin 1953, 5 Efimova 1958, 6 Baypakov 1986, 7, 11 Martens 1979, 8, 13 Hauge 1946, 9 – 10 Nihlén 1939, 12 Wallande 1977.

objects is mediaeval, beginning in the 9th century AD, the most frequent occurrences being in the 12th – 13th centuries, with some later examples. A number of the Norwegian split blooms are undated, but most probably belong to the Viking Age.

As noted above, the earliest split blooms were reported from the ancient Dacian capital of Sarmizegetusa (modern Dealul Gradiştei) in Romania (Glodariu 1975, fig. 6). According to the excavator, an incredible amount of iron in form of an unspecified number of blooms totalling 887kg in weight was discovered within a smithing area on terrace VI. A further 1 tonne was distributed throughout all of the earlier levels. The individual pieces were heavy, weighing 9 – 11kg each and ranging in size around 20 – 21cm x 24 – 26cm, with deep notches on one side apparently made by an axe when the metal was hot (Fig. 64: 1). In a later report (Glodariu 1980, 85, fig. 5) the number of split blooms was specified as 15 pieces. No scientific examination has been carried out so far. The find contexts are dated to the catastrophe horizon before the Roman conquest of AD 106 and the blooms are ascribed to Dacian smiths. However, their attributed spatial and chronological position is so unique, that one suspects that they are, in fact, later in date.

Chronologically, the next examples, the earliest from mediaeval contexts, come from some eight centuries later in the form of a very curious find from Olomučany in Moravia (see Chapter IV). Two split blooms which had been buried in a depression while still hot, so that the surrounding soil was baked red, were found in front of furnace VI (Souchopová 1986, 35, 73 – 74, pl. I: top). The diameter of both blooms was 11 – 12cm, thickness around 8cm and they weighed 2.153kg and 2.45kg respectively (Fig. 64: 2). The lighter of the two was studied metallographically by Stránský (Stránský and Souchopová 1997, 99) and proved to be compact and well-worked, with only a slight degree of porosity. Essentially, the metal was a mild carbon steel with an unevenly-distributed carbon content. Ferritic structures prevailed in the interior, while the more carburized zones were observed near the surface. The bloom, covered with clay, cooled very slowly from temperatures about 700°C which resulted in good ductility of the core. Stránský interprets this an intentional technological manipulation, which seems improbable due to the fact that both pieces were already notched. Moreover, this situation has no parallels to date and ritual sacrifice seems to be the more plausible explanation.

Elsewhere in central and eastern Europe, finds of split blooms are so far rare. Those from the fortified centre of Lęczyca, Poland, date from the 12th – 13th centuries (Zbierski 1955, 309 – 311; Piaskowski 1959). One is complete, with a deep notch and is coated with and permeated by slag. It weighs 2.205kg an measures 14.7cm x 14cm x 7.9cm. The structure is of coarse-grained ferrite, and areas of ferrite with pearlite and the metal appears high in phosphorus and manganese (0.42 – 0.79 % P; 0.31 – 0.86 % Mn; 0.04 – 0.84 % Si) although it should be borne in mind that the analysis is influenced by the numerous slag inclusions in the spongy metallic mass. Although the bloom, labelled 127/50, has hardly been forged, it was nevertheless heated up and split (Fig. 64: 3). There are a further seven halves of blooms from this site, weighing about 1.5 – 1.6kg, which are also very slaggy and show ferritic structures (Zbierski 1955, pl. 96:b, 99, 103).

Kolchin (1953, 43, fig. 13: 2, after Rybakov) reported two split-blooms from the fort of Vyshgorod in Ukraine (10th – 13th centuries), the weights of which are given as 5.92 and 4.90kg (Fig. 64: 4), but there are no results of any scientific examination. A brief note should be made of a 11th – 12th century smithy excavated in Asia, at Almatu, Kazakhstan, which produced rectangular split-blooms (Fig. 64: 6) and many half-blooms (Baypakov 1986, 163, fig. 72: 1), but no further information is available beyond the fact that they measured 10 – 15cm x 5 – 7cm.

On the western periphery of Europe, in Ireland, three split blooms come from Dernaglug and Drumaa in Co. Fermanagh (Tylecote 1986, 191, 193, tabl. 93). They were found in a bog and are considered to be of mediaeval date. One of the two which weighed 5.45kg was subjected to metallographic examination and found to be a low-carbon steel (0. 05% C, 0.06 – 0.08% P,

0.01% SiO_2) with areas of higher carburization near the surfaces.

Norway is an important finds province, with an abundance of split blooms from more than thirteen sites, several of which have yielded more than one specimen and even hoards as at Li where five specimens were found (Fig. 64: 11; Fig. 65: 3) and Edland with six (Fig. 64: 13; Fig. 64: 4). They are not precisely dated, but are all thought to belong to the mediaeval Viking period. Two categories have been identified, characterized by weight, one group weighing from 10 – 14kg and the other from 2 – 5kg. Martens (1979) has sought to identify the heavier specimens, which were presumably unforged or only slightly forged, with the *blästerjern* of written records, crude semi-products for the market and the lighter category as *fellujern*, a more highly-worked, and therefore more expensive, semi-product. The axe cut would have indicated the quality of the bloom when it was still hot, since the exposed iron would have shone more brightly than the dull and rapidly cooling slag. A metallographic study of both types of Norwegian split bloom is being carried out by Rosenqvist and, at the present time, information is available on a split bloom (*blästerjern*) weighing 12.45kg and measuring 26cm x 22.8cm x 12cm, from Hardingbukti in Møsstrond, Telemark (Fig. 64: 7), which consists of soft ferritic wrought iron with tertiary cementite particles on the grain boundaries (Martens 1979, 196 – 197). Four slightly smaller blooms from Løyningbukti weighed between 9.78 and 13.45kg while recorded examples of split blooms of *fellujern* type include those from Skeibrok in the Vest Agder (4.02kg), Egge (2.9kg) and Inset (5.75kg) in Hedmark (Martens 1979).

Similar specimens are known from Sweden, from Närke (undated) and the small blooms from the Vadstena and Riseberga monasteries (0.4 and 0,485kg), dating to the 14th – 15th centuries (Wallande 1977). They represent pieces of iron already divided up from blooms and the only notched specimen from Vadstena (Fig. 64: 12; Fig. 65: 1) seems to be unfinished with the splitting into two pieces not having been completed. Wallande considers these items as traces of the preparation of *osmund* iron, a famous form of the metal traded in the Middle Ages. A deep notch signalled that the bloom was ready to be split into two or more pieces. The iron blooms from Bölinge, Växtorp parish, Sweden (Nihlén 1939, 83 – 87, figs 41 and 42) were cut into three pieces (*cf.* Pleiner 1962, 136, fig 21: 2). In fact, this constituted a hoard of completely split blooms, consisting of 64 individual segments. Another example of this comes from Älmhult II, represented by four pieces of iron 20 – 23 cm long, cut off from the central part of the bloom and one slice 26cm long from the top or side (Nihlén, *op. cit.*, 86, figs. 45 – 46). The iron had been forged before being cut up, but no further information is available.

This reminds us of other Scandinavian blooms which are semi-split, but notched with three cuts, so that dividing them into smaller pieces, sometimes, called 'fingers', would have been easier. The example from Lamøya, Vestfold, Norway (Hauge 1946, 155 – 156, fig. 81) was 13.5cm long and weighed only 0.6kg (Fig. 64: 8). It comes from a 9th century woman's boat-grave and is the only archaeologically dated example. A specimen from Ålems socken in Småland in southern Sweden was considerably heavier at 5.22kg (Fig. 64: 9, Nihlén 1939, 81 – 82, fig. 40). Important information on blooms with 3 notches has been published by Buchwald and Voss (1991, 33 – 36; see Buchwald 1999) and it should be noted in passing that Percy (1864, 321) described the splitting or notching of iron blooms as being common in Iceland.

Some undated notched or split blooms have been discovered in museums in Denmark (Karup and Skjern) and Iceland (Mynes). They are notched into three or four 'fingers' and weigh 8.2 to 8.6kg, but their specific gravity is very low (4.5 – 5.5 g/cm^3) because they consist of 50% of slag (a wüstitic and fayalitic groundmass, high in phosphorus). According to Danish written taxation documents of the 15th – 17th centuries, such blooms were called 'kloder' ('clods' or 'lumps') and were equal in price to 1/8 of a barrel of corn or to that of a pig. Tens or hundreds of them are mentioned in individual documents, so that, taking into account the average weight of one piece (about 8kg), the taxes represented large amounts of iron. These blooms or their parts (fingers) were distributed from bloomeries to settlements and worked there in smithies into

artefacts. The origins of this practice are unknown but the circulation in Denmark of unworked split blooms survived at least until the 17th century (Buchwald and Voss 1992; Buchwald 1999; Vellev at the Jutland Conference 1999).

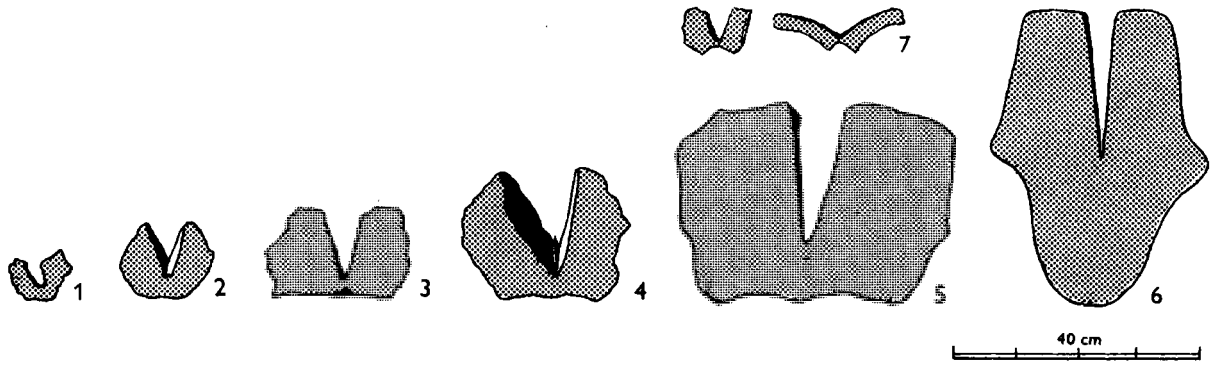


Fig. 65. Size comparison of some European split blooms. 1 Vadstena, Sweden (0.4kg); 2 Olomučany, Moravia (2.43 kg); 3 Li, Norway (ca 3kg), 4 Edland, Norway (10kg); 5 Sopron, Hungary, 6 Keszthely-Fenékpuszta (both latter undated, 47–50kg), 7 Bergheim, Austria, 15t–16th centuries AD. References: 1-4 see fig. 63; 5-6 Hegedüs 1961, Rozsnok 1979), 7 Feldinger 1996.

Having touched upon later finds, we cannot omit reference to the Ria Oria ship wreck on the northern coast of the Basque country. The cargo of 'Spanish' iron, apparently ready to be shipped abroad in barrels, consisted of 100 pieces of split blooms and 80 pieces of forged and pointed iron bars. Among the blooms, slices weighing 3.5 – 8kg each and pieces cut from edges ('endys', off-cuts) weighing 1.22 – 3kg are reported. The metal was incompletely consolidated, full of entrapped slag, very low in carbon (0.01 – 0,1% C) and contained 0.03 – 0.05% Cu, apparently derived from the copper tuyeres used in the region. Experimental reheating carried out at Plas Tan y Bwlch in Wales on one of the blooms has been reported (Crew *et al.* 1997). The pointed bars (1.2m long, 9.2kg) were well-forged but the degree of carburization was found to be uneven, giving structures ranging from purely ferritic through to ferrite-pearlite structures with some highly carburized zones. The assemblage is not directly dated (^{14}C tests are planned), but is attributed to the 14th – 16th centuries. Another sunken cargo dating from the 15th – 16th centuries AD was located in the river Salzach, near Bergheim, Austria. It consisted of unfinished marble plates and iron blooms and bars (about 121 in number, totalling some 300kg). According to a preliminary report (Feldinger 1996) the find includes smaller semi-split blooms (weighing about 1.5kg), then butterfly-shaped billets apparently worked from the split blooms (Fig. 65: 7), and oblong bars.

We must now turn our attention to an enigmatic group of large semi-split blooms from western Hungary which are significantly heavier than any of the others so far discussed. Their chronological position is far from clear, since they are unstratified finds held for many years in museum collections. Sites such as Sopron (Fig. 65: 5), Szalacska, Hévíz and Keszthely-Fenékpuszta (Fig. 65: 6) have produced very heavy iron blooms which show significant similarities in shape and their method of notching to those described above, but are clearly diferentiated by their weights, which varies from 26kg to as much as 47 – 50kg (Hegedüs 1961; Rozsnoki 1979). Most of these blooms have been investigated metallographically and shown to be heterogeneously carburized. The 26kg bloom from Szalacska, measuring 29cm x 22cm x 12.6cm and which seems to be just a cut-off half, was forged from mild steel (ferritic-pearlitic Widmannstätten struc-

ture, average 0.22% C, 0.10% Si, 0.025% P). The Hévíz example, weighing 47.5kg, consisted of heterogeneously-carburized metal with a carbon content of 1.26% in certain areas (pearlite and excess cementite), silica 0.04% and phosphorus 0.02%. The two Sopron blooms, one in the Mining Museum at Diósgyör and the other in the Ferenc Liszt Musuem in Sopron, weigh around 50kg, have similar structures and, in addition, areas of very high carburization containing ledeburite and flakes of graphite: i.e. particles of cast iron. The high silica content of the Sopron specimen (0.26% Si, 0.17% Mn) is attributable to the entrapped slag. The split-blooms from Keszthely-Fenékpuszta (Fig. 65: 6), five in number, ranged in size from around 40 – 44cm x 33 – 39cm x 12 – 25cm and weighed around 50kg each. They were examined metallographically by Rozsnoki (1979), who observed many patches of ledeburite and graphite flakes in the predominantly pearlite-cementite matrix, as well as some areas of pearlite-ferrite.

The dating of these large Hungarian blooms has not yet been satisfactorily fixed with the La Tène or late Roman being at one time the favoured periods. The Hévíz specimen was found in a lake in the vicinity of the spa which is situated some 5km NW from Keszthely. The Keszthely-Fenékpuszta finds are said to have been found in pits on or near a Roman military *castra*, from where a heavy block anvil is displayed in the local museum. The necessary information is lacking, nevertheless the literature centres around a date in 5th century AD (Gömöri 1980). Unfortunately, no relevant furnaces of Roman or even post-Roman date have yet been discovered. As Hegedüs (1961) has pointed out, the extremely heavy weight of these blooms indicates strongly that they all should be seen as of mediaeval, if not post-mediaeval date, since even the making of notches in these huge objects would have necessitated the use of water-powered chisels. (At Pilisszentkereszt, north of Budapest, a fragment of iron was found 5cm x 3.5cm x 1.5cm, 0.3 – 0.4kg, with adherent charcoal; it was hard steel with a cellular and acicular cementite network in a pearlite matrix, 2.08% C, 0.10% Si, 0.10% Mn, 0.026% P, *cf.* Hegedüs 1961, 8, pl. X: 2).

The technique of splitting large, heavy post-mediaeval blooms in order to divide them into more manageable pieces was described by several contemporary authors. Biringuccio (1540, 63) writes in chapter 7 of his treatise that iron was taken out of the furnace when still hot and broken into pieces with sledges by hand, each piece then being reheated and worked into a bloom (*masello*). According to Agricola (1556, chapter IX), lumps of iron weighing 2 – 3 *quintals* (100 – 170kg), having been roughly forged and cleared of the bulk of attached and entrapped slag, was divided by a sharp iron into four or six pieces using a water-driven hammer. A picture of a Scandinavian furnace in Schultze's treatise (1732) shows, sub M, the classical notching of a bloom; another notched piece lies by. Evenstad (1790) knows the dividing of blooms into pieces, whilst Busch (1851) mentions the cutting into two pieces, in hot state, in four minutes. A sketch dating from 1613 represents the splitting a large bloom from a *Stuckofen* with axes (Köstler 1986, 28, fig. 2).

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To date, more than 500 blooms or their separated parts, coming from 90 archaeological sites have been identified. 13 are pre-Roman (Hallstatt, La Tène, Iron Age), 13 Roman (or Romano-Barbarian, 4), and 36 mediaeval, with those from a further 20 sites or so not dated precisely. The number of items is far greater, since some reports refer to many, even tens of blooms on individual sites, without any precise details. Some 9 sites have yielded evidence of iron smelting activity and at two, Olomučany and Somogyfajsz, the blooms were found immediately beside the furnaces while at the Gallo-Roman period site of Thoste, there was a hearth bottom in the furnace. On the other hand, 7 sites which produced blooms showed evidence of smithing operations, but not of smelting. Blooms in hoards or hoards of blooms were found in six cases and blooms in came to light from eight rural or urban settlement sites, having been brought

there from nearby or more distant ironworks for further treatment. The remainder are from unknown contexts.

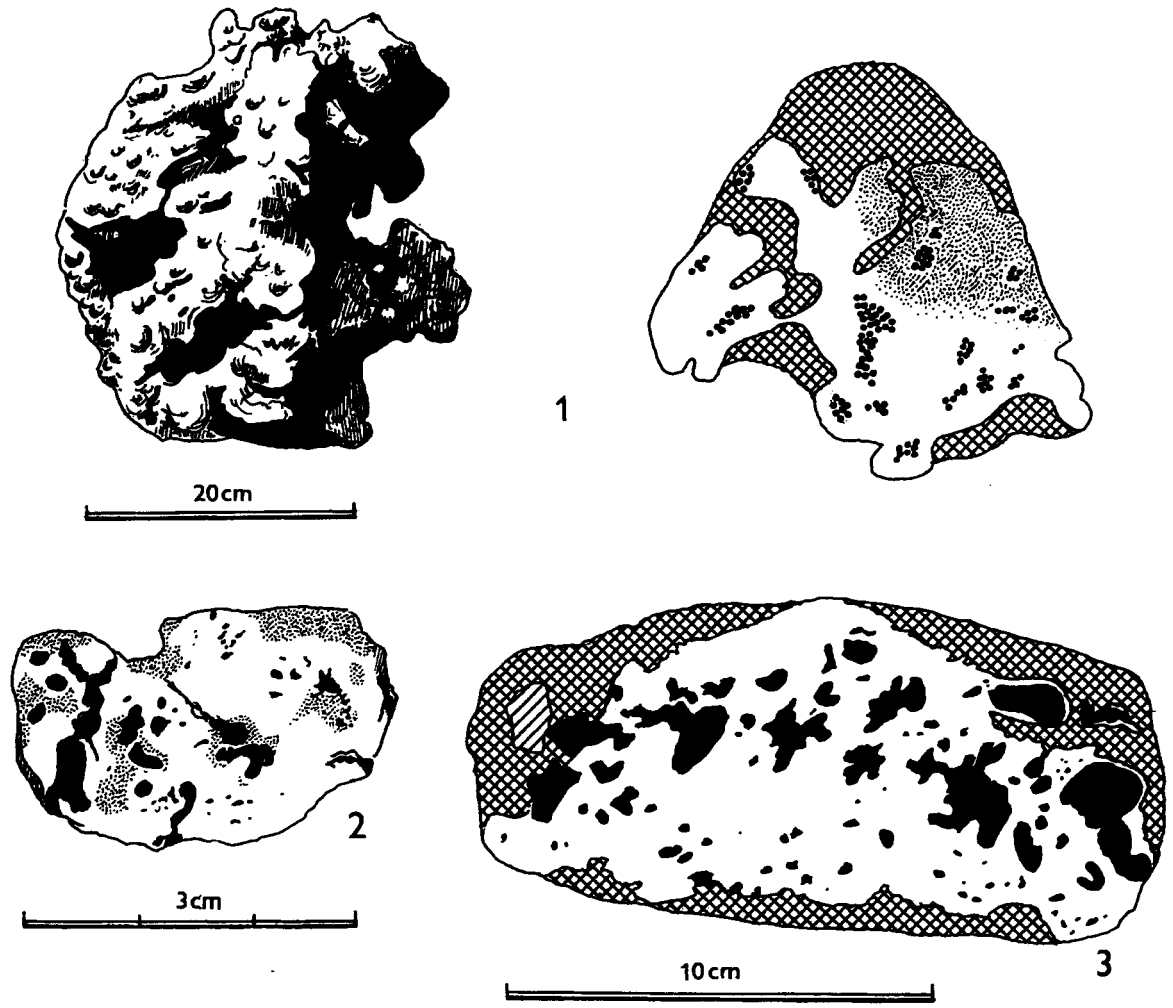


Fig. 66. Selected examples of sectioned blooms. 1 Kowel, Poland, late Romano-Barbarian period, 1.5 kg — left: the unconsolidated bloom, right: section with marked slag (cross-hatched), phosphorus segregations (coarse dots), carburized areas with ledeburite (fine dots), and ferritic metal (white); 2 Tervete, Latvia, 13th century AD – section of a small bloom as in Fig. 62: 10 – ferrite (white), spots with elevated carbon content (dots), holes, partly filled with slag (black); 3 Novgorod Velikiy, N Russia, 13th century AD — slag with minute iron particles (cross-hatched), ferritic iron (white), holes (black). References: 1 based on Mazur and Nosek 1965; 2 Anteins 1960, 3 Kolchin 1959.

About 90 blooms or parts of blooms had been cut through in order to observe the consistency of the metal. In 34 % of the cases, the iron was unconsolidated, the block consisting more or less of sintered-together iron sponge with many isolated grains, metallic fibres and nodules embedded in a slag matrix. Some 30 % of bloom finds were partly consolidated, and had evidently undergone primary reheating and were partly or wholly forged and shaped mostly to the loaf form, sometimes with flattened sides, but with their interiors still full of entrapped slag, so that further forgings would have been necessary to obtain a workable material for the manufacture of artefacts. About 21 % can be described as better consolidated blooms, which were, nevertheless, relatively porous and still requiring reforging.

In addition, on many sites, mostly those producing evidence of forging activity, amorphous

fragments of slags containing unconsolidated pieces of iron or steel have been found. These may be regarded as refuse resulting from the working and dividing of larger pieces. They range in weight from 0.1 – 0.3kg and in this survey have been found to come from some 40 localities.

The number of 65 blooms have been examined metallographically. Of these, 29 % consisted of purely ferritic iron or very mild steel, 37 % of primarily but heterogeneously-carburized metal (0.01 – 0.8 % C), 25 % of very hard carbon steel with carbon contents often exceeding 0.8 % C, of eutectoid or hypereutectoid values, in 14 cases with areas containing drops of cast iron with ledeburite, graphite, excess cementite phases in a pearlitic matrix). This indicates that smelters at the majority of ironworks exercised only a limited control over the process in terms of quality and hardness. Because of that, many bloomeries must have delivered or exported unworked blooms, the quality of which required testing and modification by dividing them up, reforging and homogenization in smithies. About a tenth of bloomery iron works yielded cast iron pieces, treated, possibly, as discarded vaste (see below).

It is worth noting that the latter named categories, comprising highly carburized metal, appear in all chronological periods and on sites of all types — in bloomeries, in smithies, in hoards and in settlements which can be characterized as import foci. Some of the ironworks, particularly those of the Mediaeval period, notched or split the blooms in order to determine the quality of the smelt in terms of the amount of iron present in the mass. In certain regions with more developed iron trades, the producers notched the blooms several times to make further division easier, possibly in relation to their local or regional systems of weights and measures. Discussion of the weights of iron blooms would make an interesting chapter but, unfortunately, this is not possible due to the scattered and fragmentary nature of the data. Not all blooms discovered have been weighed and, in some instances, where more than one example occurred in a find or on a site, the individual weights are not specified, only the range. Nevertheless, taking into account the sample at our disposal, 80 % of pre-Roman blooms ranged from 1 – 3kg (the only exception being that from Magdalensberg at 18.4kg). Of the Roman blooms, 45% weighed between 3.7kg and 7.9kg, while 36 % were heavier, weighing from 9.0 – 13.5kg. A further four contemporary pieces from non-Roman territories weighed from 1.2 – 1.5kg. The majority of mediaeval iron blooms (5th – 14th centuries AD) fall into a range between 1.6kg and 3.3kg, the typical result of the smelt of a small bloomery furnace, while another significant group (27 %) varied from 3.5kg to 8kg, with a further 14% weighing more, 8–14kg. At the absolute top of the range is the group of 9 unstratified blooms from south-west Hungary which weigh 47 – 50kg each.

It must be borne in mind that before the iron in any bloom could be transformed into useable artifacts, losses were unavoidable in course of reheating and forging, reducing the amount of metal to some 40 – 80 % of the original weight.

Experimental blooms

A set of control data for our interpretation of the character of the bloomery process can be derived from several successful smelting trials conducted in low shaft furnaces, which have produced different kinds of blooms. Very good results were obtained during experimental smelting using a laboratory reconstruction of the Romano-British furnace from Ashwicken in Kent (Tylecote *et al.* 1971, 256 – 258). Twenty-two solid blooms were produced, their weight ranging from 0.4kg to 6.5kg. Smelt 6, for example, yielded a 3.7kg bloom from 7.3.kg of ore. Sectioning revealed the existence of large internal cavities, but the metal was denser than might be expected from a process which did not develop any free-running slag.

The products of smelts 12 and 14 consisted of lumps of white and grey cast iron with pearlite-cementite and ferrite-pearlite with graphite flakes. They weighed 1.8kg and 2.6kg respectively and were produced from 7.3kg of ore and 13.7kg of charcoal, an ore/fuel ratio of 2:1. The bloom from smelt 16 weighed 4.9kg, smelted from 11.8kg of ore and 7.3kg of charcoal, showed lamellar

pearlite and ferrite (0.6 %C). Smelt 19, which consumed 27.2kg of ore and 13.6kg of charcoal, an ore/fuel ratio of 1:3 resulted in a bloom weighing 5.8kg which showed ferritic iron with cementite on the grain boundaries. Smelt 21 used 18.2kg of ore and 6kg of charcoal, an ore/fuel ratio of 1:3 and yielded a bloom weighing 6.4kg. The heaviest bloom produced, weighing 6.5kg, came from smelt 27, which consumed 22.7kg of ore and 11.4kg of charcoal which produced metal with a structure of coarse pearlite and ferrite.

The larger blooms produced by Tylecote and his co-workers measured 18 – 20cm x 14.2cm x 6 – 10cm, which corresponds well with the average dimensions of excavated blooms. Due to the composition of the ore used in these experiments, the iron contained relatively high amounts of sulphur, which was visible as sulphide inclusions in many of the polished sections. The distribution of carbon varied throughout different levels of the bloom resulting from smelt 27, with some being partially carburized while others had undergone secondary decarburization at the mouth of the tuyere. The centre of this bloom was uniformly carburized at around 0.3 %C.

Smelt II.2 on the reconstruction of a furnace of the Želechovice type (see chapter IX) consumed 44kg of pure haematite using 60kg of charcoal and produced a bloom of hard eutectoid steel with an adhering sponge of iron and slag (Pleiner 1969b). It was relatively homogeneous, having been protected and heated in the rear compartment of the furnace and only the tip, adjacent to the mouth of the tuyere, was reoxidized to ferrite. The bloom was not completely consolidated, but this is interpreted as the result of the process having been halted prematurely. The total weight of metal produced is estimated to have been 5kg, but the main bloom, which was separated mechanically when red-hot, weighed 2.41kg (Pl. XXIV).

A bloom weighing over 2kg was produced in experimental smelt II/1978 on the reconstruction of a low shaft furnace of Romano-Barbarian slag-pit type from Moravia which used 7kg of haematite and 31kg of charcoal. Smelt IV/78 was carried out on a reconstructed Slavic furnace and produced 4kg of spongy iron bloom from 33kg of ore and 70kg of charcoal. The former bloom comprised heterogeneously-carburized steel containing 0.01 – 2,4 %C showing patches of grey cast iron and graphite, whilst the latter also showed considerable variation in carbon distribution and included areas of hypereutectoid pearlite in a cementite network (Souchopová and Stránský 1983).

Experiments carried out by Crew (1991; Crew and Salter 1991), of which 16 have been published to date, revealed a similar picture. They were performed in a small shaft furnace of Iron Age type, using high-grade bog ore rich in phosphorus and arsenic. From 7 – 16kg of charcoal and 7 – 8kg of ore, fuel-to-ore ratios from 1:1 to 2:1, he obtained blooms weighing from 0.5 – 3.1kg which were not always suitable for forging. Smelt XP 17 produced a 1.6kg bloom with 0. 01 – 0.1 %C, while XP21 yielded a bloom of 3.1kg with cast iron prills remaining in the hearth. Smelt XP22 produced a bloom of 1.6kg in weight with low-C cast iron and iron phosphides surrounding the 'ferrite' grains and the bloom from XP 23 contained highly-carburized areas (pearlite and cementite cells). Smelt XP27 produced a 1.7kg bloom with 0.0 – 0.8 %C and elevated levels of P and As, which was fully smithed into a reproduction of a currency bar weighing 0.5kg.

Experimental smelts in a slag-pit furnace of the Holy Cross Mountains type yielded blooms which were submitted to reheating and further forging, but no metallographic results have so far been published. Lyngstrøm (1966) reported a smelt resulting in bloom weighing 19kg from 72kg roasted ore and 125kg of charcoal. 9kg were worked by a blacksmith over 9 hours by hammer on anvil, the work consuming a further 21kg of fuel to produce 4.3kg of iron of which only 3.6kg could be worked into tools. Faivre and Reverdy, the latter a master blacksmith, worked over 10 hours a bloom 7kg in weight, obtained by smelting 30kg of iron ore (containing 47.14 %Fe) and 400 litres of charcoal) 10 hours. The block was divided into three parts which were forged twice, first to remove the covering slag, and second to shape a lump of iron (about 18cm in dia.). After some 30 heats over 3 hours, the work resulted in a bloom 0.6kg in weight (Faivre 1994).

A Catalan open forge was tested by Simón *et al.* (1995), following data from 19th century writers such as Richard and François. A smelt lasting 6 hours consumed 30kg of high-grade ore (94 % Fe_2O_3), 15kg of roasted ore and 40kg of charcoal and produced a compact bloom (*masser*) with few pores weighing 10kg and of diameter 12cm and thickness 4cm. Subsequent metallographic examination showed it to be a pearlitic steel with hypoeutectoid areas near the base (ferrite-pearlite with Widmannstätten texture) and some hypereutectoid areas in the interior (pearlite-cementite). During experiments with an open smelting hearth of an 18th century Basque type, not dissimilar to a Catalan forge, but blown by water-driven bellows (not by trompe), there was obtained, after smelt 6, a 16kg heavy unworked bloom a part of which (4.7kg) was submitted to 13 heats and reforeged during about two hours by Dillmann *et al.* (1997), giving the result of 2.24kg ingot (surface steel 0.2–0.8 %C, ferritic core, still with inclusions of slag and trapped charcoal).

Special attention must be paid to some reproductions of the smelting process carried out by traditional iron smelters and blacksmiths. In 1989 a group of Japanese masters, headed by Wakita Ryosui and Ono Masami performed 13 smelts at Nancy-Jarville in forced draught shaft furnaces using 4 to 20kg of North African, Brazilian and Swedish ores (Merluzzo and Forrières 1995). The products were of three kinds — a porous bloom consisting of iron with relatively few slag inclusions (about 2kg), steel (predominantly), and some cast iron. After rapid cooling, martensite, bainite, excess cementite and ferrite were observed. After this bloom was removed from the furnace hearth, all of the remaining fragments of metallic iron were collected. They comprised parts of the iron sponge which were not fully consolidated, with ferritic agglomerates in a wüstite-fayalite slag mass. In addition, all of the minute metallic fragments, called 'recuperation metal', consisting of ferritic lenses and cast iron droplets, were gathered up. The latter two types underwent what was in effect a second reduction with charcoal in a smaller furnace. The metal pieces were placed out of the oxidizing air stream from the tuyere as protection against decarburization. Again, a small bloom (about 1kg) was obtained and immediately quenched. The product was crushed in the cold state to free it from its surface covering of slag and then reheated and forged on an iron spatula called called 'daigane' while covered with charred straw and clay paste, again to protect, the metal, which was steel, against seconadary oxidation. Finally, a bar suitable for making a sword blade was forged from it.

Of particular interest is the 'Inagina' project conducted by Huysecom in the Dogon region of Mali, Africa. A large induced-draught shaft furnace with 13 tuyeres was operated by the successors of traditional iron smelters for 40 hours, using 210kg of raw ore, 25kg of calcined ore from a previous process, and 150kg of charcoal (45kg of which was left unburnt). The smelt resulted in a crude product weighing 69.25kg which was divided immediately after removal from the furnace hearth into four pieces. One of these was a compact iron core (bloom), weighing 8.6kg. The peripheral lumps contained another 30.33kg of iron, embedded in slag as pieces of unconsolidated sponge. The compact bloom was found to be up to 70% eutectoid steel with around 0.8% C (locally 0 to 1,2% C, showing ferrite-pearlite, pearlite and pearlite-cementite structures). The iron pieces dispersed in the slag mass also contained 0.0 – 1.0% C, but ferritic and low-carbon metal predominated. Smithing followed, causing a loss in final weight of 65 % (Serneels, Huysecom and Fluzin 1997, 104 – 110).

In summary we can see that blooms obtained from experimental or replica smelts reveal properties very similar to those of their archaeological counterparts.

Cast iron in early European bloomeries

Apart from discussions concerning the passage in the Aristotle's Meteorologica (see Chapter VIII), it has been shown above that the early low shaft furnace was capable, under certain circumstances, of producing high-carbon metal and even small amounts of liquid cast iron. This is confirmed by theoretical calculations, by the results of smelting experiments, and by

the examination of blooms from archaeological excavations, the interiors of which occasionally conceal cast iron droplets. Excavations of early ironmaking sites have, moreover, produced a number of separated pieces of ancient cast iron that were presumably discarded waste products.

Most of these examples, mainly Roman in date, come from England. A piece of cast iron (3.49% C, 0.38% Si, 0.035% S, 0. 180% P) from Hengistbury Head, Dorset, has been dated to the 1st century AD, whilst a small block of cast iron (3.25% C, 1.05% Si, 0.353 %P, 0.403 %Mn, 0.485 %S) from what may have been the ironworks of the XXth Legion at Wilderspool, near Warrington, Lancashire, dates to the following century. The relatively high sulphur content of the Wilderspool specimen suggests the possible use of mineral coal as fuel. A pig or bar of cast iron from Tiddington, Warwickshire, measures about 18cm and weighs 0.57kg (3. 52 %C, 1,925 %Si, 0.049 %S, 0.765 %P, 0.6 %Mn). Of special interest is a small flat, round cake of cast iron from Braughing in Hertfordshire which dates from the 4th century AD. This object was subjected to metallographic examination, which showed it to have a structure of pearlite, ferrite, graphite, and phosphide eutectoid. Early cast iron from English sites, including those already mentioned, as well as others from Gestingthorpe and Sheepen, both in Essex, is discussed in studies by Coghlan (1977, 48 – 49), Tribbick (1974), and Tylecote (1986). Three cast iron fragments, interpreted as discarded waste, were found in bloomeries at Bellaires I and II in Switzerland, dating to the 4th century AD (Pelet 1973, 180 – 181; 1993, 196 – 197). The weights are not given; the carbon contents varied from 1.71 to 3.32 %.

The site of the ancient Contiomagus at Dillingen-Pachten in the Saarland produced an iron lump more than 25cm in diameter, weighing 36.3kg, with a heterogeneous structure, showing graphite, pearlite, cementite, and ledeburite (1.6 – 2.65 %C). It was interpreted as evidence of Roman cast iron production (Henkel, Kremer, Reif 1994) but the question remains as to whether the find represents the largest piece of discarded Roman waste (*Graglach*) discovered to date or an intentional product. No Roman slag-heaps including glassy wastes that might have resulted from the systematical and large-scale production of cast iron have been discovered to date in the area.

Nevertheless, such waste has been recently identified at Oulches, France, within a Gallo-Roman bloomery plant of the 4th century AD (Mahé-Le Carlier *et. al.* 1998; see Chapter IV). Chemical and mineralogical studies revealed three kinds of slag, all of them with an elevated traces of Be (40 – 140 ppm): in majority a fayalitic-wüstitic dense slag (containig particles of ferritic spongy iron) and a fayalitic-cristoballitic waste denoted as 'scorie mi-lourd' (with globular particles of ferritic iron); an amount of 1 per thousand is said to be slag denoted as 'laitier', poor in iron (8 – 9 % FeO) and enriched in Al, Ca, Mg, partly crystallized as alumina pyroxenes, partly glassy, which may have embedded ferritic or ferritic-and-pearlitic metal globules. The slag of the third type has been discovered as a concentration at water pool in front of the bloomery furnace 1. The authors compare the phases with some blast furnace slags from about AD 1900 but they do not consider any regular cast iron production at Oulches; they are inclined to see the limited use of certain local ore mixtures containing Be. The question whether a liquid iron might to be wanted at certain occasions leave the analysts unanswered.

Much more interesting are the results achieved during the investigations of Late Roman and early mediaeval sites at Ponte di Val Gabbia, near Bienno, northern Italy. Among the bloomery waste left by a rather small-scale production of iron there were found, at site III (5th century AD), apart of tapped bloomery waste, lighter slags ('laitiers') with low iron content of 5 – 24 % FeO (in total proportion the amount is 5.36 % of waste revealed) and, from the remains of a feature called smithy (*'forgia*), several pieces of white and grey cast iron: two blocks of 3.9kg and 3.5kg; the latter, an amorphous, ramified piece of white cast iron (1.7 up to 4.3 % C, pearlite, cementite, ledeburite) was investigated by Fluzin. Droplets of cast iron were discovered in slags as well, even in smithing or reheating slag 'calottes' (Cucini Tizzoni 1998, 93 – 182; Fluzin 1998, 189 – 190, pl. 25 – 26, 29 – 31). The latter of the quoted authors is inclined not to see in the

large block any discarded waste, because of its weight. However, the amorphous shape speaks for an accidental product, having been yielded during bloomery operations. On the other hand, the occurence of cast iron particles in the post-reduction slags indicates that the bloomery smelters at Val Gabbia met the pig iron relatively often. However, the question of intentional 'fining' is not ready to be solved. Sites I and II at the same locality (some 200m distant, Longobardian, 7th century AD) produced 5 % and 16 % of 'laitiers' with 9 – 19 % Fe_2O_3 and 11 – 16 % FeO among heavy iron-rich slags. From site I comes a cylindrical cast iron rod 14cm long and 2.5cm in diameter. In spite of the prevalence of bloomery relics (destroyed furnaces, heavy fayalitic slag, iron nodules) the occurence of cast iron is relatively frappant. As it seems, high-grade manganiferous ores (haematites and goethites with 87 to 90 % Fe_2O_3, 1.06 to 8.67 % MnO, and low phosphorus of 0.02 to 0.16the vicinity) and technological practices of the smelters played a role in favourable conditions for intensive carburization of the metal reduced and not neglectable formation of pig iron.

A grey cast-iron object of indeterminate shape was found in a Merovingian grave (no 18), said to be that of a craftsman, at Comblain-Fairon, Belgium (Alenus-Lecerf 1971, 25, fig. 7) and had a composition of 3.67 %C, 0.7 – 2.25 %Si and 0.2 – 1.4 %P. The 5th – 6th centuries AD ironworks at Frouard yielded 3 lumps weighing 0.43kg, 0.3kg, and 0.112kg which were corroded and covered with adhering charcoal. These proved to be white cast irons with large shrinkage cavities up to 1cm in size, showing pearlite, ferrite, ledeburite and P-eutectic (Leroy 1997, 161 – 162, figs 85 – 87). The same author quotes another, later, lump of phosphoric white cast iron of 8th – 12th century AD date, from the ironworks at Ludres, which weighed 0.61kg with a content of 2.42 %C. Szöke (1965) announced a fragment of iron of fist-size (weight not given) from bloomeries between Weilheim and Metzingen in the Schwäbische Alb, SW Germany, which was, in fact, a small block of white cast iron with 4.5% C and pearlite, cementite, ledeburite and ferrite phases. It was interpreted as discarded unmalleable waste (7th – 8th centuries AD). In the Baltic area, the 5th – 6th centuries AD site of Lieporiai 2 yielded a lump of iron weighing 0.208kg, labelled as bloom 2. In fact, it was cast iron with 3.32 %C and 0.9 % Mn showing solidified flows (Stankus 1996, fig. 5).

The question of whether early, in other words pre-mediaeval, European ironmakers recognized and made use of accidentally-produced cast iron for manufacturing artefacts has long been the subject of debate. It seems that they were capable of doing so, but only exceptionally. Leaving aside some dubious cast-iron stattuettes that are claimed to be Roman, a number of fragments of cast-iron cauldrons have occured in pre-Roman and Roman contexts, the earliest of all being three fragments of cast iron cauldrons from Nikolayevka, in the Odessa region, in the ancient Graeco-Barbarian cultural milieu. The finds were made in layers dated to the 4th–3rd centuries BC. Metallographic analysis (Solncev *et al.* 1969) showed that the fragments consist of hypereutectic cast iron with ledeburite, graphite, cementite and large globular inclusions. The analysts are inclined to believe that the metal originated in the bloomery furnace, but from where remains unknown. An early western European example comes from the Roman villa at Brading on the Isle of Wight (England) where another fragment of a cast iron cauldron was found (Cleere 1958). Discussion of these finds and their implications will be reserved for the second part of this work, on iron working as revealed by archaeology.

The situation in western Europe is different from that in western Asia, where the process of iron casting was in use from as early as the 2nd – 3rd centuries AD, under the considerable influence of cast iron production in the Far East. The site of Bolgary and other localities in the river Volga region, yielded cast-iron cauldrons as well as wheel-naves. The hillfort of Shaigin, further to the east, is known for its finds of moulding boxes with traces of cast-iron which is suggested to have been produced in crucibles (Len'kov 1974, 100). Lumps of cast iron (2.80 – 3.44 %C, weights not reproduced) are mentioned from the same site from 12th century AD contexts (*ibid.* 90).

During the Han period (206 BC–AD 220), Chinese ironmakers were capable of producing enormous masses of molten and solidified metal, known as 'bears' or 'salamanders' by virtue of their irregular shapes. A large number of salamanders were found *in situ* among the remains of a furnace during the excavation of the ironworks at Kushing, one of which measured 3.2m x 2.4m x 1.0m and weighed some 20 tonnes. These bears or salamanders of cast iron contained 3.97 – 4.52 %C, 0.18 – 0.28 %Si, 0.20 – 0.30 %Mn, 0.239 – 0.264 %P and 0.078 – 0.111 %S. The slags, which contained no more than 2 – 4 % FeO, were rich in lime (22.7 – 29 %Ca), most of which must have been added for fluxing, since nothing like this level could have been derived from charcoal ash (Cheng-Shih-Po 1978; Tylecote 1983, fig. 3, table 3).

In Europe cast iron production on larger scale started much later, in the Middle Ages. Despite the possibility of contacts with the Far East, a more important role was apparently played by the introduction of water-driven bellows yielding higher temperatures in suitably shaped furnace hearths. The Styrian *Stuckofen*, a large bloomery from the end of mediaeval and beginning of the post-mediaeval periods, produced heavy blooms (*Stucke*) of more than 100kg weight, and a proportion of liquid cast iron *Graglach* which was considered for a long time as waste, before attempts were made to convert it to steel.

Important discoveries have been made in western Germany and Sweden, as it was already mentioned. An extant blast furnace complex at Lapphyttan in the Norberg area has been excavated and analysed (see chapter IX, Fig. 23). Low-iron slags in sorted heaps came to light and, in particular, both in the tap hole of a water-wheel driven furnace and in the associated fineries, droplets of cast iron were found (white and grey, 2.79 to 4.34 %C: Björkenstam and Fornander, 1985, 211, 221 – 222). The production of cast iron and its refining is dated there to the 13th – 14th centuries, if not earlier. Our attention is focussed on the same period when we come to examine the situation in Rhineland Germany. Slags from the blast furnace at Haus Rhade were also revealed droplets of cast iron in glassy slags which were low in iron. A number of other sites in the region show the trend towards the introduction of the new technology. There are new results from south-west Germany where, at Metzingen-Kurleshau in the Schwäbische Alb a furnace hearth and a waste heap containing blast furnace slag (8 % Fe) and small pigs of cast iron of 3.11%C with ledeburite and cementite has been excavated and dated to the 11th – 13th centuries AD (3.11 %C, Hauptmann 1993).

In the light of all of this data, it seems that the transition period between the bloomery era and the full establishment of the indirect process which is depicted on several paintings of the 16th – 17th centuries, started earlier than estimates based solely on the relatively late survival of the *Stuckofen* technology, which have yielded iron of better quality, in the Alps, stretching over six centuries. Among the products of this new technology were cast iron pigs and fined iron, such as the famous Swedish *osmund* iron Sweden and western Europe which was exported in barrels to many countries.

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The iron blooms and other primary metallic products may be considered as a mirror of early iron reduction processes and must be treated as integral elements in the treasury of sources for the study of ancient ironmaking.

Chapter XIII

BLOOMERY SLAGS

References to bloomery slag as a waste product of the earliest iron production have regularly occurred in previous chapters. We must now summarize the characteristics of bloomery slags with passing reference to other kinds of waste, and stress their importance as archaeological finds which provide valuable evidence on several levels.

Slags resulting from the bloomery process belong to a large family of metallurgical wastes, and, specifically, to those resulting from iron smelting. They represent the largest group of residues originating from iron-producing operations and from the various processes involved in the working of iron. However, we meet with considerable difficulties in distinguishing between different kinds of slag from different stages of the bloomery operations, either in terms of their outward appearances or even of their chemical and mineralogical compositions. On the one hand, it is relatively easy to identify glassy blast-furnace slags which have low iron contents (well below 10%). On the other, most copper-smelting and many other non-ferrous slags are very similar to bloomery waste due to their high iron contents. The same situation exists with working residues (finery, chafery, reheating, and smithing slags), all of which are rich in iron and have similar chemical compositions and phase textures.

Bloomery slags show that ironmaking took place on or near particular sites and can be treated as survey indicators. Their solidified forms also help in the reconstruction of the shapes and dimensions of destroyed furnaces and can indicate the mode of operation of a smelting furnace, for example, slag-tapping. Study of their chemical and mineralogical compositions and other properties may yield data on the level of technical development of the smelting which produced them and indicate the type(s) of ore used and the quality of iron produced. Finally, accumulations of bloomery slags provide us with information on production volumes in individual localities and regions.

Chemical and mineralogical compositions of slags

Bloomery slags

Bloomery slags can be broadly characterized as heavy, dark grey, brown or black heterogeneous silicate complexes formed from the gangue minerals of iron ores, combined with significant quantities of those iron oxides which were not reduced under the conditions of the direct process (where in most of the furnace volume, temperatures were significantly lower than the 1200 – 1300 °C in the reduction zone — see chapter VIII). Their compositions were not necessarily derived solely from iron ores, but were sometimes influenced by reactions with furnace linings (Serneels 1993, 18) and charcoal ash (Crew 1998). It has even been suggested that some bloomery smelting left no slag traces at all. Hauptmann (1986, 9) refers to a case of primitive, slag-less smelting of high-grade haematite with charcoal from Lebanon, but considers it to be of dubious authenticity, appearing in no way to be in common practice.

There are nowadays many analytical methods and techniques at our disposal. Among them, classical wet chemical analysis still has an important place. Its main disadvantage is, above all, in giving average values, which do not always reflect the heterogeneity of ancient slags. But it is, on the other hand, very informative in terms of overall composition, the relative proportions of iron(II) and iron(III) (Bachmann 1982, 8) and, in addition, can provide a standard base for comparison with the hundreds analyses, being constantly produced by laboratories, as well as with those of earlier periods, before other modern instrumental techniques were introduced. Of these modern techniques, scanning electron microscopy (SEM) provides useful data, coupled

with electron microprobe analysis (EPMA) which allows the compositions of microscopic areas to be determined. The crystalline phases of slag can be identified by optical microscopy of polished samples or thin sections under reflected or polarized light and results may be confirmed or modified on the basis of X-ray diffraction analysis. A detailed survey of analytical methods has been presented by Riederer (1988).

Bulk chemical analysis of bloomery slags usually shows that the iron content, in particular, that of iron(II)oxide (FeO) ranges from 40 to 70% (with more than 50% being considered high). The content of iron(III)oxide (Fe_2O_3, occurring as unreduced ore or as a component produced by weathering oxidation, may reach levels between 0% and 15%. Silica (SiO_2) appears usually in amounts from 15% to 40% (more than 34% is considered to be high). Calcium oxide, CaO, should be included among the principal but minor constituents with levels normally below 8% (2% low, 2–5% slightly elevated, 5 – 10% significantly elevated, more than 10% high). When elevated, it derived partly from the ore, the attacked furnace lining; and from the fuel ash; less likely from added lime fluxes. To certain extent it might have had blocked the phosphorus from P-rich ores into iron (Krehe and Heimann 1999).

Some elements pass from the ore only to the slag, while others are partitioned between slag and the reduced metal. Alumina, Al_2O_3, is present in slag only and comes principally from the ore gangue or furnace lining (below 1% low, 1 – 6% elevated, more than 6% high), while the other components come from both ore and fuel ash. Magnesium as MgO (usually in the range *ca.* 0.5 – 3%) and manganese as MnO (below 1% low, more than 3.5% high), both of which also pass entirely into the slag. Phosphorus (less than 0.75% low, over 1.5% high — in which case it derives from the ore, see Tylecote 1987, 313) is partitioned between slag as phosphorus pentoxide P_2O_5 and the reduced metal where it causes segregations, while Ni or Cu, if present in the ore, are entirely absorbed by the iron.

The above grouping is based on the evaluation of several hundred slag analyses from Europe published by various authors (e.g. Gilles 1936, 258; 1957; Weiershausen 1939, 219 – 225; Oelsen and Schürmann 1954, 599; Pleiner 1958, 282 – 283; Bartuška and Pleiner 1965; Osann 1971; Piaskowski 1966; 1967; 1968; 1972; 1984; Pelet 1973, 165 – 180; Bielenin 1974; Sperl 1980, 41 – 45; Serneels 1993; Domergue *et al.* 1993, 241 – 243; Mihok *et al.* 1987; Mihok 1991; Abetel 1992, 67 – 85); Dunikowski and Ploquin in: Dunikowski and Cabboi 1995, 152 – 162; Leroy 1997, 259 – 276; Buchwald and Wivel 1998). Sodium and potassium oxides NaO and K_2O and titanium dioxide TiO_2 contents are rarely given in published analyses, although Na and K, which derive from the fuel ash significantly influence the melting point of slags, while Ti may be indicative of particular types of iron ore (for example, some Greek slags contain up to 20% TiO_2, Tylecote 1987, 313; Photos *et al.* 1987, 113 – 120).

Although the elements identified in bulk analyses are given as oxides, the mineralogical constituents are very complex and occur predominantly as silicates. The most important is fayalite $2FeO.SiO_2$ or FeO_2O_4 from the family of olivines, which occurs as medium gray laths, needles or thick crystals when viewed in polished section. Recent studies, such as those by Forrières (1987) and Keesmann (1989, 321) have identified an additional phase described as iscorite $5FeO.Fe_2O_3.SiO_2$, which was formed under certain specific conditions as a transitional phase from wüstite to fayalite. In slag with elevated calcium contents, the olivine tends to be transformed into kirschsteinite $CaO.FeO.SiO_2$ (Hauptmann, Keesmann and Schluz-Dobrick 1984; Pleiner and Salač 1987, 82–83; Leroy 1997, 146–158) or, in the case of slags with low silica and elevated CaO, monticellite (Fe, Mg, Mn, $Ca.SiO_2$), another mineral of the olivine family which is able to absorb some iron (Bachmann 1982, 14).

In the glassy phase, in which may also be dissolved some Mg and Mn, mineralogy and X-ray diffraction identifies as minor constituents other silicates such as the pyroxenes hedenbergite ($FeO.CaO.2SiO_2$), diopside ($MgO.CaO.2SiO_2$) and wollastonite/pseudowollastonite ($CaO.SiO_2$), felspars such as leucite ($K_2O.Al_2O_3.4SiO_2$) and anorthite ($Ca.Al_2.Si_2O_8$ or $CaO.Al_2O_3.2SiO_2$).

The iron-silicate glass matrix, the dark component on polished specimens, is only modestly represented in bloomery slags (5 – 20%). The iron phosphate, vivianite Fe_3PO_4 may be observed as a mineralogical constituent of high-phosphorus slags. Oxides such as hercynite (FeO. Al_2O_3) which contain iron and alumina from Al-rich ores (thick, grey crystals accompanying the fayalite, but only rarely), and, more frequently, magnetite (Fe_3O_4 or $FeO.Fe_2O_3$) which appears as white cubic or angular crystals and dendrites (Wingrove 1970) may be observed. Haematite (Fe_2O_3) in the form of needles has been claimed as a secondary phase produced by the oxidizing conditions to which the slag would have been exposed after its removal from the furnace (Morton and Wingrove 1969) and the same explanation is given for occurrences of goethite (FeO.OH).

Among the oxide phases, wüstite (FeO, Fe_1-yO) in the form of white globular crystals, often merged together as dendrites, plays a vital role, representing the surplus of iron ejected while the fayalitic slag mass cooled. In spite of the considerable heterogeneity of the relatively viscous bloomery slag, the area covered by wüstite in the microscope field may provide significant clues towards estimation of the metallurgical success of smelters. Slags with little or no wüstite indicate a more efficient process than those with proportions in the region of 40 – 60% (Tylecote, Austin, Wraith 1971, 357). On the other hand, wüstite slags were less viscous and enabled better separation from the metallic iron sponge or bloom. It is sometimes difficult to distinguish wüstite from magnetite by microscopic observation, since the difference in reflectivity between them is low (19% for wüstite, 21% for magnetite, Sperl 1980, 40).

The first phase analyses were presented by Neumann (1954) and by Bartuška and Pleiner (1965) and since then, much analytical and theoretical work has been done, with reports by mineralogists appearing in practically in all modern reports of excavations of bloomeries. New systems for the internal classification of slags have been proposed, based on their chemical and mineralogical compositions and normative calculations of crystalline phases have been undertaken. Keesmann, Bachmann and Hauptmann (1984) divide slags into fayalitic, fayalitic-pyroxene and pyroxene types. They propose that the slagged linings of furnace walls with elevated alumina contents, and the so-called reduction-smithing slags, apparently close to reheating slags, form a special group. Kresten and Serning (1983) proposed a classification into wüstite-normative slags from most primitive bloomery processes, olivine-pyroxene slags indicating improved reduction regimes and quarz-normative slags (blast furnace wastes).

In addition, many pieces of slag can be shown to contain minute or larger particles of metallic iron embedded in the slag mass. These sometimes occur as fibres more or less welded together as part of the process of the sintering of the iron sponge (see Chapters XI and XII). In other cases, isolated grains, ovoid or cubic in shape (Neumann 1954, fig. 47), which were transported by gravity down into the slag bed, can be observed, the bulk of the iron having come to rest above the slag mass, near the air-inlet holes. Tholander (1987) suggested a specific typology for these metallic particles in bloomery slag, with iron shells surrounding original iron ore grains, labyrinth and coral iron as fragments of these iron shells and compact pieces of iron of irregular shape, tending to be connected with other pieces and threads leading to the formation of the bloom. Gurin (1988; 1996) observed the formation of iron particles in pairs, connected by a 'bridge'. Globular droplets indicate that the metal passed through the molten state and such droplets also occur sporadically in blast furnace slags (Tholander and Blomgren 1985). All of these shapes can be met with at any level of the furnace due to the irregularity of the movement of the ore/fuel charge into the different temperature zones. Unreduced pieces of ore (haematite, limonite, see Bartuška and Pleiner 1965; Zwicker, Haase, Spitzhirn 1983, fig. 15) can be observed in slags, especially those resulting from the final charge, along with quartz grains from eroded inner furnace linings.

Ancient copper smelting slags

These slags can be very similar to bloomery slags both in terms of their chemical composition and their mineralogical phases, with fayalite, wüstite, magnetite and glass being quite common. Only isolated unreduced ore particles or sporadically-occuring metallic copper prills and some copper sulphides can show the difference (Sperl 1980, 62 – 63; Bachmann 1982, 21 – 26). Copper slags which have been chemically analysed show the presence of only very small amounts of copper (0.5 – 3%). It is also a fact that around 30% of iron ore was regularly added to the charge as a slag-forming flux. Furthermore, sulphide ores such as chalcopyrite $CuFeS_2$ also contain iron (Segal *et al.* 1998). During smelting, little or no copper passed into the slag and the same can be noted for lead slags from traditional processes, which may contain inclusions of metallic iron (Wertime 1964; Keesmannn 1998).

Iron-working slags

Iron-working (as opposed to iron-smelting) refuse comprises finery, chafery, reheating and smithing slags. This type of waste is also classified as 'post-reduction' slag, but, curiously enough, displays a very similar chemical and mineralogical picture to that observed among bloomery slags

Heavy, black finery slags were the products of the reheating and remelting, under oxidizing conditions in finery hearths, of cast iron pigs from blast furnaces in order to reduce their carbon contents and produce malleable wrought iron. During this operation, the silicon contained in the cast iron, together with oxidized iron, formed a small amount of iron-rich fayalitic slag (fayalite $2FeO.SiO_2$, about 5 % compared with the refined iron) which covered the surface of the metal and acted in combination with the air-supply in the process of oxidizing the pig iron. The trend was to attempt to produce more slag and attain a greater process effectiveness, with the result that waste hammer-scale ($FeO.Fe_2O_3$), old bloomery slag, sand and clay were added, with glass resulting in very small quantities (Morton and Windgrove 1971). Rostoker and Dvorak (1990) studied post-mediaeval wrought iron and tried to distinguish bloomery and finery samples according to the compositions of the large slag inclusions. They found difficulties due to the small number and complexity of analyses. Finery slags from Lapphyttan containing 16 – 60%Fe, 33 – 50% FeO and 8 – 40% SiO_2 were analysed by Björkenstam and Fornander (1985, 212). It would appear that what were identified as bloomery slags found at the earliest blast furnaces, such as Haus Rhade in Germany, and explained as evidence of the deliberate production both of bloomery and pig iron, are, in fact, finery slags resulting from the process of transforming cast iron into malleable metal.

Horstmann (1996) studied bloomery, early blast furnace and finery slags from ironworks in the Loope and Kaltenbach river valleys of the Märkisches Sauerland, the well-known iron-producing region in western Germany. He distinguished three types of finery waste. The first was produced by adding old blast furnace slag (*Flossofenschlacke*) to the molten pig iron and had structures containing fayalite, magnetite dendrites, hercynite, and leucite with an iron content of 40 – 50%. The second type occurred when, instead, charges of old bloomery slags from the 11th – 13th centuries, apparently deliberately exploited for this purpose were added, producing eutectic mixtures of fayalite, wüstite and leucite containing around 50% FeO. The third kind was the '*Märkische Osemundsschlacke*' from about AD 1600, very rich in iron oxides (over 70%) and calcium phosphates, resulting from the addition of lime to remove phosphorus and sulphur from the fined steel and leading to these elements being well-represented in the slags.

Chafery slag belongs among the reheating wastes formed during the subsequent reheating of refined iron. Morton and Windgrove (*op. cit.*) refer to lumps typically weighing about 25kg, characteristically with two layers formed as the slag was tapped out of the hearth. The FeO content varied from 33 to 65% with fayalite, magnetite, wüstite and anorthite as typical

mineralogical phases.

Reheating slags, referred to in chapter XI, include remelted bloomery slags removed from the surfaces of blooms along with that expelled from their interal cavities. They may be mixed with slag formed from heated and oxidized iron, combined with the refractory hearth lining and added sand and earth. It must be stated that the analytical identification of reheating slag is in its infancy and that identifications of reheating slags based on slag fragments are very provisional. Sometimes the iron content may be a little lower than in true bloomery slags, but can still reach as high as 50%, and all of the mineralogical phases observed in bloomery slags can be expected to occur (*cf.* Serneels 1993, 49 – 51).

Smithing slags form a very important group among post-reduction wastes, being found regularly in archaeological deposits from all types of habitation and settlement, as a product of the forging of iron. They appear as typical slaggy solidified plano-convex cakes, often referred to as plano-convex bottoms (PCB's,) or smithing hearth bottoms (SHB's), although they formed in the ash bed just below the tuyere-mouth of the smithing hearth. It should be stressed that smithing slags are the products of the oxidation of iron and thus include only very small amounts of the gangue constituents of ores, usually in the form of inclusions. Instead, other constituents play a major role, including silica from sand fluxes used for dissolving hammer-scale on the surface of the heated iron, and mineral oxides from the charcoal ash. The general composition may nevertheless be quite similar to that of bloomery slags, as fayalite, wüstite, magnetite and glass are again normal components. Very important analytical study which, in general, confirms the view, was presented by Dunikowski (*et. al.* 1996). In short, it is often very difficult, however, to identify smithing slags solely on the basis of analyses (Pleiner, Pelikán and Bartuška 1971; Fluzin and Leclère 1998; Dunikowski *et. al.* 1996, 1998). External shape of the PCB's and find circumstances serve as a plausible identification marks.

Blast furnace slags

These differ from the previous categories particularly in terms of their low iron contents. They were formed as the final waste-product in the lower, narrower zone of the blast furnace, the bosh, where temperatures over 1500 °C were the rule. Lighter in mass, it was tapped out through a special outlet above the level of the heavier molten iron (2 – 4 %C) which was tapped throught a hole lower down. The slag sometimes also followed the iron as it was tapped and was diverted by earthen dams into another collection area, as happened at some post-mediaeval installations. Blast furnace slags, preserved in fragments, are glassy, and black, bluish or greenish in colour. They normally contain only a little iron, from 0.5 – 5 % FeO, occasionally as high as 10% (as in certain more primitive plants such as those at Kippenheim and Metzingen), but no more. The main components are SiO_2 at around 50 – 54 % and Al_2O_3 which reaches levels in the region of 13 – 16 % (often represented by hercynite). When manganese was present in the ore, it was completely reduced (3 – 4 % MnO), while sulphur at levels of 0.2 – 0.5% appears in slag derived from smelts with mineral coal or, later, from coke.

The operators of some early blast furnaces (*Flossöfen*) smelted iron ores using lime fluxes if the ore compositions dictated (White 1980), with the result that levels of CaO may be as high as 10 – 30%). These fluxes, which also contained some alumina, had a positive effect when temperatures rose above 1300–1500 °C and assisted in the production of a less viscous, liquid slag (Tylecote 1987, 329 – 330). Moreover, the addition of CaO tied up both sulphur and phosphorus and caused them to pass from metal to slag. Minerallogically, the principal constituents are quartz glass, anorthite, wollastonite, pyroxenes (Fe,Mg,Mn)CaO.SiO_2, melilites (e.g.ferroåkermanite $Ca_2Fe^2+Si_2O_7$, iron gehlenite $Ca_2Fe^3+SiO_7$ and forsterite Mg_2SiO_4. Metallic iron can be found as solidified globular droplets. As Tholander (1987) has shown in discussing the experimental smelt conducted in an old test blast furnace at Hagfors, the upper levels of

the charge, observed after the smelt was interrupted, included all forms of bloomery slag which would have subsequently been completely transformed lower down at the level of the bosh.

As mentioned in Chapters IV and XII, in some bloomery ironworks like Oulches in France (Late Roman) and Ponte di Val Gabbia in northern Italy smaller amounts (5 – 16%) of lighter glassy and iron-poor slags came to light, often described as 'laitiers' which have some affinity with slags from indirect process, see sites III, I, and II (5 – 24% FeO, 9 – 19%, and 11 – 16% respectively); however, they cannot be called blast furnace slags.

*

Measurement of the melting-points of slags provides us with important information, although it does not indicate actual furnace temperatures, but only the lowest temperature-regime which would have led to the production of a molten, free-running slag. The most reliable method is to measure it by direct examination, either using optical pyrometry or Seger testing-cones in an inert atmosphere, reading the softening, melting, and liquidus points (the range usually being in the region of 30 – 50 °C). The published melting-points of slags have often been calculated from the proportions of FeO, SiO_2 and anorthite expressed in the form of ternary systems (Oelsen and Schürmann 1954; Sperl 1980, fig. 36; Bachmann 1982, 12 – 13, fig. 2: Morton and Windgrove 1969, 1558, fig.2, etc.). In fact, considerable errors may occur as a result of the distortion introduced by the the schematization of the actual composition (Kresten 1986; *cf.* the discussion of the problem by Freestone 1988). In addition, the melting-points of preserved slag samples are regularly observed to be higher than it actually was during the smelting process, since their alkali contents, absorbed from the fuel ash and acting to reduce the melting temperature, have been leached out by weathering (Tylecote 1986, 175). In general, bloomery slags melt in a wide range from 1100 to 1400°C, mainly in the range 1200 – 1300°C.

It seems appropriate here to add some remarks on chemical and mineralogical analyses, particularly of ores and, above all, slags from bloomery sites. The first bulk chemical analyses, few in number, of slags from some German smelting sites, appeared in the published work of Weiershausen (1939). In the post-war period from the 1950's onwards, raw and waste materials from excavated bloomeries, the numbers of which have increased in recent years, have been systematically analysed. While the charasteristics of bloomery slags are widely known, significant variants have been observed, resulting in frequent questions being raised concerning the relationship between ores smelted and resulting slags. Recently, an immense amount of effort has been devoted to analytical work, with tens of samples from individual bloomery inronworks and hundreds from different regions being subjected to modern analytical methods, all of which has greatly augmented our knowledge of trace-element contents. Analytical centres, archives and data-bases have been established in, for example, France, Germany, Switzerland, Britain and in some central European countries. However, the geographical spread of available data is patchy and there are vast areas untouched by analytical work on bloomery waste-products. It is thus not possible to produce a synthesis of analytical data either from the leading production districts or from scattered ironworks, or to solve intricate problems surrounding identifications of ore-sources exploited at any one time, even though success has been achieved in some cases. For this reason, we must resign ourselves to presenting here a general survey only.

Relationships between slags and bloomery furnaces

During the increasingly-frequent excavation of iron production sites, attention has been paid to the iron slags found in and around smelting furnaces. Efforts have been made to classify slags morphologically, according to their outward appearances and solidified shapes. Some classifications distinguish tapped slag from those remaining in the hearth, and from furnace bottoms and furnace slags (Oelsen and Schürmann 1954), while other systems encompass slags that were

formed within furnaces operated by induced or forced draught (Gilles 1957; Mayrhofer and Hampl 1958). One of the most detailed surveys has been presented by Sperl (1980). Tylecote (1987, 311), Piaskowski (1987), Serneels (1993), Dunikowski and Cabboi (1995) and Leroy (1997) have all put forward their own versions. It is obvious that all of these systems rely on the experiences of the different authors in dealing with the archaeological remains of early iron-working and many are strongly influenced by various local discoveries in their own regions and countries.

In fact, the key to understanding bloomery slags lies in the connection with the function of the furnace, as can be reconstructed on the basis of well-preserved features and experimental smelts (Fig. 67).

The majority of slags were formed within the furnace zones where temperatures of 1200 – 1300°C predominated. In shaft furnaces, this would have been in the lower part of the shaft, the walls of which (whether or not lined with special refractories), would have been attacked to some degree by fluid slag up to a level of about the first third of the height (Fig. 67: 2). The slag moved down to the hearth, penetrating the spongy iron complex and sintered together around the air-inlet. What happened to slags at the higher levels and what kinds of features were formed, depended on the type of furnace construction. In slag-pit furnaces, the deep, cauldron-shaped hearths were completely filled with slag which solidified into heavy slag blocks (Fig. 67: 4; Fig. 68). In other types of furnace, the slag was withdrawn from the hearth during the smelting process or in its final phase and was exposed to different conditions of cooling and oxidation. Such slags are common as fragments found deposited in layers and heaps around the furnaces. If the hearth had sufficient depth below the tap-hole, a cake of slag, known as a furnace bottom (*Ofensau, fond de fourneau*, Fig. 67: 5) would be left behind and a good example was found *in situ* at Thoste, a Gallo-Roman site in eastern France (Mangin *et al.* 1998, II, 191 – 192). The last slag having been formed in the smelting process was amorphous and porous, after the main bulk had been removed by tapping. It contained much charcoal and pieces of unreduced ore (cinder) and filled the lower zones of furnaces as solidified droplets and porous lumps. This is known as furnace slag (*Ofenschlacke, scorie interne*): Fig. 67: 3.

The following survey introduces the most important residues found in the interiors of furnaces and hearths, as well as found those in their immediate vicinities.

Structural furnace materials and slagged linings

As has been shown, primitive furnace shafts were built of coiled clay strips or brick-shaped blocks or stones and their interiors, along with the pits dug into the soil, were normally lined with some form of refractory material. The chemical and mineralogical compositions of clays used in furnace building offer an interesting view of the empirical practice and skill of early smelters who understood how to fullfil the two main tasks of securing optimum mechanical stability and thermal insulation and of influencing the behaviour of internal surfaces during smelts under relatively high temperatures. Specific attention was first directed towards the composition and properties of furnace walls and refractory lining materials from Bohemia and Moravia (Bartuška and Pleiner 1965). Later, similar samples were examined in the course of analytical work dealing with archaeometallurgical remains by Eschenlohr and Serneels (1991, 64 – 66, 69 – 70) and by Dunikowski and Cabboi (1995, 151 – 152).

Basically, two principal types of structural clays were used. The first were very plastic but less refractory clays consisting of calcite (10 – 20%), biotite (30 – 40%), alumina clay or mullite and up to 20of approximately 60% SiO_2, 12 – 13% Al_2O_3 and 8 – 9%CaO. Their heat-resistance was low, some 1300 °C, in other words, only about 40 °C above the melting temperature of most slags. Such linings reacted strongly with the molten fayalitic slag mass which penetrated through cracks and pores, destroying some quartz grains and creating a glassy surface on the

internal wall. There is a strong suspicion that this was not a failure of process, but rather the intentional practice of some smelters with the apparent aim of influencing slag formation and contributing to its lower viscosity.

On the other hand, this would not have been a requirement when suitably self-fluxing ores were smelted. In such cases, smelters tended towards the use of fairly refractory acidic materials, sometimes using them to cover over most of the less-resistant building clays. Such linings were highly siliceous, containing 75 – 90% SiO_2, 3 – 7% Al_2O_3 and 1 – 3% CaO. Kaolinite and mullite have been observed along with a free sand filler from 20 to 80% of composition. Such linings could withstand temperatures reaching up to 1500 – 1700 °C or more and can be compared with modern refractories. The lining of the slag-pit of the furnace from Dřetovice, Bohemia (Romano-Barbarian period) showed a deliberate mixture of crushed haematite ore with a kaolinite paste filled with some 20% of quartz. The heat resistence was 1400 °C and it had a very hard consistency in the sintered state. Skilled construction showing the use of three kinds of lining with different plasticity and refractory properties (resisting from 1200 °C up to more than 1700 °C) was noted at Želechovice, Moravia (Pleiner 1955, 14 – 17; Bartuška and Pleiner 1965, 11 – 14). Refractory linings containing 88% SiO_2) and with high heat-resistance have been reported in the furnaces investigated at Clérimois (Dunikowski and Cabboi 1995, 151 – 152), in the large units of type II at Frouard with 76 – 79% silica (Leroy 1997, 263) and at Boécourt where contents of around 88% SiO_2 and 10% alumina occur (Eschenlohr and Serneels 1991, 69 – 70.

The fragmentary, slagged lining layers and glassy coatings of many clay tuyere blocks and

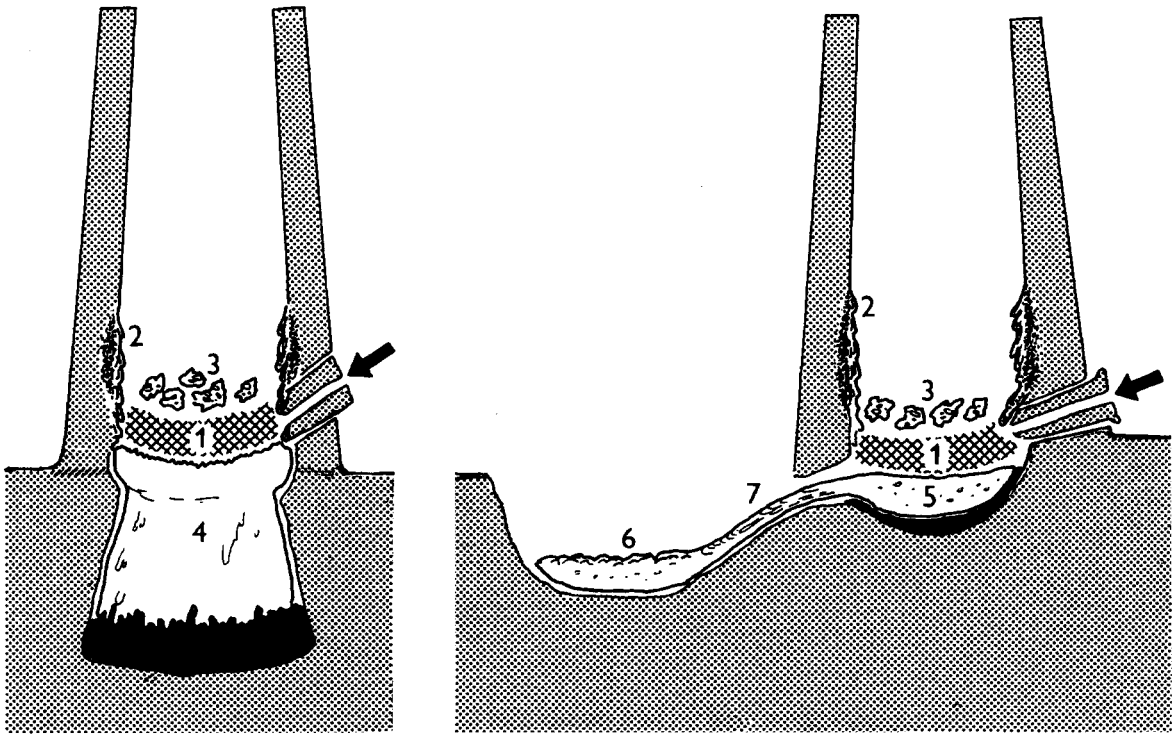


Fig. 67. Schematic representation of slag formation in a low bloomery furnace. Left: slag-pit furnace; right: flat-hearth tapped furnace. Explanation: 1 iron sponge penetrated with slag; 2 slagged wall or refractory lining; residual furnace slag with embedded charcoal and unreduced ore pieces; 4 slag block in the sunken hearth of the slag-pit furnace; 5 'furnace bottom' — a slag cake remaining sometimes in the hearth of a tapping furnace. Tapped slag: 6 fan-shaped slag cakes in the forepit pool; 7 last slag flow in the outlet channel, solidified rods (preserved mostly as fragments).

tubes, are regularly contaminated with ceramic paste and their compositions and phases have little value as evidence. They show FeO contents lower than 16 – 25% with somewhat higher SiO_2. Nevertheless, fragments of this kind of find often preserve the curvature of internal furnace walls and, since we know that slagged surfaces must originate in the interior of the lower third of the active zone, such slagged fragments, better preserved than the outer wall layers, may contribute to the reconstruction of furnaces, especially in terms of the diameter of the lower shaft.

Slag-pit blocks

These are heavy cylindrical or conical slag blocks (*Schlackenklötze*) which may be considered as cast impressions from the subterranean hearths of slag-pit furnaces. This type was common in the east Celtic and Germanic regions of Europe not occupied by the Romans in the La Tène, Roman and Migration periods (see Chapter IX). In general, they show botyroidal solidified slag flows at the bottom, sometimes with a horizontal layering on their verical walls. In many cases they completely filled the narrower hearth throat reaching as high as the wider space at the foot of the furnace shaft. Their top surfaces are rough and irregular and they may contain traces of the metallic iron sponge the bulk of which was removed from the level near the air-inlet while still hot. Unreduced or sintered ore particles derived from the early charges may also be observed near the top. The dimensions of these slag blocks depend on the size of the furnace hearth, but their lower diameters usually vary from 30cm to 80cm, the heights being 20 – 50cm (Fig. 68).

The weights of blocks from smaller slag-pit furnaces do not exceed 15 – 20kg, but most slag-blocks of the Romano-Barbarian period are much heavier, weighing some 100kg. Huge specimens weighing 300 – 350kg are known from Tarchalice and Dobrzeń Mały in Silesia, the latter having produced one block 420kg in weight (Hołubowicz 1956; Bielenin 1977b, fig. 4).

Slag pits may been considered as a curious solution to the problem of slag removal from the iron sponge adhering to the furnace walls. The slag was not tapped out by a side outlet, but downwards through the iron conglomerate and into the cauldron-shaped hearth which served as a slag container. Some Danish finds (Drengsted, see Voss 1964) and those from the adjacent German territory (Joldelund, see Jöns in: Backer *et al.* 1992, 93, fig. 18) as well as from some smelting experiments (Leineweber 1991, 119 – 126) have shown that before the smelt, the slag-pit must have been filled with straw or brushwood bundles which burnt out at the right moment leaving the space for the descending molten slag. Sometimes failures occured and additional wind channels had to be pierced or opened or auxiliary side pits dug to improve the burning of the wood at the critical time. The slag then penetrated into the holes and created the bizzare protrusions and trunnions occasionally visible on solidified blocks (Fig. 69). Such features have been observed in Poland in the Holy-Cross-Mountains, at Milanówek and Pęcice in Masovia (Bielenin and Woyda 1978; Woyda 1977; Bielenin 1983), in Germany at Isernbarg bei Hatten (Hayen 1968) and in Bohemia at Buštěhrad and Ratenice (Pleiner 1958, 34, pl. III: 1), but they are rare. In the vast fields of slag blocks still remaining from furnace hearths in the Holy Cross Mountain area, only some 5% of the excavated slag blocks show protrusions (Bielenin 1983, 55; Bielenin, Mangin, Orzechowski 1996).

Slag blocks are an important source of archaeological data. They offer great assistance in the reconstruction of the shape and dimensions of hearths and at least of the lower parts of the furnaces and, above all, represent the entire slag output from one single smelt, allowing the yield of iron to be estimated. One hundred kilograms of slag is considered to be equivalent to 18–30kg of smelted iron, bearing in mind that big slag-pit furnaces were used only once. There are also examples, seen especially in the case of the fields or furnace clusters, when an earlier hearth filled with a slag block, was cut by another unit. In sandy soils, slag often penetrated the sides of the slag-pit. This is frequent in some Danish sites, where, in addition, it was observed

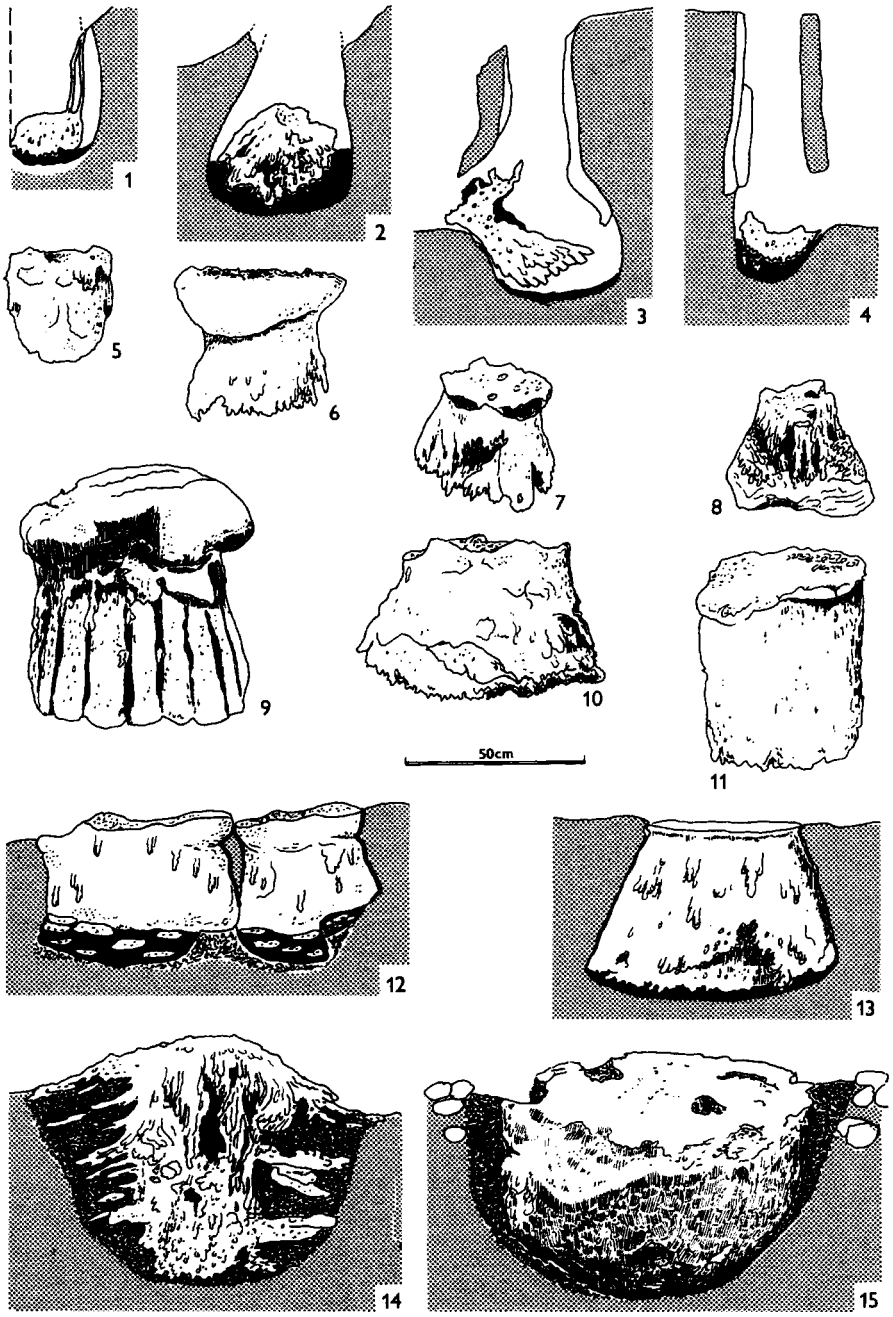


Fig. 68. Slag blocks from slag-pit furnaces showing differences in shape, size, and weight. 1 Mšec, Bohemia, furnace 1; 2 Kostomlaty, Bohemia, furnace 1; 3 Lovosice, Bohemia, furnace 1; 4 Ořech near Prague, Bohemia, furnace 2 in bloomery ironworks 35; Slag blocks *extra situ*: 5 Gardzienice, Holy-Cross-Mountains, Poland; 6 Rudki, *ibidem*; 7 Milanówek, Masovia, Poland (ca 200 kg); 8 Aylesford, England; 9 Tarchalice, Silesia, Poland (prints of wooden reinforcement, 300 kg); 10 Hodde, Denmark (131 kg); 11 Lavardin, France. Slag blocks *in situ* in the furnace hearths: 12 Hatten-Streeker Moor, Germany, two hearths (12 and 13) with slag blocks in superposition; 13 Buštěhrad, Bohemia, furnace III; 14 Drengsted, Denmark, furnace BV, flow penetrations to sides; 15 Dobrzeń Mały, Silesia, Poland in a stone-set pit (350 kg). Dating: 1–2 La Tène period; 3–4 early Romano-Barbarian period (1st century AD); 5–10, 12–15 Romano-Barbarian period; 11 7th century AD. References: 1 Pleiner and Princ 1984; 2, 13 Pleiner 1958; 3 Pleiner and Salač 1987; 4 Motyková and Pleiner 1987; 5–6 Bielenin 1983; 7 Bielenin and Woyda 1977; 8 Tylecote 1986; 9, 15 Bielenin 1977; 10, 14 Voss 1964, 11 Barrière 1972.

that on the hearth bottom, a solidified flat pool of slag appeared below the usual slag block (Voss 1993, fig. 2: D; fig. 5). In the recently-discovered and excavated slag-pit furnaces at Joldelund, slag of atypical form, not in compact blocks but in several disintegrated lumps, was recorded (Jöns 1997, pl. 27 – 35), with similar examples observed in Lusatia by Hirsekorn (unpublished). A flat slag block from an accidentally-deformed hearth (No 25) was discovered at Psary, Silesia. To avoid such occurrences, hearth walls were sometimes reinforced using wooden posts as shown by the heavy blocks from Tarchalice, Silesia (Holubowicz, *op. cit.*) and Egg, Norway (Nakkerud and Schaller 1978).

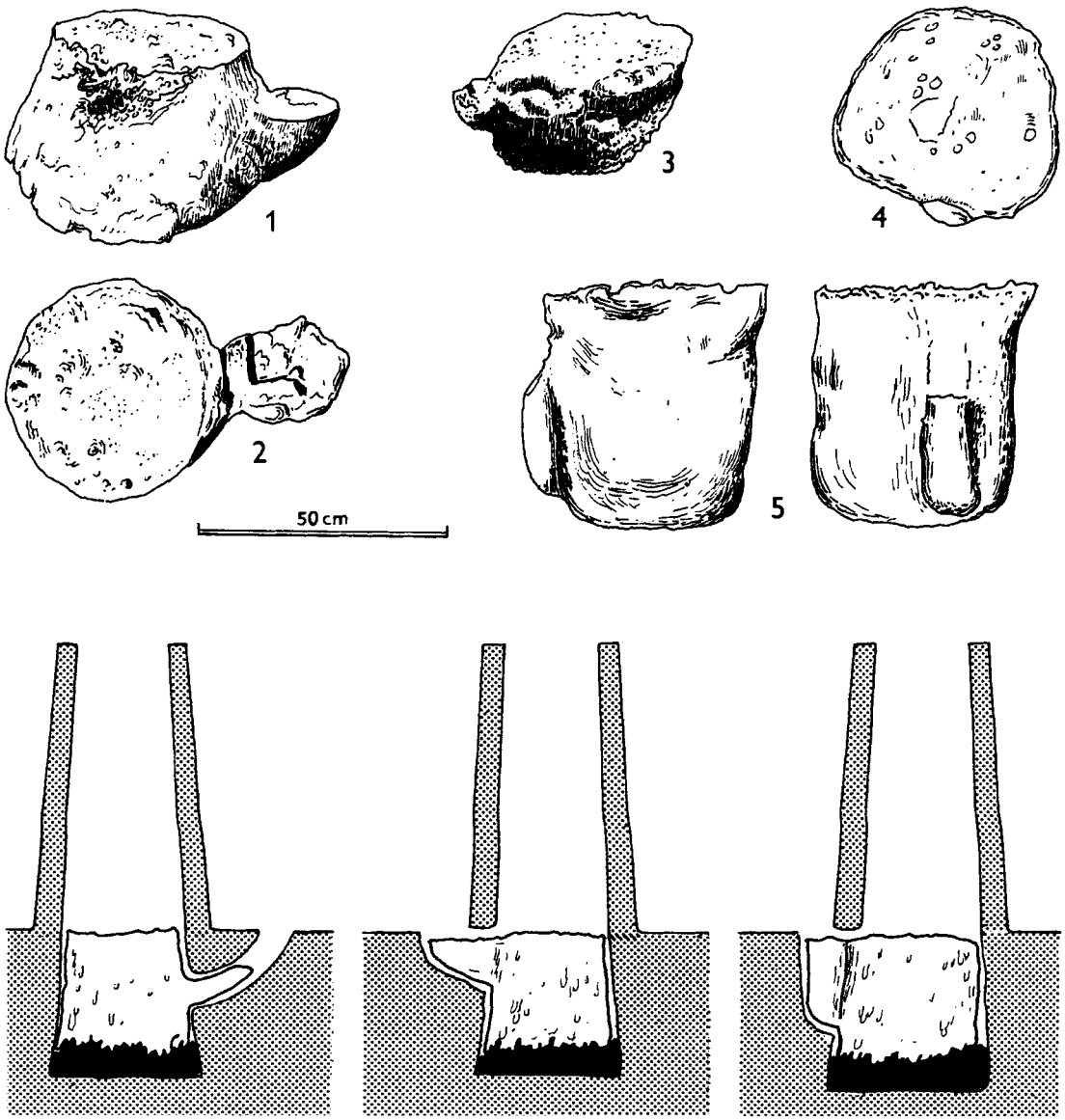


Fig. 69. Slag-pit furnace blocks with protrusions. 1–2 Milanówek, Poland, Romano-Barbarian period; Holy-Cross-Mountains area, Poland: 3 Kunów, 4 Marcinkowice. Below: Schematical representation of slag-pit furnaces with auxiliary air-channels, pointing to the hearth (out of scale). References: 1 – 2 Bielenin 1977; 3 – 4 Bielenin 1983.

Tapped slag

The facility to remove slag from the furnace through a special tap-hole in the furnace wall near the base of the hearth at one or more points during the process was an improvement which obviously led to an increase in the yield of metallic iron produced in one smelt. Tap-slags are sometimes found *in situ* alongside furnaces (Fig. 72: right), but more often as lumps and fragments thrown out onto slag heaps. True tap-slag may contain up to 70% FeO and 10 – 20% silica (Tylecote 1986, 176). Despite their the outer appearances which give the impression of a compact and dense mass, tap slags contain very many bubbles from the gases trapped during their quick cooling, as well as charcoal prints and embedded fragments (Fig. 71).

Tap-holes and channels produce pig-tail and rod-shaped pieces, roughly oval in section, with sand grains adhering to their lower surfaces and the characteristic morphology of solidified flows on their upper surfaces, sometimes in bizzare forms (e.g. Boécourt, Fig. 70: 3; Fig. 71: 6, 9). Slag-rods are known from Payerbach in Austria, a site of the 11th – 12th centuries (Mayrhofer and Hampl 1958, 82, fig. 51), from the Lahn-Dill region (Lammers 1995), from many sites in the Sauerland in western Germany, as at Wixberg, or Hülsesiepen (Fig. 72: right), dated to the 12th – 14th centuries (Sönnecken 1962, figs 1, 2) and from the 13th century site of Radětice in Bohemia (Fig. 71: 8, see Pleiner 1962a, figs 1, 2; 1971a). A curious case was observed at Altenberg in the Sauerland, where the molten slag accidentally ran down a mouse-hole, 2 – 3cm in dia. (Sönnecken 1982).

Tap-slag was allowed to flow through tap holes into channels along which it ran into pools which served as slag bays in front of the furnaces. When cooled, it created cakes, sometimes fan-shaped (*scorie coulée en forme de plaque-éventail* (Fig. 70: 1, 2; Fig. 71: 1, 5, 8), known from many proto-historic and mediaeval ironworks including Martys, Clérimois, Frouard, Olomučany and Radětice. A rather unique form, resembling the skull of a sheep (Fig. 71: 11), has been found in mediaeval slag heaps in Dalarna in Sweden (Serning 1979, 50 – 98, fig 42).

The slag from a furnace at Blahberg in Austria (Fig. 71: 7) was, for some unknown reason, tapped and cast intentionally into a series of grooves specially dug in front of the taphole. Analyses have revealed that in contrast to normal fayalitic tap-slag, the rods were wüstitic and were covered by a thin layer rich in metallic iron. Presslinger *et al.* (1983) have argued that this repressents some form of recycling process, since some of the rods were found in the furnace hearth, having perhaps already been processed. There are, however, many unknown factors and to date, there are no parallels.

The rapid cooling of slag in the open air allowed for the early solidification of the glass matrix which then occurs in the texture in higher proportions. Also, a greater degree of oxidation occurs, giving rise to the elevated contents of Fe_2O_3 quoted in analysed samples (Morton and Wingrove 1969).

At the early mediaeval smelting site of Köszegfálva in Hungary, large flat pools of slag covering areas of 60 – 80cm x 45 – 66cm in front the furnace were discovered (Nováki 1966, figs 7; 10; 12; 13). They were about 3.5cm thick and, curiously, were not connected with the hearth interiors, as the tap holes were apparently blocked up immediately after the tap (Fig. 72: left).

Viscous slags could have been raked out mechanically from the hearths of some types of smelting furnace, especially those of the La Tène period which have a large basal diameter (Sperl 1980, 16 – 17). It is difficult to identify them properly due to the distorted texture which would result.

Furnace slags

Because the tap hole was usually situated above the lowest part of the hearth, some slag remained inside as the so-called hearth-bottom (*Ofensau, scorie interne*). Numbers of these have been discovered *in situ* and many times included in discrete slag heaps and in the debris

around furmace remains. Their dimensions and weight naturally depended on the hearth size (Fig. 67:3). Should the hearth have been deep, the remaining slag formed a block similar to these from slag-pit furnaces (Fig. 67: 5).
Above the furnace-bottoms, or in emptied hearths, amorphous furnace slags, in form of droplets or flows (Dunikowski and Cabboi 1995, 155, fig. 100) or as abandoned porous pieces with much embedded charcoal may be observed. As they usually derive from the last charges before the end of the process, such slags can also contain semi-reduced or unreduced ore grains.

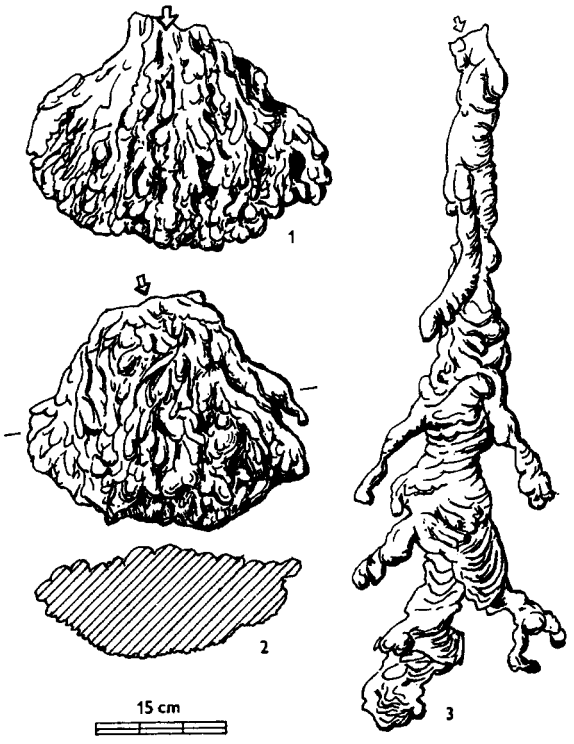


Fig. 70. Early tap slags. 1 Martys, France, 1st century AD; fan-shaped slag solidified out of the furnace (12 kg, area of F10 – 12); 2 Clérimois, France, fan-shaped slag from area around F150, late La Tène or early Gallo-Roman; 3 Boécourt, Switzerland, one stream of the last slag flows from furnace 2, 6th – 7th centuries AD. References: 1 Domergue 1993, 2 Dunikowski and Cabboi 1995, 3 Eschenlohr and Serneels 1991.

Slags and ores

As noted above, slags formed in the lower parts of the furnace in the molten state may include particles of unreduced ore, sometimes as fines. For example, primary haematite grains were observed in Bohemian slags from slag-pit furnaces of the Romano-Barbarian period. At Roztoky they were 2 – 5μm in diameter, while at Dřetovice they reached sizes of 0.03-1mm (Bartuška and Pleiner 1965, 26 – 27). An early La Tène period slag from the ca 5th century BC site of Ehrenbürg in Bavaria revealed a grain of nodular limonite in a fayalite-wüstite groundmass (Zwicker, Haase and Spitzhirn 1983, fig. 15) and further examples are known. In such cases, the relationship between ore and slag is obvious. Nonetheless the general chemical and mineral composition of slags from a site may also indicate at least the type of ore exploited, particularly when compared with local resources.

A classic example comes from ironmaking sites in the Lorraine district of northern France, where the problem of the early use of the local *minette* ores has been studied by Leroy (1997). *Minette* is a sedimentary oolitic iron ore of the limonite group, rich in phosphorus and described as self-fluxing, which outcrops across Lorraine and Luxembourg, and differs from the other type of local ore known as '*fer fort*'. These ores were submitted to detailed analytical studies for comparison with the results of analyses of early bloomery slags from a number of sites in the region (Leroy 1997, 146 – 158, 259 – 276). The *minette* ore, as noted, is rich in phosporus

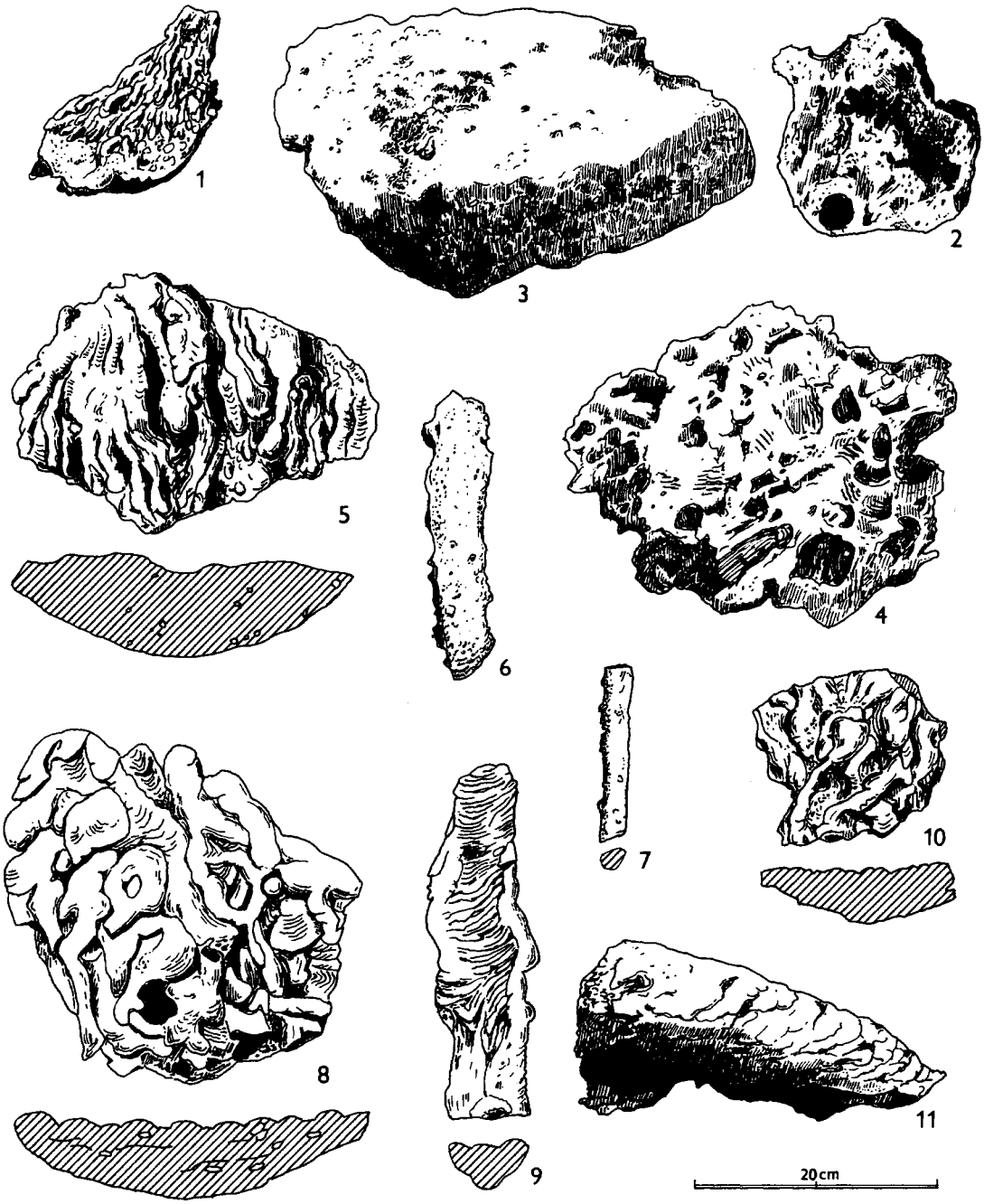


Fig. 71. Furnace bottoms and tapped bloomery slag. 1 Olomučany, Moravia, tapped slag from a debris; 2 Tarjánpuszta-Vasasföld II, Hungary, slagged lining at the tuyere mouth; 3 Payerbach, Austria, large furnace bottom from furnace 4, out of scale, dia. 75cm); 4 Brunna, Dalarna in Sweden (charcoal prints); 5 High Bishopley, England, slag from the furnace arch. Solidified slag rods from channels: 6 Wixberg, Germany (bottom side); 7 Blahberg-Dürrenschoberl, Austria, intentionally cast slag rods; 9 Radětice, Bohemia, from a heap. Slag from pools: 8 Radětice, Bohemia, from a heap; 10 Bargen, Switzerland, from a heap; 11 Trut, Sweden, solidified slag flow called 'sheep skull'. Dating: 1 9th century AD; 2 8th – 9th centuries AD, 3 10th – 11th centuries AD, 4 8th century AD, 5 12th century AD, 6 12th – 14th centuries AD, 7 12th century AD, 8 – 9 13th century AD; 10 15th century AD; 11, ca AD 1300. References: 1 Souchopová 1986, 2 Gömöri 1977/78, 3 Mayrhofer and Hampl 1958, 4, 11 Serning 1973, 5 Tylecote 1986, 6 Sönnecken 1962; 7 Presslinger, Gahm, Eibner 1983; 8 – 9 Pleiner 1971a; 10 Guyan 1965; 11 Serning in: Iron and Man in Preh. Sweden 1979.

(average content 1.9%) but also in calcium (average 6.51%) and alumina (average 6.58%), and produced slags with 10 – 12% CaO, 8 – 10% Al_2O_3 and 0. 5% P_2O_5). The mineralogical picture which such slags present is different from classical fayalitic bloomery slags and is made up of gehlenite and iron åkermanite and olivines of the kirschsteinite type. Some slags revealed clearly the *minette* ooliths transformed to wüstite and wrapped in metallic iron shells (Leroy, *op. cit.* 165, figs 89 – 90). On the other hand, the '*fer fort*' ore of the region, much less exploited in pre-industrial times, contained only 0.1% of CaO (around 0.2% in the slag), 3% of alumina (6 – 7% in the slag), and around 0.5% phosphorus (the same proportion being found in slags derived from them). The oolitic ores were characteristic for the majority of local early iron-making operations such as at the 5th–6th centuries AD site at Frouard where good siliceous refractory clays were used for the furnace linings. Manganese goes into slag under the conditions of the bloomery process and its elevated content as MnO may well point to the smelting of manganiferous limonites or siderites, as appears to be the case at Hüttenberg in Austria and Siegerland in western Germany, as well as of some bog ores as is the case in Jutland and Sweden. From 25 – 50% of phosphorus passes into the iron but the bulk remains as phosphorus pentoxide P_2O_5 in the slag. When slags show contents higher than 1 – 2%, it is likely that phosphorus-rich ores such as some haematites, as well as bog iron ores from the North European lowlands, were being exploited (Tylecote 1987, 313), although such phosphorus might also derive in part from charcoal ash. Some ores contain arsenic, an element which, unfortunately, is rarely analysed for, but must be taken into account as shown by Piaskowski's work on material from Bulgaria (Piaskowski 1984). Spherosiderites and laterites which were often used in traditional African metallurgy (Keesmann, Preuss, Endress 1983), are, in addition to silica, rich in alumina (12 – 17%). An indicator of their exploitation is the presence of hercynite ($Fe_2Al_2O_3$) in slags. As already mentioned, titaniferous sands and ores with some 7% TiO_2 gave slags with about 20% of the oxide (Tylecote 1987, 313, after Photos).

High contents of phosphorus in the slag indicate that significant amounts of the element has entered the reduced metal and influenced its quality, giving increased hardness, a certain resistance to corrosion, a silvery lustre, brittleness at low temperatures, a reduction in malleability and a higher welding-temperature (Nosek and Mazur 1995). Tylecote (1962a, 253; 1986, 175) determined the P-content in bloomery iron as being 0.25 – 0.5% of that in the slag. Piaskowski (1965), considering that in slag analyses the P-content is usually given as P_2O_5, suggested the following partition formula: P(metal) = (0.11 – 0.22).P_2O_5(slag) which he later modified, on the basis of a larger number of analyses, to P(metal) = 0.12 – 0.35 P_2O_5(slag).

To seek the exact provenance of an ore and its relationship to a deposit from chemical analyses of slags, even including consideration of the suite of trace elements, is, at present a very uncertain proposition, since iron ore bodies vary considerably in their detailed composition and slag is an extremely heterogenous mixture. Moreover, those outcrops which were exploited in the past, have gone and their compositions are not now available for study.

Slags and the metallurgical process

We have examined this question in Chapter VIII so that here, we need only to add some remarks in summary. Essentially, the composition and melting temperature of slags may be roughly indicative of the potential yield of the smelting process on the one hand, and of the possible quality of the resulting metal on the other. Both are closely connected and depend principally on the iron content of the slag. We may note that Kresten's division (1983) of slags into categories containing mainly wüstite, followed by those in which olivines and pyroxenes predominate and finally quartz-rich types, also forms a descending order in their contents of iron. It explicitly takes into account the improving metallurgical technology of the processes producing these slags. Under the conditions of the bloomery process, it may be accepted — with all due regard to their heterogeneity — that free-running slags with high iron contents were less

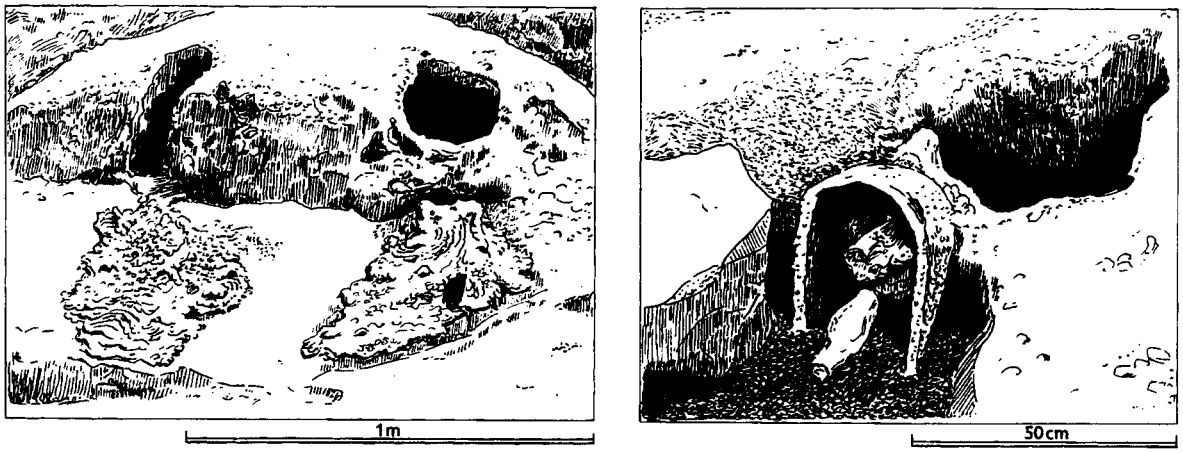


Fig. 72. Examples of tap slag found *in situ*. Left: Köszegfálva, Hungary, 11th–13th centuries AD, twin of furnaces 4 and 5, slag tapped out of the arches over an open surface. Right: Hülsesiepen (Jubach) near Balkenscheid, Germany, 11th – 13th centuries AD, a curious find of an iron sheet arch protecting the tap hole, solidified slag flow; the hearth of the destroyed furnace is behind. References: Left: Nováki 1966, right: Sönnecken 1971.

viscous and enabled better separation of the iron sponge smelted. Such iron, would, in general, have been low in carbon something usually desired by early ironmakers because of its good malleability. Against this, a low iron content in the slag would have resulted in high viscosity, leading to the iron particles not being fully coated and thus being exposed to carburization in the reducing furnace atmosphere. Under these circumstances, carbon steel or even, partly, cast iron would have resulted (Tylecote, Austin and Wraith 1971; Tylecote 1986, 135; Fluzin 1999).

Slags and economy

Another aspect to be considered is the quantity of slag found during surveys and excavations. Many archaeologists are too ready to draw conclusions about iron-making activities, and confuse smelting and smithing wastes, whose distinguishing features may be exceedingly difficult to recognize. A true bloomery slag found even as isolated fragments in occupation and working layers, at least demonstrates the smelting of iron in the vicinity. The increasing frequency of finds indicates closer proximity to the epicentre, in other words, to the ironworks proper and this is true also even of concentrations of slag on agricultural land which have been scattered by ploughing. The scale of the early industry dictated how much slag was produced and left on the surface and the larger the scale of production, the more extensive will be the remains of iron smelting.

By 'extensive', we refer to a quantitative rise in production through an increase in the number of furnaces being operated. For instance, the small sunken-floored ironworks at Ořech near Prague (e.g. No 14, early Romano-Barbarian period, see Motyková and Pleiner 1987, 379) with three furnaces which each produced a slag block around 30kg in weight, would have provided 15 – 30kg of unworked iron in one campaign. Even with repeated smelting operations and the re-installation of furnaces, the total output of iron from this site could hardly have exceeded 500kg. This type of small-scale production was improved in certain regions by bringing more and more furnaces into operation, resulting in the well-known slag-block clusters such as the huge field of 231 slag-pit furnaces found at Świętomarz 1 in the Holy Cross Mountains (Bielenin 1974, 174, 254; 1992, 118) where slag conglomerates weighing approximately 100kg each reflect a production of 4 – 7 tonnes of iron sponge during one season. For Heeten, Netherlands (5th

century AD), Joosten (*et al.* 1998) achieved, in general, similar results: 45 – 50 tonnes of slag (as slag-pit blocks) indicate 9 – 10 tonnes of unworked iron produced, however, during 30 – 35 years (0.3 tonnes annually). This indicates, as well, an excess production in terms of normal local needs.

The development of 'intensive' iron production was accompanied by improvements in the structural endurance of smelting furnaces, making them easily repairable, so that small numbers could be operated for longer periods (weeks, months, even years). The slags from furnaces used in this type of operation were regularly tapped, and could accumulate over the years into layers or heaps around the furnace, or further away, forming mounds of considerable size containing thousands and even millions of tonnes in regions producing on a large-scale (see Chapter III). In order to estimate the actual weight of iron represented by given volumes it is an unavoidable fact that the slag debris will not be a compact mass. Therefore, in rough calculations, a so-called 'packing factor' of 0.8 is used as an average. The area covered by slag in m^2 is multiplied by the depth or thickness in metres (heaps and other formations are converted into features of computable volume in m^3), by the specific gravity of the slag in g/cm^3 which is usually in the region of 3.5 and by the packing factor. The result should be the amount of slag in the accumulation, expressed in metric tonnes. For example, a slag heap of about 20 m^3 in volume produced by one single furnace on the 10th – 13th century AD site II at Köszegfálva in Hungary, has been calculated to contain some 56 tons of slag, representing the production of 11 – 19 tonnes of iron (Nováki 1966, 174 – 177, fig. 9). Calculations carried out in a similar way, based on the waste from one site appeared in the literature, for example concerning Clérimois (Dunikowski and Cabboi 1995, 121 – 131) or Laxton (Crew 1998) or from the 9th century AD Orderbos, Veluwe in the Netherlands (Joosten and Karst 1999).

Estimates based on calculations of slag volumes over wider areas may be misleading, since the mass occurence of iron-rich slag attracted the attention of modern industry and early debris was used as a raw material for ironworks. Hundreds of thousands of tonnes of bloomery slags were mined and consumed by modern industries in the major ancient production districts of France, Belgium, Poland and elsewhere. The vast quantities of slag, which once covered an extensive area around the Bay of Baratti, near Populonia, were exploited in the years after 1920, leaving only a small residue. Slags from the Yonne area in France and Namur in Belgium found their way to blast furnace plants, and those around Martys, in southern France were exploited and destroyed practically up to the present day. Nonethless, surveys and calculations of ancient smelting wastes have yielded useful information pointing to both large- and small-scale iron industries in many parts of Europe.

Where bloomery slag did not found its way into later blast furnaces, it was also used for metalling roads in areas where it was abundant. The earliest known case is the slag-metalled Roman road leading from the Wigpool mine to Ariconium in the Forest of Dean, Wales. These operations shifted the slag some distance from its original deposit and such a possibility must be taken into account during surveying and mapping.

Thus, these ugly pieces of greyish waste may lead, through the cooperation of archaeologists and analysts to an understanding of many of the mysteries of ancient and early ironmaking, one of the most fatal materials in the history of mankind.

Chapter XIV

A CONCISE HISTORY OF EARLY IRON IN EUROPE

The history of the earliest iron making, especially in Europe, is represented by the bloomery process which, as we have seen, is the reduction of iron ore under conditions which resulted, in general, in the creation of solid iron of a pasty consistency, more or less heterogeneously carburized and, after reheating and reforging, immediately malleable and suitable for the manufacture of artefacts. Small amounts of cast iron also might occasionally appear in the metal mass but they were, regularly, discarded as waste.

This era may be divided into two principal periods: the first involves the smelting of iron ores from its first appearance up to the introduction of the indirect method; the second period is that of survival when bloomery iron-making was gradually substituted and displaced by cast-iron and finery production. In terms of chronology, the 11th – 14th centuries AD are the transition phase in most European countries. In Europe, the last bloomery production was recorded about AD 1900, excluding although very special methods, called usually the *Krupp-Rennverfahren* (continued sproradically until around 1950).

The smelting of iron was not European invention. The chronological, cultural and technical existence shows that the production of iron began in the Near and Middle East stemming from the smelting of sulphide copper ores using iron-stone as flux. The long process of recognizing, separating iron fragments, followed by the occasional and, later, intentional use of minute amounts of malleable iron resulted gradually in the establishment of a new branch of metallurgy which was adopted in areas on the periphery of the theoretical epicentre and underwent several stages of development, influencing the technical and economic level of ancient civilizations. The first consumers and users of the new metal recruited from the highest and, then, upper levels of the society.

Europe adopts iron

The knowledge of iron-making was spread and accelerated in the direction of the main stream of inspiration, producing pressures for progress through strong cultural and technological influences. In Europe, this spread was from the south-east to north, north-west and west and lasted, as far as the first use of iron is concerned, from the 15th up to the 8th – 7th centuries BC. Succeeding centuries saw the introduction of iron further northwards.

In its detail the process is obscure, but involved the distribution of ready-made and rare prestige artefacts, certain small amounts of metal (e.g. for inlays) and the spread of knowledge. The latter must have been linked to movements of peoples and in particular craftsmen who consequently influenced metalworking in areas of where iron technology gained acceptance, particularly, again, among the local upper classes and, sometimes, in the form of reflux ethnic movements to the south (Italic tribes, Dorians). The 8th century BC must be considered as a critical period for most of Europe, seeing as it did the appearance of the new metal in different regions, not only as a metal of display weapons and other artefacts, including jewelry and the first tools, but also in sizeable amounts of up to 2.5kg, in the form of blooms as, for example, in Slovakia. It may be inferred that some bloomeries, not yet located, were operating in certain regions in the area between the Alps and the Carpathians. About two centuries later, a few ironworks with simple open smelting furnaces were to be found in the late Hallstatt cultural sphere, both in rural settlements and fortified sites. Illyrian, Venetian, proto-Celtic tribes and possibly also other populations, gradually put down the roots of their own iron industries.

The Celtic tradition of ironmaking

There is another problem, namely that of determining what constitutes the establishment of the fully-fledged Iron Age. We take the position that this has occurred when iron has an impact on the entire civilization, using iron as one of the principal technical materials for weapons and the whole spectrum of working tools and, in addition, for structural purposes. In the south of Europe, Greece and parts of Italy entered this advanced phase of iron-use from the 8th century BC. In central Europe the Celts, the westernmost population of the Indo-European family, played a decisive role in this respect. Although in the east considerable successes had been achieved by Illyrians, Dacians and Scythians, the Celtic realms must be recognized as the most important and progressive, including territories which became leaders in terms of subsequent technoligical developments. The homeland of the Celts broadly comprised the southern part of central Europe, including Bavaria, parts of Bohemia, Switzerland and the upper Rhineland, and was extended westwards at a very early date to France, Belgium, the British Isles and parts of Spain and eastwards to Moravia, parts of Slovakia and southern Poland. The Celts temporarily expanded into northern Italy, the Carpathian Basin, the Balkans and Greece and contact with the advanced civilizations there accelerated the development of many fields of Celtic culture and technology. Conversely, the craft skills of the Celts in many ways enriched the culture of the Roman world in terms of vehicles, textiles, weapons and a variety of handicrafts including fine metalwork. Their influence can also be traced northwards, enriching certain aspects of Germanic culture.

The evidence for Celtic iron smelting is relatively scarce until the final phase of the La Tène period, but the enormous growth of local iron production in previous phases is indicated indirectly by two facts. First, the Celtic population produced, in only a few generations, a large quantity of iron weapons, above all thousands of long swords and spearheads which were crucial factors in their expansions and raids against countries to the south — to such an extent that the ancient writers commented on this frequently. For the first time, the material culture of central Europe displays large numbers of iron artefacts. The second indirect manifestation is the large number of hoards containing heavy double-pointed iron ingots weighing 5–7kg each, with some 140 sites producing around 700 pieces having so far been recorded. The majority of these hoards remains undated, but the earliest stratified pieces come from the late Hallstatt and early La Tène periods at Mont Lassois in eastern France and the Heuneburg in south-west Germany. There are also several isolated objects of slightly different shape but of the same date which have been found outside the original homeland of the Celts, in the area of the eastern late Urnfields on sites such as Leipzig-Wahren in eastern Germany, Biskupiń in Poland and Býčí Skála in Moravia. The latest, from late La Tène (1st century BC) contexts, come from the *oppidum* of Manching in Bavaria. The geographical distribution of the majority of these hoards corresponds with the supposed cradle of the ancient Celtic tribes (Switzerland, eastern France, southern areas of Germany). The reason for making bi-pointed bars (which were made by welding together from smaller blooms) is not entirely clear, let alone the reason for burying them, unless manufacture and hoarding are in some way connected with ideology. Nevertheless they represent a large amount of smelted iron which had been taken out of circulation.

As well as the double-pointed form, the later La Tène cultural assemblage includes another type of ingot, the long, flat iron rods called 'currency bars' after Caesar BG 5.12 (*taleae ferraeae ad certum pondus examinatae*), which were used by the Celts in southern Britain in addition to coins as a mean of exchange. Currency bars also appear in hoards, not only in Britain but also in Continental Gaul as the *saumons d'epée* of France, Switzerland, Bavaria and the *Schwertbarren, Schwurschwerter* of western Germany. This terminology reflects the variability in the shaping of the sockets or handles of these bars. They might have been used both as blanks for manufacturing blades and also, at the same time, as pre-monetary currency or as tribute.

In any event, their existence demonstrates an increasing production of iron, part of which was reserved for other than utilitarian purposes. Moreover iron — still a very valuable metal — began to play an important role in early economies.

Eventually, the increasing production of iron supplied the Celtic civilization in the late and final phases of the La Tène with a variety of iron tools, agricultural implements, armament, utensils, structural objects and ornaments which affected all aspects of economic and domestic life. The construction of the fortifications of *murus gallicus* type in Gaul and in southern Germany as far east as Manching, consumed tons of heavy iron nails used to join structural beams. At the end of the La Tène period, central Europe followed its southern neighbours and entered a fully-fledged iron-using civilization, albeit, several centuries behind. Bloomery ironworks, dating from the same time, appeared more frequently in the archaeological evidence.

The emergence of iron-producing districts

Initially, because of its prestige and limited practical use, iron was smelted on a small scale by a few, possibly, famous metalworkers on behalf of the chiefs, the aristocracy and the more important members of society. The ironworks were scattered and their needs were modest — a few kilograms of good iron ore and a few tens of kilograms of charcoal were sufficient for one smelt. Even later, rural consumers were also supplied with iron in this way. When demands for iron subsequently increased (i.e. after the 8th century BC in the south and 3rd – 2nd centuries in central Europe, in connection with the emergence of settlement agglomerations), the search for suitable and abundant sources of raw materials was needed to make production effective. Deposits of high-quality iron ore necessary for the primitive process, close to supplies of wood for charring and water and clay for furnace construction were the conditions needed for the successful production of iron on a larger scale.

Ironmakers, and, presumably, their clans, became specialized groups among the population, although it is difficult to establish their status in relation to other parts of early society, the ways in which they survived in those early periods, or the whether they worked occasionally, seasonally, or full-time. However, they tended gradually to concentrate the activity in selected regions and technical developments began to focus on those which had the necessary combination of resources. The first iron-producing districts or regions emerged within or, more usually, on the periphery of inhabited agricultural settlement zones. One of the earliest archaeologically-documented regions, with at least four concentrations of iron smelting sites, developed in the ancient territory of Colchis, modern Georgia, on the coast near the foothills of Caucasus as early as the centuries around 1000 BC.

The process of the formation of ironmaking districts is not yet clear in detail. In many of the important and well-documented European iron-bearing regions, especially during the Roman period, evidence can be discovered indicating their earlier beginnings. Written records refer to the production of iron by some Celtic tribes in Gaul, which must have been more intensive than in other regions. The Bituriges Cubi and the Petrocorii excelled in the making of iron (Strabo 4.2.2) and Caesar (BG 7.22.2) praised the defenders of Avaricum in central Gaul for their underground mines and large ironworks. Ancient Noricum in the Alps became renowned for its steel production. Far to the east, a Celtic-speaking tribe, the Cotini, probably located near to the settlements of the Teutonic Marcomani, Quadi and Sarmatae (possibly in the northern Slovakia) were renowned for their production of iron (Tacitus, Germania 43: *et Cotini quo magis pudeat et ferrum effodiunt*).

In addition to written references, there is also archaeological evidence. In regions such as the Montagne Noire in southern France, the Yonne valley more to the north, the Vaud in Switzerland, the Siegerland in western Germany, the area around Kelheim in Bavaria, the Weald of Sussex, the Burgenland in Austria, the Holy Cross Mountains in Poland, there are traces of late La Tène

period or late Iron Age iron smelting which could be ascribed to any combination of Roman, Celtic and Germanic masters. Other remains of ironmaking in varying degrees of concentration are also known in western central Bohemia and the east Carpathians.

The leading centre of the early period in the development of iron-production districts was the island of Elba and the adjacent coast of Tuscany (Populonia, Follonica Bay) with its remains of huge slag deposits and heaps. Estimates of the total production vary substantially from 600 – 1000 tons of iron annually down to 3 tons, taking into consideration the possibility that some may be iron-rich copper slags and some the result of mediaeval Pisan activity. The fact that Elba-Populonia supplied Etruscans, Greek towns and Romans in the Republican period with their needs for iron argues rather for the higher of the estimates. Recent discoveries have shown that more sophisticated structures than simple small bloomery furnaces may be expected in the Populonia-Baratti Bay area. Excavations have revealed a very early feature (3rd to 2nd centuries BC) which may be explained as a kind of slag-pit furnace, as well as later furnaces with large superstructures made of clay and/or stone and adapted for slag tapping.

It is interesting that for its iron requirements, Imperial Rome looked beyond Italy to the provinces where large-scale production flourished locally in the first century BC and, at least, during first three centuries of the Christian era. In the western provinces, the Roman iron smelters combined their own knowledge with that of the Celtic population. The authorities such as the fiscal officials (*procuratores ferrariarum* in Carinthia and Gaul — also in Dalmatia) or tenants (*conductores* or even military detachments (*Classis Britannica* in the Weald of Sussex) played an important role in the control of ironworks.

Except for some iron-making in smaller economic units (the *villae rusticae* of the later Roman period in the Rhineland) the concentration of the majority of Roman provincial production was in the specialized industrial districts which flourished until the middle of the 3rd century AD. The largest was in southern Gaul, Martys and environment in the Montagne Noire. An estimate for output for this centre alone, based on undisturbed slag heaps, gives an annual production of 1100 tons of iron over 320 years. The Yonne valley was another major region where smelting activity left behind at least a million tons of bloomery slag most of which was consumed by modern industry. To the south-west and south-east, there were medium-sized production districts in the Périgord and around Bourges (which may be related to the ironmakers of the Petrocorii and Bituriges Cubi) and in the Morvan-Auxois on the territory of the Haedui. The Namur region far to the north of the Roman world and the British districts in the West may be classified as larger production complexes. The Weald of Sussex is claimed to have produced some 500 tons of iron per year from *ca.* AD 100 to 250 and the Forest of Dean was clearly also an important production centre. In the Alpine region there was an important ironmaking in the (Hüttenberg area of Carinthia which continued the tradition of the *ferrum Noricum*). Centres also existed in Dalmatia but they have not been explored sufficiently, although there have been several published reports of enormous slag deposits there. Iron was smelted on a smaller scale in the Jura ridge in Switzerland where, in particular, bloomeries in the Vaud have been well excavated. The production on Elba decreased apparently to a supplementary level, but Roman slag heaps in various bays wait for their investigation.

Roman civilization consumed huge quantities of iron which included structural elements such as clamps for monumental architecture, nails (five tons of nails were buried in a pit in the Roman fort of Inchtuthil, Scotland, which was evacuated around AD 400), and huge iron beams as supports in the construction of *thermae*. There was apparently often an emphasis on the quantitative rather than the qualitative aspect as the heavy iron beams are made of iron which is unconsolidated and spongy at the centre.

The style of Roman metallurgical work was intensive and Roman iron production can be seen as one of the earliest enterprises which resembles an industry proper. In regions such as Noricum, Dacia and Britain, ore also was mined in galleries and adits. Furnaces identified

to date were stable and effective devices of large volume, with shafts which were suitable for multiple repairs. Pliny made the interesting remark (Hist. Nat. 34.51) that bloomery furnaces differed widely (*et fornacium magna differentia est*) while, according to a passage in Virgil (Aen. 8.664), at least some were of considerable size (*chalybs vasta fornace liquescit*) which is in broad agreement with some of the archaeological evidence. It seems to have been common from the late Roman period for smelting furnaces to be bellows-blown, as witnessed by quotes from Q. Curtius Rufus (1st century AD) *admotisque follibus* and Phylargyrius (ad Aeneidem 4.171) *folles taurini habent cum liquescunt petram ubi ferrum fit.* Bloomery technology had developed to provide an effective and organized large-scale production of wrought iron.

Initially, the best types of steel were imported from different ironmaking regions of the ancient world (*ferrum Sericum, Parthicum etc.*). In Rome, the most celebrated was that from Noricum, because of its high grade ore, of which Pliny (34.58) wrote *in nostro orbe aliubi vena bonitate praestat ut in Noricis.* Believed to have been smelted from the managense-rich limonites of the Hüttenberg area, it was distributed from trading posts such as Magdalensberg via Aquileia to Italy and even to western Africa (Volubilis, inscription 81.218 at Magdalensberg). Some steels came from abroad, including Chalybean, Cappadocian and, above all *ferrum Sericum*, imported from the Middle or Far East. In the centuries around AD 0, the first samples of Indian *wootz* steel came into circulation and possibly also reached Roman smiths. Damascus was a trading post from which Damascene steel probably takes its name. The trade in iron was very developed in the Roman world, as it is directly attested by numerous wrecked ship cargoes of iron bars, often stamped, discovered along the Mediterranean coast.

Iron in the Barbarian world

During the Roman period the western world split into two, that of classical antiquity, protected by the Roman military border which stretched from Scotland down to the Danube delta and included Celtic populations, and that beyond the *Limes* in the so-called barbarian countries. The *barbaricum* lived in conditions which were similar to those among the Celts five centuries before, in non-urban communities, served by basic handicrafts and were still prepared to fulfill their needs by raids down south.

The Celtic population of the non-Roman areas managed to transmit many of the achievements of its material culture to Germanic newcomers, but succeeding generations were assimilated relatively quickly. In certain areas such as Bohemia, the smelting of iron profited from Celtic tradition. At the beginning of the Christian era, sunken-floored ironworks equipped with small slag-pit furnaces were not only identical in general lay-out but also in shape and detail. This was a typically scattered and small-scale production, satisfying limited areas of rural settlement. Mapped concentrations of earlier smelting sites, as in Bohemia, Moravia and Thuringia, do not represent large production regions but rather represent decentralized local activity. Even close to the *Limes*, in southern Slovakia and Moravia and the lands on the left bank of the Danube in Austria, the remains of barbarian iron smelting explicitly indicate small-scale production and do not show any Roman influence.

It is true that the inventories of Germanic warrior graves present the full range of long swords, spearheads and shield fittings but the general use of iron was much less than in the time of the late La Tène Celtic oppida. As Tacitus (1st century AD) expressed in his Germania 6: *ne ferrum quidem superest sicut ex genere telorum colligitur.*

The demand for iron by invading Teutonic groups gradually forced an increase in production in certain regions where natural resources were available, which was achieved by increasing the number of single smelts in slag-pit furnaces. Thus, another type of smelting district developed in non-Roman Europe and the ironworks have left fields of furnace-hearths containing abandoned slag blocks. The remains of individual smelts ranges from 20 – 300 units in some places and

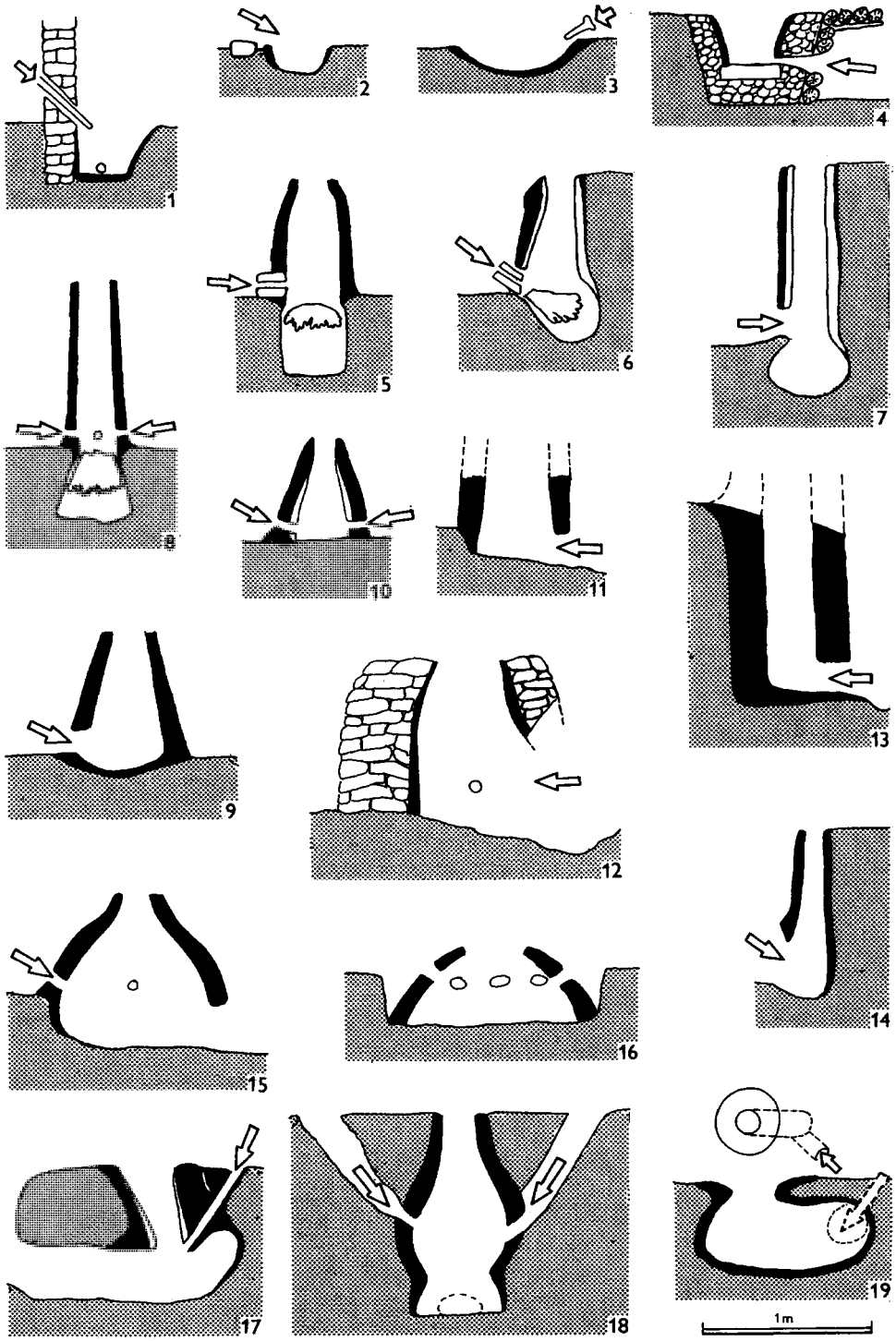


Fig. 73. Selection of principal bloomery furnace models. Hearths: 1 Catalan hearth, 19th century; 2 Kestor, pre-Roman; 3 Žerotín, 10th century AD; 4 Scandinavian bloomery 18th – 19th centuries AD. Slag-pit furnaces: 5 Podbořany, La Tène; 6 Lovosice, Romano-Barbarian; 7 Igołomia, dtto; 8 Scharmbeck, dtto. Shaft furnaces: 9 Prague-Podbaba, Romano-Barbarian; 10 Novaya Pokrovka, pre-Mediaeval; 11 Salzgitter-Lobmachtersen, Romano-Barbarian; 12 Ludres, 8th century AD; 13 Ashwicken, Roman; 14 Imola, 11th – 12th century. Domed furnaces: 15 Unterpullendorf, La Tène; 16 Mechlin, Romano-Barbarian. Underground furnaces: 17 Želechovice, around AD 800; 18 Yutanovka, 9th century AD; 19 Polovinka, pre-Mediaeval; 19 Akh Tashtar, Siberia, 1st half of the 1st millennium AD.

from thousands to tens of thousand in the most important regions. One of the largest was the Holy Cross Mountains in central Poland which was based to a great extent on high-grade, phosphorus-free haematite from underground mining (Rudki). The greatest activity was in the late 2nd and the 3rd centuries, with operations continuing up to the 4th century AD and the assemblage comprises more than 100 excavated and over 6000 recorded ironworks the numbers of which are steadily increasing as survey and research proceeds. Two thirds of the excavated sites were arranged in an organized manner, with furnaces following multiple rows in sequence or with distinctly rectangular clusters, all of which indicate a certain order of work during a clearly-defined period of time (season, seasons, campaigns).

Around 1990, the total yield was estimated to have been as much as 3800 to 5400 tons (or more) of unworked iron, representing some 17 to 25 tons annually. This is, however, 10 - 30 times smaller than in some of the major intensive production districts of Roman Gaul or Britain. The primary consumers of Holy Cross Mountains iron were the Germanic members of the so-called Przeworsk culture. It has, however, been suggested that there was possibly some export to the Danube region, at least when production was at its height, a hypothesis which is based on the presence of some items in local material culture which are Roman or influenced by Roman patterns.

Some other localities have been investigated in the so-called *Germania Libera* in which the style of working resembles that observed in the Holy Cross Mountains. These include Silesia with several focuses, north-west Moravia, Masovia west of Warsaw, north-west Germany, western Jutland, Lusatia and Pomerania, all of which have 'furnace fields' or 'clusters' but without special arrangement. They are dated, with some exceptions (e.g. Westerholz) to the later centuries of the Romano-Barbarian era (3rd – 4th centuries AD). The Schleswig-Holstein region has revealed a possibly slightly different pattern with the furnace groups relating to smaller farmstead complexes, mostly of the late Roman period. Nevertheless the general accumulation of evidence for in the region is more striking than elsewhere.

The metallurgy of the non-Roman territories was dominated by a particular smelting device — the slag-pit furnace — whose origins are unknown, but which was typical for Germanic tribes who used it in the extensive smelting works referred to above. This was a marvellous apparatus, easily adaptable to different conditions in terms of size, arrangement and style of operation. In principle it was a shaft furnace, allowing a sufficiently long exposure of the ore-and-fuel charge to the process, and was adapted for the removal of slag by gravity down to the sunken hearth. Smaller variants, bellows-blown and producing some kilograms of iron sponge, could be refitted several times at least, and were built both into and against the walls of working pits and in the open air. Larger forms may have produced 18 to 30kg (or more) of spongy iron in one single smelt and were usually demolished after the operation and replaced by a new unit erected beside. Those with tall shafts might possibly have been operated by induced, natural draught. Slag-pit furnaces were possibly in use from pre-La Tène times. The eastern Celts definitely used it as did non-Celtic populations from Volynia and Ukraine in the east, to England in the west and from Austria and Moravia up to central Norway in the north.

Scandinavia is worthy of special attention in the later phase of the Romano-Barbarian period. It is beyond dispute that research projects in Småland and Gästrikland and, in particular, Jämtland in Sweden have identified production peaks or 'booms' for that time, as well as in northern Trøndelag in Norway on sites of the Heglesvollen type.

Nonetheless, beside the innovation represented by the introduction of the various forms of slag-pit furnace, the European north was traditionally an area where the simple bowl-furnace, an open hearth, mostly funnel- or cauldron-shaped and lined with flagstones (particularly on Swedish sites) was used. This bellows-blown device, limited by capacity, is believed to be the original furnace which was adapted from the metalworker's hearth as a special iron smelting installation and in Scandinavia, it enjoyed a very long life, up to the post-mediaeval centuries.

The volume of Romano-Barbarian period production is not yet known, because the production peaks are represented not by specific sites and their outputs but by the frequency of radiocarbon dates from sampled localities.

Ironmaking in northern countries appeared to be dynamic in certain regions such as Trøndelag and Jämtland; in Sweden it took place principally on lake shores. The organization of labour is also the theme of much debate, with some being inclined to see traditional hunters operating in relevant smelting collectives, while others taking the view that smelting was carried out as part of the activities of farming societies. In any case, it would seem that all of the iron-producing communities must have included trained metallurgists who had gradually become established and who promoted the technology.

Ironmaking after the fall of the Roman Empire

The potential for development of the very earliest European iron industry was realized by considerable growth in advanced regions. This was drastically affected by the break-up of the Roman Empire with its urban civilization. In fact, the decline in this respect began long before the final fall — possibly as a consequence of the weakening of the central power, the breakdown of economic ties and difficulties in maintaining the prosperity of both urban and rural communities. In this respect, we may note that several of the major iron producing centres such as the Montagne Noire and other districts in Gaul and Switzerland, as well as the region operated by the *Classis Britannica* in the Weald, declined from their peak outputs relatively early.

Of course, the need for iron remained persisted, although at a lower level and smelting never ceased. The population who lived on the ruins of the former empire must have consumed this technical material, at least at a basic level, and the attacking tribes, while destroying substantial parts of Europe and living in conditions of the earlier Iron Age, at least fought with iron weapons. But the system of general production became decentralized into small focuses and individual plants and the large smelting centres disappeared. Even the non-Roman regions, where iron was produced on extensive sites in the Holy Cross Mountains and Masovia in Poland and in Germany and Denmark apparently lost the reason for their existence and were replaced by local small-scale working.

Within the former Roman provinces there are signs of operations of medium importance in the 5th – 7th centuries AD, as in the Vaud, in the Yonne valley and in northern France, where there is the evidence of classic shaft furnaces. The archaeological evidence for central Europe, however, is extremely sparse, with only sporadic finds of later slag-pit furnaces appearing in settlements of the same period. As regards Scandinavia, the picture is rather complicated. Some of the iron-smelting regions, Jämtland and Småland, show temporary down-turns, but during the Vendel and early Viking periods, other districts, notably Dalarna in central Sweden, show rapid rises in output.

The situation in the centuries immediately following the mid-first millennium AD is opaque apart from the visible decline in economic activity in most European regions. A revival followed the stabilization in the Middle Ages within the framework of strengthening feudal structures.

Mediaeval iron production

The following survey of the mediaeval development of European iron-making requires us to bear in mind the differences in value as evidence between of archaeological sites and literary records. The problem has been referred to in passing when discussing earlier periods, but in the Middle Ages it gains a crucial importance. Archaeology offers the physical evidence of various installations and materials (as discussed in detail in previous chapters), and their actual locations in time and space. The principal information which these provide belongs in the sphere of technology in the broad sense. Accumulation of identified features and their sizes

may throw light on quantitative aspects of production and on economic relations within various cultural areas. These material sources as such are objective although errors may arise in their interpretation.

Written sources, on the other hand, are to a great extent subjective, charged with errors which may have been caused by their authors who might have twisted reality in some way, intentionally or otherwise. In addition, similar problems of interpretation remain (dating, understanding, explanation). Nevertheless they provide information, not obtainable from the study of material remains, on such aspects as the organization of production, legal relationships between workers and the owners and users of works and resources, and them and the consumers. They present property transactions, donations of lands, licenses and concessions, tributes, taxes, toll lists, references to working collectives, information on short- and long-distance trade, the volumes of cargos, and about the material and social status of those involved in manufacture and distribution. Technology is reflected extremely poorly in mediaeval documents, although some cardinal innovations such as the use of hydraulic power in iron smelting and working are, to date, predominantly heralded by written records. In fact, there are gaps in both sources, especially geographically, with the iron production of many countries being represented solely by archaeological remains, while that of others, *vice versa*, is attested by historical documents only. Some regions show a combination of archaeological and literary records, but only in fragmentary form, while others remain *'terrae incognitae'*.

For this reason, our concise survey tries to summarize the facts as mirrored in archaeological sources which, in many areas, are rather modest for the Middle Ages, and to compare them with the most important information derived from literary records which represent, at the present time, the major bulk of information for, in particular, the high Middle Ages and early post-mediaeval times.

At the start of the discussion, it is important to introduce the Slavic and other populations who colonized vast territories of eastern and central Europe. Their iron metallurgy cannot really be considered to have given a lead during mediaeval times, but in the early period, following the Dark Ages of the 6th and 7th centuries, these peoples introduced or transmitted certain innovations involving furnace construction and rapidly achieved a considerable level of technology during the 8th – 10th centuries AD. They drew their metallurgical knowledge from various ethnic substrates (Cimmerians, Scythians, Sarmatians, Greeks), as well as from eastern tribes such as the Khazars who were moving westward from Asia and with whom they came into contact. Possibly in this way, different models of bloomery furnace enriched the European inventory, notably underground installations with their perfect thermal insulation. Thus, the last furnaces occurring in western Slavic culture are sophisticated technical devices, apparently suitable for direct steel-making.

The development of early Slavic material culture and social development, resulting in the formation of early realms, one of the first being Great Moravia in the 9th century, was associated with demands for technical materials and goods including iron. On one hand, the increasing quantity of iron produced and, on the other, its value is reflected by the introduction of standardized currency bars, axe-shaped rods which have been found in large numbers in hoards and dwellings. In regions rich in ore and forests, smelting districts arose alongside agricultural land, as in northern and western Moravia, later in south-west central Bohemia, northern and western Hungary where other ethnic groups, Avars and Magyars, were also involved and in Burgenland and the Alpine Raxgebiet. In other areas the Slavic newcomers revived the metallurgy of classic times, as in Dalmatia, Pannonia and along the south-eastern foothills of the Alps.

The western Slavs developed a specific system of goods manufacture to satisfy the upper classes of society, especially the sovereign dukes and princes, through the so-called 'servant-villages' which were settled with specialized craftsmen (*ministeriales*) who also cultivated some land. They supplied artefacts and services to the courts of the rulers. The landscape in Bo-

hemia, Poland, Moravia, southern Slovakia and neighbouring parts of modern Hungary, Slovenia and Carniola preserves numerous distinctive geographical names with suffixes denoting workers, reflecting, amongst others, iron-makers (*železniki — ferrarii*) and miners (*rudnici, jamnici, gamnici — fossores*). They delivered a great deal of their production in the shape of *ferramenta* or *massae ferri* to their feudal overlords, including the Church. In Bohemia alone, the Chapter of Vyšehrad obtained through donation vast lands dispersed throughout the country and, along with them, craftsmen *cum aratro*, among them iron smelters. During the 11th to 13th centuries, families engaged in iron metallurgy — some known by patronyms such as Sdata or Modlata (*ferrarius*) — were obliged to deliver tributes to landlords, monasteries and to the king who promoted the undertakings. After the establishment of the kindom of Hungary in the 10th century, the organization and control of iron production was very strict, with tribute being collected in kind and handled at special centres (*vasvár, castra ferri* on behalf of the central authority.

A dynamic revival of the production of iron may be observed in non-Slavic regions as well, from at least the 8th century. Written sources of the 9th - 11th centuries mention dealings involving iron ore mines, *fodinae, fossae* which, with only one exception, are not accompanied by any technical descriptions. These refer to localities controlled by the clergy or by secular feudal lords. Archaeological finds indicate a rather primitive method of exploiting iron ore by means of shallow shafts, set extensively in smaller or larger fields. Iron was, again, the subject of tributes and taxes flowing to the treasuries of kings and landowners. In England, the Domesday book of 1086 records duties to deliver iron (*plumbae* or *massae ferri.* Monasteries such as Fulda in 912 AD and Lorsch in 1187 AD, both in Germany, took iron from specialized or semi-specialized collectives as did St. Gallen in Switzerland which collected *tremissae ferri* in the 9th century, Saint-Germain-de-Près in France and Corvey in Germany in the period 1106 - 1128 AD. There is little doubt that most of these taxes came from metalworking groups who were serfs, although enjoying some traditional rights to land.

This activity was rigorously promoted by ecclesiastic orders which ruled '*per donationem*' over huge territories and organized the making of iron, particularly during the 12th and 13th centuries. The Cistercian and Carthusian orders were particularly prominent, as, from time to time, were the Benedictines. Among the Cistercian order, the most important foundation was Clairvaux (founded 1115 AD), a daughter monastery of Cîteaux in France (founded in 1096 AD) which promoted the metallurgical work in the lands under their control. These were obtained as property donated or concessions yielded by major feudal rulers, thus enabling them to exploit ores, forges and wood in order to smelt iron. Written documents indicate a boom, particularly during the 12th and 13th centuries, when Clairvaux controlled up to 14 iron making plants in forest regions of the Othe and in Chaume, Chaligny and Wassy in Champagne and north-eastern France. Archaeology does not yet contribute very much except in terms of study of the 12th century complex of works and ore exploitation at Fontenay.

Other Cistercian daughter-houses organized iron making in England, namely in the central region between Sheffield and Leeds and extending to the Furness penninsula. The abbeys of Kirkstall, Byland, Rievaulx and Furness were important in the 13th–14th centuries. Spreading to Denmark and Sweden, Cistercians carried out iron metallurgy at Soroë and on church properties in Småland, Sweden, and at the Swedish Alvestra and Nydala (11th century), the 40th and 41st daughter-houses of Clairvaux. In Germany, most Cistercian abbeys were engaged in the metallurgy of iron. There were even Cistercians in Poland who obtained land from King Boleslaw in 1261 AD at Jędrzychów in Silesia and controlled smelting plants at the former servant-village of Rudniki.

In France, the very austere congregation of the Carthusians ran ironworks in the east, in Dauphiné in the vicinity of Grenoble and Allevard, with a peak in the 13th century. They worked like the Cistercians but their operations were more limited. Documents reveal that the monastery of Saint Hugon played a major role where one of the masters, a certain brother

Gilbert, was known as '*faber de Cartusia*'.

During the 13th century, members of two or three social groups gradually began to penetrate into the iron industry. First were the feudal lords again who felt some prosperity based on exploitation and working of iron ore in times when iron was being consumed by a wider and wider range of application. They maintained their rights and, again, took the initiative. In central and eastern parts of Europe they controlled much of the industry through to the 18th century. The second element were the burgesses. In addition to the Church they became partners of the lords. In France, they won concessions in several regions during the 13th century, while in Germany, for example in Nurnberg, they controlled much of the production in the 14th century. In Sweden, the towns of Stockholm and Kalmar fulfilled this role from the end of the 14th century, enjoying royal privileges. Finally, in some European regions, specialized rural groups survived or were revived and, based on various forms of traditional rights for the common use of resources (*Bergfreiheit*), they used the concessions given to them by their overlords to produce iron. Such groups include the people of the north Italian valleys (*homines in monte Scalfi habitantes*, 1047), the *ferrons* in Normandy (13th century), the smelters in Allevard, Dauphiné (at the beginning of the 14th century), the inhabitants of Vicdessos in the foothills of the Pyrenees (late 13th century) and the *Waldschmieden* of Westphalia (14th century). The social status of the iron smelters is more or less obscure. Despite some privileges yielded to them which reflected local needs, they were serfs bound to the land from where they obtained their raw materials. Their dependence on their overlords was much stronger than in the case of urban smiths. Among these specialized groups, who could be highly renowned, outstandingly skillful masters appeared who ran the plants and were sometimes invited on visits by the rulers of other regions.

The activity of all these groups crystallised in the formation of regions with increasingly concentrated production capacities. They prospered not only from the exploitation of natural resources but also from favourable conditions of communication. Remote and dispersed ironworks were beginning to lose their importance, at least in terms of long-distance trade and the role which they played in the general provision and consumption of iron is obscure, even today.

There are more than twenty major districts which were renowned as sources of iron. Carinthia and Styria definitely come into this category from the 10th century onwards. Apart from Erzberg, Admont and *Mons Gamanara*, many recorded localities bear names of Slavic origin. However, few sites, apart from Dürrenschoberl dating from the 12th century and Erzberg-Feisterwiese dating from the 13th, have been subjected to archaeological excavation. In the Upper Palatinate (Oberpfalz), centres such as Sulzbach and Amberg with their abundant brown ores appear in records from the 10th – 11th centuries and in the 14th century, urban *consortia* were organized by the owners of ironworks to confront the problems of deforestation and the depletion of natural resources. No archaeological sources are available from the Sulzbach-Amberg region. On the other hand, around Kelheim and Augsburg to the south, traces of brown iron ore mining, dating from the 8th – 9th centuries are very common, and some shafts have been excavated and the *Pingenfelder* geodetically recorded. Specific written records are not, however, known for this area. The Schwäbische Alb in south-western Germany played a role in ironmaking of the 7th – 8th centuries and also later, in the 11th – 13th centuries. In Bohemia, the region of the Barrandien facies contains phosphoric haematites and documents on iron production date from the 14th to 16th centuries, although few ironworks have been found and excavated. Westphalia and its famous districts of Westerwald, Lahn-Dill-Gebiet (13th – 14th centuries), Sauerland (the Mark and the Bergisches Land, 8th and 10 – 13th centuries), was a very progressive area in terms of technological innovation as was the Wietze valley situated more to the north-east. The Westphalian regions have been partly explored by archaeological excavation, especially in the Sauerland while areas of the Lahn-Dill region have become the subject of a broadly-based research project.

In France, several production foci emerged after the 12th – 13th centuries. We have already

mentioned Champagne with at least four centres, followed by Dauphiné (Allevard, Bauges, 11th – 14th centuries), while Normandy flourished briefly, especially in the 14th century. Ariège and the Montagne Noire area in the south of France were important from the 13th century, and Morvan, Burgundy in the 12th – 13th centuries, a region where archaeological excavations and surveys have been carried out.

In England, according to written sources, iron-making recovered in the Gloucestershire region in the 11th century and then in the Forest of Dean in the 13th century. Many areas in the Midlands gradually became important producers, from Derby north to Birmingham and from Leeds and Sheffield up to Durham and Furness. Curiously enough, the role of the Weald shrank to that of providing some supplies to London. But it would appear that the local iron industries were not able to satisfy the demand for iron in England.

In the Middle Ages, Italian iron was produced principally in the north of the country and in Tuscany. In northern Italy, productive districts developed close to the French and Austrian borders north of Bellona from 12th century and, later, around Brescia and Bergamo from the 15th century. In Tuscany, the leading centre promoting output of iron was, from the 12th century, Pisa which extended smelting and mining operations across areas retaining the remains of ancient smelting, namely the island of Elba and the coast opposite near Follonica. Merchants from other towns such as Genoa, Lucca and Florence were also engaged in these activities. Later, in the 15th century, there was a strong technological influence from Brescia. Archaeological surveys and small excavations have stimulated analytical studies of the bloomery slags from these areas.

One important area, the Basque country in the north of Spain, seems to disappear almost totally from view when only archaeological finds are taken into account. However, this was a leading production area from which excellent iron was exported to all of the countries along the Atlantic coast, as far north as Scotland as well as to the Mediterranean. Spanish iron was a byword for quality, and will be discussed below. Recently, research projects have been organized in the region and some new discoveries of cargoes of iron bars in coastal ship wrecks have thrown light on a most important aspect of this trade.

Scandinavian iron-making began to assert itself during the Romano-Barbarian period and, by the Middle Ages, had reached the point at which it was able to supply other European countries. This is particularly true of Swedish iron in the high mediaeval period, but signs of enhanced production may be observed there in earlier centuries also and in Norway and Iceland as well as may be clearly seen from the results of archaeological surveys and field excavations. In Norway, the regions of Hardangervidda and Dokkfløy in the south-central part of the country have been studied. In the 10th – 13th centuries the scale of Swedish production exceeded strictly local needs to some degree. Mediaeval ironworks have been discovered far to the north as, for example, in the Trøndelag and Budalen areas. Unfortunately, the iron smelting sites in the eastern part of the country such as Gudbrandsdalen and Valdress are not well dated, although the area is not far from the Swedish Dalarna (Dalecarlia) region which was held by the king Sverre Sigurdson in 1177, as an iron-bearing country — *Jernbäraland.* Many excavations of ironworks, dated by radiocarbon, cluster around the periods AD 600 – 1000 and AD 1300 – 1400.

The early Swedish iron industry was located in two regions. Most of the sites which exploited rock ores were situated in central Sweden around the Lake Mäleren system, the so-called *bergslagen.* We now know that in addition to Dalarna, Jämtland, Härjedalen and Hälsingland, parts of Westmansland, Närke and Norberg have sites which date to 7th – 13th centuries. Bog or lake iron ores were exploited in the south in the more or less isolated territories of Småland, Halland and Västergotland which were somewhat in the shade of the central Swedish districts. Archaeology rarely provides evidence for export, although many types of pre-monetary iron currency bars may be noted from as far south as Jutland. We rely primarily on written documents although, while they summarize the transit of goods via Stockholm and Kalmar, Blekinge, Laholm and

other ports, none refer to any identifiable ironworks.

There is only a little archaelogical evidence from two other central European regions — the former Upper Hungary, i.e. Slovakia (Slovenské rudohorie, Slovakian Ore Mountains) and Silesia (Moravian Frývaldov-Freiwaldau in the Jeseníky mountains and the Polish Bytom-Beuthen in the lowland to the east). Both are mentioned in written records of the 14th century and these areas clearly produced iron, at least a proportion of which went to export.

There are some published estimates on productivity which suggest that the Pisan works on the Gulf of Follonica in Tuscany could have delivered 160 000 tons of iron during the 11th – 14th centuries, Jämtland around 11 tons a year during the whole period of this survey (with peaks between AD 100 and 700, and 1100 – 1700), and the Møsstrond centre in the Hardangervidda 7 – 10 tons per year in course of about two centuries. However, estimating production volume is a difficult task since the sources are fragmentary and organized and systematic research on many centres only began recently. Within the development of individual production districts, periods of rise and decline occurred, the latter may be seen particularly during the 14th century which some authors are inclined to see as a widespread crisis. These situations were caused both by environmental factors such as problems with ore and charcoal supplies, as in the Palatinate, and by catastrophic events such as the Black Death in 1348 – 1350, in England and parts of Scandinavia. Certain changes may be seen in terms of changes in technology which must have started in the preceding century. However, it is beyond dispute that there was a general increase in European iron production and the crises must ultimately have had more or less local impact.

Trade

Written sources can contribute to our knowledge. They record the existence of commerce and trade in iron as early as the 11th–12th centuries (AD 1100 a *ferronus qui vendit ferrum in foro* at Bourges in France, the Venetians in 1161 equipping the Templars with ironwork for the Fourth Crusade). Of more importance is the evidence for the shipping of iron over long distances from different countries, through the leading European ports. This comes in the form of customs and import documents e.g. *tonlieus, Pfundzollbücher*, which refer to sums paid for the transit of iron handled, or, as later, to quantities. Basque iron from Spain appeared in the import list of Damm-Brugges in AD 1252, as did Swedish iron. This port was very important in the 13th century, and in succeeding centuries it was at the forefront of supplying territories along the Atlantic coast, as far north as Scotland. England was one of the regular consumers because its own production would appear to have been insufficient to meet local demands. From Santander, Bilbao, San Sebastian and other ports, this iron, collected from iron-producing provinces, was distributed in amounts of 4 to 5 thousand tons annually, acording to documents from the later part of the 13th century, while later documents of the 15th and 16th centuries also mention Basque iron. The cargo of the Ria Oria ship wreck included some 100 pieces of split iron blooms and about 80 examples of pointed bars (radiocarbon dating is in progress). England and the Netherlands took, in addition, Swedish iron, although initially in much smaller quantities. This type, described either as *ferrum* or as *osemund* is also named in the Brugges document of AD 1252, but the volume of deliveries increased during the 14th and 15th centuries. At the end of the mediaeval era, Sweden exported around 1600 tons of iron annually, especially to countries along the coasts of the German and Baltic seas. The Hanseatic ports, particularly Lübeck in the earlier period, were engaged in this trade as intermediaries for the traffic from Stockholm and other Swedish towns to the Baltic ports such as Wismar, Rostock and Gdańsk-Danzig. There was some competition with Hamburg which also took Westphalian and other German iron, and with Gdańsk and Riga or Revall, where other kinds of iron were traded, notably Silesian, Hungarian (Slovakian) and Russian. These types came to England, again, via Hull, Newcastle and Kings Lynn. Ship's cargoes, which arrived to Hull in 1383 reveal a sample of important iron types,

with some 24 % being Spanish iron, 24 % Hungarian (*ferrum Hungaricum, Hungresyryn*), 11 % Swedish osmund, 11 % *land-yzer* and 8 % Silesian or Polish irons (*polonisium iser, Frewaleyrne, Butn yryn*). The commodity was transported as bars or rods in bundles, or osemund in the form of ingots packed in barrels.

The iron technology of the Middle Ages

The following simplified picture is based on old, established facts, supplemented by more recent results and views. In fact, in the initial phases of European siderurgy, most of the changes were economic rather than technological, although it was the technology which, relatively rapidly, was able to transform the capacities of the entire industrial field, at least in the progressive areas.

The technology of mining ore, for centuries very simple, definitely involved underground operations from the 8th–13th centuries, as we know from archaeological excavations and surveys and, in one case from literary sources, in the so-called Irmin-Polyptique (Dauphiné) dating to AD 1122.

The traditional bloomery workshops, concentrated or dispersed, chiefly operated on remote sites, in forests (which were gradually being devastated), often on slopes or on the tops of the hills. It was believed that the reason for this lay in aerodynamics in terms of wind circulation favourable to the air-supply of furnaces. This might have been true in certain areas, but in fact, attempts were made to place most of the bloomeries as close as possible to suitable outcrops of ore and supplies of wood for charring. Mediaeval ironworks were almost all bellows-blown and tube-shaped tuyeres are characteristic of the 10th – 13th centuries iron-making sites.

Furnaces, mostly incomplete, are known from archaeological excavations and there are no descriptions written in records, only occasional references (*fornacia*). Apart from the early Slavic, Hungarian and eastern underground or embanked types, bloomery furnaces ususally had low shaft superstructures but, curiously enough, simple open and shallow smelting hearths survived or were reintroduced in almost all production districts. Certain regions produced iron in specially arranged piles of ore and charcoal of the late Corsican type, a technique, which, as suggested by some scholars, appeared in the Mediterranean from the 11th century.

Fluxes were not normally added to charges but the smelting process was well controlled, if not standardized. Slag tapping which enabled a relative increase in yield, was common as can be seen from the slags.

The quality of the iron produced in the form of blooms (*loupes de fer, massiots, Luppen*) and sometimes subsequently worked into rods and bars (*endys, Schienen*) was, in most cases, a soft and malleable metal. Primarily-carburized areas occured regularly and were separated out and used commonly for the cutting-edges of tools and weapons.

Published trials seek to classify the basic bloomery process according to possible methods of its control by smelters but this requires further investigation. What is striking about most of the mediaeval irons examined from the wide European lowlands as well as from the regions in Germany, Bohemia and others is that they are high in phosphorus, in particular in the bodies of artefacts. This indicates that all possible iron deposits were being used and that bog iron ores, high in phosphorus, were widely exploited. On the other hand, the most productive regions — middle Sweden, Spain, parts of England, Westphalia, Siegerland (manganiferous), Styria and Carinthia (both manganiferous), the Palatinate, northern Italy and Elba — exploited low phosphorus ores.

The demand for iron was steadily increasing in the Mediaeval material civilization. It was stimulated by the increased exploitation of the existing arable areas and clearance of new land and increase in population, as well as by the revival or founding of urban centres, housing specialized blacksmiths who supplied all the crafts engaged in working material and building. Thus iron was, again, the basic material used in the manufacture of all tools and implements, for

many structural purposes and for military equipment including heavy pieces of armour, weapons and, as explicitly mentioned in sources, siege machines and, from the 14th century, forged gun barrels.

There were two possible ways in which the required increase in the general production of iron could be achieved. Either the number of specialized or semi-specialized small forest or rural workshops manned by the smelters' collectives and groups described above could rise, or the volumes of furnaces improved by building to much larger dimensions than previously known, even in the most productive parts of the old Roman world. The solution, in fact, was to enlarge furnace volume but coupled with the application of hydraulic energy in the making and working of iron.

Water-wheels

Water powered mill wheels (*molae*) had already emerged in late Roman antiquity. They appeared in central and western Europe in connection with ironworking as early as in the 11th century, being described usually as *mollendinae*. As expressed forty years ago, the problem is to decide whether they were adapted for driving bellows and hammers, and when. Apparently the majority, described as *molendina ad cultellas, ad secures, and ferramenta* or simply *molendina* or *mollendinae ferri* (France, 12th century), *Smidimulni* in the Palatinate, 11th century) were, in fact, grinding plants using rotary motion applied to whetstone wheels for sharpening blades. Pulling rods, lifted by cams to operate bellows required the transformation from rotary to linear motion. Installations of that type are mentioned in documents of the 13th century and later: for example, *molendina ubi fabricatur ferrum*, AD 1224 in Tvååker, Sweden; *molendina quae hutte (Hütte, casa conflatia* (ironworks) *dicuntur*), in Moravia in AD 1215, or *molendina sive hutte* (here the German term *Hütte* or *casa, casa conflatoria*, a smelting plant was used); *une forge faisant fer par eaue* (AD 1323 at Pont-à-Mousson, eastern France); a furnace, a water channel and wheel were noted at Bornino in northern Italy AD 1226. Sporadic archaeological investigations have not clarified the question with any precision — the mill-race and even wooden fragments of water wheels rarely provide an unambiguous picture (Fontenay in France, Chingley in England in the 14th century). The *molinum fornacium* referred to in AD 1073 in Spain, which might be evidence of the much later system (known from northern Spain and south-west France) of blowing by water trompes, did not need any wheels.

Similar questions arise over hammer-mills. They may be distinguished under various descriptions as *mollendinae ferri*, except in the case of descriptions such as the 13th century reference to *molendinum quod ibidem materiam massae ferri molet* (AD 1261 Rudniki in Poland) or where the term *martinetus* was used, as in France (Allevard AD 1220, Saint Hugon AD 1374: *arbores malleorum utriusque martinetum*). The 14th century documents, however, do not leave us entirely in the dark: *malleatores qui vulgariter hamry dicuntur* (Bohemia AD 1390), *molendinum volgo hamor dictum* (Slovakia AD 1399). Here, again, the Latin-French or Latin-German *bilinguae* explain the term malleus: *martinet* or *Hammer*.

Hundreds of hammer-mills, often (but not always) associated with smelting plants were spread over Europe at that time, sited in valleys, by streams. The problem of identifying the original area which saw the first water-powered iron mills, adapted for blowing and forging, is much discussed. In the light of the capacity of streams and mills for other production, the Alps and their broad periphery are claimed as the cradle of the practical application of water-driven works, which were introduced as early as during the 13th century.

It is argued indirectly that in Styria, for instance, written documents dating to after the middle of the 13th century herald the delivery of large blooms which were 2.5 times heavier than traditional ones. This is ascribed to the introduction of water-driven bellows for furnaces. The consequence must have been a change in the smelting furnace itself. Water-driven bellows

applied to a small device of some 0.2 cubic meter in volume would have only produced slag. Furnaces must have been increased by two or three times in size. This is possibly the way in which the high *Stückofen* came into being. This development is obscure as yet, particularly in regard to the proportion and numbers of the new constructions, because traditional bloomeries did not suddenly disappear from hilly areas. Some ironworks, especially those hammermill-and-bloomery plants shifted down to the stream valleys from the 13th century in France, Germany, Bohemia, Sweden and other regions and were able to use the energy of flowing water for effective mechanical operations. There is little information among archaeological sources so far available about the course of events. In any case, larger and heavier blooms could have been worked with water-powered hammers.

Another effect followed necessarily, namely the change in conditions of the metallurgical process favouring the smelting of carburized and liquid cast iron which was not produced accidentally and in small amounts as it usually was during the traditional bloomery process, but step by step, intentionally, influenced by furnace design, dimensions and the temperature regime.

The emergence of the indirect process

The overall effects of the application of water power on the metallurgy of iron in fact became clear immediately in the 12th and through the 13th and 14th centuries and was made possible through innovations in management. The ironworks which were able to implement new technical innovations had to be an organized and complex plants with sophisticated equipment, the installation of which was beyond the power of individual smelters or smaller teams. Furthermore, the foundation and running of such a *l'usine*, forge, or *casa conflatoria* required considerable funds. Thus, the drive towards the establishment of such productive units came from the top, from sources, which promoted production according to increasing demands. It is beyond dispute that the initial advantage lay with integrated organizations such as the abbeys of the various religious orders, rather than with scattered and decentralized secular feudal systems and networks. Possibly this was the reason why the monastic production of iron played a leading role during the critical times. The introduction of the new technology happened against a economic and social complicated background. The purely technological impact of eastern traditions, nowadays under active consideration, seems at least to have only been to complement European developments.

The scene was thus prepared for the emergence of the blast furnace. In the light what has already been described it is not surprising that the roots of and first steps in this evolution can be detected almost immediately, earlier than was believed some decades ago. In the light of our present knowledge, these processes began in a north-south oriented geographical tract of Europe, including Württemberg, the Italian foothills of the Alps and the Rhineland, stretching as far north as Scandinavia possibly through links with Baltic and, later, Hanseatic trade, but with only a limited (and later) spread to the west and south-west, and finally to the east. Surprisingly, within these more backward areas, there were the highly-productive regions of Styria and Carinthia which developed their own high-bloomery process, the *Stuckofen*. It was not until the 15th century that the new trends spread west of the Ardennes and one century later reached east of the Elbe as a result of invitations extended to specialists, mostly of Walloon origin, by local interests.

The formation of pig iron in the furnace hearth, recognized from many sites as an almost regular part of blooms of relatively very early date, does not signify the general introduction of the process. This metal, which was not malleable, was originally discarded as waste (the *Graglach* of the Styrian *Stucköfen*), perhaps added to the next furnace charge, or cast into smaller or larger artefacts from fittings up to the first cannon balls in the 14th – 15th centuries.

The *Flossofen* or subsequently the blast furnace worked under high temperatures, above 1500°C. The effect of blowing by water-powered bellows was increased by a narrowing of the

hearth at the bottom. Thus, the well-known design of the blast furnace with a narrow throat and high biconical shaft, with a typical 'bosh', became the norm.

Instead of the blooms weighing tens or even hundreds kilograms, yielded by the last bloomeries, 3–9 tons of iron, tapped out continuously, could be produced in campaigns lasting initially days, and later (by the 18th century) weeks. The consumption of charcoal was high but more favourable in terms of the so-called 'coke rate' (fuel to iron ratio); nevertheless the total need was enormous in comparison with earlier periods. Deforestation caused heavy environmental problems (particularly in countries like Ireland). The liquid metal which contained 3 – 4 % of carbon, had to be converted to wrought iron or steel when not cast. Special installations such as the finery hearth, used for the decarburization of cast iron, consumed additional amounts of fuel, as did the reheating of blooms. The addition of fluxes, improving the formation of lighter glassy slag was gradually introduced, depending on the composition of the ore used. In the main, the flux used was lime, and in the case of finery processes also crushed old bloomery slag. The blast furnaces came into their own when linked with fineries and their complexity characterizes the indirect process.

There is ongoing and vigorous discussion of when and where this development proceeded. There some are some indications of not well cristallized types of cast iron producing installations in SW Germany, especially in thjr Schwäbische Alb which date from around AD 1000 and from the 12th century. Surveys and excavations in the Sauerland and Märkischer Kreis in western Germany have revealed the sites of genuine *Flossöfen*, the earliest of which at Haus Rhade dates to the 13th century. Ironworks of the 14th century comprising a furnace and several finery and smithing hearths, has been recently uncovered on the bed of the emptied Jubach dam, near Kierspe. Iron samples with lamellar and globular graphite indicate beyond any doubt that the indirect process was being carried out there. Possibly a little earlier are two blast furnaces dating to the 13th – 14th centuries at Kerspe, near Meinerzhagen/Lüdenscheid. The finds at the Middle Swedish site at Lapphyttan with its slags and pig iron samples, a *Flossofen* and fineries suggests that it might have commenced operations during the 13th century. Radiocarbon indicates dates from the 13th to 15th centuries for another mediaeval blast furnaces at Vinarhyttan, and from the 14th to 15th centuries for Jutaboda (some very early radiocarbon datings of blast furnaces in the Noraskog area which have been published in preliminary form are not commented upon here). The site of Lapphyttan yielded some iron lumps which might have been fined. This would accord with the Swedish iron known as *osmund* and referred to in documents from AD 1252, the production of which gradually increased during the 14th to 16th centuries. Despite the remaining uncertainties and discussions on the precise meaning of this word, osmund was likely to have referred to a type of soft and highly-malleable fined iron.

The 15th century is marked by the introduction of blast furnace metallurgy to France and England, presumably under the direct influence of the important focus which crystallized in Belgium as the Walloon process. This had reached maturity by the 16th century and is described in literature as well as presented on contemporary paintings. Walloon metallurgy spread over all of the northern part of Europe, and, after AD 1600, far to the east. The south, comprising the Alpine regions, Lombardy and south-eastern France, was dominated to a great degree by the Brescian technology with its *caneccio* furnaces, approximately during the same period. These are the initial steps in the later part of the history of iron in Europe which is beyond the scope of this book.

The last European bloomeries

The gradual victory of the new process did not eliminate the bloomery process at once, and several bulwarks of that traditional technology survived. In Styria and Carinthia, the Erzberg and Hüttenberg areas, the so-called *Stuckofen*, a stone-walled high bloomery with a shaft about

4 – 5m in height and with water driven bellows operated until the 18th century, alongside the first *Flossöfen*. The average parameters are interesting: from 5 tons of ore and 4 tons of charcoal during a day's shift, such a furnace produced a heavy bloom, consisting of very good quality iron, of about 1 tonne (which had to be reheated and forged) plus about 5 % of pig iron (*Graglach*) which was more often recharged than cast.

Traditional Scandinavian bloomery furnaces resembling open hearths (1m high, more than 1m wide, the hearth bottom being about 60cm) were in operation until the mid-19th century. The process was described by Evenstad (18th century), Busch (19th century) and others. The smelters used bog iron ore mixtures and wood which was charred in the hearth during the smelt, the process consuming around 18kg of ore in three charges over 3–4 hours. According to recent experiments, the yield could have been in the region of some 8kg of iron. Blowing was carried out using bellows driven by man-power or by a water wheel.

Corsican iron smelting, known from the north-eastern part of the island, is believed to represent a very old tradition going back to the Middle Ages and traceable back to the industries of Pisa, Genoa and Lucca. Instead of a stable furnace, the smelt was run against a wall in heaps consisting of pre-packed charcoal and ore (about 120cm high and wide). The operation was performed in two stages, the roasting-sintering and the smelting. In the 19th century it was possible to smelt a 40 – 50kg bloom Air was supplied by the so-called *trompe*, where air was drawn in by water falling through a pipe, compressed in a box and blown into the tuyere. Apart from Corsica, this device was in use over a wide area of Italy and the eastern Pyrenees, from at least the 17th century. The blooms were forged with a water wheel-driven hammer propelled from the same water reservoir.

The most successful bloomery operations were traditionally performed in the Pyrenees. It is necessary to distinguish between the bloomery hearths of Andorra, Navarra, Gipuzkoa, and the Catalan forge used on both the French and Spanish sides of the eastern Pyrenees. The first type used larger stone-reinforced hearths over 1m high, producing blooms weighing about 100kg from *ca.* 300 kg ore and 500kg of charcoal over 4 hours. The shape, size and practices varied little from place to place. The genuine Catalan process (the term comes from the late 18th century but the system must have been in use since at least the 17th century, using a *trompe*) was three to four times more efficient than the Corsican method. It is characterized by its specific pre-packing of the charge in a square, stone-walled hearth (80cm high, 80cm x 65cm at top, and 60cm x 55cm at bottom). Charcoal was put at the bottom, the roasted ore at the wall opposite from the tuyere and a mixture of charcoal and fine ore (*grillade* was placed close to the air-inlet and on the top. Over some 6 – 8 hours, blooms of 150 – 180kg or even 500kg were produced from 1 tonne of ore and 1 tonne of charcoal and immediately forged under the martinet. Slag was tapped and sometimes partly returned to the charge. Catalan smelting was perfectly described by leading contemporary metallurgists such as Richard, François, Percy and others. The process, which disappeared during the second half of the 19th century, yielded hard steel (with some liquid metal) and also wrought iron, sometimes deliberately by modifying the angle of the tuyere and the fuel-to-ore ratio. Recently, the process has been under intensive study through experimental smelts and the analyses of products.

There is some evidence, for example from Bohemia, for the occasional bloomery smelting in blacksmith's hearths of 19th century hammer-mills, in cases when scrap iron which was normally used was not available, but such cases did not influence industrial production by the indirect process of that time.

In the 20th century, the episode of the so-called *Krupp-Rennverfahren*, the appearance of which proceeded by some 67 other patents (Wiberg, Högenäs, Kalling and others), should be noted) A huge rotary kiln smelts iron ore with a coal mixture by gas at relatively low temperatures (up to 1250°C) to small, porous, granulated pieces (about 1cm) of wrought iron. These were used to a great extent in steelworks and the process was operated during shortages of good

ore in Germany and Japan during World War II and sporadically up to the 1950's in Bohemia.

Traditional bloomeries existed in the world until the mid-20th century, but outside Europe. Tens of furnace variants, blowing systems, styles of work, operational parameters and differing yields have been recorded not only from Africa, but also from India, south-east Asia, Japan and Siberia. Many of them have been referred to when discussing different aspects in previous chapters, but it is not possible to present any specialized and summarizing comments in pages of this book which is focussed on the work of European bloomery smelters.

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We may conclude that the bloomery process was the very earliest method of supplying mankind with malleable tough iron and hard steel, step by step from shekels, ounces and grammes, through talents, pounds and kilograms, to tons of that material which formed the basis of the Age of Iron. It became an integral part of human culture. We are still living in the Iron Age, despite the fact that the modern iron industry, exposed to serious economic influences, is passing through a time of recession and critical change, which are leading towards far-reaching transformations.

GLOSSARY OF TECHNICAL TERMS

archaeomagnetic (palaeomegnetic) method of dating archaeological finds is based on the fact that soils containing iron oxides are polarized along the ancient magnetic field which existed at the time (the magnetic pole changes its position). When such soil was heated (burnt-red, e.g. fireplaces, kilns, furnaces, hearths) the remanent values (inclination, declination, intensity) may be measured when the sample is exactly oriented *in situ* by compass. A curve of data is constructed for different areas which must be calibrated by a network of reliably dated finds. The application is still rather rare in case of archaeometallurgical features.

austenite, a solid solution of carbon (or other elements) in face-centred γ-iron. In carbon steels, austenite appears only above the critical temperature (about 720°C in metal with about 0.02% C, 906°C in that with about 0.7% C). Cooling of austenitic structure leads to crystallization of ferrite and pearlite, while rapid cooling (quenching) develops martensite. Austenite was named by Osmond (1901) in honour of W. C. Roberts-Austen (1845–1903), a renowned British metallurgist.

billet, in recent archaeometallurgical literature a well-forged iron bloom, suitable for making a bar.

bloom, a product of the direct iron smelting process (see Chapter XII).

bosh, tapering lower part of the blast furnace shaft between its largest diameter and the narrow hearth.

carbon in iron. As an alloying component, carbon increases its hardness (carbon steels) and simultaneously brittleness. Carbon is absorbed by iron in its austenitic state during the reduction of ore in the smelting furnace or during secondary carburization.

carburization, introduction of carbon into iron in the austenitic state, mostly at temperatures above 780–906°C in contact with carbon-containing substances, essentially charcoal, by carbon monoxide or by carbon. The process takes place, under favourable conditions, in the furnace in the advanced phase of the smelting process, in spite of the fact, that in the bloomery at the tuyere mouth much of the metal would be secondarily oxidized (decarburized). Prolonged heating (over several hours) of ready-made cutting-edges of tools and weapons in contact with carbonacous material was used to carburize items to steel. Nitrogeneous substances accelerate the carburization, phosphorus blocks it to certain extent.

cast iron (see also pig iron), the product of a *'Flossofen'* or blast furnace, an iron-carbon alloy the carbon content of which exceeds the solubility in austenite at the eutectic temperature (above 1148°C from 2 %C onwards). **Grey cast iron** contains pearlite, as well as segregated flakes of graphite which cause a grey-coloured fracture. **Malleable** or **ductile cast iron** has the graphite granulated; in the **white cast iron** the excess carbon appears as cementite or ledeburite and is very hard and brittle and makes the metal unmalleable. In modern metallurgy, cast iron is the product of special cupola furnaces and is destined for foundry purposes.

cementite Fe_3C, hard and brittle iron carbide which occurs in steel and cast iron either as an intercrystalline phase in very low carbon steel ('tertiary cementite') or as a component of pearlite or as white cells (appearing as a network in section) surrounding the pearlite grains in hypereutectoid steels.

chafery (derived from French *chauffer*, to heat), a second fining hearth in early blast furnace plants of the Walloon type (Belgium, France, Luxembourg, England, later Scandinavia), destined to reheating of iron from the finery at temperatures about 1400 – 1450°C. The products were

forged to bars. Sometimes chaferies were fed with mineral coal.

chalcopyrite, sulphidic copper ore containing iron ($CuFeS_2$), occuring in cementation zones of hydrothermal veins.

coppicing periodic cutting of tree branches and small wood, as well in order to maintain regular growth to provide raw material for charring coal, not clearing the forest.

cupola furnace, a shaft installation used in modern foundries for remelting crude pig iron to cast iron.

dendrochronology, a dating method based on comparison between patterns of annual tree-ring growths, where thickness of individual growth rings depend on humidity and temperature changes over wide areas. Individual blocks, logs or timbers of preserved wood from archaeological sites and other contexts are compared by shifting the relevant ring patterns and the sequence of long-termed weather changes. Completed with datable archaeological finds and ^{14}C dendrochronological curves for wide regions may be established, giving a base for exact chronology. Dendrochronology of California giant pines (sequoia) growing thousend years enabled to reconstruct the so-called 'calibrated' radiocarbon chronology. The master chronology for Europe is based on oak (*Quercus robur*).

eutectoid steel, hard steel of about 0.86%C content. The structure is pearlitic. Steel with a lower carbon content is called hypoeutectoid, showing ferrite in various proportions; that with higher carbon content is hypereutectoid steel (with the excess cementite seen in form of a network around pearlite grains on polished samples).

fayalite, iron orthosilicate Fe_2SiO_4 from the family of olivines, melting at 1175–1180°C, is a constituent of iron and most of copper slags or occuring in volcanic rocks. It appears as dark grey laths or fields on polished sample blocks, studied by microscope. Combined with other elements (Ca, Mg, Mn) it forms different mineralogical phases. The name comes from the island Fayal, Azores, where it was discovered.

ferrite, ductile crystals of almost pure body-centred α-iron, containing no carbon or a minimal amount (0.02–0.03%) which does not appear as pearlite. During the very first phase of reduction ferrite creates a thin skin around the ore fractions or charcoal particles. Ferritic iron is easily malleable and relatively soft. In the optical field of the microscope, ferrite appears as a light structure with a network of grain boundaries.

finery, a hearth in the early blast furnace ironworks in which the first stage of conversion from cast iron to wrought iron took place. Cast iron pigs were passed over the rim or later through a special hole so that the tip was melted and decarburized in front of the tuyere mouth. Simultaneously, the silicon content was reduced to very small amounts. The finery produced heavy fayalitic slag rich in iron oxides (50 – 60% FeO). Fineries were still in use during the 18th century. In NW Europe the fining proceeded in two separated hearths, see chafery.

flux, a substance lowering the melting point of metals and minerals, promoting the liquefaction of slag. In metallurgy, siliceous or calciferous components, according to the ore composition, may be added to the charge. Lime fluxes were exceptional in bloomery technology; silica could be added in case of high-grade iron oxides. Old bloomery slag with its high FeO content was used as flux as well. Sand flux (fine quartz) was used to remove hammerscale during forging by melting to fayalitic slag.

furnace see Chapters VIII and IX.

gangue, non-metallic constituents of any ore.

geomagnetic survey. Deviation of the intensity of magnetic field is identified by using electron magnetometer. Data obtained by measurements, plotted on a map or plan, show anomalies indicating buried stone-walled structures, pits filled with

different kind of soil, bloomery slag agglomerations and furnaces. Due to steady improvements, the technique has been more widely and more successfully used in recent years to locate archaeometallurgical features.

graphite, in the metallography of iron, elementary carbon segregating during slow cooling of grey cast iron as microscopical black flakes. In malleable cast iron it occurs as granulated particles.

gromps, from Polish *grądpie*, groats. Minute particles of iron which have flaked off the iron sponge or bloom when it was being removed from the furnace and during the initial handling nearby. These are very heterogeneously carburized, revealing structures changing in 1mm from ferrite to pearlite and, sometimes to ledeburite. Gromps were mentioned for the first time by Rożdzieński in 1612.

hammer-scale, magnetic bluish-grey flakes of iron oxides (wüstite and magnetite) formed on the surface of iron when heated for forging. It could be knocked off or melted by sand flux, especially before welding. Hammer-scale can be identified during the excavation of bloomery sites and smithies.

hearth, in modern metallurgy the bottom of the reverberatory, cupola or blast furnace where molten products (slag, metal) collect for periodical removal. Hearths of bloomery furnaces received slag. An open hearth is used by metalworkers and blacksmiths to heat the metal. Open bowl hearths were used for the smelting of iron ore as well (see Chapter IX).

hypereutectoid steel see eutectoid steel

hypoeutectoid steel see eutectoid steel

inclusions, non-metallic impurities in the crystalline metal matrix. In wrought iron and steel they appear as deformed, elongated silicate (slag) inclusions, often following the lines of welds or folds. They may be glassy or containing light oxide phases (fayalite, wüstite, the latter also in dendritic form, often occuring in carbon-poor areas of the metal). Globular oxides (or/and sulphides) of various types may also occur. The slag inclusions in bloomery iron may correspond to a certain extent with the composition of the ore smelted; they are now beginning to be studied by microanalysis.

iron, *ferrum* Fe, a metallic element (group VIII of the periodical system, at. n. 26), melting at 1529–1532°C; malleable in cold and hot state, and weldable. Principal modifications: body centred α-iron (up to 1906°C, up to 760°C magnetic), face-centred γ-iron (906–1403°C, austenitic phase, absorbs carbon, non-magnetic), δ-iron (1403°C to liquidus, non-magnetic). Types of iron: native terrestrial (rare), meteoritic (Fe-Ni-Co), iron bound in its ores or in many soils, and technical iron smelted from ores. Modern nomenclatures denote all technical iron below 1.75% C as steel. This usage is not held consequently (wrought iron) and the carbon-iron alloys above 1.75–2%C bear the name of iron (pig iron, cast iron). See steel.

iron mines see Chapter V.

iron sponge, spongy iron. Iron having been reduced and sintered together in the solid state in the slag mass or around charcoal particles in front of the tuyere mouth or air-vent of the bloomery furnace. It may be sometimes severely decarburized to ferrite. When removed in that state from the hearth it is also denoted as unconsolidated bloom.

ironworks see Chapter IV.

ledeburite, eutectic alloy of iron and carbon (4.7%C), appearing mainly in cast iron or steels with more than 1.7%C hindering their malleability. The term was given in honour of A. Ledebur (1837–1906), a German metallurgist.

magnetite, magnetic iron oxide Fe_3O_4 in the spinel group of minerals. 1. A high-grade iron ore; 2. The product of heating of any iron ore (Fe_2O_3) by CO_2 in roasters or upper parts of the furnace shaft; 3. Constituent of hammer-scale; 4. Mineralogical phase (light quadratic crystals) occuring especially in post-reduction slags.

martensite, a metastable solid solution of carbon in iron, cooled rapidly from the

austenitic stage, forming a grey acicular structure, typical for quench-hardened carbon steels. It is very hard and brittle. When heated it is transformed to softer structures on the base of pearlite. It was named in memory of A. Martens (1850–1914), a German metallurgist.

martquenching see quench-hardening

metallography, the study of minute crystalline structures (phases) of metals and their alloys, and of their changes during various conditions of treatment (deformation, heating and cooling, hardening, heat treatments). The classical method is the observation of polished sample blocks, unetched and etched by different solutions, on microscope in reflected light, or on electron microscope, and by X-ray diffraction, hardness and microhardness tests.

meteorites, cosmic mineral bodies impacting the Earth from interplanetary space. There are stony meteorites or aerolites (chondrites, achondrites) of rock-forming silicates, and iron meteorites or siderites, being iron-nickel alloys, containing some cobalt, with taenite (26–65% Ni) and kamacite (5–18% Ni). Pallasites are mesosiderites, consisting of olivines embedded in iron-nickel cellules. According to crystalline arrangement there are being distinguished hexaedrites, octaedrites and ataxites.

meteoritic iron, a nickel-iron alloy originating from siderites, containing more than 4% Ni and some Co, with practically no slag inclusions. It has been very occasionally used by man for making smaller artefacts (from beads, amulets up to ceremonial daggers or axe-heads), especially in earliest times. Meteoritic iron was apparently very soon identified as being similar to the first smelted samples and inspired the earliest nomenclature, reflecting the 'metal of heaven'. Some hypotheses deny such a use and consider all of the nickel-rich iron as smelted from nickel-bearing iron ores, which is hardly defensible. Exploiting of known iron meteorites e.g. by the Inuit Eskymos is attested.

osmund iron, in the late 13th to 16th centuries AD a Swedish fined wrought iron which was principally exported to England and Baltic ports. Small bars were packed in barrels containing 480 pieces each. In western Germany of the 17th century, osemund was also fined wrought iron as well, especially suitable for making iron wire in the so-called *Osemund-Hammermühlen.*

PCB, plano-convex bottom, recently introduced term for calotte-shaped cakes of post-reduction slag. In the majority of cases smithing slag were created by the melting of hammer-scale with sand flux, resulting in fayalitic-wüstitic-magnetitic waste. Also SHB, smithing hearth bottoms.

pearlite, a lamellar conglomerate of ferrite and cementite plates found in carbon steel. Its pearly lustre is due to the fine and regular alternation of the two constituents. Cementite being more resistant than ferrite throws, after etching of polished samples with acids, minute shadows. Thus pearlite appears darker, when observed under the microscope. When annealed, the lamellae of cementite coagulate into globulae (globular cementite). Pearlite is the basic crystalline microstructure of carbon steel.

phosphorus, in bloomery slags could be partly derived from the ore, partly from charcoal ash minerals as phosphorus pentoxide P_2O_5, combined with iron as the mineral vivianite $Fe_2(PO_4)_2).8H_2O$. In ferrite, phosphorus can be partly reduced as phosphide Fe_3P, mostly forming segregations, particularly along slag inclusion chains and welds. When present in amounts above 0.03% P, it increases the hardness and brittleness of iron. To a certain extent it hinders carbon penetration into iron and improves its resistance to atmospheric corrosion.

pig, the product of a blast furnace, representing bar-shaped or plate-like iron, tapped to beds in front of the furnace outlets. Pigs used to be fined to produce steel or wrought iron, or melted to cast iron for foundry purposes.

pig iron, in modern metallurgy, crude impure iron produced in blast furnaces, containing 2–4.4% C, and destined for making cast iron in cupola furnaces for foundries. Melts below 1200°C. According to the ore used or smelting practices applied, pig iron contains manganese which facilitates the absorption of carbon, silica hinders it causing the formation of graphite flakes. Phosphorus penetrates into pig iron completely. Sulphur represents an unwanted impurity. In is difficult to distinguish between the pig- and cast irons produced in the early phases of the indirect process.

quench hardening, a kind of heat treatment applied to steel, comprising a rapid cooling usually from temperatures above 900°C in water or more drastic acidic liquids etc. The result is the coarse or fine acicular martensitic structure. Quench-hardened steels are brittle, the brittleness increasing with higher carbon content and speed of cooling.

radiocarbon dating, ^{14}C, a method of determination the chronology of archaeological situations or objects (steels, cast iron as well), involving organic substances. The isotope ^{14}C, produced by cosmic radiation, is absorbed by plants and animals. After their deaths it decays with a half-life of 5730 years. Measurement of the remaining uncontamined ^{14}C isotope enables determine the age within a range of $\pm$ 100 or $\pm$ 50 years. Calendar radiocarbon dates were first 'calibrated' by dendrochronological analyses of *Pinus aristata* (California) and later, in Europe, against oak (*Quercus robur*). The reliability of data may be diminished by insufficient stratification of samples. As to the wood, the dates indicate the time of the tree being felled, not the time of the use (up to 50–100 years come into question). In later historical periods, the dating may be less precise and often (not always) misleading when not controlled by other means of dating.

reduction, in metallurgy, the extraction of metals from their ores by a reductant (mostly carbon oxides, in early times produced by combustion of charcoal) at a relevant temperature and gas pressure. The result is the released metal and waste consisting of the constituents of the gangue, ash, fluxes, and furnace lining.

reheating of blooms see Chapter XI

SHB, smithing hearth bottom, see PCB

sintering, in modern metallurgy the fritting together of powder particles of metal with different melting points. In ceramic and glass technologies joining of smaller fractions to conglomerates, not exposing them to any pressure. In the bloomery process the austenitic iron particles coagulate in the liquid or viscous slag to larger complexes (spongy iron), without being artificially welded.

slag, waste product of smelting processes (see chapters XI and XII).

smelting of iron see reduction.

steel, a malleable alloy of iron, carbon and, sometimes other constituents as well. Until the beginning of the 20th century carbon steel was understood as a hardenable metal with more than 0.30–0.35%C. The practical use reflected this in most languages: e.g. *sidéros*×*stómoma*, *ferrum* x *acies* (the latter two denoting the sharpness of steel cutting-edges), *Eisen*×*Stahl*, iron×steel, *fer*×*acier*, *żelazo*×*stal*, *železo*×*ocel*. Nowadays, according to standardized nomenclature, all malleable iron with carbon content below 1.75% is called steel, however, inconsequently (wrought iron). As to their hardness and tensile strengths, carbon steels are distinguished as mild, medium, and hard. As to their use there are construction and tool steels etc. Carbon steels consist of varying proportions of ferrite and pearlite, in old times often heterogeneously distributed (hypoeutectoid steels) or pearlite and cementite (hypereutectoid steels, above 0.86% C). Alloy steels, containing considerable amounts of other intentionally-admixed other elements (Cr, Mn, Ni, Mn, Mo, Si, Ti etc.) are not relevant for the bloomery period.

tempering, the reheating of quench-hardened steel below the critical range

(usually up to 500–600°C, according to purposes required), in order to decrease the brittleness and, to certain extent, hardness. Martensitic structures decay to pearlite-based fine structures (formerly known as sorbite and troostite).

tuyere, a nozzle protecting the mouth of blowing devices (see Chapter X).

viscosity, the resistance of a fluid to shear forces and hence to flow. Bloomery slags are more or less viscous, a fact that has influence on their removal (e.g. tapping). Low viscosity is typical for blast furnace slags.

Walloon process, an early blast furnace technology developed during the 15th century in Belgium, Luxembourg and northern France and spread to many countries (England, Sweden, central Europe), often by invited Walloon specialists. Walloon charcoal blast furnaces, depicted on several contemporary paintings (de Blès, Brueghel) produced prolonged iron pigs, tapped to sand beds, which were transformed to malleable products by oxidation in two kinds of reheating installation: finery and chafery hearths. About one third of metal was lost during these latter processes.

welding, the bringing together of two or more pieces of metal (here iron and/or steel) at temperatures 720–1200°C and then hammering. Until recently the basic process was fire-welding in which the pieces of metal were joined after being heated with charcoal or mineral coal in the blacksmith's hearth.

wootz, a kind of hypereutectoid cast steel (1–2 % C) having been produced by intensive carburizing to ingots 7cm×7cm x 5cm of iron fragments in sealed crucibles, filled with charcoal and other organic admixtures. The crucibles were heated in sunken hearths, blown by skin bellows. This steel has been produced since the 6th century AD at least, in other views not before the 10th century AD, in four main districts of southern India (Hyderabad, Srí Lanka, Mysore, and Tamilnadu, each with modifications). Several sites with heaps of broken crucibles were investigated. The ingots were traded mostly to Persia where they were worked above all to damascene blades. In the 17th century this trade was controlled by the Dutch East India company. In European smithies, the working of wootz ingots was unsuccessful and the wootz steel was veiled by many myths and legends.

wrought iron, a malleable and relatively soft iron, low in carbon, containing much entrapped slag. Bloomery iron belongs to this category. In post-medieval metallurgy wrought iron was a kind of fined metal destined for smithing and rolling.

wüstite, iron monoxide FeO ($Fe_x - 1O$ or Fe_nO can contain some MnO or NiO, a phase in the reduction of iron ore, forming subsequently, combined with SiO_2, the fayalite. Excess wüstite appears in bloomery slags and slag inclusions, in carbon-poor parts of iron/steel as light crystals (also arranged to dendrites). Apart of magnetite, it is present in the hammer-scale. It is named after Fr. Wüst (1860 – 1923), a German metallurgist.

GLOSSARY OF HISTORICAL AND ARCHAEOLOGICAL TERMS

The following items are not treated in detail in the main body of text.

Achaemenid period in ancient Persia, 6th–5th centuries BC, called after the Achaemenid dynasty, the most famous ruler of which, Cyrus the Great, was the second grandson of the legendary ruler Achaemenes. His capital was Pasargadae where his mausoleum was erected.

Agricola, Georgius, proper name Bauer, Georg (1494–1555), a German physician, employed in 1527 in Joachimsthal, Bohemia, a silver mining centre. Among several of his treatises the most important is The Twelve Books on Mining and Metallurgy (*De re metallica libri XII*, 1556), which was translated into German in 1590. Book IX deals with iron.

Akkadians, a Semitic population settled from the beginning of the 3rd millennium BC in central Mesopotamia. Under Sargon I (1369 BC) they overran the Sumerians, accepting their cuneiform script. The Akkadian language remained official in Babylonia until the mid-1st millenium BC.

Anglo-Saxon period in Britain covers the period 5th to 11th centuries AD. The immigrations of the Angles, Jutes and Saxons fall in the so-called Pagan period (the 5th–6th centuries AD), while the establishment of England after the conversion to Christianity begun by St. Augustin in AD 596, ends at the beginning of the 9th century. Scandinavian raids continued up to the Norman conquest in AD 1066.

Archaic period, a style in ancient Greece in the 7th–6th centuries BC comprising applied zoomorph and floral ornaments in arts and crafts.

Aristotle, Aristoteles of Stageira in Thrace (384–322 BC), a pupil of Plato, teacher of Alexander the Great, the leading philosopher of antiquity, and founder/promotor of the Peripatetic school (Lycaeum) in Athens. Some of his works deal with natural history, and the Meteorologica IV.6 contains remarks on iron. The same notes appear in a collection called Mirabiles ausculatationes, which was ascribed to an anonymous writer known as **Pseudo-Aristoteles**.

Avars, Asiatic nomadic tribes of Turkic-Tatar origin. They arrived in central Europe in the mid-6th century AD, having come into contact with the early Slavs. They ruled the greater part of Pannonia from AD 568. The realm of Avars was destroyed by Charlemagne towards the end of the 8th century AD and the remains of the population were rapidly assimilated by Slavs.

Balts, Indo-Eeuropeans inhabiting the area south of the eastern Baltic sea. Their languages (Lithuanian, Lett, and the now-extinct Prussian) show considerable affinities to the languages of the Slavs, their southern neigbours. The concept of a prehistoric Balto-Slavic unity used to be promoted by some linguists.

barbarians, originally ancient, non Greek-speaking tribes, as seen by the Hellens. After the Persian wars, the term had pejorative overtones. In Roman times the *barbaricum* denoted territories beyond the Imperial border.

bergslage, a mediaeval and later mining district in Sweden.

Biringuccio, Vannoccio (1480–1539), author of the treatise 'De la pirotechnia libri X', Venice 1540, which was edited one year after his death. Iron is treated in books I.6 and III.3. During his dramatic life, he was the director of iron mines and, in his last years, head of the papal foundry and armoury.

Black Death, a catastrophic plague epidemic which in 1347–1350 attacked and depopulated most of southern, western, and northern Europe, also reaching the British Isles, causing, as one consequence, serious economic difficulties. In some countries, for example Norway, a considerable decline in iron production, has been ascribed to this disaster. Thereafter, the traditional smelting technology changed after a gap of one or two generations.

Bologna culture, a north Italian facies of the Villanovan culture, named after large cemeteries discovered at Bologna, including Benacci, Benacci Caprare and Arnoaldi. The period Bologna II, (according to Müller-Karpe) covering the 8th century BC, saw the first appearance of iron objects.

Bronze Age. In general, the archaeological term for the period of human culture characterized by use of weapons and tools made of bronze (a copper-based alloy, primarily with tin or arsenic). It is a very relative term when considered in time and space. In the Near East, the Bronze Age (involving historical times and advanced civilizations) ends about 1200 BC,

whilst in central Europe it is prehistoric, continuing up to about 800 BC (Reinecke Hallstatt B_3). In Scandinavia, the latest stages are considered to last until around 500 BC (Montelius VI). During the Bronze Age, in particular the latter phases, the first isolated iron objects appeared over wide areas.

Carthusians, a monastic order founded by St. Bruno at Chartreuse near Grenoble, eastern France in AD 1084. The Carthusians were engaged in handicraft and also in ironmaking.

Celts, the western-most Indo-European population in Europe, whose ethnogenesis must have been completed at the decline of the Bronze Age (upper Danubian Tumuli and Urnfields, i.e. in the southern part of Europe, north of the Alps - *Keltiké* known by Herodotus). They expanded westwards, colonizing Gaul and parts of the British Isles and areas of northern Spain (Celtiberians). During the 5th–3rd centuries BC they raided and partly settled northern Italy (*Gallia Cisalpina*), the Balkans, Carpathians, and regions in Asia Minor. Most of these territories they left until the 1st century BC or were there assimilated. The Celts in fact founded the progressive tradition of European iron metallurgy. Celtic dialects have survived in Brittany, Wales, Ireland, Scotland.

Chalybes, an ancient tribe in Pontic Asia Minor, legendary ironmakers (*siderotektones* as they were called by Aeschylus, 525–485 BC). Despite the relatively late evidence, the tradition of their metallurgy must be old, since already by the 5th century BC, the terms *chalyps* or *chalybos* became literary expressions for steel. The Chalybes were still renowned in the 4th century BC (Xenophon, Anab. 5.5.1.).

Cimmerians, tribes of semi-nomadic horsemen of Iranian, i.e. Indo-European orgin, possibly related to ancient Thracians, mentioned by Homer, Neo-Assyrian epigraphy and Herodotus. They advanced from the north-Pontic steppes in the direction of the Carpathians taking with them their so-called Thraco-Cimmerian style and, in the 8th century BC, along the eastern coast of the Black Sea to Asia Minor where they founded a kingdom which was destroyed by the Lydians in the early 6th century BC. In the Ukrainian steppes they were subordinate to the Scythians in the 7th–6th centuries BC.

Cistercians, members of a monastic order of Benedictine rule, founded by St. Robert at Cîteaux (Cistercium) in France in AD 1098. The Cistercian monastery at Clairvaux (Clara vallis), north of Cîteaux, became, in the 12th–14th centuries, the progenitor of many daughter monasteries in many European countries, especially in England, Germany, and Scandinavia. The monks were much engaged in handicraft, especially the metallurgy of iron, during the 12th–15th centuries.

Classis Britannica, one of the Roman Imperial fleets (Syriaca, Pontica, Lybica, river fleets), operating from Gesonium (Boulogne-sur-Mer) and later Bodian and Dover in the Channel and off the coast of Britain. In the second phase of the iron smelting activity in the Weald, the Classis Britannica controlled the ironworks, as attested by numerous stamped tiles (CL BR) found on the bloomery sites and public buildings (at Beauport Park 1600 stamped fragments). A part of the iron produced may have been shipped to Roman troops on the Limes.

Classical period in ancient Greece, the 5th–early 4th centuries BC.

Colchis, a historical territory in the south-western promontories of the Caucasus (part of modern Georgia) and the adjacent Black Sea coast, the home of the Kolchoi. The gold-bearing rivers there gave rise to the ancient legends of the Golden Fleece of the Argonauts. Ancient Colchis also exported timber for ship-building. It is less well known that already in pre-Classical antiquity, the region was home to several important iron smelting districts which have been studied by excavation in the 1960s and 1980s.

Cotini, a Celtic tribe inhabiting, during the 1st–2nd centuries AD, according to Tacitus, the territory to the rear of the Marcomani and Quadi, presumably in northern Slovakia. The Cotini produced iron and were obliged to deliver tributes to the Marcomani, Quadi, and Sarmatians. The emperor Marcus Aurelius displaced them to Pannonia.

currency bars, a term adopted for iron bars of different type and dimensions, often in form of stylized weapons or tools, used in trade, and sometimes serving as a pre-monetary means of exchange (in German *Gerätgeld*; in Caesar BG 5.12 *'taleae ferreae ad certum pondum examinatae pro nummo'*). Such iron bars, often in hoards, are known from the La Tène period through to the late Middle Ages.

Dacians, *Daci*, the Roman name for the southern Thracians (Greek Getes) in south-eastern Europe (Romania, parts of Hungary and eastern Slovakia), an Indo-European population, mentioned by Herodotus. The material cul-

ture of the Dacians was similar to that of the Celts. Their capital was Sarmizegetusa. Dacia was a Roman province between AD 106–275.

Damascus steel, Damascene steel (*fulad* in Persia, *bulat* in Russia), a hypereutectoid hard carbon steel which was traded through Damascus in Syria from at least the 6th century AD. Damascene blades were produced up to the 18th century especially in Persia, are characterized by their wave-like pattern (*moiré*) revealed after etching by the dispersion of globular cementite in the pearlite matrix. Despite some successes in making replicas of damascene blades during the 19th century (Anosov, Tchernov, Belaiev, Johansen *et.al.*) the original techniques for the manufacture of Damascus sabres remain obscure.

Diodorus Siculus, a Greek historian of the 1st century BC, author of the Bibliothéké Historiké, in which he left some remarks on the Elban iron industry.

Este culture (*civiltà Atestina*) of the Early Iron Age in Italy, characterized by the assemblages from cemeteries in the vicinity of Padua. Its material culture was strongly influenced from the south (Bologna). The absolute date is much discussed, although H. Müller-Karpe placed it in the period 10th–5th centuries BC.

Etruscans, Lat. *Tusci*, Greek *Tyrrhenoi*, *Rasena* with their own language, a non-Indo-European population in western Italy (Toscana) and subsequently northwards, whose origins are much discussed. As the ancient tradition says, beginning with Herodotus and other sources (Lemnos inscription), they sailed from southern Asia Minor (Lydia) and settled in coastal western Italy in the earlier 1st millennium BC (despite the views of Dionysius of Halicarnassus). The reason for the unanswered problem is the fact that their language, in its entirity, is not deciphered, although their script derived from that of the Greeks. In Italy, they developed an advanced urban civilization, brought in much of the siderurgical knowledge and mined iron on large scale. They expanded to northern Italy, and through trade influenced the Alpine cultures and beyond. The Etruscans organized a religion-based confederation of 12 towns and ruled over the early Romans until the late 6th century BC. One century later the decline of their political power began.

Evenstad, Ole (1739–1806), who described himself as 'sheriff and yeoman of Aamonds parish in Østerdalen', Norway, where he lived and organized various activities on behalf of his countrymen. In 1782 he presented an treatise on bloomery iron smelting, entitled 'Avhandling om Jern-Malm etc.' (see bibliography) which was evaluated by the Royal Danish Agricultural Society and edited in Coppenhagen in 1790. It was published in German translation 1801, and in English in 1968.

Gallo-Roman period and culture, in Gaul (France, Belgium) the period involving the Roman occupation of Celtic territories between the mid-1st century BC up to 5th century AD (Gallia as Roman province). The 1st and 2nd centuries AD use to be called (Roman) Haut-Empire, the later period Bas-Empire. The symbiosis of Gauls and Romans resulted in creating an advanced romanized urban civilization.

Gaul, the continental territory of the western Celts (modern France and Belgium) including, according to Caesar (Bellum Gallicum), *Aquitania* in the south, *Gallia Lugdunensis* (Lugdunum-Lyon) up to the north of Seine, and Belgium up to the Ardennes. On the southern coast, around Massalia (Roman Massilia), and Narbonne, was *Gallia Narbonnensis*, and in northern Italy *Gallia Cisalpina*, inhabited by Gauls who settled down after their raid. Gaul proper was known as the most prosperous Roman province.

Geometric pottery of ancient Greece, a painted ware characterized by geometric ornament (meander, triangles etc.) of the 9th–8th centuries BC. Stylized figural motives appear in the final phase.

Germania, the Latin name for territories inhabited by Germanic (Teutonic) tribes. Only parts became Roman provinces: *Germania inferior* between the Ardennes and lower Rhine, and *Germania superior*, a strip of land on the left bank of the middle Rhine. Beyond the Rhine and Danube, except for the corner of the *Agri decumates*, fortified by the Limes, lay *Germania libera* described by Tacitus, or *Megalé Germania* as it was called by Claudius Ptolemaios (i.e. Ptolemy of Alexandria) having been extended in the east originally to the Vistula river, and far to the north.

Germanic (Teutonic) **tribes**, Indo-European populations, which settled, presumably from Neolithic times, in Scandinavia and the northern part of central Europe. They exerted pressure westwards, southwards and eastwards, and in the late 2nd century BC the Cimbri and Teutoni (who lend their name for all of the Germanic folk in English usage) invaded Gaul. After the breakdown of Celtic power one cen-

tury later, Germanic groups conquered territories lying along Rhine and Danube and thus became the neighbours of Rome. In course of time, they expanded south-east as well, as far as to the Ukraine. Classical sources enumerate tens of Germanic tribes, grouped according kinship or political confederations through to larger entities. The collective name *Germani* (mentioned for the first time by Posidonius) was used by Caesar, Tacitus and others in order to distinguish them from the Gauls. Germanic peoples were in contact with Rome with different intensities in time and space (military events, raids, trade). After the late 2nd century AD, the impact of Germanic tribes on Rome became more and more seriously detrimental to the stability of the Empire.

Great Moravia, in Byzantine sources 'Megalé Moravia', the first attempt at the establishment of a realm among western Slavs in the 9th century AD. Having a good economic background, but in conflict with the East Franconian empire, it spread over modern Moravia, southern Slovakia, and finally Bohemia and southern Poland (Cracovie). The rulers (*duces, reges*) of the Mojmír dynasty are known by name. In AD 863, Christianity of a Byzantine type was introduced by Constantinus and Methodius from Thessaloniki. The invasion of the Magyars (early Hungarians) brought down Great Moravia in the early 10th century. The tradition of its material culture can be followed back to the 8th century and survived some time after the fall of the realm.

Hallstatt, an archaeological site in a valley above the eponymous town and lake in the Alps, Upper Austria. In the 18th century a large, richly equipped cemetery was discovered, containing both cremations and inhumations in some 1300 graves, 26% of which had iron weapons. The cemetery dates to the period between ca. 800–500 BC, and has several chronological phases. The mountain community, very prosperous, controlled the nearby underground salt mines and trade with salt over long distances. The site is eponymous for the Hallstatt period, cultures, style.

Hallstatt period, in its early stages (HA–HB) comprising the European Late Bronze Age, followed by what is called Early Iron Age (HC–HD, the 7th–5th centuries BC).

Hanse, the mediaeval league of German ports and towns, promoting the long-distance trade (initially in fish) from the 13th century in the Baltic and northern Europe, with the leading town being Lübeck. It originally embraced the trading posts of German merchants in foreign centres. In the 14th century it developed into a political union of 164 towns, in the hinterland as well. Hanseatic commerce involved iron from different parts of the Continent. The Hansa disintegrated in the 17th century. Hanseatic trade contributed, from its beginning, strong contacts between central and western Europe, and mediaeval Scandinavia.

Hellenistic period, in the eastern Mediterranean and part of the Near East, the period covering the late 4th century (Alexander the Great) to the 1st century BC (30 BC, the fall of the last Ptolemaic kingdom).

Hittites, the collective name for ancient tribes (partly Indo-Europeans), which from the 3rd millennium BC inhabited Asia Minor, some having been Indo-Europeans (cuneiform Hittite, 2nd millennium BC). They developed an advanced urban civilization and a mighty political confederacy, making dependent parts of Syria and Mesopotamia and fighting with Egypt. The Hittite realm collapsed during ethnic movements in the Mediterranean and the Near Est during the 12th century BC. The territory of Hittites housed some of the earliest groups of ironmakers, apparently not numerous. However, Hittite written records mention iron frequently for the first time in the history.

Holy Roman Empire, a loose confederation of German, Italian and other territories under the suzerainty of an emperor and existing from the 9th century AD to AD 1806 when the Austrian emperor Francis II resigned.

Illyrians, an Indo-European population who settled in the NW Balkans during the 2nd millennium BC. They were related linguistically to the Thracians on one side, and the Venetians and other Italic tribes on the other. Illyria became a Roman province presumably during the 2nd century BC, although Illyrians fought Rome until the rule of Tiberius. As pirates they controlled much of the Adriatic sea. During the 2nd millenium BC they would appear to have transmitted much knowledge of making iron northwards to central and northern Europe.

Iron Age, a term originally denoting that period of human history in which, among archaeological finds, iron objects occurred. Detailed analyses have shown that this thesis is undefensible in the above sense. Moreover, it is a very relative notion in terms of general chronology and geography. In most areas, the Iron Age

has been divided into phases, distinguished in particular by distinctive artefacts such as fibulae, into early, and late periods. In terms of absolute chronology, there are substantional differences. Whilst in the Near East the beginning of the IA has been accepted by archaeologists as being around 1200 BC, in central Europe the 7th–6th centuries BC (Hallstatt periods C–D) are understood as the early IA and the subsequent La Tène period as the later IA. In Scandinavia, the term pre-Roman IA denotes the second half of the last millennium BC, but, for example, Ireland lived, from the 8th century BC to the 3rd century BC in the earlier IA, whilst the later IA involved the Middle Ages up to about the 9th century AD. None of these classifications respect the technical and economic role of iron. Therefore, it has been suggested that it is necessary to classify other phases in the development of the IA, taking into account the above aspects. These spread differently in time and space as well (see Chapter I). In fact, the fully-fledged Age of iron rules until the present day, something which eludes any of the classifications adopted for earlier times.

Italic tribes, Indo-European populations, related by their linguistic characteristics, who settled down in the Apennine penninsula during the Bronze Age, presumably from the Danube regions, and formed, according to some linguists, a Celto-Italic entity. The following tribes and groups belonged to the Italic family: the Sabellian group, Umbri, Osci, Latini, Falisci. They subsequently underwent considerable pressure from the Etruscans, the coastal Greek cities, the dominant Latini and, in the north, between 500–200 BC, the Gauls.

Khazars, an ancient Turkic population which spread south-westwards from the Urals and played a dominant role in the 7th–9th centuries AD in southern Russia. During the 10th–11th centuries they were mostly assimilated by the Slavs. The Saltovo culture of southern Russia and Ukraine (9th century AD) is associated with the Khazars.

Khorsabad, ancient Dur Šarukkén in northern Iraq, with its palace of the Assyrian king Sargon II (771–725 BC). In the 19th century, Victor Place discovered there a huge store full of iron (160 tonnes, about 5,300 talents) in form of double-pointed perforated bars (some of them cut), 5–9kg each, picks and chains, apparently booty or a series of tributes. Some of the bars are preserved in the Louvre, and at the Oriental Institute, University of Chicago.

Kizzuwatna, an ancient country in south-eastern Asia Minor (Taurus mountains, Cilicia), related to the Hittite realm. The king Hattushil (13th century BC) is supposed to have had there his 'sealed' store or treasury, containing, among others, rare iron objects.

Kyjatice culture, archaeological monuments of the final Bronze Age in southern Slovakia and northern Hungary, affiliated with middle-Danubian Urnfields, where there have been rare, but important, finds of iron objects of the 8th century BC.

La Tène, an archaeological site on the eastern shore of Lake Nauchâtel, Switzerland, on the territory of the ancient Celtic Helvetii. During land development in the late 19th century there was discovered, in swamps, an enormous deposit of iron objects (especially weapons, arms, and tools), wooden and leather artefacts etc. The finds concentrated around two timber jetties, protruding into the lake, which indicates an important place of sacrifice dating to about 100 BC). The site of La Tène became eponymous for the entire period of the later pre-Christian millennium, ancient Celtic culture and style.

La Tène period, in Continental Europe the time between about 500 BC – 0, characterized by Celtic material culture as revealed by archaeology. Tischler distinguished three periods of evolution: I (400–300 BC), II (300–100 BC), and III (1st century BC). The three-period classification is still used in France. For central Europe, Reinecke elaborated a new system of four periods or phases: A–D; the first preceded the Tischler's I (500-400 BC). Numerous scholars have contributed to more detailed subdivisions of individual periods (e.g. LC_1, LD_2 etc.).

Laurion, a range of hills in eastern Attica, north of Cape Sunion, Greece, where were operated the famous ancient lead and silver mines, the yield of which was the economic base of classical Athens. Their output declined from about 160 BC. The adits and shafts were explored as early as the 19th century.

Limes Romanus, in the Roman Empire (the 1st to 4th centuries) it denoted the Imperial Roman border; in Europe it divided advanced urban civilization from the barbarian rural world. The spine of the *limes* was military roads, connecting the bases as *castra, castella, burgi* along Danube, Rhine and across the land, from which Roman expeditions were organized into the *'barabaricum'*. In Scotland there was the Antonine wall and

in northern England, Hadrian's wall (abandoned after AD 400), and on the Continent the Germanic-Raetian *limes* between Koblenz and Kelheim (abandoned AD 260). On the middle Danube the *limes* was protected by wide buffer-zone of territories in modern southern Moravia and south-western Slovakia, while the Dacian-Moesian *limes* defended the lower Danube. During the 4th and 5th centuries it was penetrated by Germanic and Sarmatian tribes and gradually ceased to be defended.

Longobards (Lombards), a Germanic tribe inhabiting originally regions on the Lower Elbe river. At the decline of the 5th century AD they moved southwards, temporarily colonized Bohemia (and/or Silesia), Moravia, and Pannonia. AD 568 under king Alboin Longobards, together with parts of other tribes, migrated to northern Italy where they settled down (Lombardy).

Luristan, a territory of the nomadic population of the Lurs in western Iran. In the Late Bronze Age and the Early Iron Age (about 1200–700 BC), Luristan bronzes, manufactured there, originate apparently from different phases. Those with iron blades and iron daggers belong to the latest period. They come from destroyed cemeteries so that there is a lack of stratified finds. Most of the objects were purchased on the antique markets.

Magyars, early Hungarians, a Finno-Ugrian nomadic population which moved, as early as the Bronze Age, from the Oka and upper Volga rivers down south. Magyars split from the other related tribes in the 5th century AD, absorbed very much from the Turkic tribes and in about the 9th century, settled in the Carpathian basin. Shortly after AD 900 they destroyed the Slavic Great Moravia and very rapidly created their own early state, Hungary.

Marcomani, a tribe belonging to the early Germanic group of the Suebi, who lived during the Romano-Barbarian period (the 1st to 4th centuries AD), principally in Bohemia, and, later, also in Moravia. In the time of the rule of the Roman emperor Marcus Aurelius, (AD 161–180), they took part in the Germano-Sarmatian wars against Rome (Marcomanian wars). During the Migration Period, in the 5th century AD, the Marcomani settled in Bavaria.

massa ferri, in Latin a lump of iron, the technical meaning of which is ambiguous. It denoted a bloom of wrought iron (e.g. in the Domesday Book, or *massiot* in French), as well as a pig of cast iron in some regions of Europe (*Massel* in the Sauerland of Germany).

Meroë, the capital of the Kushites on the territory of modern Sudan, some 200km north of Khartoum. Within the area were discovered 8 voluminous iron slag heaps and, subsequently, the remains of bloomery shaft furnaces. One of the heaps was cut by the railway. The date of the mounds is the matter of discussion: the earliest phase might have started during the 2nd century BC, a *terminus ante quem* is mid-3rd century AD provided by the Lion Temple standing on one slag heap.

Merovingian period, the western European Migration period is characterized by the Frankish Merovingian dynasty (named after king Merovech, late 5th century AD) which ruled up to AD 751. The last king Childerich III was dethroned by Pépin le Bref. Numerous pattern-welded sword blades were buried in Frankish inhumation cemeteries of that time.

Migration period, called sometimes the Great Migration period, in Europe the period from the late 4th up to the 6th/7th centuries AD. The events started with a savage invasion of Huns, Mongolian nomads from Far-Eastern steppes, who moved westwards in AD 375 and controlled most of eastern and central Europe. Under Atilla they reached Gaul in AD 451. Entire tribes and groups moved from their settlements to distant regions (Visigoths AD 356–400, Alani 378, Vandali 400, Burgundi 407–471, Ostrogoths 454–490, Longobards 496–568, Franks). They destroyed the Roman *limes* and completed the collapse of the Roman empire. Angles, Jutes and Saxons left their territories in north-western Germany and crossed for Britain. New ethnic waves, Slavs, Avars, Magyars, colonists and invaders as well, arrived in Europe.

mina, *manna, mnă*, an ancient Greek weight unit (about 430g) comprising 100 drachmae, or 60 shekels.

Montelius, Oscar (1843–1921), a leading Swedish archaeologist, the promotor of Scandinavian prehistoric typology and chronology, based on the evolution of bronze artefacts. Periods M V, and especially M VI (the 7th–6th centuries BC) represent the coming of the Iron Age to Scandinavia (comparable with central European Reinecke system HB_3, and above all HC–HD).

NBP pottery, North Black Polished Ware, a typical pottery in ancient north India (*ca* dating from the 6th to 3rd centuries BC, characterizing the period of the developing

Iron Age).

Nok culture, the Nsukka region, Nigeria, Africa. A group of archaeological finds (including clay figurines and iron objects), are dated by radiocarbon to the time span between 440–280 BC.

Noricum, an ancient Celto-Illyrian kingdom on the territory of modern Austria (2nd–1st centuries BC), with an outstanding trading centre at Magdalensberg, Carinthia. In 16/15 BC it was occupied by the Romans who established the province of Noricum with the administrative centre of Virunum. The Noricans produced not only excellent iron but also gold and salt.

Ochre grave culture, an archaeological complex with burial mounds containing inhumations powdered with ochre, which spread over a much of the territory of Russia. The individual phases are known as Pit grave (*yamnaya kul'tura*), Catacombe (*doneckaya k.*), and Timber grave (*srubnaya k.*), covering the period from the Neolithic up to the beginning Iron Age. The complex involves many local archaeological cultures with different chronological stages.

oppidum, a Latin term for any fortified settlement (*ab opi dictum quod munitium opis causa*, ancient etymology already by Varro, or *ob pedem*). Caesar in his BG uses the word *oppidum* for Celtic fortified centres in Gaul (one of them, Avaricum, was titled *urbs*, city). He does not refer to their economic and productive role as numerous large-scale excavations of the oppida over all of the Celtic world have shown. The ramparts of oppida delimited large circumferences, so that, in the case of danger, entire herds of cattle could be protected. Large areas were reserved for dwelling and craftworking, in some cases, above all for their own inhabitants. Otherwise, oppida were administrative, commercial, and religious focuses for extended territorial and tribal entities.

Otomani (Füzeszabony) **culture**, an archaeological complex in western Romania, Hungary, and Slovakia showing affinities to the Balkan area on one side, and to the Tumulus grave cultures on the other. Phases II and III, corresponding with the Reinecke Bronze Age BA–HA, date from the 2nd millennium BC. One of the earliest central European iron artefacts, the dagger hilt from Gánovce, comes from an Otomani context (about 1500 BC).

Pliny the Elder, C. Publius Secundus Plinius Maior (AD 23–79), an outstanding Roman officer, who was interested in the sciences. His surviving encyclopaedic collection *Naturalis historia* is based on excerpts from other authors as well as on data gained from various rapporteurs. It contains valuable data on botany, mineralogy, geology, metallurgy, and medicine, however some do present problems in the form of the terminology used.

Protogeometric pottery a period of ancient Greece, the 11th–10th centuries BC, characterized by pottery with circular and semicircular motives, following sub-Mycenaean style.

Ptolemy of Alexandria, Claudius Ptolemaios, a Greek astronomer and geographer of the 2nd century AD. His *Geografiké hyfégésis* was a direction for the construction of a map of the known world according to longitude and latitude. The section entitled '*Megalé Germania*' is an important historical source for central Europe, enumerating its tribes, leading settlements etc. of the time (e.g. the iron mines of the Quadi).

Quadi, a Germanic tribe of the family of the Suebi, which settled in modern southern Moravia and Slovakia, and were immediate neighbours of the Roman Empire north of the Danube river (with friendly relations in the earlier time under king Vannius, and antagonistic during the Marcomanian wars). Ptolemy of Alexandria in his Geografiké Hyfégésis II.11, 2nd century AD, mentioned iron mines (*sidérorucheia*) on their territory.

Reinecke, Paul (1842–1958), an outstanding German archaeologist, the founder of the central European chronological system covering the Bronze Age, Hallstatt and La Tène periods, each comprising four phases A–D. These were later subdivided my many authors.

Roman period involves the history of ancient Rome. In Italy it comprises phases like the Royal (ca. 8th century BC to 500 BC), Republican (the early, the peak, and crisis periods, ending around 30 BC), and Imperial (the early 30s BC to AD 284), and the late period from AD 284–476. In the Imperial period, Roman provinces were established to include a great part of Europe (at that time Rome shifted most of its production of iron to these territories). The symbiosis of different local populations with Roman colonists, officers, merchantmen, and soldiers led, in France and Britain, in historical classifications, to the introduction of the terms Gallo-Roman and Romano-British periods.

Romano-Barbarian period denotes the time

span between the 1st to the 4th centuries AD (the Imperial period of Rome) in territories not occupied by the Romans, in continental Europe especially the land inhabited by free Germanic tribes. Terms like 'the period of Roman influence' or, briefly, 'Roman period' are used as well. According to the classification of archaeological finds from cemeteries, Eggers divided the Romano-Barbarian period (*Römische Kaiserzeit*, RKZ) into three main phases and some subphases: A being the transition from the la Tène period (years around 0), B_1 AD 0–5O, B_2 *ca* 50–180, incl. the Marcomanian wars AD 160-180, C_1, C_2 180–300, and C_3 AD 300-400. In general there are terms for the early (the 1st to 2nd centuries AD), and later Romano-Barbarian periods (the 3rd to 4th centuries AD), which take into account the results of investigations of many settlements.

Romano-British period the Roman Iron Age in Britain, a chronological phase in which there was a symbiosis between the Celtic tribes and Romans occupying the country (province *Britannia*), from AD 41, as far the Hadrian and Antonine walls in the north). Under the emperor Honorius, the Romans withdrew in the period AD 407–425.

Rożdzieński, Walenty (1546?–1622?), a forge master at Różdzień, Poland, who compiled a treatise in form of a poem 'Oficina ferraria', Cracovie 1612, which contains many details on the bloomery process, still extant in many areas in his time.

Saltovo culture, named after the finds from the hillfort Verkhne Saltovo on the Don river, Ukraine, involving archaeological objects ascribed to originally nomadic tribes of the Khazars who were pushed westwards by the Huns and settled in the Don and Donec river valleys. The bearers of the Saltovo culture were skilled iron makers and workers.

Sarmatians, *Sarmatae*, a population of the Indo-European family, related to the Scythians, mentioned as *Sauromatoi* by Herodotus. Their nomadic tribe, the Yazygi, penetrated to the Hungarian lowlands during the early Romano-Barbarian period. The Sarmatians were allies of the Germanic tribes during the wars with Rome during the reign of the emperor Marcus Aurelius.

Scythians, a large complex of nomadic Indo-European (Iranian) tribes who lived from the 8th century BC in the steppes and forest-steppes north of the Black Sea between the Danube estuary and the river Don. They expanded to many countries in the Near East. The huge burial mounds (*kurgans*) of Scythian chieftains are well known. During the 4th century BC, the so-called 'Scythian kingdom' was established on the lower Dnieper river, and existed up to Roman times (3rd century AD). Among the Scythians there were skilled ironmakers, blacksmiths and armourers, as revealed by metallographic examinations of their artefacts.

Sea Peoples, names of both non-Indoeuropean and Indo-European populations in ancient Egyptian sources. These groups raided in the eastern Mediterranean and performed sea piracy during the times of great ethnic movements during the 13th and 12th centuries BC. Egyptian defence was successful in clashes in 1236/23 and 1191/66 BC. Attempts were made to identify the names with historically attested folks: Ekvaš-Achiava-Achaeans, Tereš or Turša-Tyrrhenoi (early Etruscans) originally in Asia Minor, Šerdu-Sards, Šekeleš-Siculi, or Pelišti-Philistines. Some of them may have contributed to the spread of iron.

Seres, a population the location of which remains unknown (Middle or Far East, from India to China). According to Pliny (34. 41) they traded in furs, clothes, and excellent steel which also came onto he Roman market and was renowned as the best of all.

servant villages, mediaeval rural settlements inhabited by specialist craftsmen, delivering their products, and people who yielded services on behalf of local lords and rulers. Their professions are reflected in numerous surviving place-names in Slavic languages (having Latin counterparts in certain written sources), because this economic system (about the 10th–12th centuries AD) was established in the early realms of the western Slavs.

shekel, an ancient unit of weight in the Near East, representing some 7g (60 shekels = 1 mina).

Slavs, a mighty ethnic branch of Indo-Europeans, from a linguistic point of view having been formed as the youngest. Their ethnogenesis and geographical cradle is much discussed. Possibly it was the territory between the Carpathians and north-eastern Balts, eastwards from the Vistula river. The main ancient Slavic groups are known in Frankish and Byzantine written documents as Sloveni, Antoi, Venedoi. During the 6th–7th centuries they colonized wide areas as far as the river Saale in Germany. Their common language survived up to about AD 1000,

then individual western, eastern, and southern Slavic languages (and nations) were formed, the latter being split by the invasion of Magyars (Hungarians) to Pannonia and Bavarians north of the Alps.

Strabo (64 BC–AD 19), a Greek historian and geographer, author of the *Geografika*, a description of the world known in his time.

Sumerians, a population of unknown origin which settled the southern part of Mesopotamia, probably at the end of the 4th millennium BC. They were the first founders of a developed urban civilization in the Near East. Sumerian city states were subjected to the Akkad, but Sumerian survived as a highly educative and liturgical language until the mid-1st millennium BC. The Sumerians are thought to be inventors of cuneiform script (originally pictographic, transformed later to cuneiform records on clay tablets).

Swedenborg (Swedberg), Emanuel (1688 – 1772). Swedish scholar and mystic whose studies concerned philosophy and natural sciences. In 1734 he published 'Opera philosophica et metallugica'. The treatise *De ferro* (Leipzig) was later translated into Swedish (Om Järnet, Stockholm 1923).

Tacitus, Publius(?) Cornelius (about AD 55–about 120), a leading ancient Roman historian. Among his numerous works there is a treatise entitled *'Germania'*, describing the ethnography and civilization of the free Germanic tribes.

talent, Gr. *talanton*, Lat. *talentum*, a unit of weight corresponding to about 26kg, in Attica 26.2kg, equal to 60 *minae*. Used in ancient Greece and the Near East.

Tashtyk period on the Upper Yenissey river (Minusinsk area) comprises the time from the 1st century BC to the 5th century AD, a period for which numerous pieces of iron smelting evidence have come to light. It was preceded by the **Tagar** period (The 7th to 2nd centuries BC) which saw the first occurrence of fine iron artefacts. The region could have played a role in the spread of iron metallurgy knowledge north-eastwards.

Teutons, *Teutoni*, a Germanic tribe inhabiting the western coast of Jutland, mentioned by Pytheas of Massalia in the 4th century BC. Together with the Cimbri they attacked Gaul in about 120 BC and were defeated 102 BC by the Roman *legatus* Marius. The name 'Teuton' became a common synonym in English for all of the Germanic tribes of the Romano-Barbarian period.

Theophrastus of Ephesus, 373/1–288/6 BC, an ancient Greek encyclopaedist, a pupil of Aristotle. He was the author of some 200 treatises, mentioned by Diogenes Laërtius, including items on botany (*Peri fyton, Historia plantarum*), mineralogy (*Peri lithon, De lapidibus*), and metals (*Peri metallon, De metallis*, in fragments).

Timber grave culture see Ochre grave culture.

tremissa, a third of the golden Roman coin solidus (introduced in AD 312), weighing 1.32g. The solidus survived as a means of exhange not only in the Byzantine empire but in other European countries as well. It was cancelled by Charlemagne. Taxes in iron delivered, for example, to monasteries such as St. Gallen were called *tremissae ferri*.

Tutankhamen, an Egyptian pharaoh of the 18th dynasty (about 1350 BC), whose the tomb was discovered by H. Carter in 1922. It contained, among many luxury goods, rare and valuable artefacts made of iron.

typology, originally a method of relative dating (chronological sequences) of archaeological artefacts based on the evolution of their shapes through time. It was developed during arrangements of unstratified finds in Scandinavian museums by H. Hildebrand, O. Montelius and others. In broader sense also comparison of identical or similar shapes of artefacts ('types') in space (geographical spread and affinities).

Urartu (Biainu, Nairi), an ancient realm on the territory of Armenia, north-eastern Anatolia and northern Iran (9th–6th centuries BC). It paid taxes in iron to Assyria in the 9th century BC.

Urnfield cultures, an important complex of archaeological groups of the European Bronze Age (from about the 13th to 8th centuries BC - in Reinecke's chronology, the periods Hallstatt B and C). They are distinguished by their dominant funeral rite: incineration in a burial vessel, although the large cemeteries comprise burials apart from the urn, or well-equipped barrows, showing a social stratification. There are three main groups of Urnfield cultures: that on the middle Danube, the Lusatian, and the Urnfields on the upper Danube (south German Urnfields).

Vendel period, ca AD 550–800, the pre-Viking period in Swedish archaeology, after Vendel near Uppsala, with its richly equipped boat-graves.

Veneti, a tribe of the Illyrian family of Indo-Europeans, who settled, perhaps during the

final Bronze Age, in the territory around modern Venice and Trieste (*Caput Adriae*).

vicus, a Roman unfortified rural village (later a town quarter as well) which housed, apart from a *forum* many craftsmen, including blacksmiths. They were close to towns (*municipia*) or estates (*latifundia*) and some were market places (*fora conciliabula*).

Viking Age or period, in Scandinaia, the time between about AD 800–1200, characterized by the Vikings and their coastal and inlet communities (*vik*) of sea-farers and sea-raiders and conquerors of north-Germanic origin. They included skillful craftsmen, metalworkers and blacksmiths.

villa rustica, a Roman private farmstead of medium size, run by the owner's family and its slaves, tending to a considerable autarchy (agriculture, crafts) and representing an economic complex. *Villae rusticae* also were spread over the Roman provinces and the inhabitants of some engaged in iron working and making. From the 2nd century AD many of them were ousted by large estates *latifundiae.*

Volga-Bulgars, a mediaeval Turkic-Tatar population which inhabited the 7th century AD the region on the middle Volga, at its confluence with the Kama river. In the 10th century they established a flourishing city, production and trade centre, Velikiye Bolgary, which was destroyed by the Russians in AD 1431. Long before, a group of them moved south-westwards across the territory of the Khazars, were assimilated by Slavs and settled in what became modern Bulgaria.

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ADDENDA

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Frühe Eisengewinnung in Joldelund, Kr. Nordfriesland. Ein Beitrag zur Siedlungs- umd Techmikgeschichte Schleswig-Holsteins, Teil 2, Naturwissenschaftliche Untersuchungen zur Metallurgie- und Vegetationsgeschichte, (A. Haffner, H. Jöns, J. Reichstein eds). Universitätsforschungen zur prähistorischen Archäologie (Kiel) Vol. 59. R. Habelt GmbH, Bonn.

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SELECTED ABBREVIATIONS

AJA: American Journal of Archaeology. The Journal of the Americal Archaeological Institute.

Archeol. Rozhledy, AR: Archeologické rozhledy (Archaeol. Inst.), Praha.

Bull. Hist. Met. Group: Bulletin of the Historical Metallurgy Group. Iron and Steel Inst. London (from 1974 HM).

cf: *confer*

CPSA: Comité pour la sidérurgie ancienne de l'Union des Sciences Préhistoriques et Protohistoriques affilié à l'UNESCO.

EAZ: Ethnographisch-Archäologische Zeitschrift, Berlin.

Ferrum: Ferrum. Nachrichten aus der Eisen-Bibliothek, Stiftung der Georg Fischer Aktiengesellschaft, Schaffhausen.

HM: Historical Metallurgy. Journal of the Historical Metallurgy Society, London.

Jahrbuch RGZM: Jahrbuch des Römishch-Germanischen Zentralmuseums, Bonn.

JESHO: Journal of the Economic and Social History of the Orient. Leiden.

JISI: Journal of the Iron and Steel Institute, London.

JNES: Journal of the Near Eastern Studies, Chicago.

KS: Kratkiye soobshcheniya o dokladakh i polevykh issledovaniyakh Instituta Arkheologii, Moskva.

Kwartalnik HKM: Kwartalnik Historii Kultury Materialnej, Warszawa.

Kwartalnik HNT: Kwartalnik Historii Nauki i Techniki. Warszawa.

MAGW Mitteilungen der Anthropologischen Gesellschaft in Wien, Wien.

MIA: Matèrialy i issledovaniya po arkheologii SSSR, Moskva.

PACT: Journal of the European Study Group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology. Council of Europe, Strasbourg.

Pam. arch.: Památky archeologické, Praha.

R.A.E.: Revue Archéologique de l'Est et Centre Est, Dijon.

RGZM: Römisch-Germanisches Zentralmuseum Mainz.

SDGH: Studia z Dziejów Górnictwa i Hutnictwa, Kraków.

Slov. arch.: Slovenská archeoloógia, Archeol. Inst., Nitra.

Sov. arkh.: Sovetskaya arkheologiya. Moskva.

VDEh: Verein Deutscher Eisenhüttenleute, Düsseldorf.

VDI: Verein Deutscher Ingenieure, Düsseldorf.

ZAK: Zeitschrift fü schweizerische Archäologie und Kunstgeschichte, Basel.

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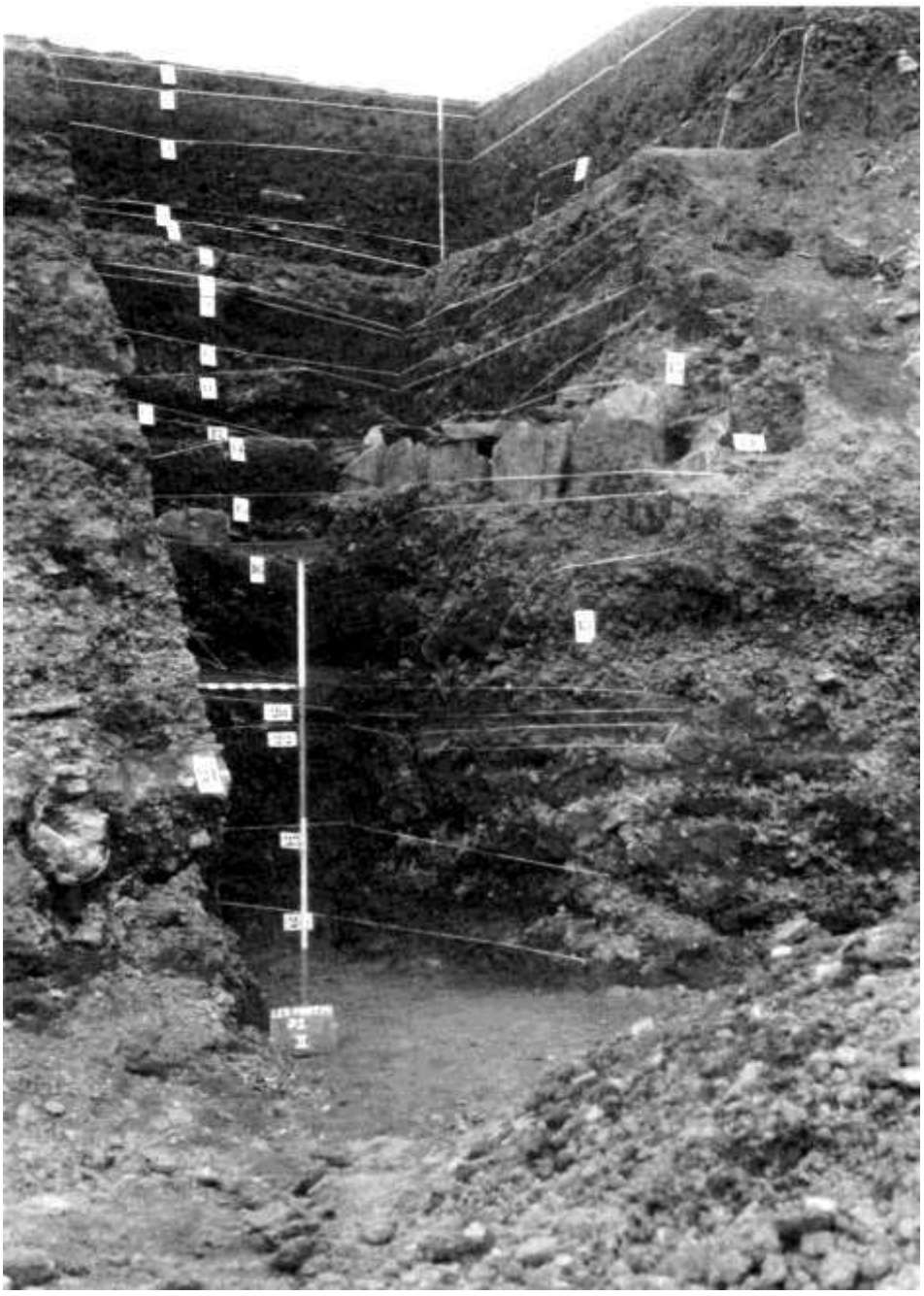
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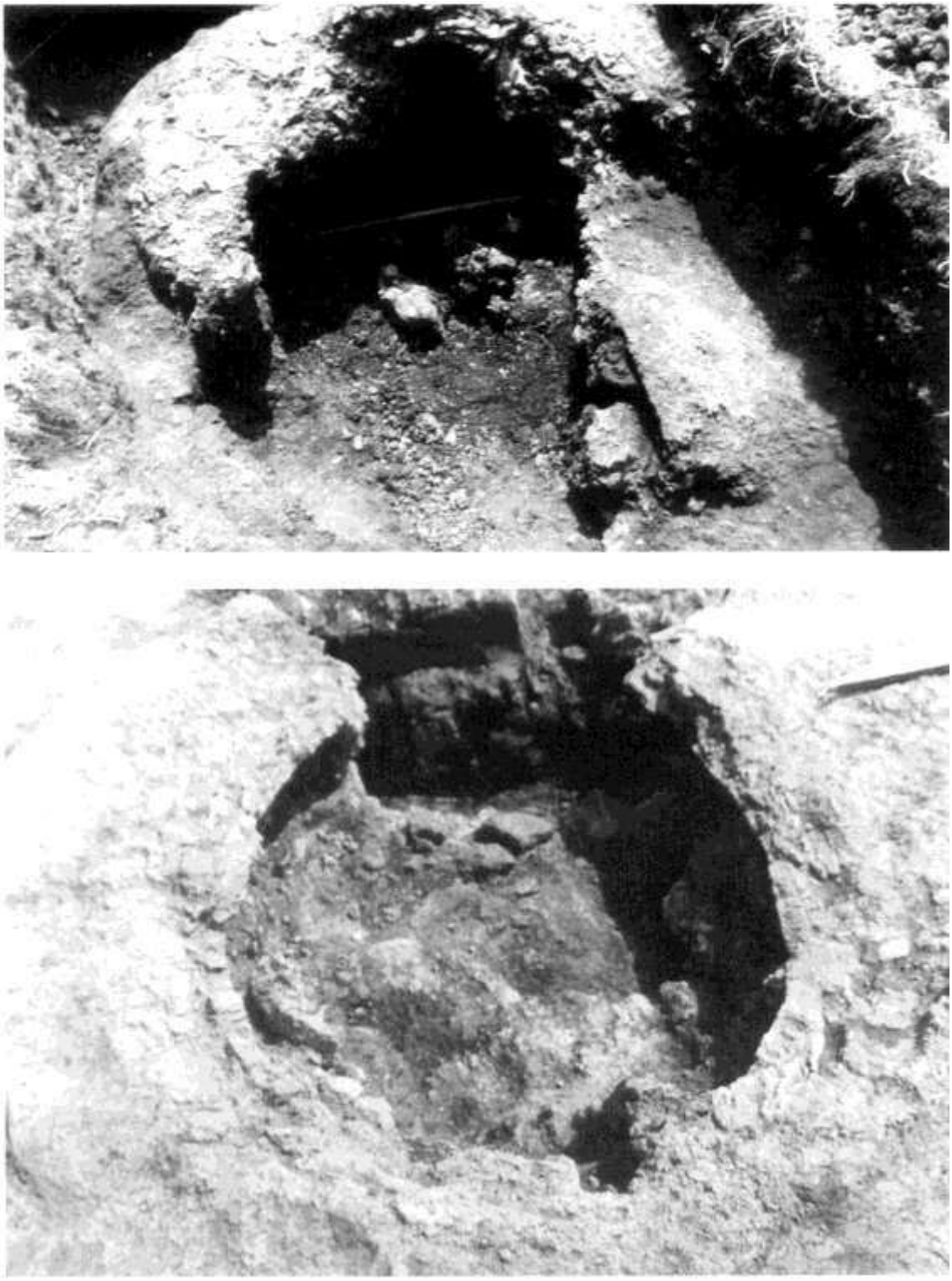




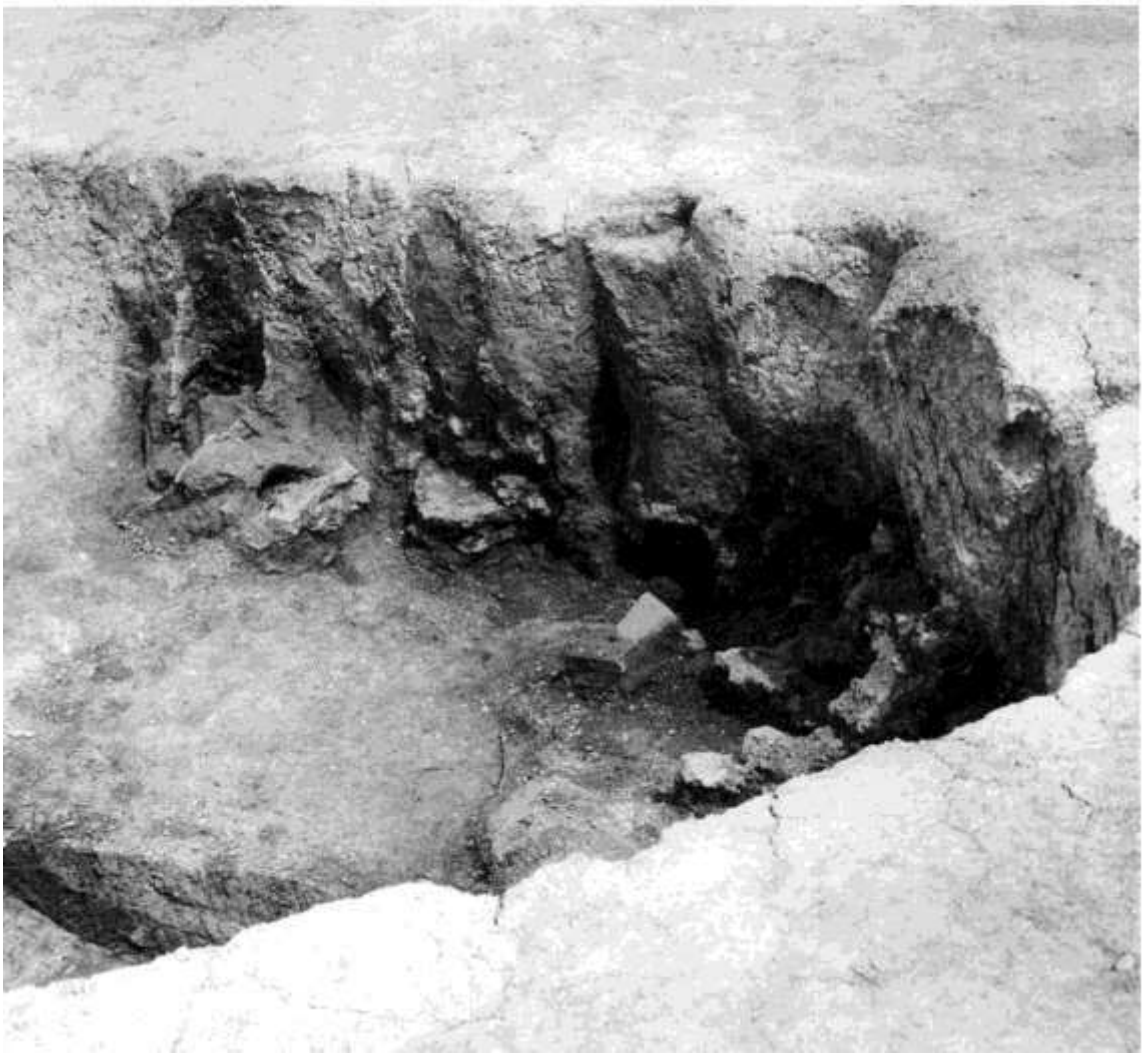
Pl. I. Early smelting furnaces in the Mediterranean and southern France. Top: Populonia — Baratti Bay, Tuscany. Sunken hearth of a smelting furnace (diameter 50cm) discovered in the slag deposit, 2nd century BC (courtesy of O. Voss). Bottom: Martys, Montagne Noire, southern France. Base of furnace F 11 (1990), 1st century BC (courtesy of C. Domergue).



Pl. II. Early large-scale production of iron at Martys, Domaine des Forges. Section of a slag heap in trial trench 1972-II, consisting of 25 layers dating from the last years decline of the 1st century BC at the base, up to 3rd century AD (courtesy of C. Domergue).



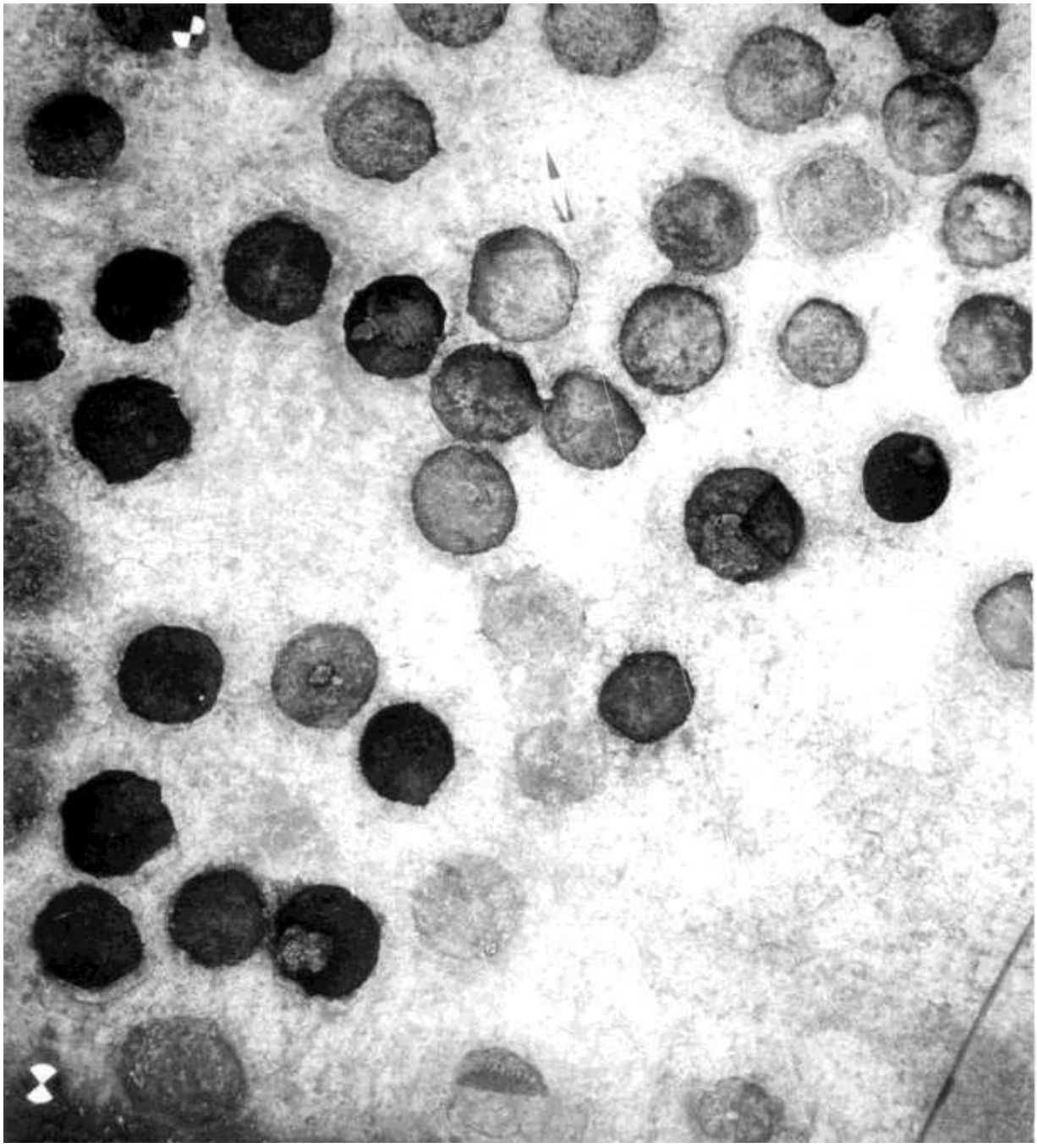
Pl. III. La Tène period domed furnaces from Burgenland, Austria. Top: Unterpullendorf 2, with partly preserved cupola. Bottom: Klostermarienberg 1, base of a domed furnace. Courtesy of K. Bielenin.



Pl. IV. Sunken floored huts as ironworks of early Romano-Barbarian period. Ořech near Prague, Bohemia. Sunken-floored bloomery 14 with three embanked slag-pit furnaces (one with preserved front wall), 1st century AD, Romano-Barbarian period.



Pl. V. Slag-pit furnaces of the Romano-Barbarian period in Bohemia. Prague-Podbaba XI. Two slag-pit furnaces with partly preserved shafts (up to 80cm) in a settlement of the Romano-Barbarian period.

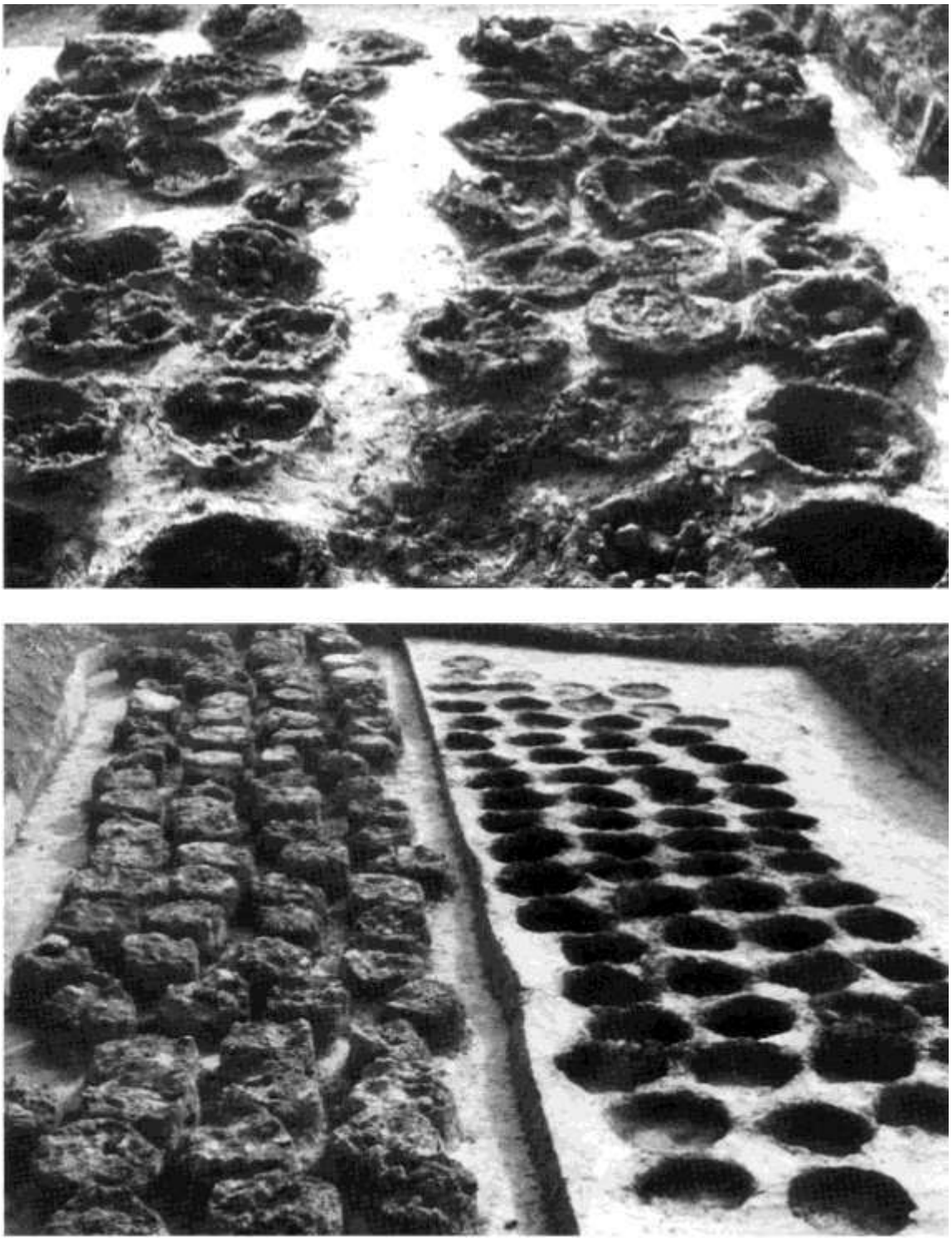


Pl. VI. The southernmost 'field' of slag-pit furnaces: Sudice, western Moravia. Photogrammetric view of part of an unorganized furnace cluster, late Romano-Barbarian period. After Pleiner and Ludikovský.

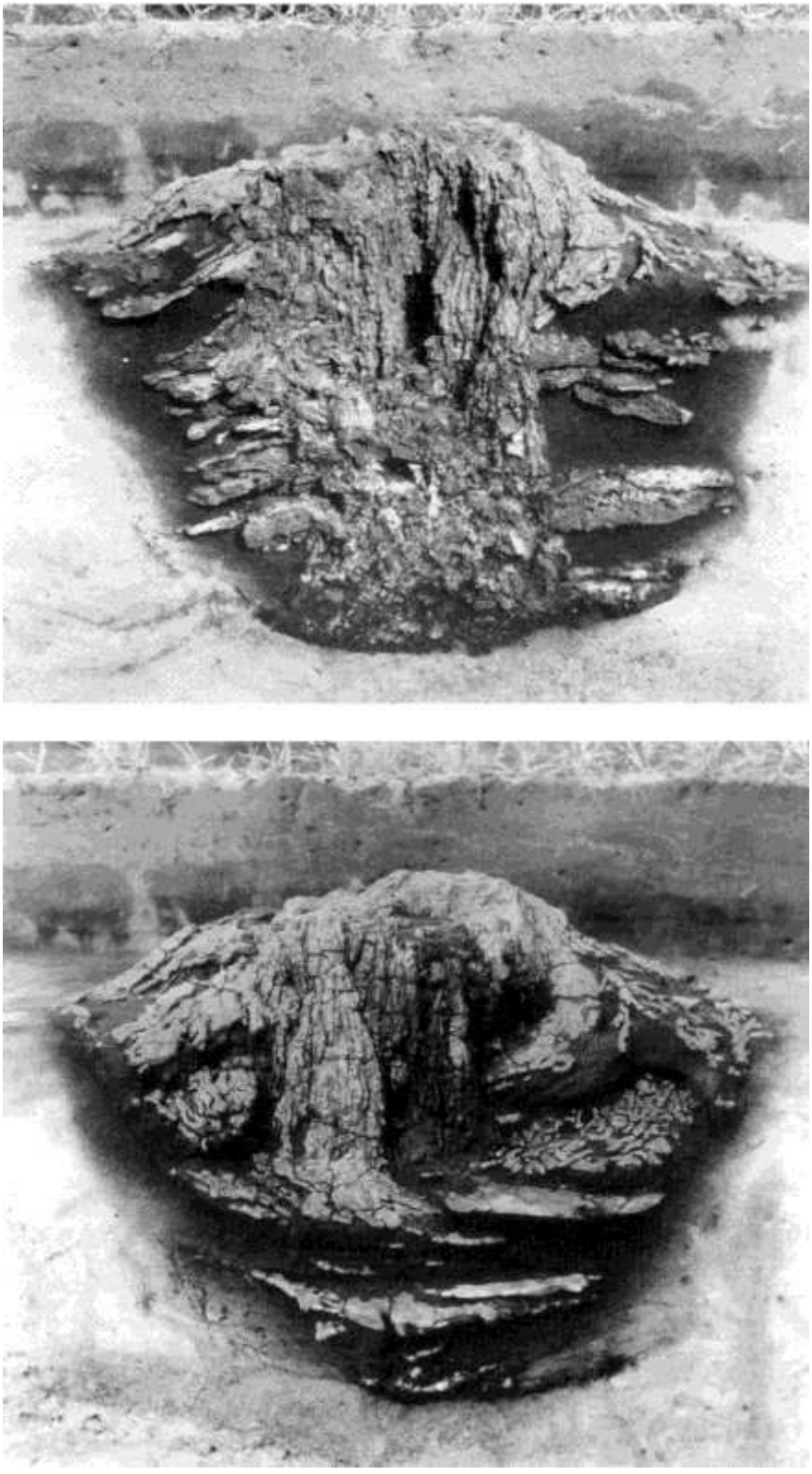




Pl. VII. Poland, the Holy Cross Mountains Romano-Barbarian iron production. Top: Rudki "Staszic", timber-clad shaft of an underground iron mine (16–18m deep), 2nd century AD. Bottom: Słupia Nowa 6, slag-pit furnace cluster organized in 2x4 system (1965). Courtesy of K. Bielenin.



Pl. VIII. Organized slag-pit furnace clusters in the Holy Cross Mountains. Top: Słupia Stara 4, 2x3 system. Bottom: Słupia Stara 3, 2x4 system in two phases of excavating. Courtesy of K. Bielenin.



Pl. IX. Romano-Barbarian slag-pit furnaces in Jutland. Drengsted, Denmark. Section of slag-pit furnace BL (max. dia. 100cm) in two different stages of excavation (1961), Romano-Barbarian period. Courtesy of O. Voss.



Pl. X. The largest agglomeration of slag-pit furnaces in Jutland. Snorup, Denmark. A 25m long line of paired slag-pit furnaces, Romano-Barbarian period. Courtesy of O. Voss.

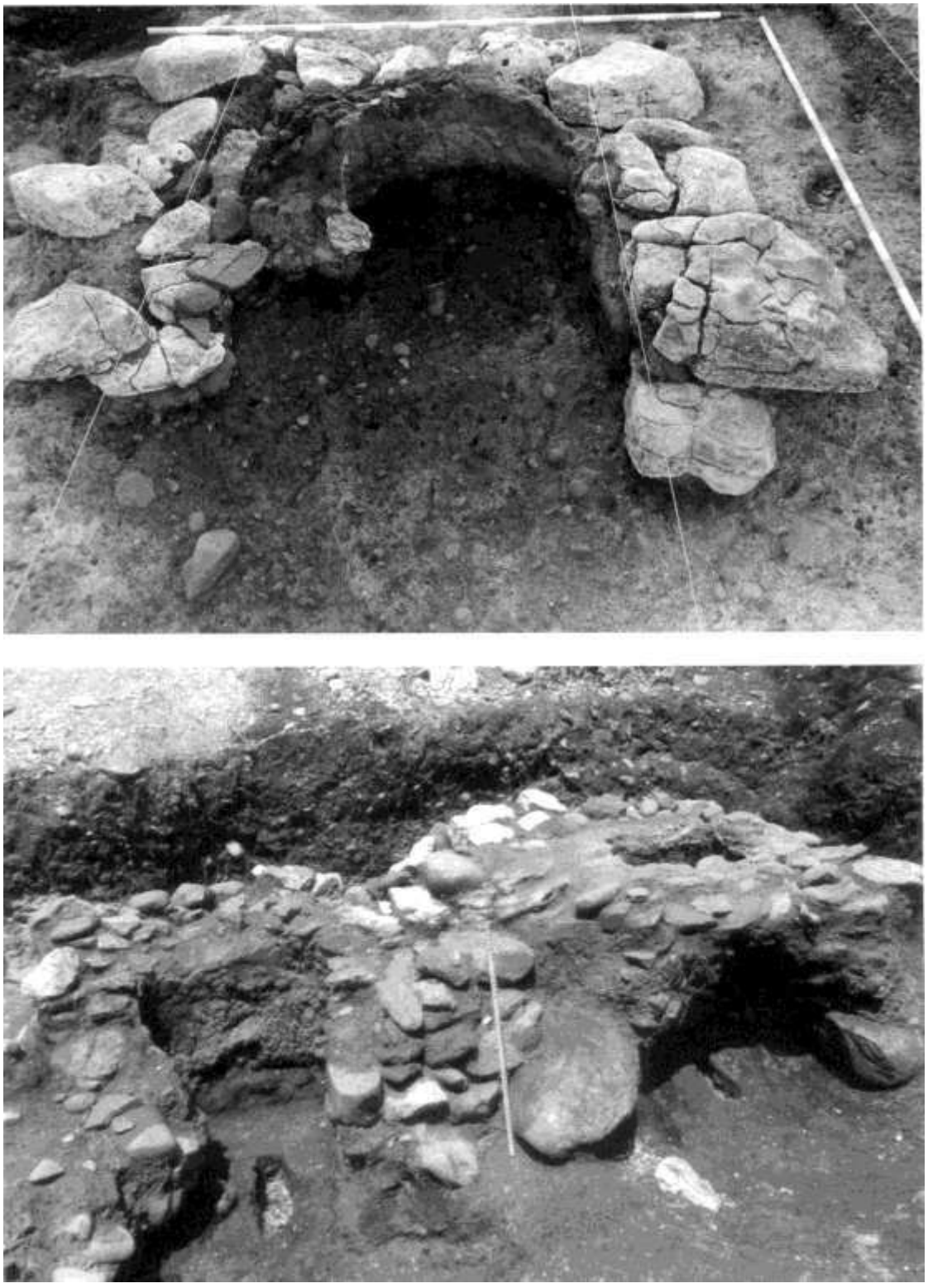




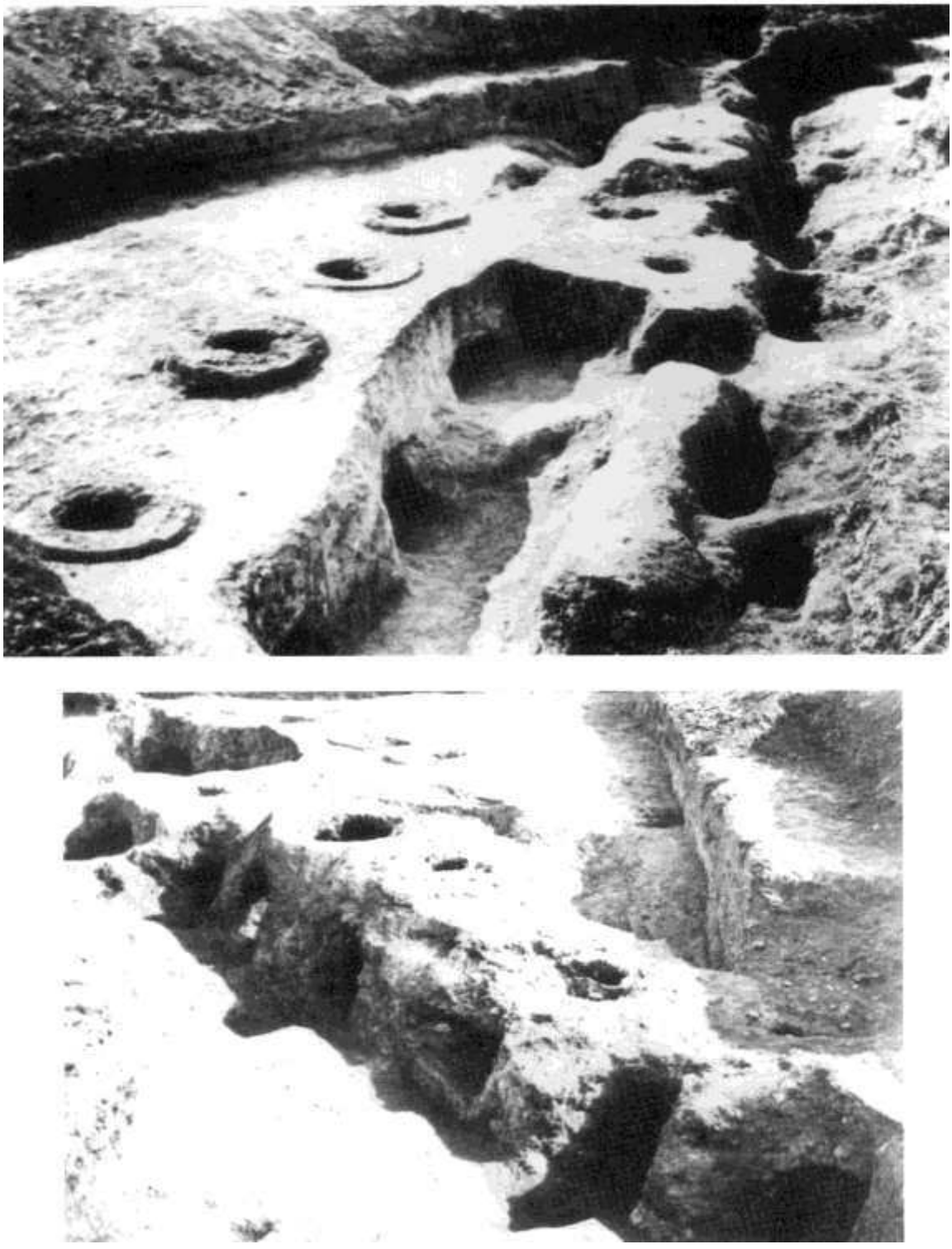
Pl. XI. Top: Slag-pit furnaces in Trøndelag, Norway. Heglesvollen, hearth of furnace C 2 (1982) after removal of the slag block (internal diameter 80cm). Late Romano-Barbarian period (courtesy of A. Espelund and L. Stenvik). Bottom: Paired shaft furnaces from Jernvirke-Tvåker, Halland, southern Sweden, about 1200 AD, as discovered 1995 (courtesy of G. Magnusson and J. Vellev).



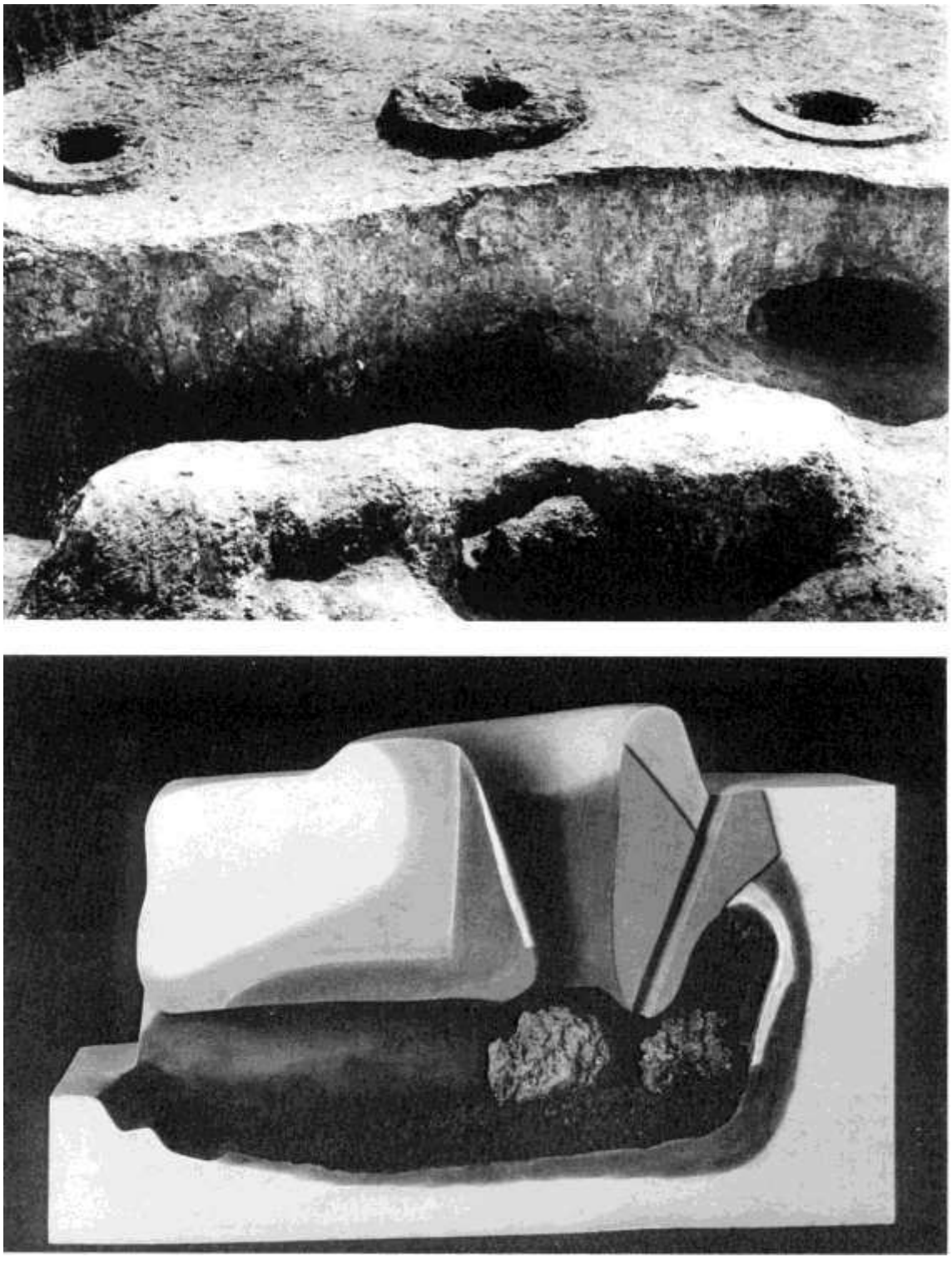
Pl. XII. Late Romano-Barbarian slag-tapping shaft furnaces. Loděnice, Bohemia. Furnace (height 80cm) with slag tapping hole. Late Romano-Barbarian period. After Pleiner.



Pl. XIII. Late Roman and Migration period bloomery furnaces of Switzerland. Top: Boécourt, Jura, base of furnace 2 (1989). Courtesy of L. Eschenlohr and V. Serneels. Bottom: Bellaires III, Jura, furnaces XIX–XX. Courtesy of P.-L. Pelet.



Pl. XIV. Slavic batteries of embanked furnaces: Želechovice, northern Moravia, 8th century AD (1951). Top: central part. Bottom: eastern wing. After Pleiner 1955.



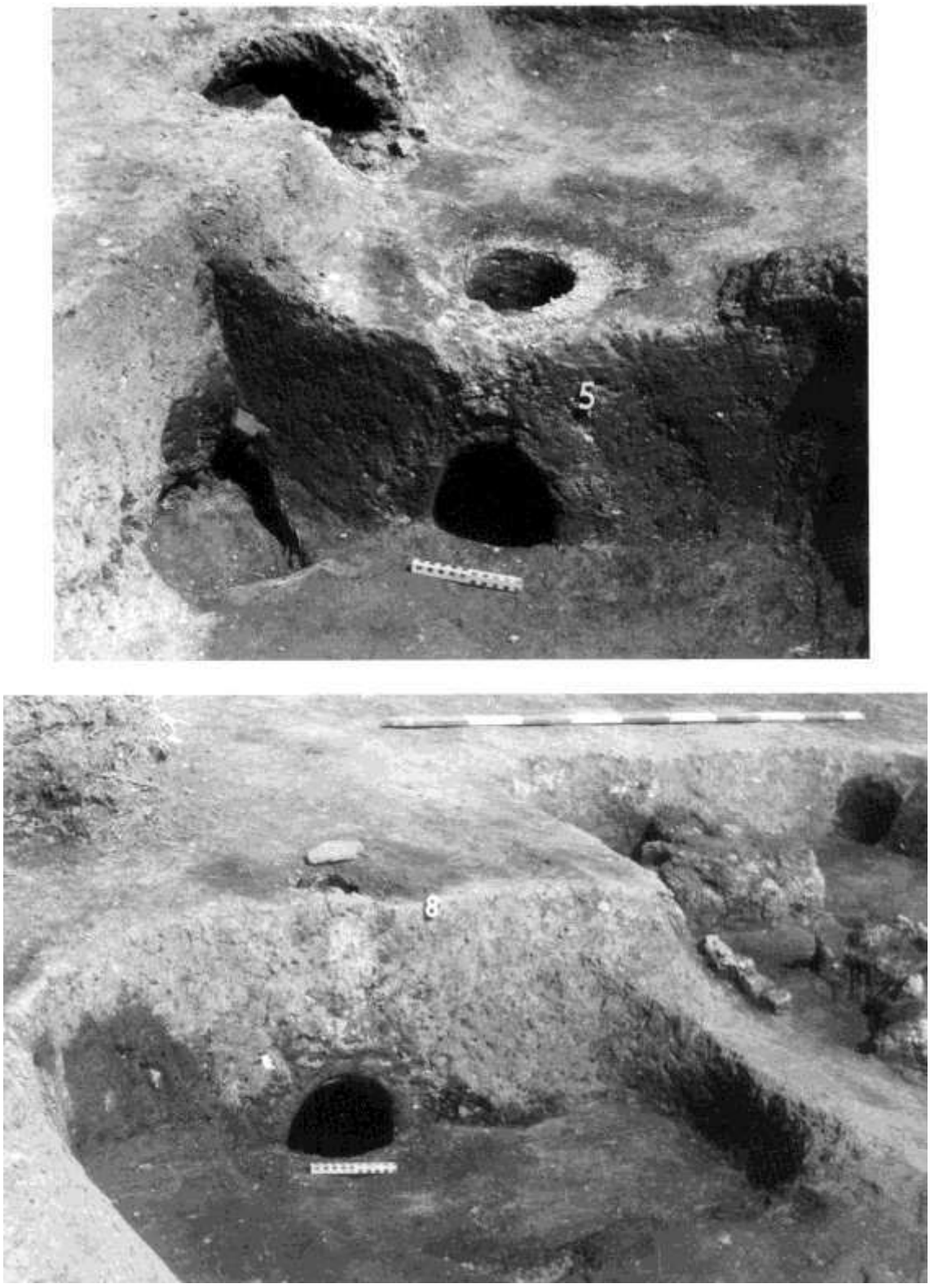
Pl. XV. The Želechovice battery and furnace construction, northern Moravia. Top: central part of the battery. Bottom: Section of furnace XXV as in a model: mind the rear cavity with two final positions of bloom conglomerates. After Pleiner.



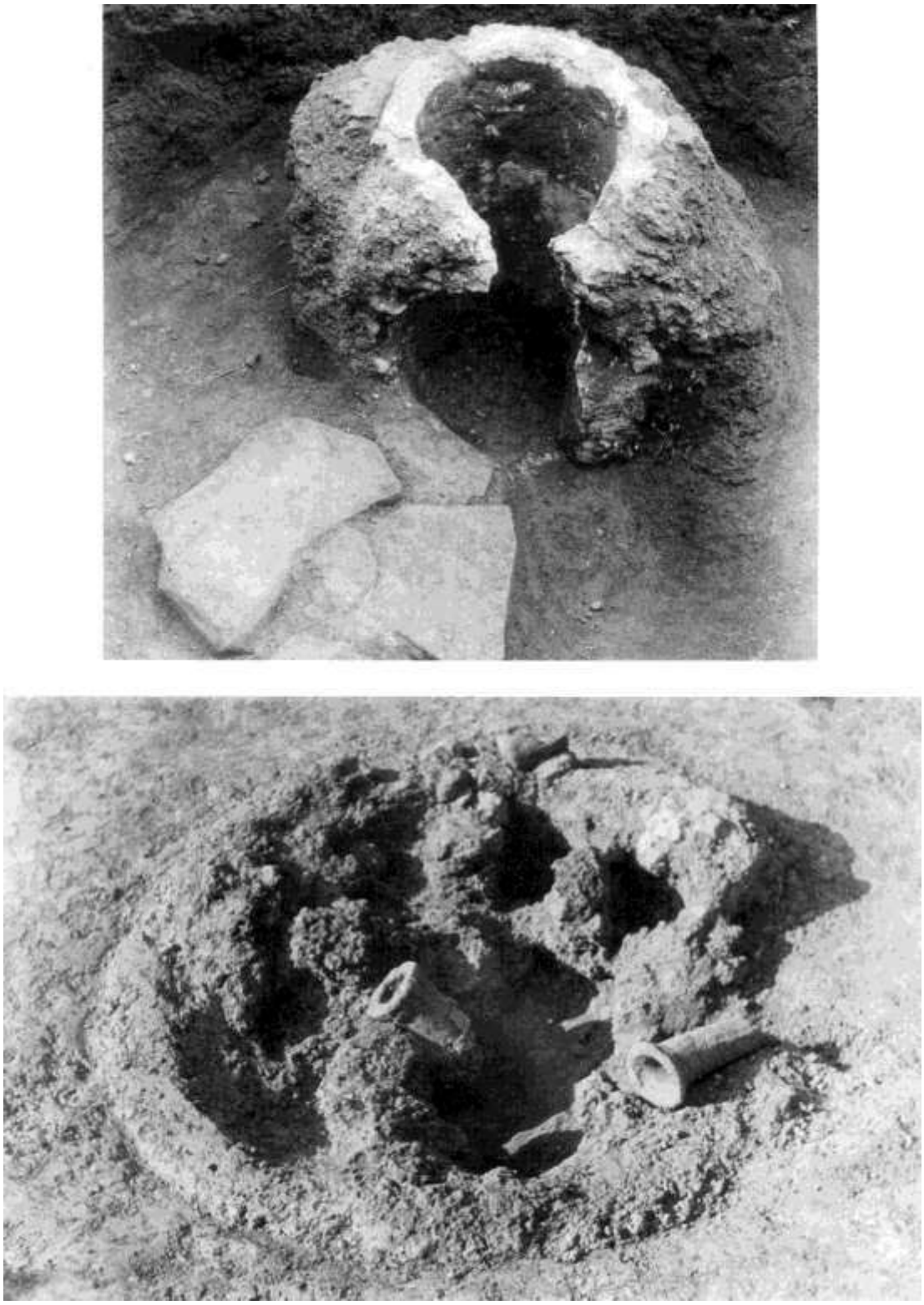
Pl. XVI. Early mediaeval ironworks in western Moravia. Battery 98/2 of underground smelting furnaces of Želechovice type. Courtesy of V. Souchopová.



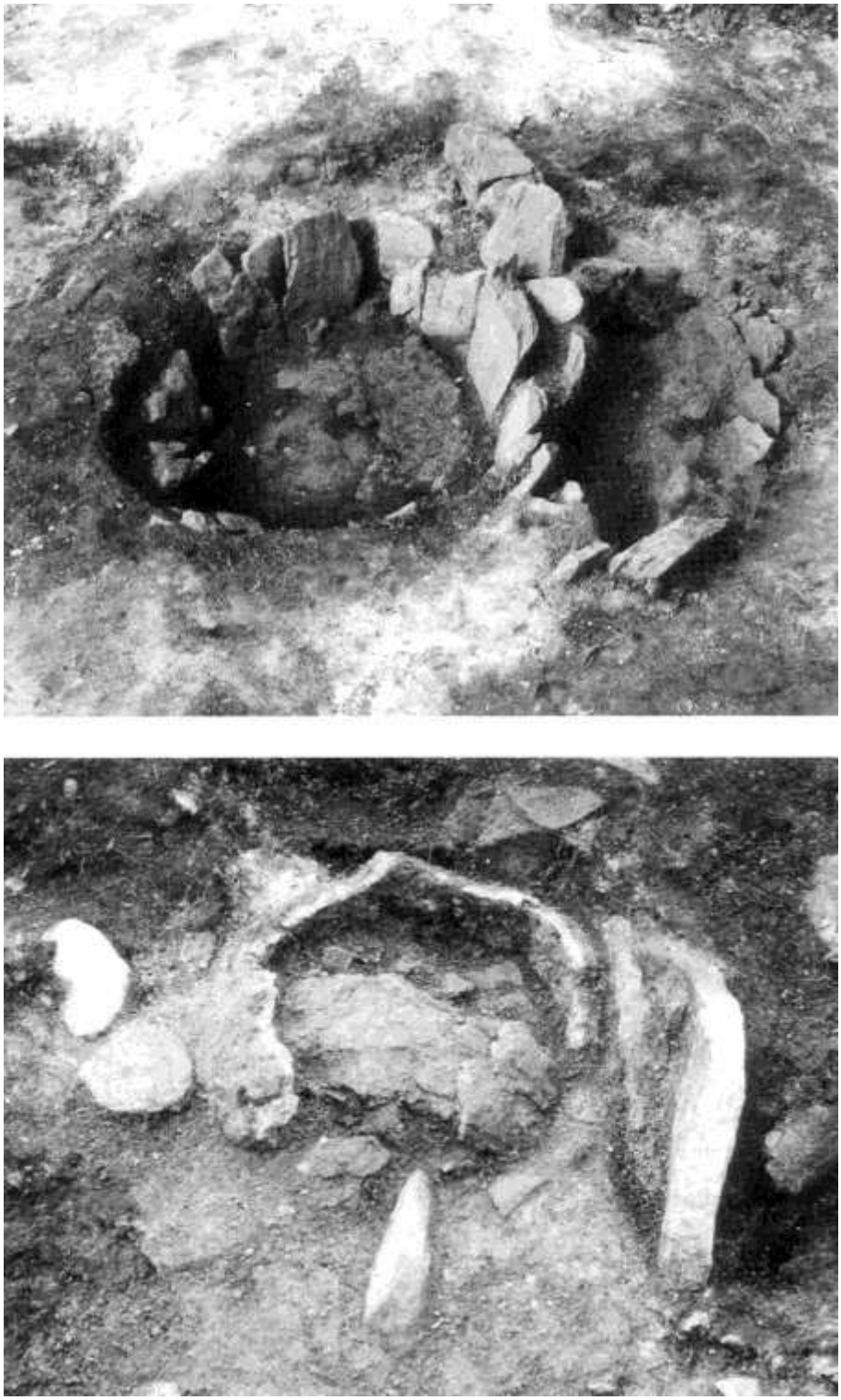
Pl. XVII. Embanked shaft furnace of the 9th century in Moravia. Olomučany, furnace IX with thin front wall and domed arch. Courtesy of V. Souchopová.



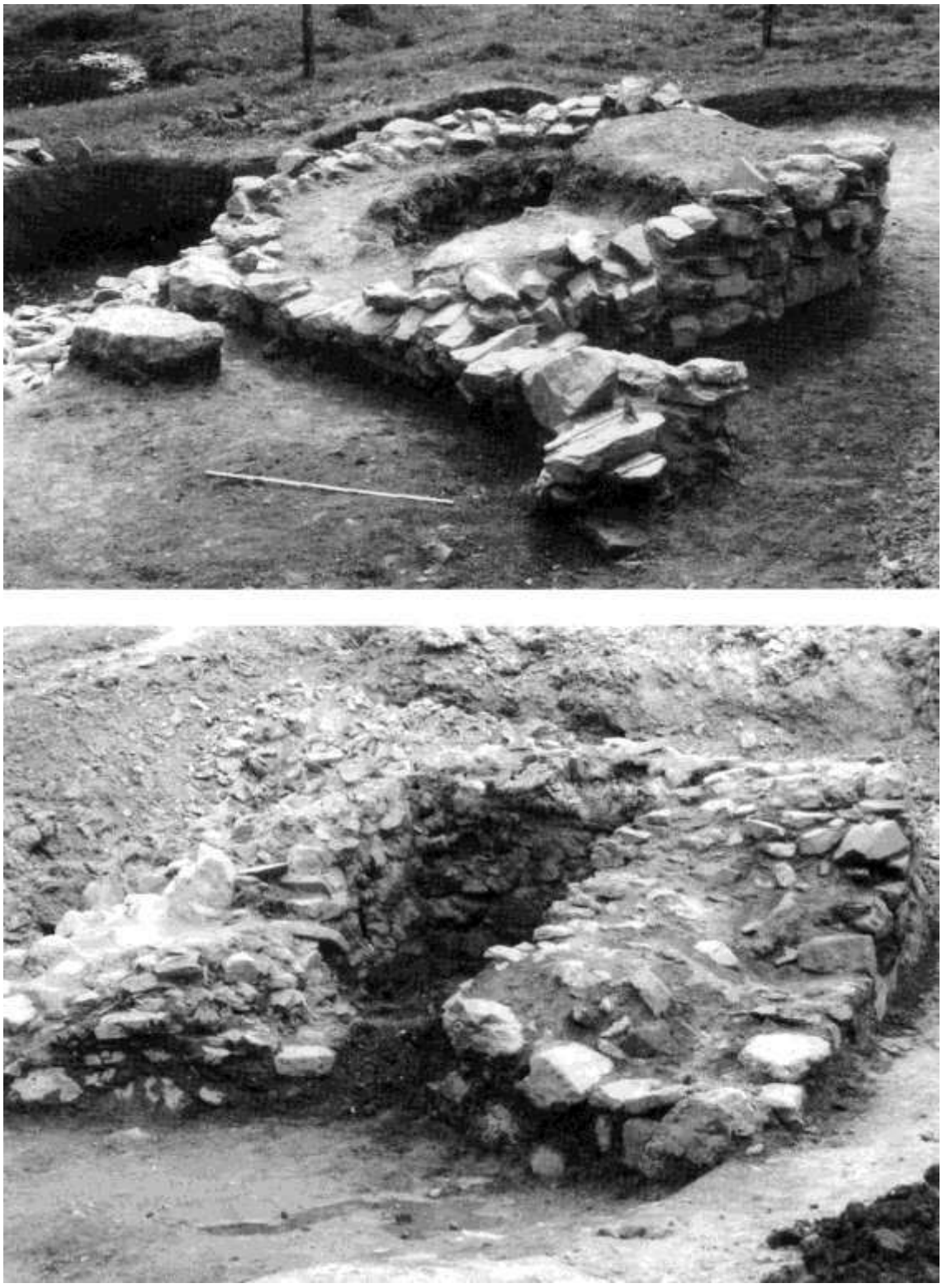
Pl. XVIII. Hungarian embanked furnaces of the 11th century. Szákony, western Hungary. Furnaces 5 (top) and 8 (bottom), ironworks 5. Courtesy of J. Gömöri.



Pl. XIX. Early mediaeval bloomery furnaces from Bohemia and Moravia. Top: Nučice near Prague, low shaft furnace, probably embanked and denuded (1937), after Pleiner. Bottom: Žerotín. Moravia, boel furnace 1 with tuyeres, after Ludikovský.



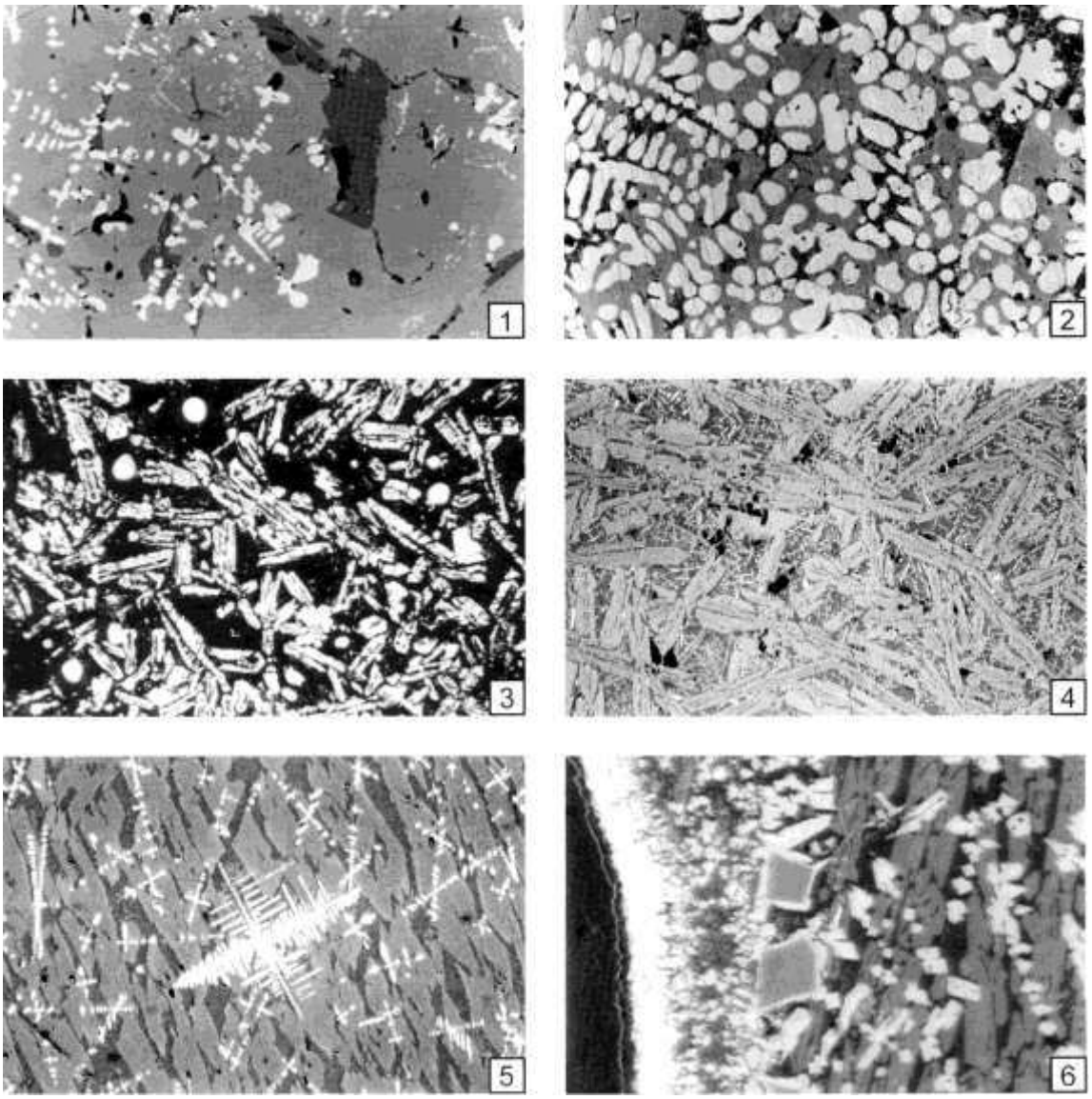
Pl. XX. Norwegian smelting furnaces of the Middle Ages from Hardangervidda (13th century). Top: Nystaul 7, superposition of furnaces I A and B (right). Bottom: Velurhaugen, base of a shaft furnace. Courtesy of I. Martens.



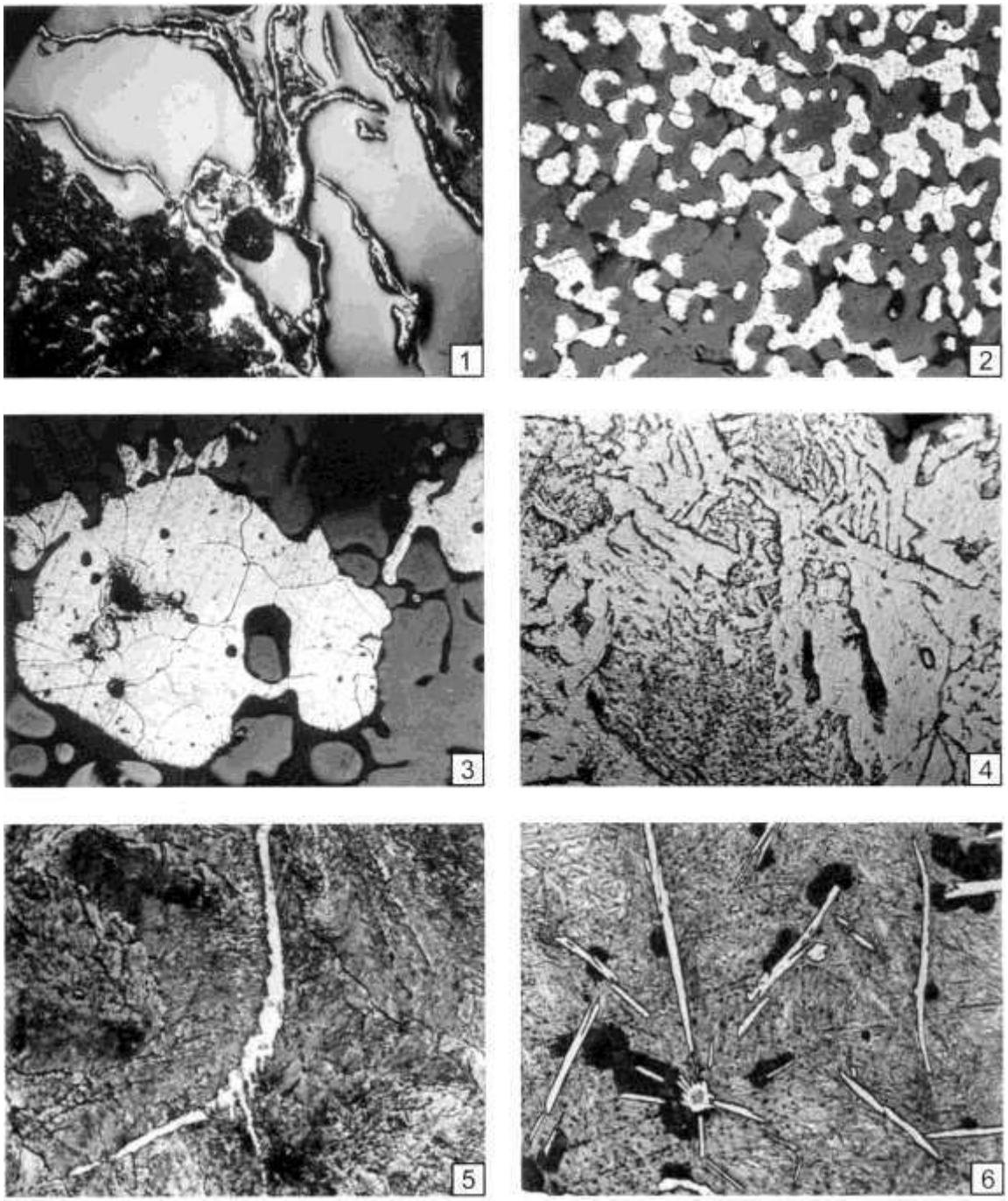
Pl. XXI. Early blast furnaces in Germany. Top: Haus Rhade, Mark, the rounded base of of a *Flossofen*, 13th century (courtesy of M. Sönnecken). Bottom: Kierspe dam, Märkischer kreis, rectangular base of a *Flossofen*, 14th century (courtesy of H. L. Knau).



Pl. XXII. Early blast furnaces in Sweden - Lapphyttan near Norberg. The base of a blast furnace (probably 13th century) with a preserved lining of a bosh, bellows bed at the right side. Courtesy of G. Magnusson.



Pl. XXIII. Principal mineralogical phases of bloomery slags. 1 – 2 Mšec, Bohem., slag-pit furnaces I and VIII, 2nd century BC: wüstite dendrites (white) in large fayalite crystals (grey), intercrystalline glass (dark). 3 Roztoky, Bohem., slag-pit furnace I, 1st century AD: fayalite (light), glass (black), 35x. 4 Mont Chemin, Switz., 7th century AD: Laths of fayalite (grey), glass (dark, with small secondary fayalite), 2.5x; 5 – 6 Liestal, Switz. (9th – 12th centuries AD): 5 wüstite dendrites (white), calcium rich fayalite (grey), and glass (black), 20x; 6 square dark cores of hercynite with magnetite rims (white), and magnetite dendrites; laths of fayalite (grey), and glass (black), 50x. 4 – 6 courtesy of V. Serneels.



Pl. XXIV. The birth and carburization of a bloom. Based on experimental smelts II and II/2 in the Żelechovice model of furnace. 1 Ferrite fibres surrounding a charcoal fragment, 10x. 2 Ferrite grains in a fayalitic slag matrix, 50x. 3 Nodules of ferritic iron embedded in slag, 100x. 4 Ferrite and pearlite (dark) in an isolated iron conglomerate. 5 – 6 Compact bloom: 5 ferrite (white) on boundaries of pearlite grains, 300x; 6 Excess cementite in the grey martensite matrix with spots of dark troostite in a quenched bloom, 300x. Etched with 2% nital.