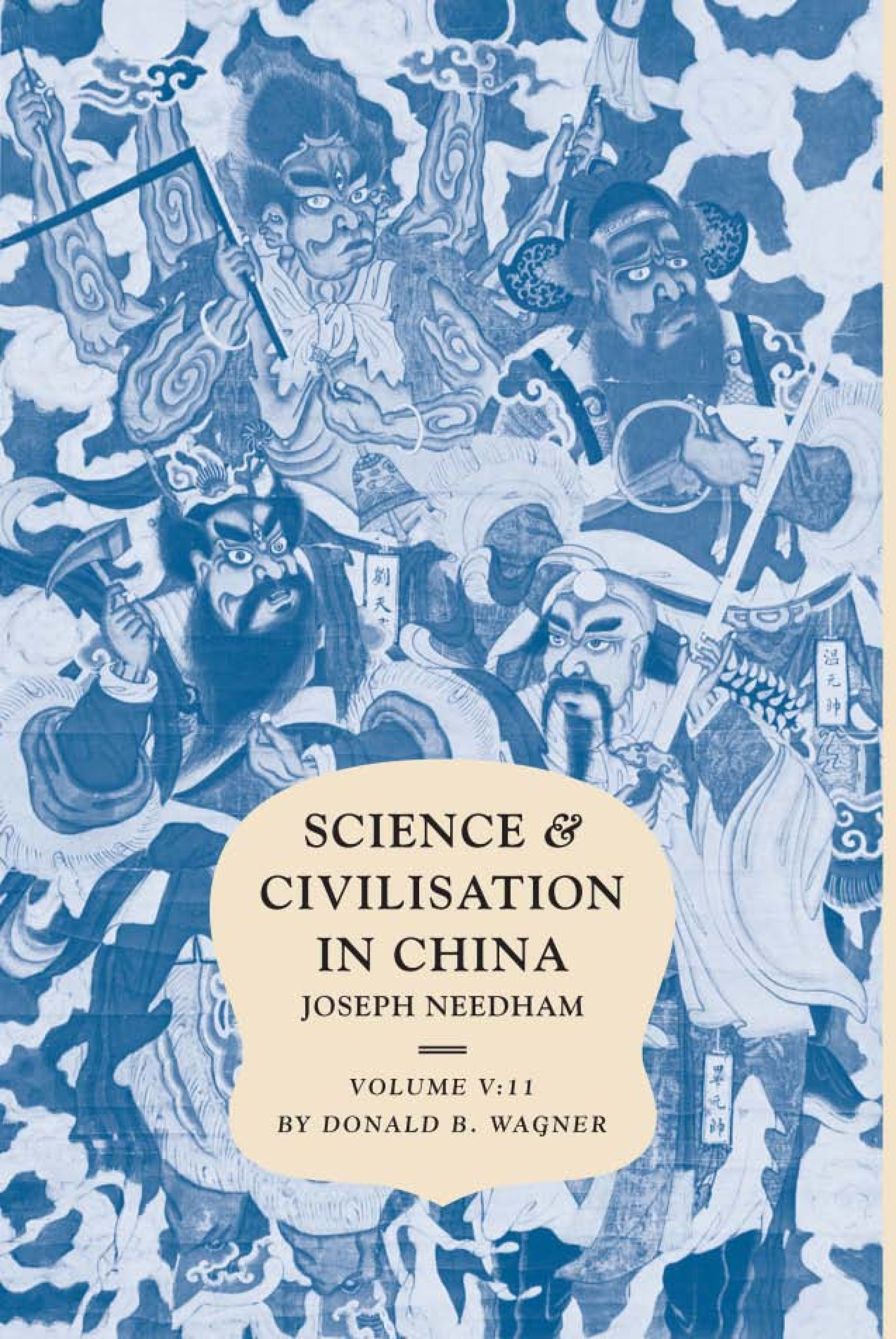

SCIENCE & CIVILISATION IN CHINA

JOSEPH NEEDHAM

VOLUME V:11

BY DONALD B. WAGNER

SOME REVIEWS OF VOLUMES I, II, III, IV AND V

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Times Literary Supplement

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A. W. HUMMEL in *American Historical Review*

'Joseph Needham, working outside intellectual fashion in a vast and patchily explored field, has produced one of the greatest and most captivating works of scholarship to grace our age.'

Times Educational Supplement

'...one of the great European contributions to the understanding both of the sweep of Chinese civilisation and of its contributions to Western scientific society.'

New Scientist (London)

'...abundant evidence of tremendous research and learning spread over a breath-taking range of knowledge coupled with personal observation and experience gathered through long years living and travelling in the East.'

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Times Higher Education Supplement

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LAURENCE PICKEN in *The Guardian* (Manchester)

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DONALD B. WAGNER holds degrees in Mathematics and Chinese from MIT and the University of Copenhagen, and has studied Metallurgy at the Technical University of Denmark. He has taught at the University of Copenhagen, the University of Victoria (British Columbia), and the Technical University of Berlin. He has written widely on the history and archaeology of science and technology in China.

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JOSEPH NEEDHAM

SCIENCE AND CIVILISATION IN CHINA

VOL. V:11

by

DONALD B. WAGNER

CAMBRIDGE

Donald B. Wagner provides a comprehensive historical account of the production and use of iron and steel in China in their political and economic context. An initial chapter on the traditional Chinese iron industry introduces the important technical concepts and the ways in which technology, geography, and economics interact and influence political phenomena. Recent archaeological work indicates that the earliest production of iron in China was in the Northwest, and that the technology was introduced from the West via Central Asia. It was, however, the invention in South China of large-scale technologies which put China on a very different developmental path from that of the West. Further chapters deal with developments from the Han to the Tang, the technical evolution and economic revolution of the Song period, and economic expansion under the Ming. A final chapter investigates the debt of the modern steel industry to Chinese developments.

THE PICTURE OF THE TAOIST GENII PRINTED ON THE COVER of this book is part of a painted temple scroll, recent but traditional, given to Mr Brian Harland in Sichuan province (1946). Concerning these four divinities, of respectable rank in the Taoist bureaucracy, the following particulars have been handed down. The title of the first of the four signifies 'Heavenly Prince', that of the other three 'Mysterious Commander'.

At the top, on the left, is Liu *Tian Jun*, Comptroller-General of Crops and Weather. Before his deification (so it was said) he was a rain-making magician and weather forecaster named Liu Jun, born in the Jin dynasty about +340. Among his attributes may be seen the sun and moon, and a measuring-rod or carpenter's square. The two great luminaries imply the making of the calendar, so important for a primarily agricultural society, the efforts, ever renewed, to reconcile celestial periodicities. The carpenter's square is no ordinary tool, but the gnomon for measuring the lengths of the sun's solstitial shadows. The Comptroller-General also carries a bell because in ancient and medieval times there was thought to be a close connection between calendrical calculations and the arithmetical acoustics of bells and pitch-pipes.

At the top, on the right, is Wen *Yuan Shuai*, Intendant of the Spiritual Officials of the Sacred Mountain, Tai Shan. He was taken to be an incarnation of one of the Hour-Presidents (*Jia Shen*), i.e. tutelary deities of the twelve cyclical characters (see vol. 4, pt. 2, p. 440). During his earthly pilgrimage his name was Huan Ziyu and he was a scholar and astronomer in the Later Han (*b*. + 142). He is seen holding an armillary ring.

Below, on the left, is Gou *Yuan Shuai*, Assistant Secretary of State in the Ministry of Thunder. He is therefore a late emanation of a very ancient god, Lei Gong. Before he became deified he was Xin Xing, a poor woodcutter, but no doubt an incarnation of the spirit of the constellation Gou Chen (the Angular Arranger), part of the group of stars which we know as Ursa Minor. He is equipped with hammer and chisel.

Below, on the right, is Bi *Yuan Shuai*, Commander of the Lightning, with his flashing sword, a deity with distinct alchemical and cosmological interests. According to tradition, in his early life he was a countryman whose name was Tian Hua. Together with the colleague on his right, he controlled the Spirits of the Five Directions.

Such is the legendary folklore of common men canonised by popular acclamation. An interesting scroll, of no great artistic merit, destined to decorate a temple wall, to be looked upon by humble people, it symbolises something which this book has to say. Chinese art and literature have been so profuse, Chinese mythological imagery so fertile, that the West has often missed other aspects, perhaps more important, of Chinese civilisation. Here the graduated scale of Liu Jun, at first sight unexpected in this setting, reminds us of the ever-present theme of quantitative measurement in Chinese culture; there were rain-gauges already in the Song (+12th century) and sliding calipers in the Han (+1st). The armillary ring of Huan Ziyu bears witness that Naburiannu and Hipparchus, al-Naqqās and Tycho, had worthy counterparts in China. The tools of Xin Xing symbolise that great empirical tradition which informed the work of Chinese artisans and technicians all through the ages.

SCIENCE AND CIVILISATION IN CHINA

Joseph Needham
(1900–1995)

Certain it is that no people or group of peoples has had a monopoly in contributing to the development of Science. Their achievements should be mutually recognised and freely celebrated with the joined hands of universal brotherhood.
Science and Civilisation in China VOLUME I, PREFACE

*

Joseph Needham directly supervised the publication of seventeen books in the *Science and Civilisation in China* series, from the first volume, which appeared in 1954, through to Volume VI.3, which was in press at the time of his death in March 1995.

The planning and preparation of further volumes will continue. Responsibility for the commissioning and approval of work for publication in the series is now taken by the Publications Board of the Needham Research Institute in Cambridge, under the chairmanship of Dr Christopher Cullen, who acts as general editor of the series.

李約瑟著

中國科學技術史

冀朝鼎

JOSEPH NEEDHAM

SCIENCE AND CIVILISATION IN CHINA

VOLUME 5

CHEMISTRY AND CHEMICAL TECHNOLOGY

PART 11: FERROUS METALLURGY

BY

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Dedicated to

LI JINGHUA 李京華

and to the memory of

RONALD FRANK TYLECOTE

Two archaeometallurgists, East and West, who can represent
here the hundreds of metallurgists, archaeologists, and historians
on whose work this volume is based.

*Nous nous devons premièrement à notre Patrie; mais nous nous
devons aussi au reste du monde; ceux qui travaillent pour
perfectionner les Sciences & les Arts, doivent même se regarder
comme les Citoyens du monde entier.*
René Antoine Ferchault de Réaumur (1722)

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TEXT BOXES

ABBREVIATIONS

CSJC	*Cong shu ji cheng* 叢書集成.
DMHD	*Da Ming hui dian* 大明會典.
DNB	*Dictionary of national biography* (Anon., 1885–1901).
GSR	*Grammata Serica recensa* (Karlgren, 1957). References give entry number.
HHS	*Hou Han shu* 後漢書.
HMJS	*Huang Ming jing shi wen bian* 皇明經世文編.
HS	*Han shu* 漢書.
MSL	*Ming shi lu* 明實錄.
SBBY	*Si bu bei yao* 四部備要.
SBCK	*Si bu cong kan* 四部叢刊.
SCC	Joseph Needham, *Science and civilisation in China* (1954 ff).
SHY:SH	*Song hui yao ji gao* 宋會要椲稿, *Shi huo* 食貨 section.
SHY:XF	*Song hui yao ji gao* 宋會要椲稿, *Xing fa* 刑法 section.
SHY:ZG	*Song hui yao ji gao* 宋會要椲稿, *Zhi guan* 職官 section.
SJ	*Shi ji* 史記 .
SKQS	*Si ku quan shu* 四庫全書.
SS	*Song shi* 宋史.
SSJZS	*Shi san jing zhu shu* 十三經注疏.
TGKW	*Tian gong kai wu* 天工開物.
TPYL	*Tai ping yu lan* 太平御覽.
WX	*Wen xuan* 文選.
WXTK	*Wen xian tong kao* 文獻通考.
XZZTJCB	*Xu Zi zhi tong jian chang bian* 續資治通鑑長編.
YTL	*Yan tie lun* 鹽鐵論.

SERIES EDITOR'S PREFACE

As I have mentioned before in prefaces to books in this series, in the first volume of *Science and Civilisation in China (SCC)*, published in 1954, Joseph Needham gave outline plans for subsequent volumes. Volume 5, then labelled as 'Chemistry and Industrial Chemistry', was to contain Section 33 on Alchemy and Chemistry, section 34 on Chemical Technology, section 35 on Ceramic Technology, section 36 on Mining and Metallurgy, and section 37 on the Salt Industry. We have to recall that, in those days, 'volume' in *SCC* terms meant simply 'book': it was not until the appearance of volume 4 that the splitting of volumes into physically separate parts began. So what was to go into Mining and Metallurgy? According to the plan (*SCC* vol. 1, p. xxxv) we were to be given:

36 MINING AND METALLURGY

Ancient Chinese bronze and bronze-casting. Metallurgical formularies in Han books.
Ancient iron technology: the mastery of cast iron in the Han; iron ploughs and sword forging.
Metallurgy of the precious metals.
Knowledge of coal in China and tentatives at coke for smelting. Types of smelting furnaces. The great Ming metallurgical compendium.
Mining of tin and zinc. Brass and other alloys, some unknown to the West till the +18th century

Now all this was to go into a fifth part of a single book, and even if we imagine that book to have been as large as *SCC* volume 3 at about 680 pages of main text, that would have given Mining and Metallurgy about 136 pages. If we give ferrous metallurgy (as opposed to mining and non-ferrous metallurgy) one third of that space, we come to about 45 pages. Interestingly, that is almost exactly the same as the count of the main pages (48) in Needham's monograph *The development of iron and steel technology in China*, published in 1958, which grew out of a lecture to the Newcomen Society in 1956. So there was the job done and at least provisionally published while awaiting the appearance of the volume as a whole. How then did we get to the present stage, when half a century later a book of 512 pages appears on the subject of ferrous metallurgy alone?

The explanation is to be found in the fact that when his monograph on ferrous metallurgy was published in 1958, Joseph Needham was on the most optimistic view several years from being able to produce the rest of volume 5, even on the modest scale of the plan laid down in 1954. In the first place, work for volume 4 (Physics and Physical Technology – including mechanical, civil and nautical engineering) clearly took priority, since Needham's broad approach was to write the volumes in sequence. This volume, nearly all of which Needham researched and wrote himself, appeared in three parts from 1962 to 1971, a decade's work during which his immense ability to organise and digest pioneering explorations was given full play. As Don Wagner points out, Needham seems to have put work on ferrous metallurgy to one side after a longer version of his 1958 monograph was drafted in typescript in 1959, and it is quite understandable that he should have done so.

Needham himself made only limited progress in researching and writing the rest of the planned content of volume 5. Part 33 was the striking exception: it did indeed get written two decades later, and was published as a series of books (volume 5, parts 2, 3, 4, and 5 on Alchemy, which appeared from 1974 onwards), while part 34 became a book on its own (published 1987), substantially written by Ho Peng Yoke, dealing with gunpowder (though relabelled as coming under part 30, Military Technology). But Ceramic Technology, Mining, and Non-ferrous Metallurgy, together with the Salt Industry did not make substantial progress towards publication in *SCC* form under Needham's hand, although varying quantities of research notes are to be found in the archival files of the Needham Research Institute. The Institute, with the generous support of the Andrew W. Mellon Trust of New York, is currently completing the project of cataloguing the whole of Needham's research files, and this will make it possible for future researchers to trace the story in full detail. Such researchers will owe a debt to Joanne Meek, a professionally qualified archivist, who is now undertaking this task. But the main point is that by 1960 Needham had laid ferrous metallurgy aside and turned to other things, mainly meaning volume 4, which he completed 11 years later at the age of 71.

So at an age when many people would not be expecting to begin major research and writing tasks, Needham could look back on a series of books constituting only a part of the task he had set himself to complete: volumes 1 to 3, each in a single book, and volume 4 in three massive parts. He was – as the expansion of section 33 into no less than four books showed – in the grip of what can only be called a fascination with alchemy far out of proportion with the original plan for *SCC*. The only way to make progress was to call on the help of collaborators who would research and write books under their own names, as in the case of volume 5 part 1 (Paper and Printing) by Tsien Tsuen-Hsuin, which appeared in 1985, volume 5 part 9 (Textile Technology: Spinning and Reeling) by Dieter Kuhn (1986), and volume 6 part 2 (Agriculture) by Francesca Bray (1988). And in a file whose first dated documents come from 1981, we find a scrap of paper with the note in Needham's hand 'Donald Wagner @ Ostasiatika Institutet Copenhagen / v. keen on hist. of i.&s. in [China] might collaborate.' Don Wagner's fate was sealed. Since Needham was always the same age as the 20th century, he was in his ninth decade at the time he scribbled this note. It was clear to him by that stage that without a collaborator prepared to work independently like Tsien, Kuhn and Bray there would never be an SCC section on iron and steel: here at last was a sinologically and technically qualified young scholar who could do the work.

By February 1982 it had been agreed that Don Wagner would 'revise' the 48-page monograph on iron and steel that Needham had put to one side 23 years earlier. It did not take long before it became clear to everybody involved that this was to be another case where a section of *SCC* originally planned to fill a few dozen pages would be expanded to an independent book – not a decision any reader of the present work will regret. And so the work began, mainly supported in those years by a series of fellowships and grants from Danish sources.

When in 1992 I started work as chair of the NRI Publications Board, ten years after Wagner began his task, one of the first tasks before me was to review the status of various collaborations, almost all of which had expanded from small beginnings as a few dozen pages planned for one of Needham's original one-book volumes to become (at least in the hopes of the authors) full-sized books. Much of this expansion – one might almost call it inflation – had taken place when Needham was already advanced in years, and was unable to give all parts of the project as much personal attention as he once had. The situation was both complex and delicate. In some cases it was clear after investigation that the proposed author was nowhere near writing anything and probably never would be, and that in any case the topic they had claimed was not appropriate for a book-length treatment: the remedy was obvious, and I am happy to say that Needham gave his full support to the necessary polite but firm communications that followed on behalf of the Publications Board. In others it was clear that the topic deserved substantial coverage, but that the scholar responsible either could not or would not finish the job in the foreseeable future. There it was necessary to begin the search for new authors who were not only qualified for the job, but were actually likely to be able to do it. There were other more complex cases still, but in others it was clear that a book of high quality was 'in the works' and would in due course be ready for the press. In the case of Ferrous Metallurgy, it was immediately obvious that the task was one that deserved a full-size book – one on Mining was already in preparation by Peter Golas – and that the scholar responsible was extremely well equipped for the task in intellectual terms, as well as fully committed to the job. There was however an obvious problem: the task was huge, and Don Wagner was doing it without a secure academic base, on a series of short-term fellowships interspersed with other ways of gaining a living. What the author needed was the time for continuous work, in an environment with the proper facilities for research. I therefore had no hesitation in applying in my own name to the Leverhulme Trust for a grant sufficient to enable Don Wagner to spend two and a half years living in Cambridge and working at the NRI. The application was successful, and the work began.

At the time both Don Wagner and I were convinced that by the time the grant matured in 1997 we should be very close to the first draft of the book so long awaited. But the middle nineties were, in the 20-20 vision of hindsight, the wrong time for such optimism. Quite apart from the unpredictability of academic projects based on research (which, strangely, has a way of producing unexpected results, a feature which is one of its chief merits), those years saw a great increase in research reports from China based on new archaeological findings and scientific analyses from the whole field of historical metallurgy, all of which had to be taken account of in writing and rewriting the typescript. When Wagner left Cambridge to return to Denmark, it was possible to report considerable progress, not the completion of a draft book. It was however clear that when the book did appear it would have been worth waiting for – and hence its completion was looked for with a sense of keen expectation. Finally, in August 2003 a first draft arrived at the Institute, and according to *SCC* practice was sent out for detailed comments by a group of expert readers. After revisions in the light of their suggestions, a final version was handed over to Cambridge University Press in July 2006. All of us, especially the staff of the Institute who had seen such events several times before, knew how much work there was still to go before the book reached its readership. But success was now only a matter of time. And finally, here is the result in all its glory.

I have taken it for granted that the reader will appreciate the reasons why it has been felt worthwhile to devote so much by way of time and resources to a book on this subject. Anyone with doubts can simply skim a few of Don Wagner's chapters to find that, whatever its broader historical significance may be, the story told here is simply of immense interest in its own right. But surely anyone who contemplates China's present rapid rise to industrial pre-eminence in the 21st century can see why it is worth the effort to understand the series of triumphs and vicissitudes that make up one of the great stories of industry outside Europe before what Europeans still confidently call *The* Industrial Revolution? Our confident expectation is that in any case this book will still be seen as an authority in its field at a time when the question why one should study the technical history of China seems a clear failure to appreciate the obvious.

So the journey from 48 to 512 pages is over at last. We can only express gratitude for the work of the authors of both pieces of writing, who in their different ways have given so much to the world of learning.

CHRISTOPHER CULLEN
General Editor
Director, Needham Research Institute, Cambridge

PREFACE

Vita pro ferro, the title of a Festschrift for the metallurgist Robert Durrer,[1] gave me a laugh when I first saw it. Now, years later, I find that I have spent half my life researching and writing on ferrous metallurgy and its history. How did this happen?

I was about 25, a beginning student of Chinese with a degree in mathematics and a brilliant future in computer systems behind me, when a teacher introduced me to *Science and Civilisation in China*. I was attracted immediately to Joseph Needham's erudition, to his clear and precise language, and perhaps most of all to his use of his scientific background in a constant concern for 'brass tacks'. At that time four volumes had appeared; I devoured these, and most of the following volumes as they appeared. Today I count Joseph Needham's work as one of the most important components of my basic sinological education, and one of the models constantly before me in my career of research and writing.

My first research was in the history of mathematics in China, but after a conversation with Professor Noel Barnard in 1978 I began looking seriously at the history of iron technology in ancient China. The need to 'get my hands dirty' soon became apparent, and in 1981 I began studying metallurgy with Dr V. F. Buchwald at the Technical University of Denmark.

When, around that time, Joseph Needham asked me to be his collaborator for Ferrous Metallurgy, I readily accepted, but felt that it was important to finish the book I was currently working on, *Iron and steel in ancient China*,[2] before starting on this chronologically broader work. That book required much longer to complete than I had ever expected – a phenomenon I had seen before with other publications, and would see again. It was essentially finished in 1990, and published in 1993.

In all that time I had been preparing on the side for this volume for SCC, gathering bibliography and reading up necessary historical and technical background. Actual writing could begin in 1994 when, thanks to the efforts of the Publications Board of the Needham Research Institute, I received a grant from the Leverhulme Trust for two and a half years of research in Cambridge. The work continued after my return to Denmark, with ups and downs due to unstable employment, and now, in 2006, I feel that the volume is as finished as I can make it.

Though I count myself among Joseph Needham's admirers, long-term readers of *Science and Civilisation in China* will notice that I disagree with him on a number of matters large and small. I cannot believe in the essential virtue of Progress, or in

[1] Guyan (1967).
[2] Wagner (1993).

modern natural science as a measure of historical value, in quite the same way that he did; and my socialism is not his socialism.

The title page of this volume presents Ferrous Metallurgy as a branch or aspect of Chemistry, but this is a categorisation that I have never found especially useful. As another of Joseph Needham's critical admirers, Francesca Bray, has pointed out, the hierarchy of knowledge on which the structure of *Science and Civilisation in China* is based, with all technology seen as applied science, was already considered old-fashioned when the first volume was published in 1954.[3] But structure is as structure does, and this old-fashioned structure, with its emphasis on the brass tacks of modern science, continues to serve well after 24 volumes published over a period of more than 50 years.

Among more specific disagreements, I find the social sciences more useful than Joseph Needham did. As a young man at a technical university I fell in with the crowd in sneering at 'the social so-called sciences', but working in the history of technology has forced me to change that opinion. There are more appeals in this volume to theoretical economic and geographical considerations, in particular, than elsewhere in his work. Other social-science approaches, especially sociology and anthropology, would also have been useful in considering some of the broader aspects of the production and use of iron, but getting a book finished means recognising some personal limitations.

Among the goals of this volume is a demonstration of some of the ways in which technologies influence the course of history. Not some monolithic Technology – Lewis Mumford's *technics*[4] – but the many technologies which people have used to satisfy their practical needs. It has been said often enough in the 20th century that *technology has consequences*, the latter seen by various pundits with either hope or despair; but for the historian it is more important to realise that *particular technologies have particular consequences*. As we shall see further on in this volume, most agricultural implements in Han China were made of cast iron (more precisely, the kind called *malleable cast iron*), while in Roman Europe at the same time they were made of wrought iron. It will also become clear that these two different technologies had significant social and political consequences, though perhaps not as direct or extreme as those which Karl Marx suggested in his aphorism about hand-mills and steam-mills.[5] At the same time, technologies are clearly shaped by the context in which they develop, and we must also ask the question, how it came to be that two societies with roughly similar practical needs adopted such different technologies to meet those needs.

Treating a technology as a historical factor requires us to understand it technically, and this volume includes a good many discussions which are based on

3 Bray (2000, p. 67).

4 Mumford (1934).

5 'The hand-mill gives you society with the feudal lord; the steam-mill, society with the industrial capitalist.' In *Misère de la philosophie*, 1847, Marx (1963, vol. 1, p. 79); tr. Marx (1936, p. 92); cf. MacKenzie (1984, p. 473).

detailed technical considerations. As in most of my publications, I attempt to explain these matters with readers in mind who know some chemistry and are accustomed to technical thinking. Others will find, I think, that they can skip the more technical discussions and still follow the basic lines of the argument.

The archives of the Needham Research Institute show that Joseph Needham began studying the history of ferrous metallurgy in China in the early 1950s. He gathered a good deal of primary and secondary source material, using his excellent contacts in China, and initiated two laboratory projects, to reconstruct Qiwu Huaiwen's 'co-fusion' steelmaking process, and to study the microstructures of ancient Chinese cast-iron artefacts.[6] His monograph *The development of iron and steel technology in China,*[7] completed in 1956, was for several decades all that was available on the subject in English. He was dissatisfied with it, however, especially after a friendly but very critical letter from the great metallurgist Cyril Stanley Smith, and in about 1959 he wrote a draft revision of the monograph which approximately tripled its size. But in the draft one can see him still struggling with the technical mysteries of ferrous metallurgy; he remained dissatisfied, and never published the revision. At about that time he quite suddenly abandoned the subject, even leaving several letters unanswered, and never returned to it.[8]

When I began studying the subject I had the great advantage that Chinese historians, archaeologists, and metallurgists had begun doing important work on all aspects of archaeometallurgy, but Joseph Needham's monograph, and later the draft revision, were my best guide to the older literature and to the Chinese primary sources.

Another useful guide was John Percy's *Metallurgy. Iron; steel* (1864). Percy was an admirable Victorian polymath, and in his book he summed up what was known of the science and technology of metallurgy in his time as well as their history worldwide. He wrote at a time of great change, but the older technologies were still alive, and he was able to describe them in useful technical detail.

Among other authors whose works guided this perplexed beginner were Ronald F. Tylecote, Noel Barnard, Yang Kuan 楊寬, Hua Jueming 華覺明, Li Jinghua 李京華, and the group which in troubled times hid under the pseudonym Li Zhong 李眾.[9] Robert Hartwell's Ph.D. dissertation on the Song iron industry (1963), and Bernd Eberstein's on Ming mining and metallurgy (1974), were also immensely valuable as starting points in dealing with those periods.

In the years that followed I have enjoyed the advice and assistance of numerous friends and acquaintances, experts in the various archaeological, historical, and

[6] See pp. 167, 257–8 below.

[7] Needham (1958).

[8] The article Needham (1980a) was largely written by Colin Ronan on the basis of the 1959 revision.

[9] The group, at the Beijing University of Iron and Steel Technology (Beijing Gangtie Xueyuan 北京鋼鐵學院, now the Beijing University of Science and Technology), was led by Ke Jun 柯俊. The most active participants were Qiu Lianghui 丘亮輝, Huang Wudi 黃務滌, Wu Kunyi 吳坤儀, and Sun Shuyun 孫淑雲. I am grateful to Mei Jianjun for this information.

technical fields that make up the background for this volume. Some of this help I have acknowledged in footnotes, and in the list further below I have tried to show my wider indebtedness.

Portions of this volume have appeared in earlier publications,[10] and I am grateful to the editors and publishers for permission to use this material here.

Thanks are also due to numerous libraries and librarians: here I shall single out the staff of the public library in the small town of Frederikssund, where I have lived since my retirement in 2003. They have been unfailingly helpful, far beyond the call of duty, in obtaining books for me on many subjects in a variety of languages, including Chinese and Japanese.

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And my greatest debt is, as always, to my dearest friend, Annie Winther.

Matters of Form

This volume of *Science and Civilisation in China* is the first to use the Pinyin transcription for Chinese instead of Joseph Needham's modification of the Wade-Giles system, in which for example Qin is transcribed Chhin. The Publications Board of the Needham Research Institute made the decision to change the transcription in April 2004; I spent two weeks changing the transcription in an almost-complete manuscript, but this I was delighted to do, as I have always felt that the previous system formed a serious barrier between Joseph Needham's work and its readers.[11]

Another change made at about the same time was to combine Bibliographies B and C into one, so that all modern publications are to be found in one list.

As throughout *Science and Civilisation in China,* years before and after the Common Era are usually indicated by – and +, so that +1200 means the year 1200 CE and –117 means 117 BCE. The + is ommitted for early modern and modern dates.

Unless otherwise specified, all translations from Chinese texts are my own. Wherever possible, however, I have also cited published translations of the same text. Readers may find it useful to consult these in order to see more of the context of the passages translated here.

[10] These are listed in the bibliography under Wagner (1985–2006). In particular, Koninklijke Brill N.V., the publishers of my *Iron and steel in ancient China* (1993), kindly permitted the extensive reuse of material in that book.

[11] An artefact of the transcription change is that the abbreviation 'ch.' in bibliographical references can mean either 'chapter' or *juan* 卷 (JN's *chüan*).

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Alan Williams
Frances Wood
Wu Laiming 吳來明
Xie Lijun 謝立軍
Kenneth Zysk

July 2006 DONALD B. WAGNER

Plates I–VIII The first eight in an album of twelve gouache paintings preserved in the Bibliothèque Nationale, Paris ('Fer', C.E. Oe 119 in-4°, 1–8)

I 'Exploring the soil' (*tan tu* 探土).

II 'Testing the iron [ore]' (*yan tie* 驗鐵).

III 'Extracting the iron [ore]' (*qu tie* 取鐵).

IV 'Separating the lead' (*fen qian* 分鉛). This picture clearly shows the calcining of iron ore (see pp. 14–15 above); the idea that lead is somehow involved is curious.

v ‘Purifying the dirt’ (*qing ni* 清坭). The ‘dirt’ is the calcined ore.

vi ‘Removing the fire’ (*chu huo* 出火). This probably shows the slag from the blast furnace being disposed of.

VII 'Tipping out the iron' (*dao tie* 倒鐵).

VIII 'Making bars' (*zuo tiao* 作條).

Plate IX 'Pouring molten iron' (*luo tie shui* 洛鐵水), gouache painting by an unknown Chinese artist, probably in Guangzhou, mid-19th century. This is no. 8 in a series of 10 showing the casting of woks. Reproduced with the permission of the British Library (Oriental and India Office Collections, Add. Or 2333–2342; see Wagner, 1999b).

Plate X Melting iron? Gouache painting by an unknown Chinese artist, probably in Guangzhou, mid-19th century. Reproduced with the permission of Martyn Gregory Gallery, London; see also Gregory (2004, p. 60).

Plate XI A wok repairman, gouache painting by the Chinese artist You-qua in Guangzhou, mid-19th century (The Royal Library, Copenhagen, Ny kongl. Saml., 346[b], 2°, no. 33). An illustration by Van Braam Houckgeest (1797, pl. 1, facing p. 281) shows that this is a copy of an original which is at least as early as the late 18th century.

Plate XII Photographs and sketched reconstructions of two bronze–iron weapons of the early Zhou period, reproduced from Gettens et al. (1971, frontispiece, p. 12, fig. 6, p. 20, fig. 12). *Top: ge* 戈 dagger-axe head, remaining dimensions 18.3 × 7.0 cm. *Bottom: qi* 鏚 axehead (or *yue* 鉞 axehead), remaining dimensions 17.1 × 10.8 cm. These are believed to come from a single tomb excavated in 1931 somewhere in the vicinity of Anyang 安陽, Henan (Gettens et al., 1971, pp. 57ff).

Analysis indicates that the iron parts of both contain significant amounts of nickel and cobalt; they are therefore most probably meteoritic. In addition, the distribution of nickel and cobalt in the microstructure of the Qi-axehead indicates a Widmanstätten structure distorted by heating to a temperature above 600°C for a few minutes (Gettens et al., 1971, pp. 23ff). This strengthens the conclusion that it is meteoritic iron, and may perhaps also indicate that it was shaped by hot-working. The *ge*-axehead was too badly corroded to permit the detection of a Widmanstätten structure, and no conclusion is possible as to how it was shaped.

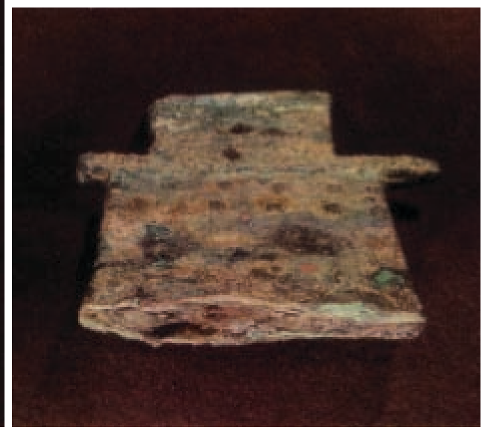



Plate XIII Two photographs of a bronze–iron *yue* 鉞 axehead from a late Shang city-site at Taixicun in Gaocheng County, Hebei 藁城臺西村, reproduced from Tang Yunming and Liu Shishu (1973, pl. 1). On the site see Anon. (1977a); Tang Yunming (1979; 1985). Remaining dimensions 11.1 × 8.5 cm.

Analysis shows that the iron part contains significant amounts of nickel and cobalt, and their distribution in the microstructure suggests a Widmanstätten structure which has been severely distorted by hot-forging (Li Zhong, 1976b; Li Chung, 1979). The iron is therefore most probably meteoritic.

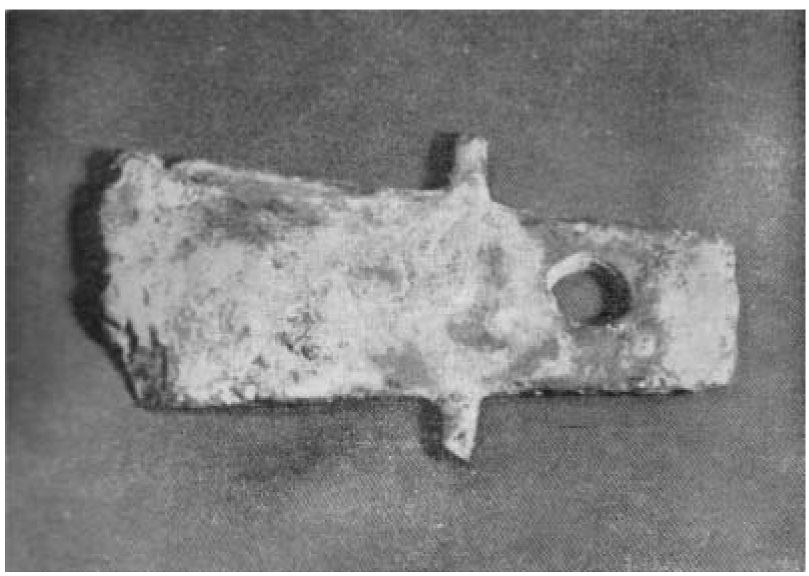


Plate XIV Photograph of a bronze–iron *yue* 鉞 axehead found in a Shang-period grave excavated at Liujiahe in Pinggu County, Beijing Municipality 北京市平谷縣劉家河, reproduced from Yuan Jinjing and Zhang Xiande (1977, pl. 1.1); cf. Anon. (1990b, pp. 37–9). Remaining dimensions 8.4 × 5 cm.

Laboratory studies indicate that the iron part contains a significant amount of nickel, and that the distribution of nickel in the microstructure is consistent with that in a Widmanstätten structure severely distorted by hot-working. The iron is therefore probably meteoritic (Zhang Xiande and Zhang Xianlu, 1990).

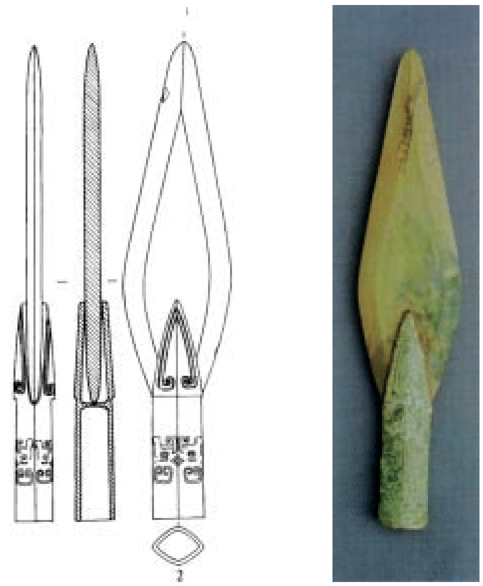


Plate XV Sketch and photograph of a spearhead of bronze and jade from a Shang-period tomb at Huayuanzhuang in Anyang, Henan (artefact no. M54:349), reproduced from Xu Guangde and He Yuling (2004, p. 17, fig. 13.2). Total length 24.5 cm.

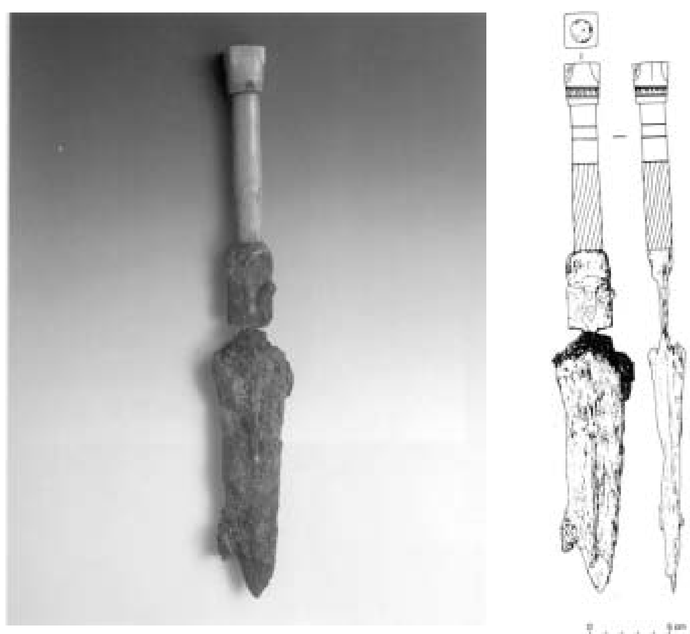


Plate XVI Photograph and sketch of an iron short-sword with hilt of bronze, jade, and turquoise (artefact no. M2001:393) from the tomb of Guo Ji 虢季 in Sanmenxia, Henan, dated to the –9th or –8th century. Total length 34.2 cm, blade breadth 3.8 cm. Reproduced from Anon. (1999, vol. 1, p. 128, fig. 105.1: vol. 2, colour pl. 11.1; note also pl. 44). Note also Anon. (1992, pl. 104); Ru Yu (1999).

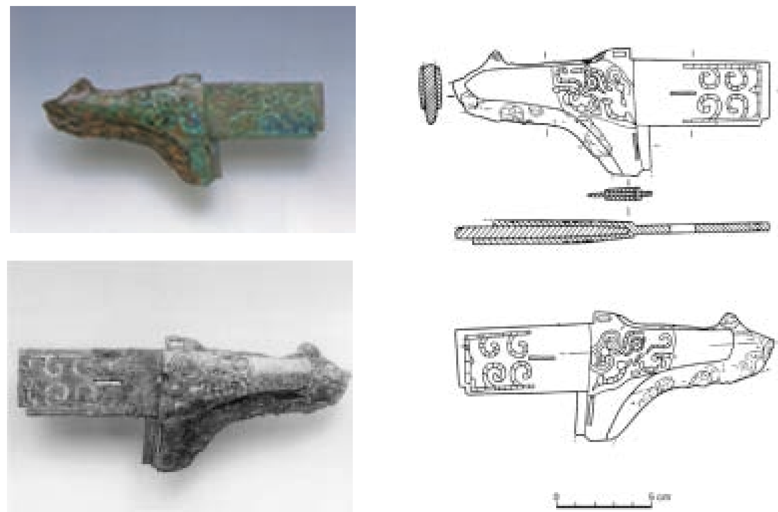


Plate XVII Photographs and sketches of a bronze–iron *ge* 戈 dagger-axe head with turquoise inlay (artefact no. M2001:526) from the tomb of Guo Ji 虢季 in Sanmenxia, Henan, dated to the –9th or –8th century. Total length 17.4 cm, thickness 0.5 cm. Reproduced from Anon. (1999, vol. 1, p. 128, fig. 105.3–4; vol. 2, colour pl. 11.2; pl. 45.2).

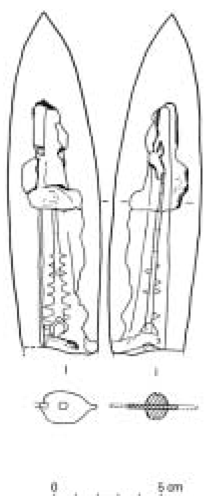


Plate XVIII Sketch of a bronze–iron spearhead (artefact no. M2009:730) from the tomb of Guo Zhong 虢仲 in Sanmenxia, Henan, dated to the –9th or –8th century. Remaining length 12.7 cm, remaining breadth 2.9 cm. Reproduced from Han Rubin et al. (1999, p. 561, fig. 1.2).

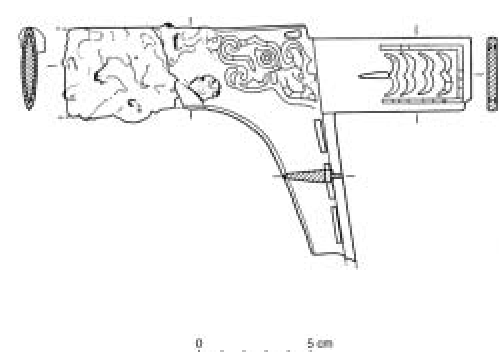


Plate XIX Sketch of a bronze–iron ge 戈 dagger-axe head with turquoise inlay (artefact no. M2009:703) from the tomb of Guo Zhong 虢仲 in Sanmenxia, Henan, dated to the –9th or –8th century. Remaining length 19 cm, thickness 0.4 cm. Reproduced from Han Rubin et al. (1999, p. 561, fig. 1.1). A photograph of the same artefact is given by Han Rubin (2002b, p. 85, fig. 1).

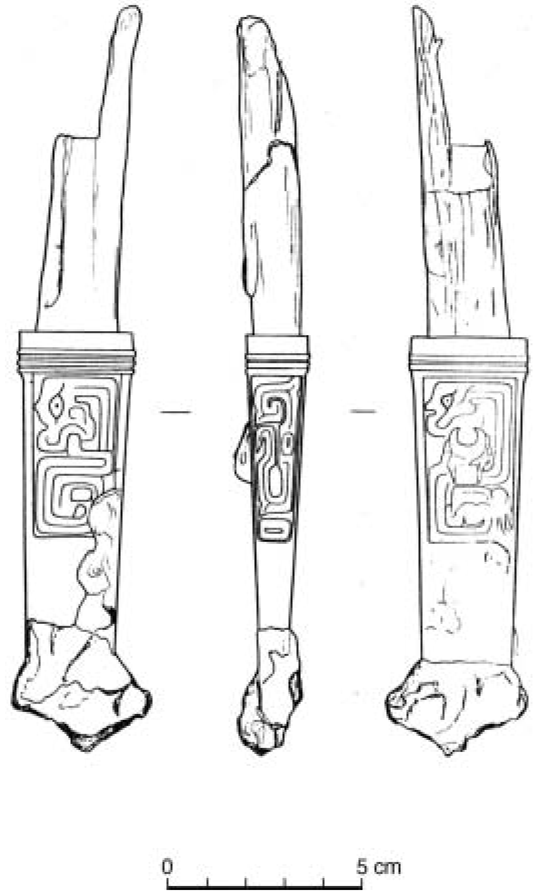


Plate XX Sketch of a bronze–iron adze-head with remains of a wooden insert (artefact no. M2009:720) from the tomb of Guo Zhong 虢仲 in Sanmenxia, Henan, dated to the –9th or –8th century. Remaining length 11.3 cm. Reproduced from Han Rubin et al. (1999, p. 561, fig. 1.4).

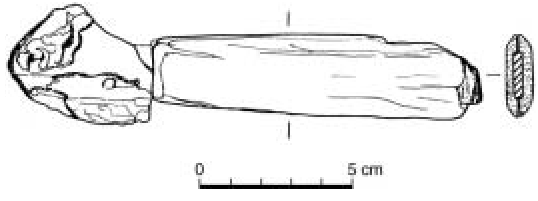


Plate XXI Sketch of a bronze–iron scraper-blade in a wooden sheath (artefact no. M2009:732) from the tomb of Guo Zhong 虢仲 in Sanmenxia, Henan, dated to the –9th or –8th century. Remaining length 11.2 cm, blade thickness 0.2 cm. Reproduced from Han Rubin et al. (1999, p. 561, fig. 1.4).

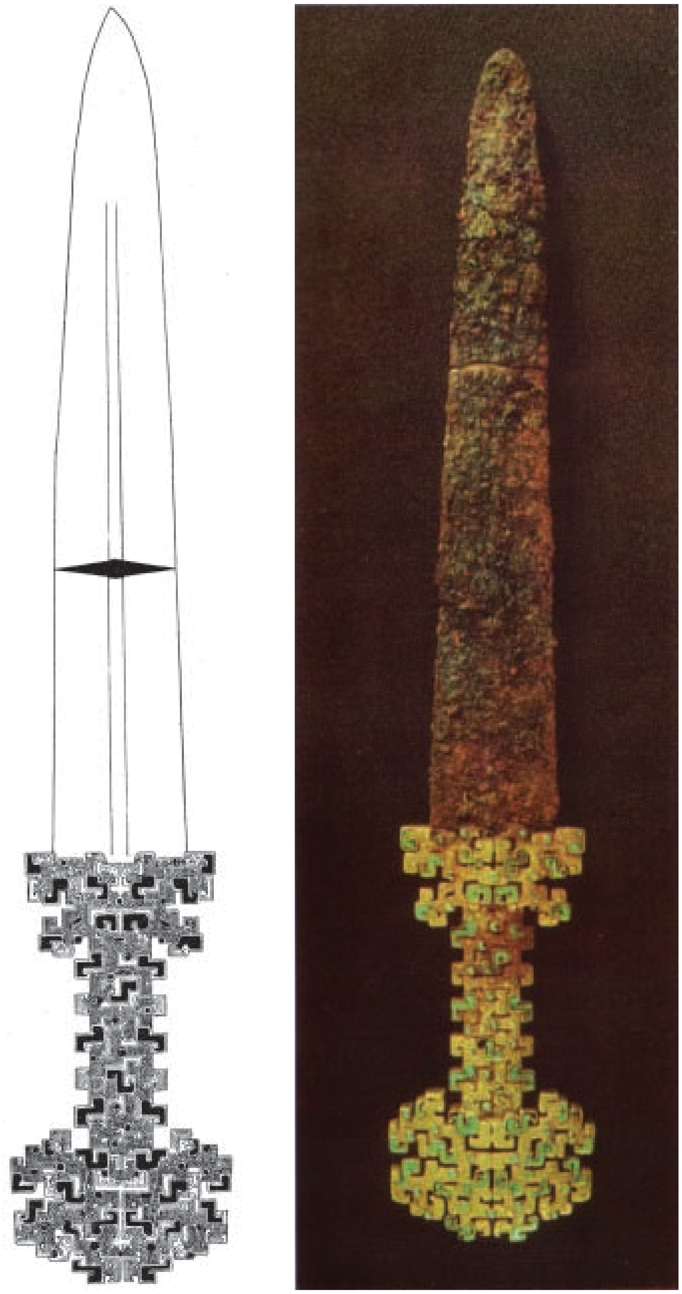


Plate XXII Sketch and photograph of an iron short-sword with inlaid gold hilt from Grave no. M2 at Yimencun in Baoji Municipality, Shaanxi 寶雞市益門村 (artefact no. M2:1), reproduced from Tian Renxiao (1993, p. 4, fig. 7.1, colour pl. 1). Total length 35.2 cm, breadth of blade 4 cm.

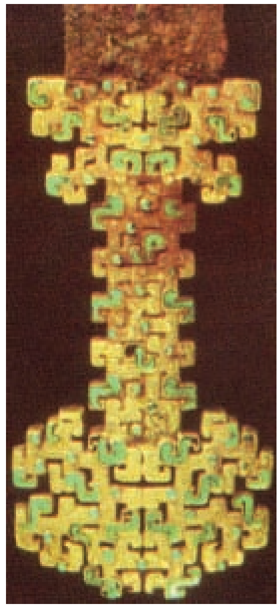


Plate XXIII Detail of Plate XXII, showing the décor of the gold hilt of the short-sword.

Plate XXIV Photograph of an iron short-sword with inlaid gold hilt from Grave no. M2 at Yimencun in Baoji Municipality, Shaanxi 寶雞市益門村 (artefact no. M2:2), reproduced from Tian Renxiao (1993, colour pl. 2). Fragmentary length 30.7 cm, breadth of blade 3.8 cm.

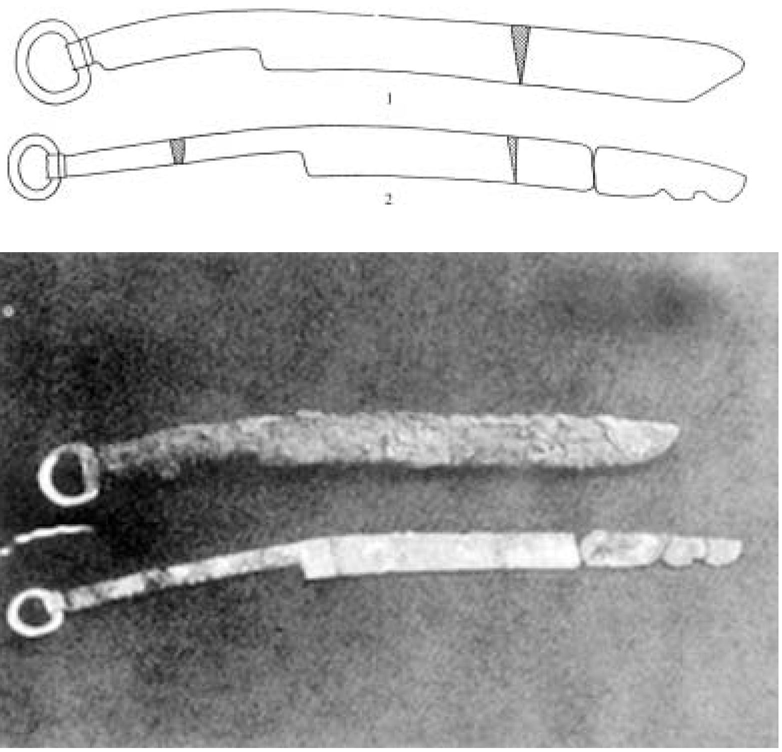


Plate XXV Sketch and photograph of two knives with gold ring-heads from Grave no. M2 at Yimencun in Baoji Municipality, Shaanxi 寶雞市益門村, reproduced from Tian Renxiao (1993, p. 6, fig. 11, pl. 1.5). *Upper* (artefact M2:4): iron blade; total length 23.4 cm. *Lower* (artefact no. M2:18): bronze blade, fragmentary length 24 cm.

Plate XXVI Photograph of an iron short-sword with inlaid gold hilt from Grave no. M2 at Yimencun in Baoji Municipality, Shaanxi 寶雞市益門村 (artefact no. M2:3), reproduced from Tian Renxiao (1993, pl. 1.6). Fragmentary length 35 cm, breadth of blade 3.7 cm.

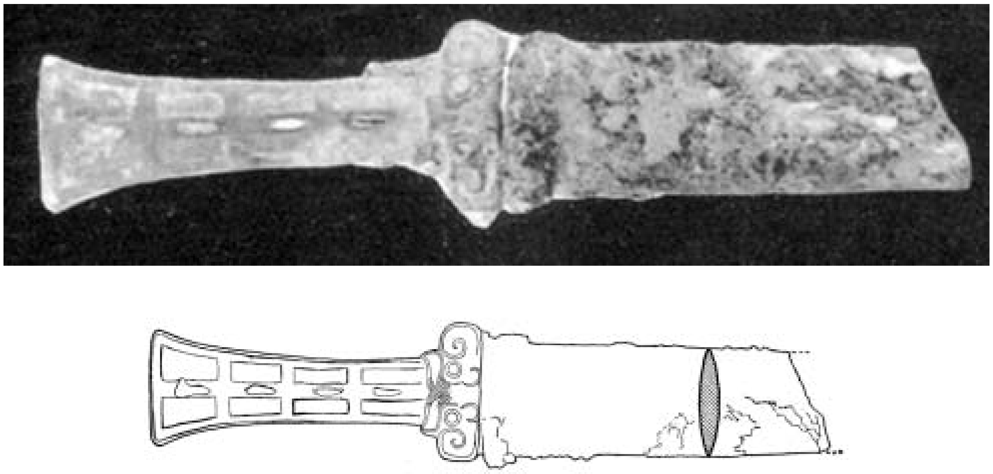


Plate XXVII Photograph and sketch of a fragment of a bronze–iron short-sword from Tomb no. M1 at Jingjiazhuang in Lingtai County, Gansu 靈臺縣景家莊 (artefact no. M1:14), reproduced from Liu Dezhen and Zhu Jiantang (1981, p. 299, fig. 2.7, pl. 5.10). Length of bronze haft 8.5 cm, fragmentary iron blade 9 cm.

a **b** **c**

Plate XXVIII Three Chinese iron coins in a private Danish collection. **a**. *Ban liang* 半兩 (Western Han period). **b**. *Chong ning zhong bao* 崇寧重寶 (+1102–6). **c**. *Xian feng tong bao* 咸豐通寶 (1851–61). Diameters: **a**. 24 mm; **b**. 32 mm; **c**. 23 mm.

Plate XXIX The four cast-iron warriors guarding the 'Depository of Ancient Spirits' (*Gu shen ku* 古神庫) of the Zhong Yue Temple 中嶽廟 in Dengfeng 登封, Henan photographed by Édouard Chavannes in 1907 (reproduced from Chavannes, 1909–15, pl. 968). Heights range from 254 to 260 cm. An inscription cast into one indicates that they were cast in +1064 (Shi Yan, 1988, p. 35); Chavannes appears to be mistaken when he gives the date 1213.

Plate XXX One of the warriors shown in Plate XXIX. Photo by DBW, 1987.

Plate XXXI Detail of the casting shown in Plate XXX. Photo by DBW, 1987.

Plate XXXII The 'iron men' and 'iron oxen' cast in +724 as anchors for the floating bridge over the Yellow River at Pujin 蒲津, in modern Yongji 永濟 County, Shanxi, under excavation and conservation. Photos: *left*, Tang Huancheng 唐寰澂; *right*, John Moffet. Archives of the Needham Research Institute.

Plate XXXIII The 'Iron Rhinoceros' in the village of Tieniu 鐵牛, 2 km northeast of Kaifeng, dated 1446. Photo by DBW, 1987.

Plate XXXIV Detail of the back of the 'Iron Rhinoceros' shown in Plate XXXIII.

Plate XXXV The Cangzhou Lion, photographed by Thomas T. Read at some time between 1907 and 1910. His caption reads, in part: 'It . . . was cast in 953 A.D. in sections, like a concrete building. It was broken, in falling over, into four separate pieces, one of which, the lower jaw, is lying on the ground, not visible in the picture, while the head and the "lotus seat" have been awkwardly propped in place with slabs of stone, so something of the original appearance has been lost.' (Read, 1937, p. 383).

Plate XXXVI The Cangzhou Lion photographed in 1987. Note the modern repair and the missing lower jaw. Photo by DBW, 1987.

Plate XXXVII Inside the head of the Cangzhou Lion, showing more of the modern repairs. Part of the cast-in wrought-iron reinforcement can also be seen extending from the centre of the photograph to the lower right corner. Photo by DBW, 1987.

Plate XXXVIII The rump of the Cangzhou Lion. Photo by DBW, 1987.

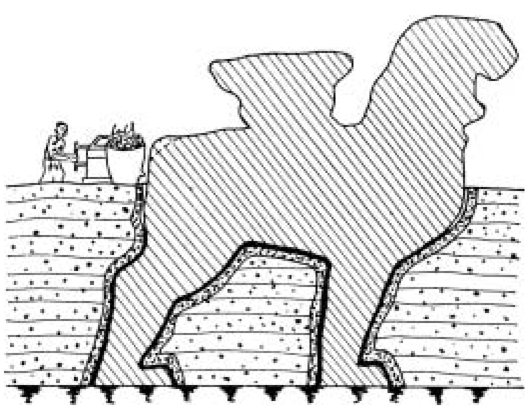


Plate XXXIX Sketch showing how the Cangzhou Lion was cast, reproduced from Wu Kunyi et al. (1984, p. 83).

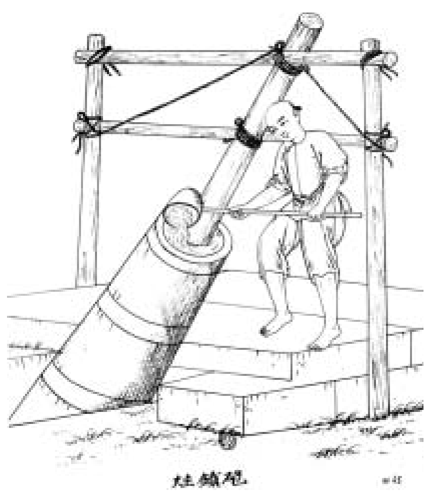
Plate XL A Qing-period cast-iron gun, photographed at the Great Bell Temple, Beijing, 1984. In 1987 it was no longer there, and I do not know its present whereabouts.

Plate XLI A cast-iron gun, cast in 1841, photographed in front of the Guangzhou Museum, 1984.

XLII

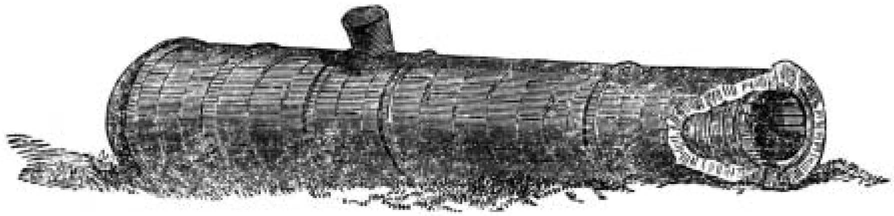
XLIII

XLIV

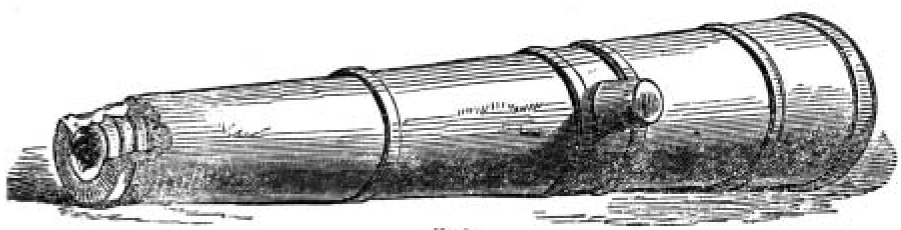


XLV

Plates XLII–XLV The moulding and casting of a gun: line drawings and gouache paintings by unknown Chinese artists. Purchased by members of the Mission Lagrenée in Guangzhou, ca. 1842, and now in the Bibliothèque Nationale, Paris. ('Métallurgie du fer', Oe 114 4°, nos. 3–4; 'Métallurgie du fer', Oe 118, nos. 3–4. Cf. Huard and Wong (1966, pp. 199, 217–19).)



No. 1.



No. 2.

Plate XLVI Two Chinese guns sketched in 1860 by George Banks at the Dagu 大沽 Forts, in modern Tianjin. Banks believed that these were 'evidently very old', from the 17th century or before; while this dating is quite plausible it is not clear what evidence he could have had for it. He does not mention any inscriptions.

'No. 1 had a piece broken from the muzzle, which enabled me to see how it was made. The inner part or bore was made of longitudinal bars, one inch wide and half an inch thick [2.5, 1.25 cm], welded together, and forming a lip where they terminated at the muzzle. Round these, and binding them together, were rings, one inch thick and three inches wide [2.5, 4.5 cm], also welded. Outside these, again, is a layer of cast iron, two inches and three-quarters [7 cm] thick at the muzzle, and of course much thicker at the breech, giving shape to the gun. The faint lines on the surface are caused by the crevices between the bricks of which the mould was built in which the casting took place. This piece is 9 feet 6 inches long, 23 inches diameter at the breech, and 15 inches diameter at the mouth [291, 60, 39 cm]. No. 2 is a similar gun, but with only rings welded together and encased in cast iron. It is very singular that both these guns should be broken in the same way. It is 9 feet 7 inches long, 2 feet 1 inch diameter at the breech, and 16 inches at the mouth [292, 64, 41 cm]' (Banks, 1861).

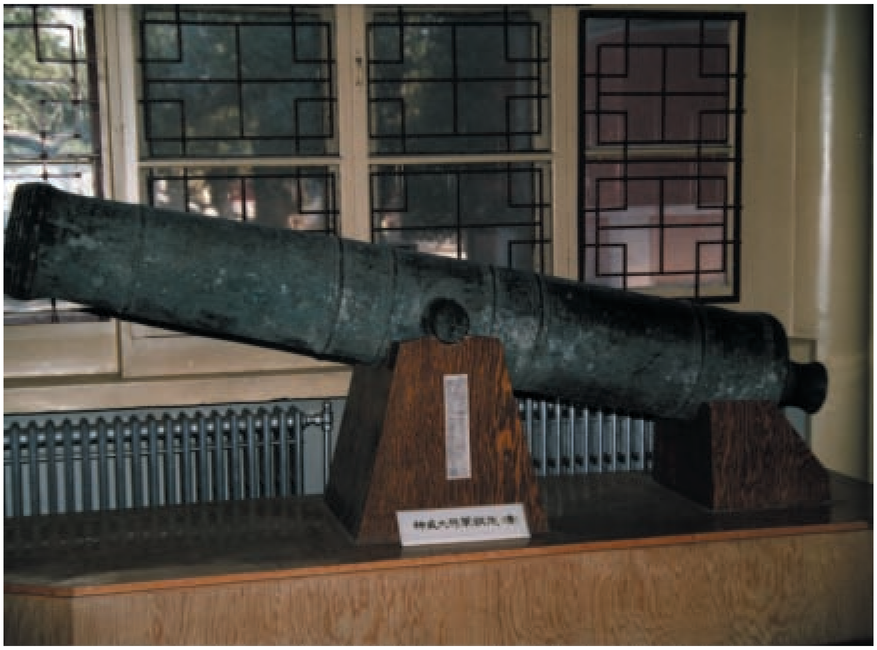


Plate XLVII A large gun in the Capital Museum (Shoudu Bowuguan 首都博物館), Beijing, cast in 1643. Cf. Plate XLVII Photo by DBW, 1987.

Plate XLVIII The muzzle of the gun in Plate XLVII**.** Note that it is iron on the inside and bronze on the outside. Photo by DBW, 1987.

36(c). FERROUS METALLURGY

1 INTRODUCTION

> Iron seemeth a simple metal, but in its nature are many mysteries, and men who bend to them their minds shall, in arriving days, gather therefrom great profit, not to themselves alone but to all mankind. *Attributed to Joseph Glanvill (1636–80)*

The metallurgy of iron has long presented numerous mysteries to which craftsmen and philosophers have bent their minds. The craftsmen – smiths, ironfounders, and others – accumulated over millennia the amazing variety of techniques which made this the most useful and versatile of metals. Today we see the ancient craftsmen darkly, through folklore and through scientific examination of their works, and we know little of how they thought about their work and explained it to apprentices.

The challenge of explaining what the craftsmen knew provided important impulses to natural philosophers interested in the nature of matter. The names of Wang Chong 王充, Shen Gua 沈括, Descartes, and Réaumur are perhaps the best known, though there were dozens of others. Wang Chong in the +1st century, attempting to explain thunder and lightning, found a useful model in the iron-founder's furnace.[1] Shen Gua in the +11th century speculated that steel was a kind of gluten, which could be extracted from iron as gluten is extracted from flour.[2] Descartes and other corpuscular philosophers of the 17th century found an enormous challenge to their theories in the quench-hardening of steel.[3] Réaumur in the 18th century, in a long programme of experiments on the technologies of iron and steel, 'alone proceeded to develop corpuscular theory into something useful', in fact developing techniques of great industrial importance; thus began the repayment of the philosophers' debt to the craftsmen.[4]

Ferrous metallurgy had no less influence in economics than in philosophy. Certain fundamental facts about iron and its production have had enormous consequences. First, it has for millennia been a necessity in both agriculture and war. These two fields of endeavour have very different economic circumstances: while an army needs weapons of the best quality, and governments pay what is necessary to supply them, the tools of the farmer always represent a more complex compromise between quality and cost. Thus we shall see that in the Han period weapons were nearly all of wrought iron or steel, while agricultural implements were usually of cast iron. It is safe to assume that a Han peasant would have preferred an axehead,

1 P. 252 below.
2 P. 321 below.
3 C. S. Smith (1988, pp. 71–85). On quench-hardening, and on Chinese ideas about it, see pp. 133–7 below.
4 C. S. Smith (1988, p. 85). See also pp. 161–2 below.

for example, made of steel by a smith, but the many cast-iron axeheads which have been found in Han excavations must have cost much less to produce, and no doubt were preferred for this reason alone.

Iron ores, and the fuel needed for smelting, are found nearly everywhere in the world in quantities sufficient for pre-modern production levels, and iron is relatively cheap by weight. These two facts mean that transportation costs are an extremely important factor in the geography of pre-modern iron production. In Europe, until late medieval times, iron was most often a local product, and only especially high-quality grades were traded over long distances. The situation was rather different in China. Blast-furnace iron production, which was practised from very early times in China but only much later in Europe, is efficient only at high production levels, and in addition provides great economies of scale: efficiency increases as production increases. Thus it was economic to produce for much larger markets than in Europe, with the cost of transportation and marketing a less important factor in the cost of iron.

Another implication of the widespread availability of raw materials is that, in large markets, competition between iron producers will be intense and profits low. So that whenever marketing conditions encourage large-scale production, this production will tend to be located in regions which do not have the resources to produce more profitable goods – their 'comparative advantage' is in iron production. Thus, in pre-modern China, iron production was often located in the poorest regions.

Of course numerous other factors also influenced the geographic distribution of the industry, including transportation conditions and the availability of ores with special properties. Of great importance is that, in early iron production, the limiting factor is wood for charcoal. For this reason, large-scale iron production should be located close to abundant forest resources and distant from competing consumers of fuel, especially the populations of cities. This consideration has often led to the appearance of specialised industrial villages, isolated in forests, whose activities were entirely centred about the production of iron. These were called 'iron plantations' in colonial America and *järnbruk* in 18th-century Sweden. The same sort of situation seems to have existed in the province of Guangdong in recent centuries, and in many parts of China in the –3rd and –2nd centuries.[5]

Here I have described a few technical aspects of iron production and the ways in which they influence the economics and geography of the industry. In this volume we shall see many examples of how such influences play against each other to produce different results in different times and places, in turn influencing wider historical developments.

The rôle of the Chinese state in the iron industry is one of the threads running through this volume. Any state will attempt to extract a share of all economic activity, and the early Han period saw a curious 'self-assessed' tax (about which

[5] Pp. 47–59 and 144–6 below.

virtually nothing is known) on iron production.[6] This was seemingly because the early Han state lacked both the personnel and the technical competence needed to assess the tax. One can imagine that an entirely self-assessed tax was not very effective, and the need for revenue was one of a number of reasons for the establishment in –117 of a state monopoly of all iron production and marketing. The full background for this action, and for the intense opposition which it provoked, have been a matter of dispute, and Section 5 takes up the question in detail.[7] One important reason for the monopoly was surely that the ironmasters, commanding large labour forces deep in mountain forests, were perceived as a danger to the power and prestige of the state and its servants. The monopoly seems to have brought these 'primitive "capitalists" or industrialists' (as Joseph Needham called them[8]) into the Han civil service, making them more manageable. It also brought the blast furnaces to the cities – a disposition which was economic and ecological madness, but good sense from the point of view of administration and control. Later in the Han period, the monopoly arrangements were first reformed and then abandoned, no doubt because of political and economic developments: transportation and markets were improving, making contraband production and sale easier, at the same time that the central government's decline relative to local power centres made enforcement doubly difficult. This at the same time that the forests were receding and the supply of charcoal for the state blast furnaces, in competition with the needs of urban populations, was becoming more and more costly.

The state's involvement in the industry took other forms after the Han, and there was never again any attempt to take full control of iron production and marketing. In the Period of Disunion, between the Han and Tang periods, we often hear of military ironworks, and there were also some civil ironworks established by the state, but these do not reflect a monopoly.[9] In the Tang period there seems to have been a tax on iron production, but we have no information on how it was assessed or enforced.[10]

From the Song period onward, better sources give a clearer view of the interaction between the state and the iron industry. In the Song there was a bewildering variety of *ad hoc* local arrangements to provide tax revenue and raw materials to the state and protection and legitimacy to the industry.[11] The Song central government was never very powerful, and we see in the sources constant negotiation about these arrangements between local and state interests.

The development of the use of mineral coal rather than charcoal in iron smelting, seemingly from about the +10th century, brought a major change in the geography of the industry. In the heavily forested south, charcoal continued to be used, and the

[6] P. 181 below.
[7] Pp. 221–9 below.
[8] Needham (1958, p. 7).
[9] Pp. 249–52 below.
[10] Pp. 251–2 below.
[11] Pp. 294–305 below.

best iron came from here. In the badly deforested north, most iron production used mineral coal. The problem of sulphur in the iron produced seems never to have been solved before modern times, so that most of the iron produced in the north was used for cast-iron products, in which sulphur was not a major problem, rather than being converted to wrought iron and steel.

The government's need for high-quality iron and steel weapons led to the establishment in the early Ming period of a state ironworks in Zunhua, near the capital, Beijing. It produced charcoal iron at great financial and ecological cost in order to obviate the need for transportation of iron from the south. As transportation and the market economy developed in the course of the Ming, and high-quality iron and steel from the south became easily available in north China, the Zunhua ironworks became more and more of an expensive anomaly. It was finally closed in 1581, after 150 years of continuous production, and from then until the end of the dynasty the state's need for iron and steel was supplied by the open market. A brief attempt to reopen it was made in 1623 by the now-failing dynasty, without success.[12]

It is here at the end of the Ming that the chronological part of this volume ends, for Joseph Needham's plan for *Science and Civilisation in China* sets the year 1600 as its terminus. Outside the chronological narrative, Section 2, immediately below, gives an introduction to the technology and economics of iron production in China, based on detailed studies of the iron industries of four regions in recent centuries. Section 3 then goes back to the beginning and considers the first use of iron in China. Succeeding sections proceed more-or-less chronologically. It will be seen from the Section titles that in each period some single aspect has seemed to me most important, but in fact I have attempted to cover all aspects which the archaeological and textual sources make available to us. Finally Section 9 takes up a question which was dear to Joseph Needham, the debt of modern industry to the pre-modern Chinese iron industry.

[12] The story of the Zunhua ironworks is told in detail in Section 8(i) below, pp. 327–39.

2 INTRODUCTORY ORIENTATIONS: THE TRADITIONAL CHINESE IRON INDUSTRY IN RECENT CENTURIES

It will be useful to distinguish here between *primary* iron-production techniques, for the production of cast or wrought iron from ore, and *fabrication* techniques, those used by the ironfounders and smiths to make useful products from this raw material. It happens that the primary techniques differed greatly from place to place in China, while the fabrication techniques, to the extent that we can see them clearly in the sources, seem to have varied much less.

In the following we shall consider the traditional primary iron-production techniques of four parts of China: the Dabieshan 大別山 region of southern Henan and northern Hubei, and the provinces of Sichuan, Guangdong, and Shanxi. These places were chosen partly because of the availability of good documentation and partly because of the special interest of their technologies. The traditional fabrication technologies will then be considered without geographic restriction.

The flow diagram of Figure 1 will serve to show the general structure of the traditional iron industry in the first three places mentioned. That of Shanxi, with its 'crucible smelting' technology, was quite different and will be discussed separately.[1] As in the modern steel industry, the process generally used in China was 'indirect'. Cast iron with a high carbon content was produced from ore in the *blast furnace*[2] (see Box 1 below[3]); this product could be used directly in a foundry, but most of it was converted to wrought iron (or more correctly, mild steel)[4] with typically 0.1 per cent carbon. This was the basic material of the smith; when something harder was needed, for example for the cutting edge of a knife, it was necessary to put some carbon back into the iron, to make a medium-carbon steel. High-carbon steels, with over 1 per cent carbon, were rarely used. Some steelmaking techniques could be used by the smith himself, but he could also obtain steel stock from specialised producers.

The indirect process is the most efficient way of producing wrought iron, in spite of the curious roundabout way in which it works, with carbon first being put into the iron to make cast iron, then removed again. The modern blast furnace is in principle not much different from the traditional Chinese blast furnaces, though it is

[1] Pp. 38–46.
[2] The modern Chinese word is *gaolu* 高爐, literally 'high furnace', which must have come from the German *Hochofen*, probably through Japanese (Liu Zhengtan, 1984, p. 114). A number of Chinese terms for 'blast furnace' have been used traditionally in particular localities, but there seems to have been no single widely understood term for this particular type of furnace. Curious but probably not significant is the fact that a Song text, *San shan zhi* (ch. 14, pp. 7749–51) refers to blast furnaces using the modern term *gaolu*.
[3] Pp. 14–15.
[4] See pp. 65–6.

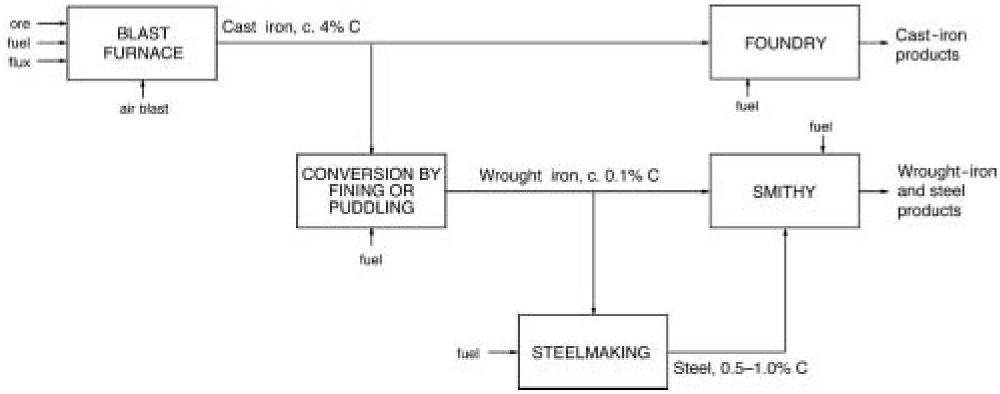


Figure 1 Flow diagram of traditional Chinese blast-furnace iron production.

much larger and has been improved in a variety of ways. The means by which carbon is removed are quite different, and in the West have changed a number of times, from the fining hearth of medieval times (with some resemblance to the traditional Chinese fining hearth) to the puddling furnace, patented in 1784, to the Bessemer converter of 1855, and on to a variety of ever more efficient devices.

An important fact about indirect iron production is that it provides unusually large economies of scale: the greater the production, the lower the cost of the product per unit.[5] This fact has had enormous historical importance: for example it is surely one of the factors in the rise of capitalism in the West. In China, as we shall see, it may have been an important factor in the rise of the state of Qin in the −3rd century.[6] It is therefore curious, and in need of explanation, that the Chinese blast furnaces which we shall see in the following are found in such a range of sizes, from the 'dwarf' furnaces of Dabieshan, only 2–3 metres high, to the very large furnaces of Sichuan and Guangdong, up to 10 metres high. The explanation lies in the fact that large-scale production requires heavy investment and a large and stable market, so that potential economies of scale can be exploited only in regions with good transportation. In more isolated regions, such as Dabieshan, transportation costs added so much to the cost of iron that it was economically rational to set up a small-scale production for local needs in spite of its relative inefficiency.[7] And these small furnaces are not all that inefficient: though at first sight they look 'primitive', it is probably more correct to see them as a highly sophisticated development out of the larger furnaces, providing reasonable efficiency on a production scale which fills the needs of the population of an isolated region.

[5] See Section 2(viii) below, pp. 81–2.
[6] Pp. 146–7.
[7] The same point was made by Mathias (1959, p. xxiii) for the English brewing industry. (I owe this reference to G. Hollister-Short.)

Figure 2 Map of the Dabieshan region.

(i) Small-scale Ironworks of the Dabie Mountains

Dabieshan 大別山, around the point at which the provinces of Anhui, Henan, and Hubei meet, comprises a region of rugged mountains and fertile valleys where poverty is severe.[8] Until the 1960s there was hardly a road here, and most transport within the region was on foot or horseback. It has also traditionally been very isolated from other regions, for there is no good water transport available. The

8 On the physical geography of the region see *SCC*, vol. 1, esp. p. 66. On its human geography very little has been written, but see McColl (1967); Di Xianghua (1987); Li Runtian (1987, pp. 328–40).

Beijing–Hankou Railway, completed in 1906, touches the region only at its extreme western end, at Xinyang 信陽, and seems to have had little impact on the local economy. The principal natural resources here are forests and minerals, but the isolation of the region has made any large-scale exploitation of these unprofitable. A small-scale iron industry has, however, been important in the local economy, and this survived at least until the Great Leap Forward of 1958–59, when it was the model on which many other regions based their attempts to build up small-scale ironworks.

In a small book of mine on the iron industry of the Dabieshan region[9] I drew on two accounts by travellers who visited there, the Swedish geologist E. T. Nyström about 1917 and the Chinese geologist Guo Yujing 郭玉璟 in 1932, and on several technical studies prepared in connection with the Great Leap Forward.[10] The late Professor Zenshirō Hara, in a review of that book, pointed out several other descriptions in local gazetteers,[11] and I have also found a few more descriptions. Further work has been done by a Chinese team which visited the region in 1993. They investigated archaeological remains and interviewed a 92-year-old man who had worked in an ironworks in his youth.[12] With all this material it is now possible to give an account of the technology in its geographical and economic context. We start with the technology.

Ironsand

The ore used in all these ironworks was ironsand, washed from river sand in sluices of the kind described in Section 36a on mining;[13] see also Figure 134.[14] This was a very rich ore, with iron content from 49 to 65 per cent according to different reports.[15] The richest ironsand contained about 90 per cent iron oxides and only about 5.5 per cent silica; with so little silica in the charge, blast-furnace operation was greatly simplified, since a flux could be dispensed with.[16]

The blast furnace

The small blast furnace in which this ironsand was smelted was of roughly the same type throughout the region. Photographs of three are shown in Figures 3–5; the first two were taken in Henan in 1917, the third in Anhui in 1958. A lively impression of their operation is given by the wood-block print of Figure 6. They are only about

[9] Wagner (1985).
[10] E. T. Nyström in Tegengren (1923–24, pp. 179–80, 334–5); Zhang Youxian and Guo Yujing (1932, pp. 239–41); Anon. (1958a; 1958b); Liu Zhichao and Tang Youyu (1959a). Note also Liu Zhichao and Tang Youyu (1959b); Anon. (1958g).
[11] Hara Zenshirō (1991).
[12] Huang Keying et al. (1995); in English, Miao Changxing and Li Jinghua (1994); Huang Keyang et al. (1996).
[13] *SCC*, vol. 5, part 13, pp. 152, 164–5; also Wagner (1985, pp. 8–9, 28–32).
[14] P. 344 below.
[15] Respectively Nyström in Tegengren (1923–24, p. 180); Anon. (1958a, p. 6), tr. Wagner (1985, pp. 12, 49).
[16] The exotic character of the iron-production technology of this region caused reviewers considerable confusion. Bennet Bronson (1987, p. 97) claims that ore with 65 per cent iron is impossible, and William Rostoker (1987b, p. 347) claims that blast-furnace operation without a flux is impossible. Neither reviewer explains the reasons for his disbelief, but both are clearly mistaken.

Figure 3 Blast furnace in Xinyang, Henan, photographed ca. 1917 by E. T. Nyström. Reproduced from Tegengren (1923–24, vol. 2, pl. 34, left).

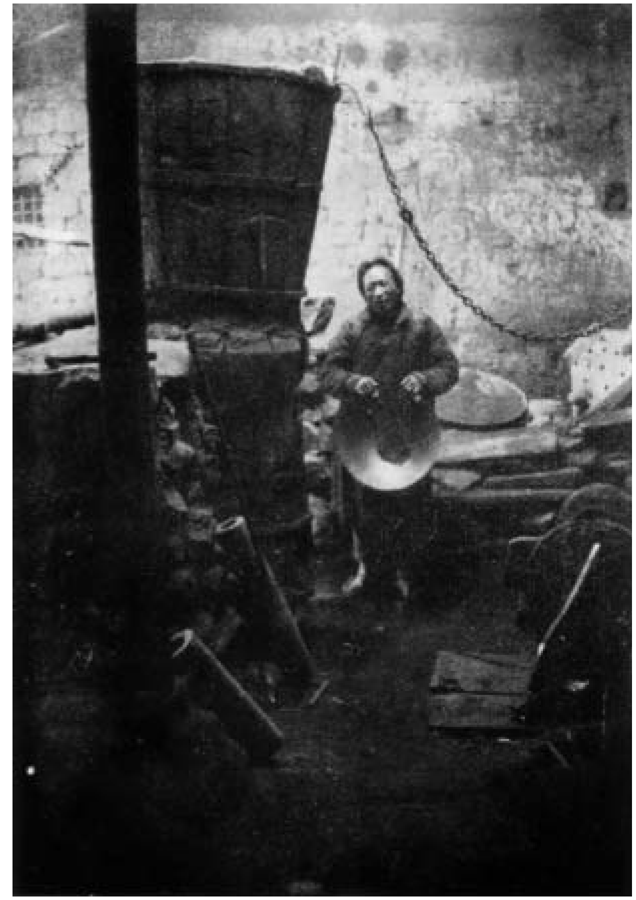


Figure 4 Blast furnace in Xinyang, Henan, photographed ca. 1917 by E. T. Nyström. Reproduced from Tegengren (1923–24, vol. 2, pl. 34, right).

Figure 5 Blast furnace in Jinzhai, Anhui, ca. 1958. Reproduced from Anon. (1959d). Cf. Figure 9.

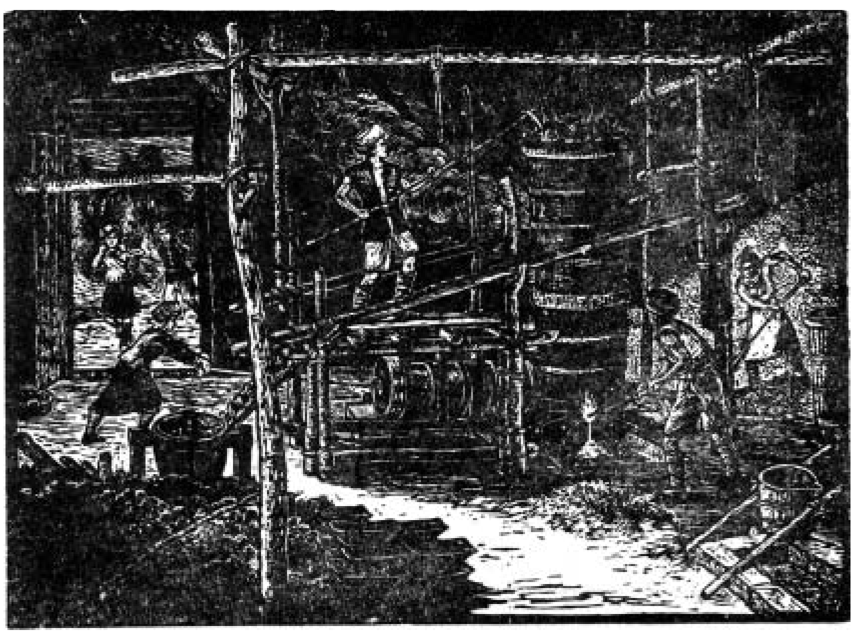


Figure 6 Iron smelting in a traditional blast furnace. Wood-block print by Lei Shikang 雷時康, reproduced from *Yejin bao* 冶金報, 1959, no. 1.

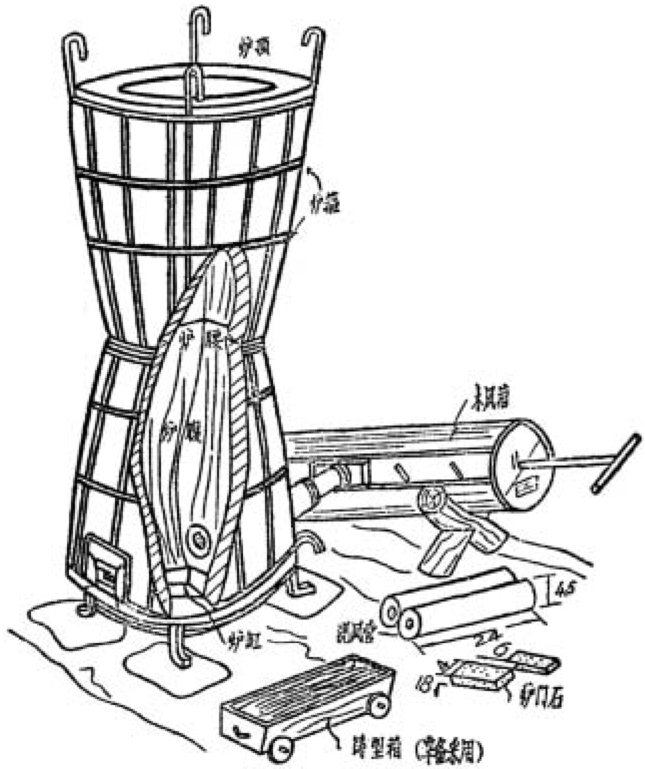


Figure 7 Sketch of the Huang Jiguang blast furnace in Macheng, Hubei, as used in the Great Leap Forward period, and associated requisites, reproduced from Anon. (1958c, p. 22). Cf. Figures 8–9.

2.2 metres high, and are built almost entirely of locally available materials. The instructions for building the Huang Jiguang Furnace[17] 黃繼光爐 used in Macheng 麻城 County, Hubei, diagrammed in Figures 7–8, indicate that the walls of the furnace, which are 10–13 cm thick, are made of a mixture of loess soil, sand, and straw, reinforced with iron bands. This is then lined with a more refractory material, which contains 60 per cent finely powdered charcoal. Around the taphole, where the highest temperatures are encountered, blocks of sandstone are used. In other reports it appears that these 'taphole stones' were the only part of the furnace which could not be obtained locally, but were brought in from as far as 200 km away.[18] The taphole was kept constantly open, since plugging it would have required refractory clay, which was not available locally; slag and iron were tapped by tilting the

[17] Anon. (1958c; 1958l); note also Liu Zhichao and Tang Youyu (1959b). This furnace was named for Huang Jiguang (1930–52), a hero of the Korean War.

[18] Guo Yujing reported in 1932 that in Xinyang the taphole stones were of sandstone from Jiayu 嘉魚, Hubei, while in Shangcheng 商城 they were of diatomite ('diatomaceous earth') from Qishui 蘄水, Hubei (Zhang Youxian and Guo Yujing, 1932, p. 240); cf. Wagner, 1985, p. 50).

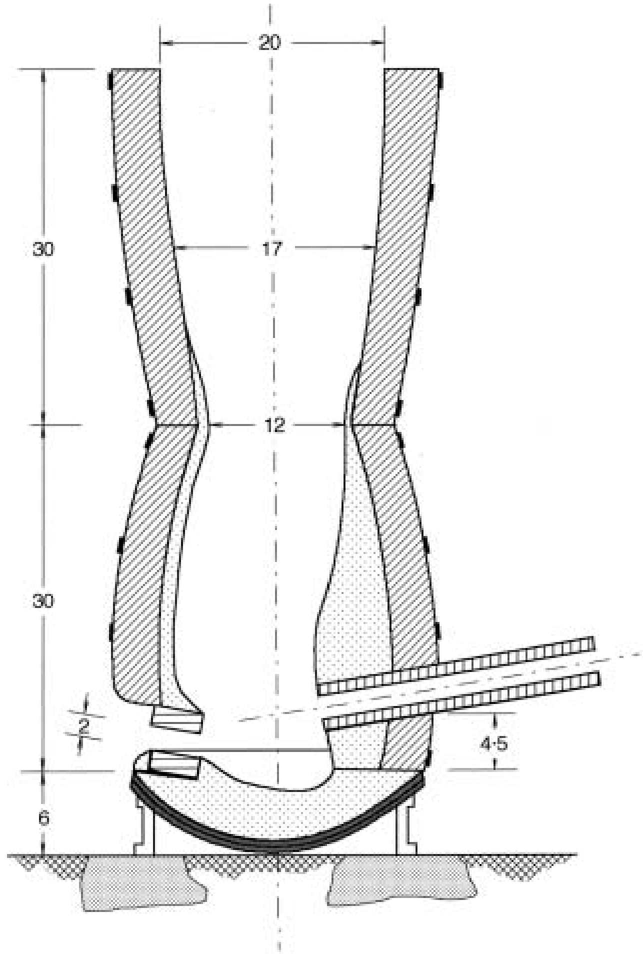


Figure 8 Vertical section of the Huang Jiguang blast furnace in Macheng, Hubei, as used in the Great Leap Forward period, redrawn from Anon. (1958c, p. 22). Dimensions are given in 'market inches' (*shicun* 市寸, 3.3 cm). Cf. Figure 7.

entire furnace, as can be seen in Figure 5. The cross-beams seen in Figures 3, 5, and 6, and the chain in Figure 4, were used to limit this tilt.

The fuel used was charcoal,[19] and blast was provided by a traditional 'windbox' (*feng xiang* 風箱, double-acting piston bellows).[20] The furnace could operate continuously for 6–7 days before it was necessary to repair the inner lining and replace the taphole stones. During this period charcoal and ironsand were charged, and molten iron tapped, several times per hour. Reports from different times and different

[19] On Chinese forestry and charcoal-production methods see *SCC*, vol. 6, part 3 and Wagner (1985, pp. 33–7).
[20] *SCC*, vol. 4, part 2, pp. 136ff; note also Anon. (1958i).

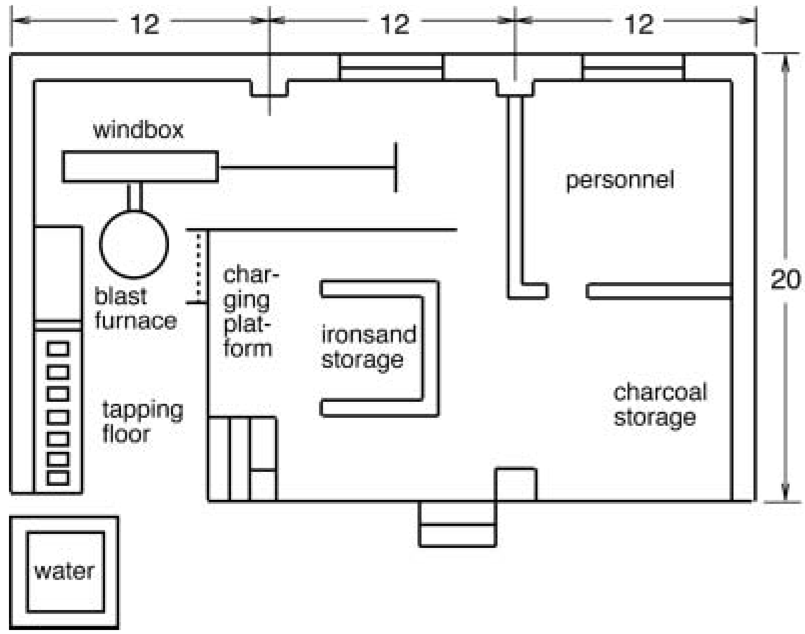


Figure 9 Plan of a 'smelting house' at East Wind People's Commune in Muzidian, Macheng County, Hubei 麻城木子店東風人民公社, reproduced from Anon. (1958c, p. 22). Dimensions are given in 'market feet' (*shichi* 市尺, 33 cm). Note the close correspondence to Figure 5.

places in the region indicate that daily production of pig iron was between 0.6 and 1.2 tonnes, and that the amount of charcoal needed to produce one tonne of pig iron was between 2 and 7.5 tonnes.[21] Labour at the furnace was on the order of 10 worker-days per tonne of iron produced.

In a blast furnace the combustion of the fuel maintains a high temperature, at least 1200°C, near the bottom, and also provides an atmosphere with a large concentration of carbon monoxide (CO). In this highly reducing atmosphere iron oxides are reduced to metallic iron. This iron takes up carbon, reaching a maximum carbon content in the range 4–5 per cent; at this carbon content the melting point of the iron is as low as 1147°C, and it melts. The molten iron collects at the bottom of the furnace until it is tapped. Box 1 gives a more detailed explanation of the operation of a blast furnace.

As was noted above, the ironsand used here contained about 5.5 per cent silica (SiO_2). It was necessary to get the silica out of the furnace in a free-flowing molten slag: silica itself has a very high melting point (over 1700°C), but a mixture of silica and wüstite (FeO) can have a melting point as low as 1177°C.[22] The furnace

[21] The latter figure is that given by Nyström, but Tegengren (1923–24, p. 334 fn.), quoting it, considers it 'fantastically high'. It is quite possible that Nyström was misinformed.

[22] Muan and Osborn (1965, p. 62, fig. 45a); Rosenqvist (1974, p. 345).

Box 1 *Technical details of the operation of an iron blast furnace.*

Empirical research provides considerable detail on what happens inside the modern blast furnace, and that is what will be described here. Of large charcoal blast furnaces like those traditionally used in Sichuan it is possible to say that the basic principles are the same but with the major difference that all temperatures are lower.[a] Of small charcoal blast furnaces like those of Dabieshan it is reasonable to assume that the basic principles are approximately the same, but with the possibility of surprising differences.

A modern blast furnace operates continuously for months or years at a time, with coke, ore, and flux being charged in the top, air being blown through numerous tuyères near the bottom, and molten iron and slag being tapped out of tapholes at the bottom. Operation continues until the furnace lining has been so damaged by the high temperatures that it is necessary to repair it.

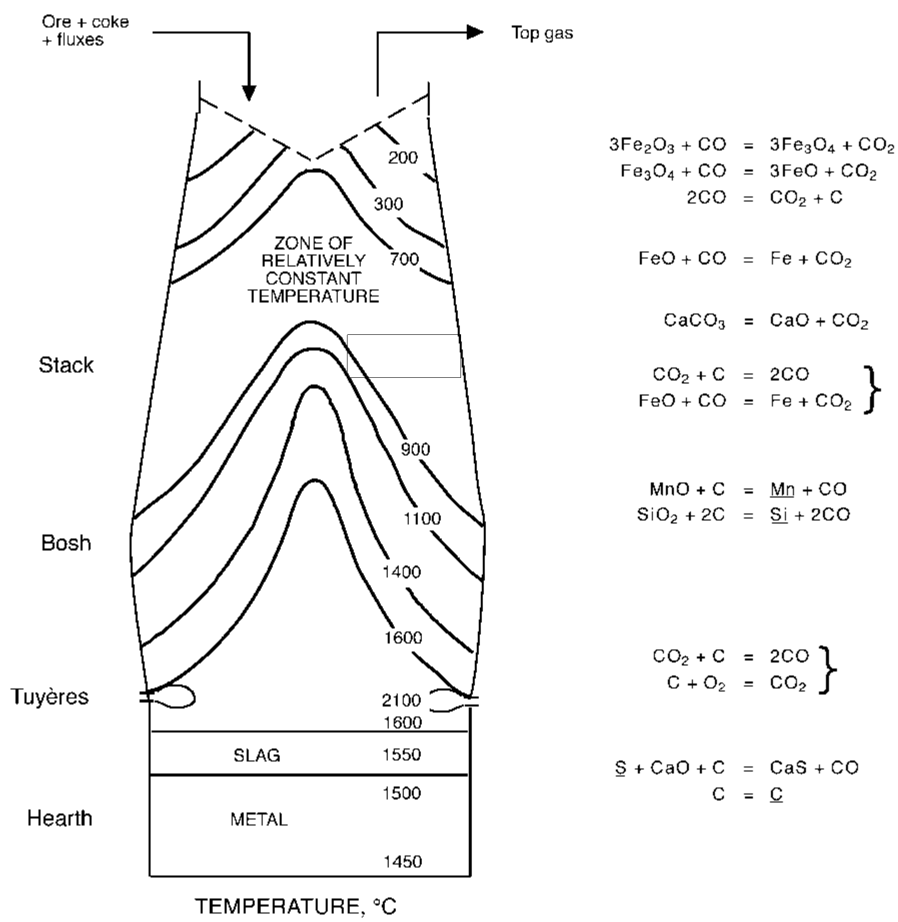


Figure 10 Diagram of a modern large-scale coal-fuelled iron blast furnace, after Peacey and Davenport (1979, p. 17, fig. 2.1) and Rosenqvist (1974, p. 274, fig. 9–4). The height is typically 20–30 m. Temperatures in °C are indicated for isotherms inside the furnace. The reactions which take place are indicated at the right; underlined elements are in solution in iron.

Box 1 *Continued*

The ore has been **calcined** (roasted) before charging, so that the iron in it is entirely in the form of Fe_2O_3 (ferric oxide, hematite). The fundamental reactions in the blast furnace are the reduction of this by CO (carbon monoxide), first to Fe_3O_4 (ferrosoferric oxide, magnetite), then to FeO (ferrous oxide, wustite), and finally to metallic iron. Some carbon, typically about 4 per cent by weight, dissolves in the iron near the bottom; with this carbon content the melting point of the iron is under 1200°C.

The combustion of coal at the tuyères produces CO_2 (carbon dioxide), and this reacts with carbon to produce the necessary CO. The CO reacts with the iron oxides to produce CO_2 again, this reacts with carbon to produce CO, and so forth in a cycle. The necessary conditions for each reaction are diagrammed in Figure 41 (p. 92 below). What is important is that high temperatures and very high concentrations of CO in the furnace atmosphere are required for the reduction of FeO. The necessary concentration of CO is more readily obtained with charcoal as the fuel than with coke (because charcoal is more reactive), and therefore charcoal blast furnaces operate at lower temperatures.

Iron smelting would be easy if the ore were composed of nothing but iron oxide. In fact all ores contain significant amounts of SiO_2 (silica) as well as other minerals: this unwanted material is collectively called the **gangue** of the ore. If the furnace is to operate continuously the gangue must be removed in molten form, but it will normally have a melting point which is much higher than the temperatures required for the reduction of iron oxides. Therefore a **flux**, typically $CaCO_3$ (limestone), is charged along with the ore and the fuel. The flux is chosen to form with the gangue a slag with a practicably low melting point (less than 1400°C in modern practice). $CaCO_3$ decomposes in the furnace to CaO (lime) and CO_2, and the mixture of CaO and SiO_2 has a much lower melting point than either mineral alone. Other minerals in the charge, either incidentally present in the gangue or intentionally added in the flux, may further depress the melting point of the slag. Especially important here is Al_2O_3 (alumina).

Limestone not only is an excellent flux, it also has the property that it can remove sulphur (S) from the liquid iron by the reaction shown. In modern practice, using coke with fairly high sulphur, large amounts of limestone are used, giving a CaO/SiO2 ratio in the slag as high as 1 : 2; in charcoal-fuelled blast furnaces sulphur is rarely a problem, and much smaller amounts of limestone are used.

In some pre-modern Chinese blast furnaces no flux is used. It seems that in these cases one or more of several special conditions must hold: (1) the ore used may be very rich, i.e. contain only a small amount of gangue; (2) the ore may be 'self-fluxing', the gangue containing significant proportions of limestone or alumina; (3) the charcoal may be from a wood which has grown on chalky ground and therefore contains a significant proportion of lime; (4) in operation enough of the furnace lining may be consumed to add significant amounts of alumina or other minerals to the slag; (5) the internal form of the furnace may be arranged in such a way that a small amount of the reduced iron is re-oxidised to FeO near the bottom, providing a very effective flux for silica. In pre-modern furnace operation it also appears possible to tolerate a slag which is rather viscous and does not separate well from the iron: the product is a 'slaggy' iron which ironfounders, finers, and puddlers nevertheless are able to use without great problems.

[a] See e.g. Bohm (1982).

is therefore arranged to have an oxidising zone near the bottom, where a small amount of iron is oxidised to FeO which mixes with the silica to form a reasonably low-melting slag.[23] Probably about 9 per cent of the iron in the ironsand was thus oxidised and lost in the slag; this was the cost of not using a flux, which presumably was not available locally. Limestone ($CaCO_3$) can form a slag with silica, and is one of the commonest fluxes used in modern blast-furnace operation.[24] Nyström in 1917 described an ironworks in Xinyang, Henan, which used a much less well-concentrated ironsand, with 49 per cent iron and 26 per cent silica; with so much silica a flux would have been necessary to avoid too much loss of iron, and he notes that limestone is available in the neighbourhood of the ironworks.[25]

The fining hearth

Cast iron from the blast furnace contains about 4 per cent carbon. It can be used directly by a foundry, but if it is to be used by a smith most of the carbon must be removed by a process which in Chinese is called *chao* 炒. This is an apt word for the process, for its usual meaning is 'stir frying',[26] and the removal of carbon from cast iron involves carefully stirring about lumps of very hot iron. Various English words have been used to translate *chao*, including 'roasting', 'refining', 'converting', and 'puddling', but for the process used in the Dabieshan region I have chosen to use the 19th-century word 'fining', defined as 'the operation of converting cast into malleable iron . . . in a hearth or open fire, urged by a blast of air with charcoal as the fuel'.[27] Further below, discussing the more sophisticated process used in Sichuan, I shall translate *chao* as 'puddling'.[28]

The hearth in which fining was done in Shangcheng 商城, Henan, in 1958 is diagrammed in Figure 11, and a pair of similar fining hearths in Xinyang in 1917 is sketched in Figure 12. (Fining hearths were normally built in pairs in this region because alternating between the two helped to save the refractory lining and give each a longer effective life.) Wood, charcoal, and broken pieces of cast iron were charged into the hearth and ignited; air was pumped in, and the charge was stirred about with an iron rod. When the carbon content of the iron was sufficiently reduced it was removed in small balls which were hammered to remove slag and

[23] Miao Changxing and Li Jinghua (1994) report one slag analysis as follows, giving a total of 99.64 per cent.

	SiO_2	CaO	TiO_2	Al_2O_3	FeO	K_2O	MgO	P_2O_5
%	38.47	17.95	18.15	10.74	7.09	3.24	2.43	1.57

[24] E.g. Peacey and Davenport (1979, p. 7).
[25] Tegengren (1923–24, pp. 180, 335).
[26] One of the basic processes in Chinese cooking; see e.g. *SCC*, vol. 6, part 5, p. 89.
[27] Percy (1864, p. 579). See also the long footnote on this subject in Wagner (1993, pp. 290–1, fn. 37).
[28] Pp. 30–4.

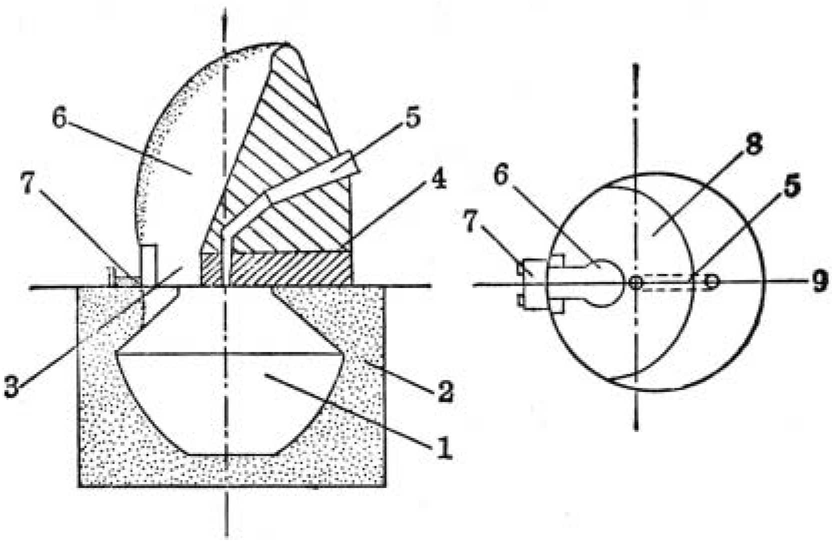


Figure 11 Diagram of a fining hearth used in Shangcheng, Henan, in 1958. (Reproduced from Yang Kuan (1982, p. 225); orig. Anon. (1958b, p. 23).) **1.** Hearth. **2.** Tamped fireclay. **3.** Hearth opening. **4.** Cover. **5.** Blast pipe. **6.** Hearth opening. **7.** Iron reinforcements. **8.** Nest. **9.** Ground level.

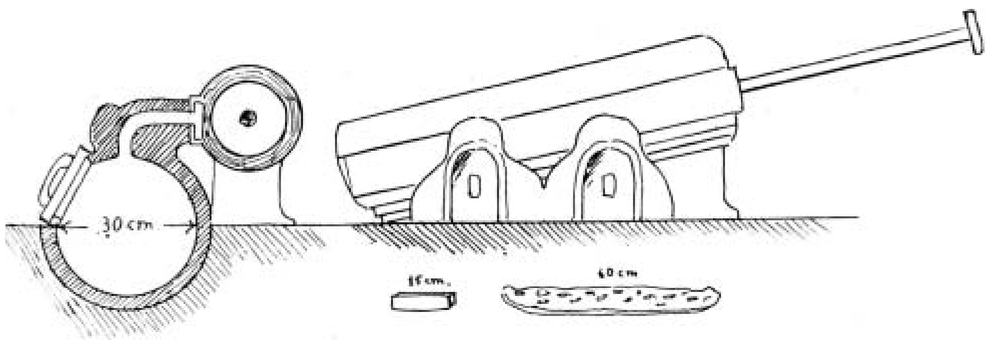


Figure 12 Drawing by E. T. Nyström of a pair of fining hearths in southern Henan, ca. 1917. In the background a traditional Chinese 'windbox', in the foreground a plate of pig iron and a wrought-iron bar. Reproduced by courtesy of Tom Nyström and the Museum of Far Eastern Antiquities, Stockholm.

form them into bars. I have described the process in more detail elsewhere.[29] I have not seen a photograph of a fining hearth in use in the Dabieshan region, but Figure 26, which shows a similar hearth in use in Shanxi in 1958, will give a general impression of the operation. According to a description of the fining operation as practised in Shangcheng, about 70 kg of wrought iron were produced in one fining cycle, and there were eight or nine cycles in a 12-hour shift. To produce one tonne

[29] Wagner (1985, pp. 22–6, 60–7); see also Anon. (1958g).

of wrought iron the inputs were about 1.2 tonnes of cast iron, 85 kg of wood, and 100 kg of charcoal; the labour used was about 170 worker-hours.[30]

Temperatures of at least 1400°C must have been reached in this hearth. In the fining operation carbon in the iron was oxidised both by the oxidising atmosphere in the hearth and by an oxidising slag.[31] The pasty lumps of wrought iron removed from the hearth were heavily intermixed with this slag; hammering the iron on an anvil 'squeezed' the slag out like water from a sponge.

Some analyses of cast iron and wrought iron produced by traditional techniques in the Dabieshan region are:

		C	Si	Mn	P	S
Cast iron	1958[a]	4.29	0.198	0.257	0.345	0.027
	1958[b]	3.65	0.13		0.59	0.042
		3.9	0.06		0.26	0.019
		3.02	0.01		0.42	0.044
Wrought iron	1917[c]	0.34	0.37		0.16	0.045
	1958[d]	0.101	0.096	0.06	0.206	0.00324

[a] Anon. (1958a, p. 15); Wagner (1985, pp. 20, 25, 87 n. 18).
[b] Liu Zhichao and Tang Youyu (1959a).
[c] E. T. Nyström in Tegengren (1923–24, p. 336).
[d] Anon. (1958a, p. 23); Wagner (1985, p. 25).

The sulphur content of this iron is very low, even compared with the best modern steel. The silicon content of the cast iron is also exceedingly low in comparison with the iron used in most modern iron foundries: this is a feature of most pre-modern cast iron, and it has a number of technical implications which we shall have occasion to examine.[32]

The Dabieshan region has never held much interest for Chinese historians, nor has the iron industry. These two factors frustrate the search for information on the history of this region's iron-production technology.[33] The first sign is two incidental mentions of iron-production activity in a 17th-century geographical work, Gu Zuyu's *Du shi fang yu ji yao* 讀史方輿紀要: he explains the names of Tielu Shan 鐵爐山, 'Iron Furnace Mountain', in Huoshan County 霍山縣, and Dalu Shan 大爐山, 'Great Furnace Mountain', in Susong County 宿松縣, by noting

[30] Anon. (1958b, pp. 11–16); Wagner (1985, pp. 60–6).

[31] The slag consisted of FeO produced by the oxidisation of some of the iron together with SiO_2, CaO, and Al_2O_3 from the hearth lining. It may be supposed that the most important reactions in the fining operation were: $2Fe + O_2 = 2FeO$; C (fuel) + $O_2 = CO_2\uparrow$; C (in Fe) + $CO_2 = 2CO\uparrow$; and C (in Fe) + $2FeO = 2Fe + CO_2\uparrow$.

[32] Pp. 29, 112, 162, 163 (fn. 151), 257 (fn. 55), 316, 317, 319 below.

[33] Some very early ironworks sites have been excavated in the region, but their relation to the much later industry which concerns us here is unclear. See Table 2 (pp. 201–9), item 21.

that there are iron smelters near these places.[34] Presumably there were iron smelters elsewhere in the region which neither Gu Zuyu nor the authors of his sources had any reason to mention.[35]

In local gazetteers there are signs of an upswing in this iron industry in the 19th century. In Yingshan 應山, Hubei, according to a gazetteer published in 1990,

> In the Jiaqing 嘉慶 period [1796–1820] a man surnamed Ai 艾, from Huangpi 黃陂 [Hubei] established at Xiadian in Jiangxidian 漿溪店下店 an iron smelter where iron woks were cast using handicraft methods, with the local ironsand as the raw material and charcoal as the fuel. Its products were marketed in the county seat and in Guangshui 廣水 and Sui 隨 Counties [Hubei], as well as in Henan. From that time, over a hundred years ago, its production has never stopped.[36]

And in Xinyang, Henan,

> At the beginning of the Daoguang 道光 period [1821–50] a man from Guangzhou living in Xishuanghe 西雙河 noticed that the sand was rich in iron. He was the first to teach people the method of washing and smelting it; he established factories for [smelting] iron and [casting] woks, and made an annual profit of more than a hundred thousand taels (*jin* 金).[37]

It is unlikely that either of these entrepreneurs actually introduced a new technology. More probably, they saw the potential of an existing small-scale industry, given capital investment and broadened marketing. Around this time the market price of iron in Hankou, not very far away, was much higher than in Guangdong; this was the conclusion of an official investigation in 1841.[38] It may be that this price differential was relatively new towards the beginning of the 19th century, and was the reason for the new entrepreneurial activity.

From the beginning of the 20th century there are numerous mentions of a flourishing small-scale iron industry in the region. A gazetteer for Huoshan 霍山, Anhui,

[34] *Du shi fang yu ji yao*, ch. 26, pp. 8a, 12a. A Ming-period local gazetteer, published in 1584, mentions illegal mining in Huoshan and also in neighbouring Huoqiu 霍丘 County, but it is not clear whether this was iron mining (*Lu an zhou zhi*, ch. 4, pp. 16a–b).

[35] There seem also to be mentions of iron production in Macheng 麻城 and Huang'an 黃安 Counties in the early Qing period. Xia Xiangrong et al. (1980, pp. 165–8) give a table of places in all of China which were found, in a search of a long list of early Qing sources, to have iron production. Here Macheng and Huang'an are listed, but the specific sources which mention them are not indicated. A local gazetteer for Macheng County states that the *Du shi fang yu ji yao* mentions an 'iron mountain' here, but I have been unable to verify this (Yu Jinfang, 1935b, ch. 3, p. 37b; cf. *Du shi fang yu ji yao*, ch. 76, p. 24a).

[36] Anon. (1990a, p. 261). The passage continues with some further data on this factory as it was in the 1930s and 1940s.

[37] Chen Shantong (1936, ch. 3, p. 6).

[38] William T. Rowe (1984, pp. 74–5, 361 n. 72) tells of this investigation by Yutai 裕泰, governor-general of Hu-Guang 湖廣. 'Yü-t'ai had been ordered by the imperial government to procure iron at Hankow to be cast into cannon for use against the British in Kwangtung. When he approached some local iron brokers as mediators for the transaction, the governor-general was aghast at the price the metal commanded on the market, and initiated an investigation. Yet the investigation proved to Yü-t'ai's satisfaction that the price was neither fixed nor artificially inflated, but was kept up merely by the mechanisms of supply and demand, as successfully mediated by Hankow's iron brokers.' Rowe cites a memorial by Yutai dated Daoguang 道光 21/11/28 in the Qing Palace Archives.

published in 1905, in a section on mining which uses a curious mix of modern and traditional terminology, states:

There is no information on copper or tin here. There are many places with iron ore, but as yet few know how to recognise the outcrops. The iron produced within the county is made by washing sand and smelting it. The method of smelting is as follows. First the sand is blown [*shan* 煽] in a blast furnace [*gaolu* 高爐] and transformed to liquid [*zhi* 汁] which is tipped out [of the blast furnace – cf. Figure 5] to form plates [*wa* 瓦] of cast iron [*sheng tie* 生鐵]. This is used in casting bells and gongs, woks and pots, agricultural implements, and the like. The cast iron can [also] be charged into a furnace in the earth [*di lu* 地爐, cf. Figures 11–12] and fined [*chaolian* 炒煉] to make wrought iron. Steel is purchased from Wuhu 蕪湖 [Anhui] or from overseas; the local people are not able to make it . . .[39] But the quality of the iron is excellent, and in the subprefecture [Lu'an Subprefecture 六安州] many people are pleased to buy and use it. Because the waterways are shallow and impassable, shipping it is laborious and costly; therefore very little goes outside the borders.[40]

This last is what we should expect on ordinary principles of economic geography: in a region without adequate water transport, iron will be produced only for local use. But before long the Dabieshan region was producing iron on a large scale and marketing it over a wide area. Nyström estimated in 1917 that in the part of the region which lies in Henan about 100 ironworks were in operation, producing some 14,000 tons of iron per year, which was carried by coolies all over southern Henan.[41] Further statements to the same effect, though without numerical estimates of production, are found in several local gazetteers published in the 1920s and 1930s.[42]

It may safely be assumed that these small-scale ironworks produced in normal times only for local needs, but they acquired a wider importance in the early 20th century. By the end of the 19th century competition with cheap foreign iron had ruined the iron industries of most regions, and China was largely dependent on imports for its iron. In isolated regions, however, the price of transport made the foreign imports more expensive than products of the local ironworks, and these were able to continue production. When World War I caused the price of European iron to rise, and especially after the American embargo on iron exports of January

[39] The elided passage is a brief discussion of Western steelmaking techniques, printed in smaller characters than the rest of the text.

[40] Qin Dazhang and He Guoyou (1905, ch. 2, pp. 28a–b).

[41] Tegengren (1923–24, p. 334, 336). He estimated that there were fifteen ironworks in Xinyang 信陽 County, ten in Guangshan 光山 County, and seventy-five in Shangcheng 商城 County. It is unfortunate that we do not have Nyström's report itself, but only Tegengren's brief summary, for we should like to know how these estimates were arrived at. Nyström was elsewhere cited for a production estimate of 14,400 tons per year, which seems curiously precise. It may have been arrived at indirectly from his estimate of ironsand production, 36,000 tons per year. He estimated that the wet ironsand was about 40 per cent iron (49 per cent dry), and $36{,}000 \times 0.40 = 14{,}400$. How he could have estimated the ironsand production remains a mystery. We appear to have no serious estimates for iron production in the rest of the region, the parts which lie in Anhui and Hubei.

[42] Yingshan County 英山縣 (Xu Jin et al., 1920, ch. 1, pp. 26a, ch. 8, pp. 11b–12a); Qianshan County 潛山縣 (Wu Lansheng et al., 1920, ch. 4, p. 21b); Susong County 宿松縣 (Yu Qinglan et al., 1921, ch. 17, pp. 9a–b, ch. 18, pp. 1a–4a); Macheng County 麻城縣 (Yu Jinfang, 1935b, ch. 3, p. 37a); Xinyang County 信陽縣 (Chen Shantong et al., 1936, ch. 7, pp. 16a–b, ch. 12, p. 5b, 6a); Guangshan County 光山縣 (Yan Zhaoping, 1936, ch. 1, p. 8).

1918,[43] the price of iron in China rose catastrophically.[44] Generally, the traditional iron industries of less isolated regions had already succumbed to foreign competition several generations before, and their techniques had been forgotten. On the other hand, at the new prices it became profitable for the ironworks of the Dabieshan region to expand their production and sell iron well outside the region, transporting it on the backs of coolies for lack of cheaper means.

(ii) Large-scale Ironworks in Sichuan

The Red Basin of Sichuan is a hilly region of intense agriculture surrounded on all sides by high mountain ranges. Communication within the region is facilitated by the famous Four Rivers from which the province derives its name, but communication with the rest of China is difficult. The Yangzi River (Changjiang) joins Sichuan to eastern China through a series of gorges, and the famously arduous 'Road to Shu' (*Shu dao* 蜀道) joins it to Shaanxi to the north. The fertility of the soil and the mildness and dependability of the climate make this one of the breadbaskets of China; it has attracted immigrants throughout Chinese history, and its population density is extreme.[45]

In 1872 Ferdinand von Richthofen, after defining the limits of the roughly triangular Red Basin, summed up the human geography of the region as follows:

> Within this triangle there is life, industry, prosperity, wealth, intercommunication by water. Outside of it, as a rule, no river is navigable, with the exception of the Yangtze where it leaves the basin. To the south and west commence immediately territories occupied by *I-jên* [*Yi ren* 夷人] or 'barbarians,' and in every direction we ascend from the elevated region of the Red Basin into the rugged mountainous countries which surround it. From the basin is derived that large and valuable produce which has justly attracted attention of late years. Outside of it, on all sides, the country is thinly inhabited and little productive.[46]

These geographical considerations mean that there are good conditions for a local large-scale iron industry here: the demands of a large population, excellent intra-regional transportation, and isolation from the iron industries of other regions. The

[43] The background to this action in the conflict between the American government and the steel industry is made clear by Urofsky (1969, esp. chs. 5–6), but unaccountably he nowhere mentions the embargo itself. A highly partisan account of the conflict is given by James Bowron in Norrell (1991, pp. 217–36, esp. p. 230).

[44] Huang (1919); Zhu Xingzhong (1932–33, p. 49); Hou Defeng and Cao Guoquan (1946, p. 816); Zhu Sihuang et al. (1948, p. 283); Hu Boyuan (1946, pp. 799–800); Reardon-Anderson (1991, p. 271).

[45] On the physical and human geography of Sichuan see *SCC*, vol. 1, pp. 61, 72; Willis et al. (1907, vol. 1, pp. 13–15; vol. 2): Richard (1908, pp. 104–19); Dautremer (1911, pp. 173ff); Lattimore (1942); Anon. (1944, pp. 85–92); Wiens (1949); or any of the many available geographies of China. On the region's economic history, Kapp (1973); P. J. Smith (1988); Bramall (1993); Zhang Xiaomei (1939); Meng Xianzhang (1943); Zhou Kaiqing (1972); Chen Shisong and Jia Daquan (1986); Du Shouhu and Zhang Xuejun (1987); Zhang Xuejun and Zhang Lihong (1990). On its geology and mineral resources, *SCC*, vol. 5, part 13, pp. 53–6; von Richthofen (1872, pp. 115–34; 1877–1912, vol. 3, pp. 53–265); Abendanon (1906); Tegengren (1923–24, pp. 281–3); Way (1916); DuClos (1898); Lei Baohua (1943); Zhou Lisan et al. (1946, maps 52ff). Of numerous travel descriptions the most important for our purposes appear to be: Széchenyi (1893); Cremer (1913); Robertson (1916); Hosie (1922); Richardson (1945); Needham and Needham (1948).

[46] von Richthofen (1872, p. 115).

traditional salt industry of Sichuan consumed enormous numbers of very large salt-boiling pans, and this extra demand, over and above the normal iron consumption of a dense agricultural population, made from early times for a very large iron industry. In recent centuries the Sichuan iron industry used the largest blast furnaces to be found anywhere in China.

The iron industry has in recent centuries been concentrated in two parts of Sichuan: at the edge of the Red Basin southwest and south of Chengdu, and in the mountains along the Yangzi.[47] Some iron production is also reported in and near the mountains north of Chengdu. Iron ore and fuel are very widely found in sufficient quality and quantity for production on a pre-modern scale, and the location of iron production would seem to be determined more by the need for water transportation of raw materials from the mines and forests and of finished products to consumers. In particular the concentration of salt production south of Chengdu meant a concentrated demand for cast-iron salt-boiling pans in the same region.

The technology of this iron production is again as in Figure 1, but in comparison with the Dabieshan iron industry the scale of production was much larger, and water power was often used to power the blast of the blast furnaces. Detailed descriptions are available from 1878, 1936, the Second World War, and the Great Leap Forward,[48] as well as brief descriptions in local gazetteers and by many travellers.[49] In addition it seems that the technology of iron production in Sichuan has much in common with those in Yunnan and in Hunan, and there are a number of published descriptions of these.[50]

The blast furnace

The earliest description of blast-furnace iron smelting in Sichuan[51] appears to be that of the Hungarian traveller Béla Széchenyi.[52] He visited an ironworks about

[47] Xia Xiangrong et al. (1980, p. 167); von Richthofen (1872, pp. 123–4); Tegengren (1923–24, pp. 281–3); DuClos (1898, pp. 311–14); Zhou Lisan et al. (1946, map 55).

[48] Széchenyi (1893, pp. 678–9); Luo Mian (1936, pp. 18–35); Zhang Xiaomei (1939, pp. Q13–Q14); Zhu Yulun (1940); Wang Ziyou (1940); Hu Boyuan (1946, pp. 800–1); Anon. (1958d; 1960); Li Renkuan (1959); Zhang Chengji (1959).

[49] Chen Buwu et al. (1928, ch. 13, pp. 9a–11a); DuClos (1898, pp. 313–14); Cremer (1913, *passim*); Robertson (1916, p. 269); Way (1916, pp. 22–3).

[50] **Yunnan**: Huang Zhanyue and Wang Daizhi (1962); Rocher (1879–80, vol. 2, pp. 195–218); Moore-Bennet (1915, pp. 220–1); Coggin Brown (1920a, pp. 82–97; 1920b, pp. 337–9); Tegengren (1923–24, pp. 347–64). **Hunan**: Tegengren (1923–24, Chinese pp. 234–6, English pp. 338–9); von Richthofen (1877–1912, vol. 3, pp. 455–6); Lux (1912); Mao Zedong (1990, pp. 105–7); Yang Kuan (1960, pp. 135–7).

[51] We may note here the possible existence of an earlier description. The 1928 edition of the local gazetteer for Dazhu County 大竹縣 contains a curiously garbled description of blast-furnace iron smelting which seems to be based on a much older description, edited by a person with modern technical knowledge (Chen Buwu et al., 1928, ch. 12, pp. 3a–b; ch. 13, pp. 10b–11a). But I have been unable to find this earlier description.

[52] On Széchenyi and his expedition see Kreitner (1881); and an obituary in Hungarian by L. Lóczy (1923), which includes a long bibliography. Dr László Ottovay of the National Széchenyi Library, and Dr Csaba Horváth of the Hungarian National Museum, both in Budapest, have informed me that most of the material collected by the expedition was destroyed in Count Széchenyi's manor house in Nagycenk during World War II. The palaeontological, mineral, and zoological materials, in museums in Budapest, were destroyed in 1956. What survives is the botanical material, in the Hungarian National Museum.

150 km southwest of Chengdu in 1877. Figure 13 is his diagram of the furnace, and his description is translated in Box 2. This is one of several early descriptions of iron-works in Sichuan which indicate that the blast was water-powered.[53] The latest description of water-powered blast in Sichuan refers to observations in 1900;[54] after that only human-powered blast is mentioned.

Széchenyi notes that the ore used here is 'blackband', an ore consisting largely of siderite (ferrous carbonate, $FeCO_3$), which has a theoretical iron content of 48.3 per cent.[55] His estimate of 40–60 per cent iron in the ore is therefore over-optimistic,[56] but it does indicate that a very rich ore was used. The 'calcining' or roasting of the ore, seen at the extreme left of Figure 13, serves to drive off water, to convert hydroxides and carbonates to oxides,[57] to eliminate sulphur,[58] and to make the rock more porous and friable.[59] The calcined ore would be charged into the top of the blast furnace together with charcoal as the fuel and limestone as a flux. The flux serves two purposes: to form with the gangue of the ore a free-flowing slag, and to remove to the slag some of the remaining sulphur in the furnace charge (ore and fuel).[60] The British mining engineer R. Logan Jack visited an ironworks in the same place, and his description specifically mentions the use of limestone:

The works turned out to be not only a foundry, but also a smelter, operating on hæmatite, limonite, and a clay-band ironstone, the latter of which had been calcined at the mine. We were informed that the grade was 40 or 45 per cent. – of course on the basis of extraction [rather than laboratory analysis]. A quantity of limestone was stored for flux. At the time of our visit the furnace was not in blast, all hands being busied on the conversion of the pig-iron into pots in the foundry. The blast . . . was furnished by a turbine and wooden, double-acting cylinder of considerable size. The furnace was about 30 feet [9 m] in height, [with inside diameter] 5 feet [1.5 m] at the tuyères, and 10 feet [3 m] at the boshes [the widest part], and was fed through a very small opening at the top. It was built in part of hewn stone, and was not unlike the old English charcoal furnaces. The iron was cast into plates about 4 × 2 × 1¼ inches [10 × 5 × 3 cm], and was fine-grained, and appeared to be of good quality. After breaking up the plates, the iron was melted in small cupolas[61] with hand-bellows, and carried in iron hand-barrows to the casting department.[62]

53 See e.g. DuClos (1898, p. 313); Cremer (1913, p. 58); Way (1912, p. 232; 1916, p. 22); Tegengren (1923–24, p. 344). A water-powered blast arrangement very similar to that shown in Figure 13, in use in Yunnan in 1982 for lead production, is described and illustrated by Sun Shuyun (2002, pp. 22–5, pls. 2–4).

54 Way (1912, p. 232; 1916, p. 22).

55 *SCC*, vol. 5, part 13, p. 163; Rostoker and Bronson (1990, pp. 42, 53).

56 DuClos (1898, p. 312) describes a deposit of sideritic ore near Chongqing with 35–40 per cent iron: still a very rich ore. Note also Tegengren (1923–24, p. 281).

57 By such reactions as $FeCO_3 = FeO + CO_2\uparrow$.

58 By such reactions as $2FeS_2 + 5.5\ O_2 = Fe_2O_3 + 4SO_2\uparrow$. Rosenqvist (1974, p. 245).

59 See e.g. Percy (1861, pp. 19–20); Rosenqvist (1974, pp. 238–59). In Széchenyi's description the calcination was done in an open heap, but descriptions of other ironworks indicate that it was done in a special stall furnace. See e.g. Luo Mian (1936, p. 18).

60 Percy (1861, pp. 18ff; 1864, pp. 349–50); Rosenqvist (1974, pp. 392–5); Peacey and Davenport (1979, pp. 7–8, 179). See Box 1.

61 See pp. 60–5, 147–70 below.

62 Jack (1904, pp. 93–4).

Box 2 *Description by Béla Széchenyi of the operation of a water-powered blast furnace at Huangnipu in Rongjing County (modern Yingjing), Sichuan, ca. 1877. Translated from Széchenyi (1893, pp. 678 ff); cf. Kreitner (1881, pp. 805–6); Tegengren (1923–24, p. 342). Dr Katalin T. Biro of the Hungarian National Museum kindly corrected my translation from German against the Hungarian original, Széchenyi (1890, pp. 606 ff).*

Hoani-pu lies in a narrow valley, and bears throughout the stamp of a typical mining district. Everything here is black with coal dust from coal mining and iron industry.

In the neighbourhood chain bridges cross over the streams. Coal and iron occur together in the immediate vicinity. On the opposite bank is a blast furnace, some 8–9 m high and 5.5–6 m broad at the base. In form it is quite similar to a European blast furnace; it is built of stone and held together by an external wooden construction.

The blast is provided by a [piston-]bellows 1 m in diameter and 3.5 m long. This bellows, or rather cylinder, is constructed on the same pattern as the common Chinese kitchen blowing cylinder, except that the piston is driven by a water-wheel.

For the tapping of both ore [i.e. iron] and slag there is only one opening, at least I did not see a special opening for the latter.

The ore smelted here is an ironstone (blackband), with 40–60 per cent iron, which occurs between the coal measures. Next to the shaft of the blast furnace the ore is first mixed with charcoal and roasted. As the works stood empty and out of operation, I was unable to obtain further data on the smelting process. I give the construction of the furnace in [Figure 13].

In the storehouse of the works was a large number of cast-iron slabs measuring 1 m long, 0.60 m broad, and 0.02 m thick. The surface of this cast iron is very slaggy because of the lack of a separate outlet for the slag; its fracture is steel-grey and full of blow-holes throughout. Next to the blast furnace was the foundry, which however was also out of operation . . .

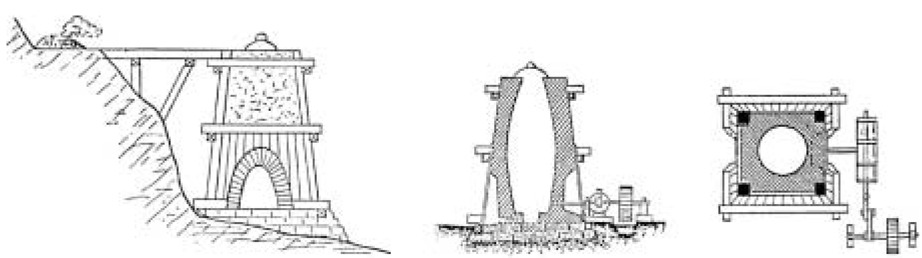


Figure 13 Sketch and sections of a water-powered blast furnace at Huangnipu 黃泥鋪 in Rongjing County 榮經縣 (modern Yingjing 滎經), Sichuan, ca. 1877, reproduced from Széchenyi (1893, p. 678, figs. 116–18). Height 8–9 m, base 5.5–6 m.

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Curiously, I have been unable to find any other early description of a blast furnace in Sichuan which explicitly mentions the use of limestone as a flux.[63] Several descriptions, in fact, explicitly state that limestone was not used.[64] An example is the geologist L. Cremer's description of an ironworks in 1905 in the southern part of Nanchuan County 南川縣, which also gives other useful details:

> Li-yün-pa[65] lies in a broad valley which we passed through to the NW, upstream on a river exploited by large and small bamboo scoop-wheels. Before us ascended a thick column of smoke produced by the blast furnace works Mu-tu-ba'rh, which we reached after a short hike. The ore which comes here for smelting is limonite [*Brauneisenstein*] from Kan-ya-dse,[66] 15 *li* [7.5 km] from the blast furnace on the road to Wan-schou-tschang.[67]
>
> There is one blast furnace, 8 m high, with a square cross-section outside and with an outer framework of wooden poles. The taphole is located in an arch of coarse masonry, while on the opposite side is the opening through which the blast is led to the hearth. There is only one taphole, used for both iron and slag. The blast is produced in a cylindrical wooden [piston-]bellows. It is blown diagonally downward to the furnace bottom through bamboo pipes fitted with a tuyère of fireclay. The fuel and reducing agent are charcoal, half-charred wood, and fresh wood. The only flux used is slag, not limestone. The top-gas escapes to the open air through a circular mouth, 38 cm in diameter. A mortared inclined plane, over which the charge is carried in baskets, leads to the mouth of the furnace.
>
> The furnace is tapped 10–11 times per day, producing in all 900 kg of pig iron and using 1400 kg of fuel [per day]. The workers receive 120 Marks per year each, and a similar sum is paid by the owner in tax to the government. The refractory stone for the lining of the furnace comes from Tschang-tschung-kou, 15 *li* [7.5 km] away.[68]

If this ironworks at some time in the recent past had used limestone as a flux, then the old slag from that time would have contained a fair amount of lime (CaO), and could have been of some use as a substitute for limestone; otherwise it is difficult to imagine what advantage there would have been in the continuous recirculation of slag through the furnace.[69] In the following pages we shall see several clear examples of highly developed techniques being degraded in the nineteenth and twentieth centuries under the pressure of changing economic conditions,[70] and this works, I suggest, is likely to be another such example. Note also that water power apparently was not used for the blast here.

[63] Yang Kuan (1960, p. 109) notes the use of bone ash as a blast furnace or cupola flux in the Ming period, somewhere in China.

[64] A 1940 survey states that traditional ironworks in Sichuan 'do not add, or add only small amounts of, limestone'. It points out that this practice means that the slag produced is acid and does not attack the sandstone lining of the furnace as severely as a basic slag would (Wang Ziyou, 1940, pp. 2, 3, 4). It gives analyses of slag from ironworks in two counties which show that large amounts of iron (8.74 and 6.32 per cent iron in the slag respectively) lost to the slag were necessary to bring the melting point down to a practicable level. Hu Boyuan (1946, p. 801) and Li Renkuan (1959, p. 199) also discuss the composition of the slags of the traditional blast furnaces of Sichuan.

[65] Probably Liyinba 里隱壩, a small village (pop. 800 in 1993) in approximately the vicinity described here. See Pu Xiaorong (1993, p. 448).

[66] Ganbazi 干壩子.

[67] Wanshengchang 萬盛場, in modern Nantong Mining District 南桐礦區.

[68] Cremer (1913, p. 51).

[69] Percy (1864, p. 520) discusses a report that old slag can be used as a flux in British blast furnaces. Note also Anon. (1958k).

[70] Pp. 35–7, 45–6, 59, 78–9.

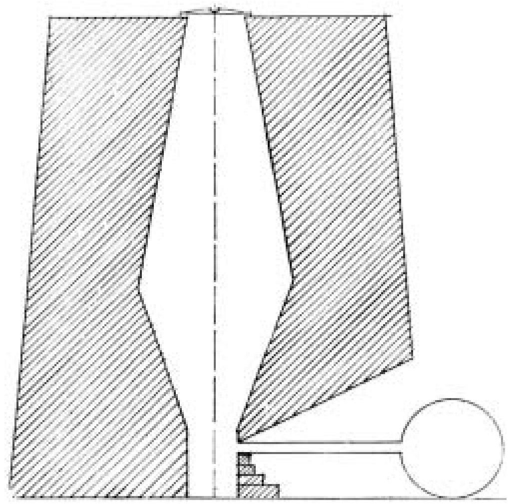
Mineral coal was rarely if ever used in blast furnaces in Sichuan. It was sometimes used here in copper smelting,[71] ironfounding, blacksmithing,[72] puddling (see immediately below), and steelmaking,[73] and it was also used in large and small blast furnaces in Hunan,[74] but there would seem to have been severe technical problems involved in using mineral coal in the Sichuan blast furnaces. In 1940 *one* traditional ironworks in Sichuan used mineral coal as its blast furnace fuel. This was the Shujiang Ironworks 蜀江鐵廠 at Longwangdong 龍王洞 in Jiangbei 江北 County, where it is said that the engineer Deng Langqin 鄧郎琴 succeeded with the new fuel only after over 100 unsuccessful attempts.[75] The whole subject of the transition to the use of coal in iron smelting, East and West, will be discussed in Section 7(iii) below.[76]

A more detailed description of blast-furnace iron smelting in Sichuan was given by Luo Mian in the early 1930s. His illustrations are reproduced in Figures 14–15, and the essential part of his description is translated in Box 3. It will be noticed that the internal form of the furnace is quite different from that shown by Széchenyi (Figure 13). A survey in 1940 states that this more angular form was more modern (see Figure 16);[77] it is reminiscent, in fact, of some 19th-century British blast furnaces, and it is quite possible that its adoption was due to some Western influence. Another curiosity is that this furnace does not have the wooden frame mentioned in the earlier descriptions.

A survey published in 1940 gives chemical analyses of samples of cast iron produced in three counties in Sichuan:[78]

	C %	Si %	S %	P %	Mn %
Qijiang 綦江	2.10	0.20	0.05	0.70	0.05
Weiyuan 威遠	3.00	0.18	0.06	0.22	0.25
Fuling 涪陵	3.30	0.19	0.05	0.22	0.01

71 Cremer (1913, p. 58).
72 Cremer (1913, p. 43).
73 Luo Mian (1936, p. 27).
74 von Richthofen (1877–1912, vol. 3, pp. 455–6); Lux (1912).
75 Wang Ziyou (1940, p. 3).
76 Pp. 212–20.
77 Note also the somewhat similar diagram of older and newer blast furnaces in Sichuan given by Hu Boyuan (1946, p. 800).
78 Wang Ziyou (1940, p. 5, table 11). Analyses of eight pig iron samples published by Luo Mian (1936, p. 22, tables 6–7) are very different from these analyses, and in fact seem so bizarre that one must suspect an error on the part of the analyst: the reported silicon contents approach that of modern pig iron, the sulphur contents are so high as to make the iron useless for many purposes, and the phosphorus contents are also high in comparison with the analyses given by Wang Ziyou. Several observers mention poor separation between iron and slag, owing to excessive slag viscosity, and the cast-iron plates from the blast furnace are described as 'slaggy'. A chemist asked to analyse such a physical admixture of very different materials has a choice to make, according to the purpose of the analysis: he can separate out the metallic phase by physical means (e.g. by melting it) and analyse that alone, or he can use a variety of means to bring the entire sample into solution so that the analysis will apply to the heterogeneous sample as a whole. The first approach would be more appropriate in an analysis of pig iron, but it would seem that the chemists who did the analyses reported by Luo Mian (perhaps more accustomed to analysing ores than metals) took the second approach, and the analyses include the slag inclusions. These would contain a large amount of silica (SiO_2), and might contain a fair amount of sulphur if calcining was imperfect but a limestone flux was used in the blast furnace. Some curious analyses are also reported by Hu Boyuan (1946, p. 801).



14

15

Figures 14 and 15 Blast furnaces in Sichuan in the 1930s, reproduced from Luo Mian (1936, pp. 19–21, figs. 1–3). **14.** Vertical section through a blast furnace in Qijiang 綦江 County, Sichuan. **15.** Blast furnace somewhere in Sichuan.

Box 3 *Description of blast furnaces in Sichuan in the 1930s, translated from Luo Mian (1936, pp. 18–21).*

The smelting furnace. The dimensions of the furnace are different in different places. Usually the height is 2 *zhang* 4 *chi* [8 m], mouth [diameter] 2 *chi* 8 *cun* [93 cm], [inner diameter of the] belly at the widest point [the boshes], 5 *chi* 8 *cun* [193 cm], bottom [diameter] 9 *cun* [30 cm].[a] The interior has the shape of a vase [*tan zi* 罈子] of the above dimensions, widest in the middle and diminishing towards the top and bottom, as in Figure 14, which shows a section of the smelting furnace at the most recently built ironworks in Qijiang 綦江 [County]. The mouth is a round hole into which wood, charcoal, and ore are charged and from which smoke escapes. The taphole is about 6 *cun* [20 cm] higher than the bottom; it has diameter 8 *cun* [27 cm, surely a typographical error for 8 *fen* 分, 2.7 cm], and is used for tapping both iron and slag.

The exterior of the furnace is square. It is narrowest at the top, about 1 *zhang* 4 *chi* [4.7 m], and widest at the bottom, 1 *zhang* 8 *chi* [6 m]. Figure 15 gives an overall view. The work area [the tapping arch] looks like a city gate. The place where blast is blown in [the blowing arch] is at the side or the back, and has the same form as the work area [tapping arch]. The mouth [tuyère] of the pipe from the windbox [*feng xiang* 風箱, double-acting piston bellows] is inserted into the furnace at a height of about 1 *chi* [33 cm]; it has an adjustable prop, so that the height can be varied as desired. The blast is operated either by human power or by water power. The blast is cold, though some ironworks in Qijiang have recently changed over to hot blast.

The furnaces are built of refractory sandstone, which is acidic. In the interior, above and below the tuyère, it is plastered with a mixture of salt, loam, and sand to prevent the corrosion of the sandstone by basic materials. The plaster is usually composed of about 1 part salt, 4 parts clay, and 5 parts sand; some use *dan ba* 胆巴 (a magnesium salt) mixed with salt and clay.

The sandstone is supplied seasonally by stoneworkers. The furnace as a whole can last more than 200 days, but it is never worked for more than 200 days in a year. The next year it is rebuilt. The expenditure [per year] for the furnace and tuyères is somewhat over 1000 yuan 元 . Assuming the worst case, a production of only 250 tonnes of pig iron per year, then the cost of the furnace is about 4–5 yuan per ton, which is not expensive; the disadvantage of this type of furnace lies rather in the quality of the pig iron produced.

Production of pig iron. After the bottom of the smelting furnace has been dried, a layer of 400 jin [240 kg] of semi-charred charcoal is laid out on the bottom, followed by 600 jin [360 kg] of calcined ore. Further layers are added, alternating in the same way, until the top of the furnace is reached, giving a total of about 14,000 jin [8.4 tonnes] of ore. Then the bottom layer is ignited and the blast is started to maintain combustion. After about a day [morning to evening] the molten iron begins to flow. Outside the taphole the workers prepare a bed of fine sand which they rake to form a mould for a flat plate. The taphole is opened by striking with an iron rod, and iron and slag flow out together. As they flow into the mould the rake is used to remove the slag; the iron left behind in the sand mould, when it has cooled, is the cast-iron plate [the pig]; it is about 2 chi 5–6 cun [about 85 cm] long, 1 chi 4–5 cun [about 50 cm] wide, and weighs about 100 jin [60 kg].[b] After the first day, tapping can be done from time to time as convenient. The quantity of iron tapped is highly dependent on whether the 'heat'

Box 3 *Continued*

[*re li* 熱力] is sufficient; therefore it is important not to neglect the heat. After the first tapping, fuel and calcined ore continue to be charged alternately as described above. As a general rule more than 4,000 *jin* [2.4 tonnes] of cast iron can be produced from 12,000–13,000 *jin* [7.2–7.8 tonnes] of calcined ore. By custom more than 5000 *jin* is considered excellent, 4000 *jin* normal, and 3000 *jin* inferior. [These quantities are 3, 2.4, and 1.8 tonnes respectively, presumably per day.]

[a] Clearly the furnace diagrammed in Figure 13 does not have the same proportions as these dimensions.
[b] The thickness of the plate would then be about 1.8 cm.

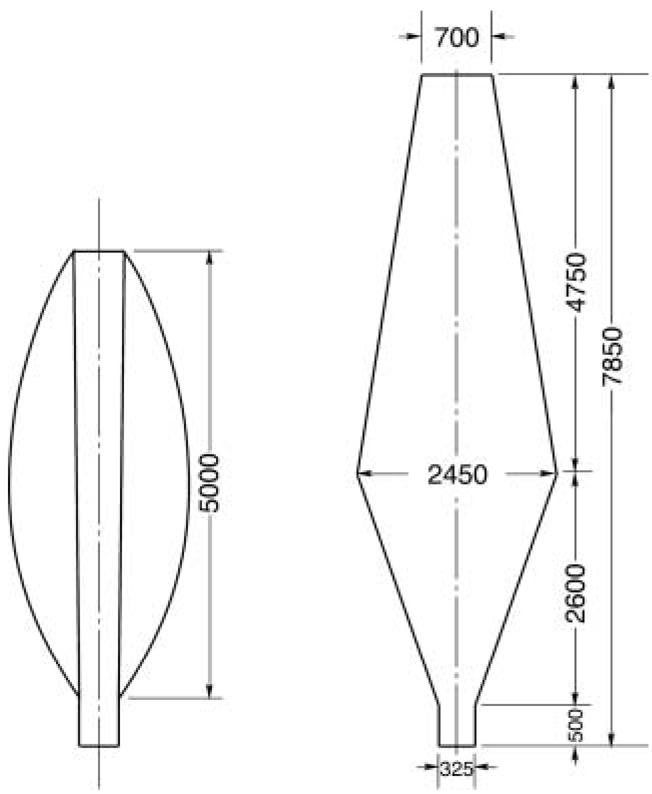


Figure 16 Internal form of two traditional blast furnaces in Sichuan in 1940, redrawn from Wang Ziyou (1940, foldout fig. 1). Dimensions are given in millimetres. On the left is the 'older' form, on the right the 'newer' form. Cf. Figures 13, 14.

The sulphur content of this cast iron is low because the ore was carefully calcined to remove sulphides, and because charcoal has very low sulphur. The high reactivity of charcoal means that it burns at a lower temperature than mineral coal or coke, and this means that not much silicon is reduced and enters the iron. It is surprising to see the very low carbon contents in these analyses: we should expect the carbon content of pig iron from a blast furnace to be between 3.5 and 5 per cent. The liquidus temperature (melting point) of the sample from Qijiang would be quite high, about 1380°C.

The puddling furnace

The cast iron produced in the blast furnace was converted to wrought iron in what I shall call a *puddling furnace*. In Chinese it was called a *chaolu* 炒爐; the same word was used for the Dabieshan *fining hearth* described earlier,[79] but as we shall see, the operation of the Sichuan *chaolu* had many characteristics in common with the 'puddling' process patented by Henry Cort in 1784.[80]

Cremer observed this process in Sichuan in 1905, and he was the first to refer to it as 'puddling' (*Puddeln*).[81] The furnace and its operation were described in detail by Luo Mian in 1936. He gives the diagram reproduced here as Figure 17 and the two photographs of Figures 18 and 19, which unfortunately are not very clear because of poor reproduction. The furnace is built entirely of a type of refractory sandstone which is common in Sichuan.[82] Charcoal is burned in the closed firebox. Blast is blown into the firebox, and the flame proceeds downward into the puddling bed.

Operation. [See Figure 17.] First semi-charred charcoal [*chaitan* 柴炭] is burned in the stone firebox **a** to heat the puddling bed. Then broken pieces of pig iron are charged into the puddling bed **b** and the blast is increased, blowing through **c** to **a**. The flame passes through the stone aperture **d** and heats the cast iron thoroughly. The flame gradually becomes the colour of mung beans; [the iron] is stirred [puddled] with a wooden pole; then the colour [of the iron] turns from red to white, the temperature being about 1000°C. It is puddled again with a wooden pole until the iron breaks up into a granular form. Then a small amount of ironsand (iron oxide, commonly called *hongzi* 紅子 ['red stuff']) is added while the blast is worked and stirring continues. [The iron] gradually melts, and as puddling continues it goes from free-flowing [*xi* 稀] to 'dry' [*gan* 乾 , i.e. viscous] and transforms to a plastic state. At this time the blast is reduced and [the iron] is formed into a ball; this is wrought iron [*shu tie* 熟鐵], commonly called *mao tie* 毛鐵 ['semi-finished iron']. The entire operation takes about 20 minutes.

The semi-finished iron is then heated in an ordinary smithy hearth and hammered to force out the slag which it contains. From 100 *jin* 斤 of semi-finished iron about 75 *jin* of wrought iron can be obtained. This is then hammered into plates, bars, rods, and the like and sold in the markets.

. . . It is customary to pay the puddler a combined price for his labour and the charcoal which he uses. For the puddling of 100 *jin* [60 kg] of pig iron to semi-finished iron the fixed price for labour and charcoal is 3 *jiao* 角 [0.3 *yuan* 元; the pig iron itself cost 5 *yuan*]. The labourer is not permitted an allowance for lost metal [*huohao* 火耗], but he is permitted to add as much ironsand as he wishes; therefore for every 100 *jin* of pig iron given to the puddler the return is about 100 *jin* of [semi-finished] wrought iron. However, when this is hammered in the smithy hearth, although the price of labour and charcoal is the same, 3 *jiao*, so much slag is forced out of the iron that the allowance for lost metal is about 25 per cent: if the smith is given 100 *jin* of semi-finished iron the return is only 75 *jin*.[83]

[79] Pp. 16–18.
[80] Pp. 33–4 below.
[81] Cremer (1913, p. 51). Earlier von Richthofen (1907, p. 501) referred to *Puddelöfen* in parts of Shanxi, but gave no details.
[82] Yang Kuan (1960, p. 187) calls this *Bai pao shi* 白泡石, 'white afrodite'.
[83] Luo Mian (1936, pp. 23–6).

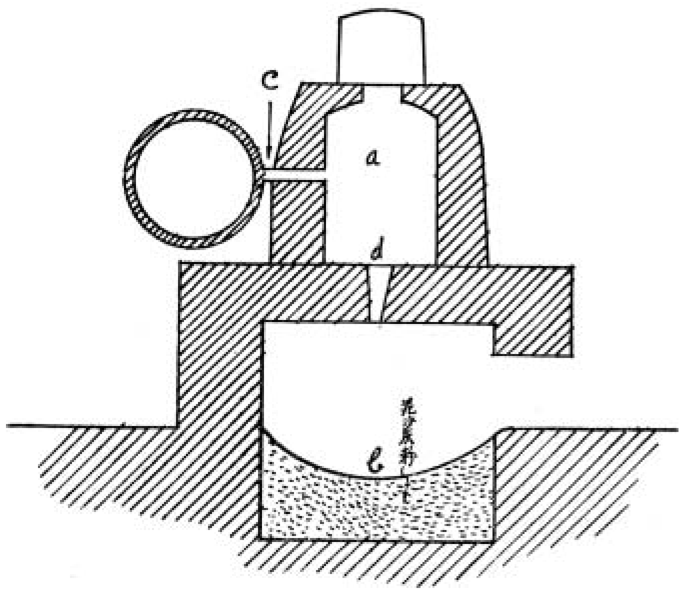


Figure 17 Diagram of a puddling hearth in Sichuan, reproduced from Luo Mian (1936, p. 24, fig. 4). **a.** Firebox, height 2 *chi* 尺 8 *cun* 寸 (93 cm). **b.** Puddling bed, diameter 2 *chi* (67 cm). **c.** Blast pipe. **d.** Flame channel.

Figure 18 Photograph of the front of a puddling hearth in Sichuan, reproduced from Luo Mian (1936, p. 24, fig. 5).

Figure 19 Photograph of the back of a puddling hearth in Sichuan, reproduced from Luo Mian (1936, p. 25, fig. 6).

As the iron is melted the carbon in it is oxidised by the oxidising flame together with a slag rich in FeO. The slag is formed partly by the addition of red ironsand (presumably a mixture of quartz and hematite, SiO_2 and Fe_2O_3), partly by the combustion of some 25 per cent of the pig iron charged. Unfortunately Luo Mian gives very few quantitative data on this process, and I have not found any elsewhere, but the small size of the puddling bed and the short time required for the puddling operation suggest that the amount of pig iron charged was perhaps 10–20 kg. The amount of fuel needed probably varied greatly with the skill of the puddler: this would be the reason for requiring him to supply the fuel himself.

In the puddling process, as the carbon content of the iron decreases, its melting point (liquidus) rises. At the same time the temperature in the furnace also rises, probably coming close to 1500°C. Therefore the iron in the puddling bed is through most of the process in the form of a paste composed of microscopic crystals of lower-carbon iron in a higher-carbon liquid. In the neighbourhood of 1500°C the liquid has about 0.5 per cent carbon and the solid about 0.1 per cent.[84] As the carbon

[84] See the iron–carbon phase system, Figure 110, p. 259 below

content continues to decrease, more low-carbon iron precipitates from the melt, the proportion of liquid decreases, and finally the plastic state mentioned in the description above is reached, at which time the iron has been nearly fully decarburised. English puddlers spoke of the iron 'coming to nature', and in the large puddling furnaces of the 19th century this was quite a spectacular phenomenon.[85]

In the 'fining' process used in the Dabieshan region, described above,[86] the fuel was mixed directly with the iron. There the temperature appears to have been lower, and the decarburisation presumably took place with much of the iron in the solid state. Decarburisation of iron in the solid state is much slower than in the liquid state, and that process, though efficient compared with early Western fining processes, was probably less fuel-efficient than the puddling methods described above. Its great advantage was no doubt the use of a lower temperature, which meant that local materials, less refractory than the sandstone available in Sichuan, could be used for the furnace.

The 'puddling' process patented in Britain by Henry Cort in 1784 was in principle very like the Sichuan process described above.[87] Mineral coal was burned in a firebox and its flame was used to heat cast iron in a separate 'puddling bed'. The puddler performed essentially the same operations as described here; 'to puddle' is an obsolete English word meaning 'to stir about'. There were two essential differences: the British process used mineral coal as the fuel,[88] and it was a much larger-scale operation than the Sichuan process. The puddling bed was many times larger, tons of iron per day were converted to wrought iron, and puddling was 'probably the severest kind of labour in the world'.[89] It is unlikely that the work of the Sichuan puddlers was equally severe, but it cannot have been as effortless as the above description might suggest.

It is a surprise to see that mineral coal was rarely used in puddling in Sichuan. The great benefit of Henry Cort's innovation was that it separated the fuel from the iron and therefore made possible the use of coal in converting cast iron to wrought iron. European fining processes consumed prodigious amounts of charcoal,[90] and mineral coal could not be substituted directly because its high sulphur content was

[85] Percy (1864, p. 656). Gale (1977, figs. 38–43) gives some marvellous photographs of the English puddling process as it was still being practised in the 1950s.

[86] Pp. 16–18.

[87] On the Western puddling process the best general technical discussion seems still to be that of John Percy (1864, pp. 627ff). A few other useful references, among many, are Turner (1895, pp. 281–314) (detailed description and technical explanation); Rosenholtz and Oesterle (1938, pp. 89–96); Gale (1977, figs. 38–43) (marvellous photographs); Mott and Singer (1983) (the history of the invention); Paulinyi (1987) (a broader historical study).

[88] Though wood was sometimes used when the process was adopted in heavily forested regions such as northern Sweden and the Carinthian Alps. Percy (1864, pp. 686–8).

[89] John Percy, himself a physician, wrote in his *Metallurgy* (1864, pp. 656–7): 'Most puddlers work until 50 years of age, and many even afterwards. Puddling is probably the severest kind of labour in the world; yet many puddlers attain the ripe age of 70 years, or more. The majority die between the ages of 45 and 50 years; and, according to the returns of medical men to the Registrar, pneumonia, or inflammation of the lungs, is the most frequent cause of their death. This is what might have been anticipated from the fact of their exposure to great alternations of temperature under the conditions of physical exhaustion. Mr. Field, optician, Birmingham, informs me that puddlers are moreover liable to cataract, induced by the bright light of the furnace; that he has seen a great number of such cases, and supplied the patients with glasses.'

[90] See e.g. Percy (1864, pp. 596, 601, 607, 615).

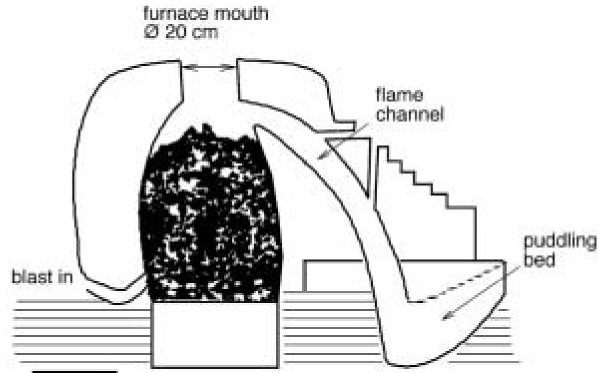


Figure 20 A type of puddling furnace used in Sichuan in 1958, redrawn from Yang Kuan (1960, p. 187, fig. 69). Mineral coal or charcoal is burned in the large chamber; blast is blown in at the left. The flame travels through the long passage to the puddling bed at the right.

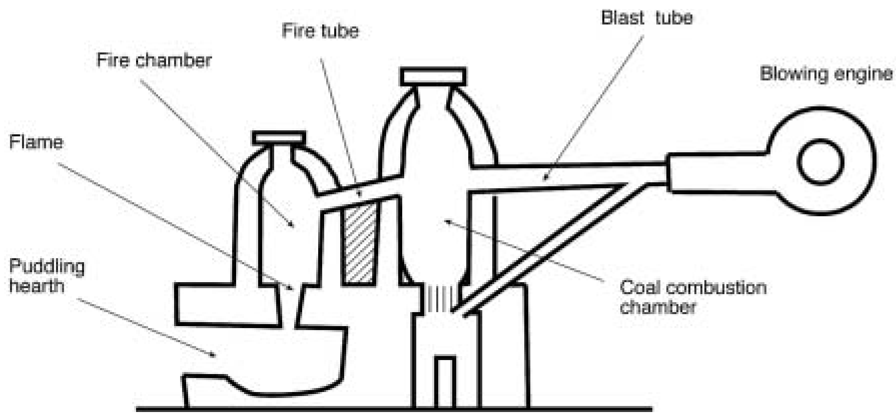


Figure 21 A type of puddling furnace used in Sichuan in 1958, redrawn from Yang Kuan (1960, p. 187, fig. 69). The dimensions are not given. Anthracite coal is burned in the firebox at the upper right. Ashes fall into the ashbox at the lower right. Blast is blown into both the firebox and the ashbox. The flame travels through the large empty chamber and then into the puddling bed at the lower left.

in large part taken up by the iron. Chinese fining processes were much more fuel-efficient, as we have seen above,[91] and the separation of the fuel from the iron in the Sichuan puddling process no doubt increased this efficiency to some extent; perhaps, then, a need for a cheaper fuel was rarely felt.

Two types of puddling furnace in use in Sichuan which did use mineral coal are described briefly by Yang Kuan.[92] They were used in the Great Leap Forward period, and presumably also earlier. He gives the diagrams reproduced in Figures 20 and 21. It can be seen that these furnace designs provide much greater separation between fuel and iron than the one discussed above (Figure 17).

[91] P. 17.
[92] Yang Kuan (1960, pp. 187–8); see also Anon. (1958h).

The Sichuan iron industry

We shall see further on that there was a major iron industry in Sichuan in very early times.[93] Under the state monopoly of the Han period a number of 'Iron Offices' (*tie guan* 鐵官) produced iron in large blast furnaces.[94] I shall suggest further on as a fair guess that in the +11th century Chinese iron production was on the order of 1.2 kg per capita.[95] If we were to suppose for the sake of argument that per capita production in Sichuan was of the same order of magnitude whenever there was peace and prosperity, we might arrive at an annual production as high as 20,000 tonnes in the early 19th century.[96] This production might have required 100 blast furnaces. Obviously the highly speculative reasoning I give here has no great value, but it shows the sort of scale which the Sichuan iron industry may have had in recent centuries.

Virtually nothing is available in the way of economic statistics for Sichuan in the 19th and early 20th centuries.[97] We do not know how many ironworks there were or, with any degree of reliability, how much iron they produced.[98] We may guess that China's generally unhappy conditions in this period were felt in Sichuan, and that industry suffered to some degree. On the other hand, Sichuan's isolation probably protected the iron industry from the worst shocks. Production had probably always been very largely aimed at local demand. This demand may have decreased because of bad times, but competition from cheap foreign iron would not have been severe before steamship transport through the Yangzi Gorges became a commercial reality in the 1920s.[99]

Though we know something of the economic history of iron production in Sichuan, we know nothing of its technology before the late 19th-century descriptions discussed above. We see it here in a time of change. Two important features of blast-furnace operation seem to have been going out of use: limestone flux and water-powered blast. In addition, it seems that the technology may have been improved in some ways by foreign influence.

The use of a limestone flux appears to have disappeared almost completely by 1900. The primary functions of the limestone flux were to reduce the loss of iron to the slag, to lower the melting point of the slag, and to reduce the sulphur content

93 Pp. 140–1.
94 Pp. 231–7 below.
95 P. 280 below.
96 Skinner (1987) has shown that the reported population statistics for Sichuan in the 19th century are the result of systematic falsification by provincial clerks. Careful analysis of the methods of falsification leads to the result that a population of 22 million in 1813 is the result of a reliable census. Other reasoning gives the provincial population in 1833 as 25.4 million and in 1853 as 28.5 million. Cf. the much higher estimates of Bielenstein (1987, p. 118).
97 Cf. Bramall (1993, pp. 1–6).
98 Zhang Xiaomei (1939, p. Q1) estimates annual iron production by traditional methods in Sichuan at 21,500 tonnes, but does not tell how this estimate was arrived at.
99 A Japanese steamship had negotiated the Gorges as early as 1895, and English attempts succeeded in 1898. In the period 1911–21 three American and four British steamships plied the Yangzi as far as Chongqing. The real impact of steamship transport was not felt here, however, until Chinese firms came into the trade in the 1920s. Jiang Tianfeng (1992, pp. 224–5); cf. Dautremer (1911, pp. 6–7); Rawski (1989, pp. 44, 191ff).

of the pig iron produced. It would seem from the analyses reported above that sulphur in iron was not a major problem here. The pig iron is several times described as 'slaggy', because the high melting point of the slag meant poor separation of slag and iron. This was probably not a major problem, since the pig iron was to be melted again in the foundry or puddling furnace, where better separation could be effected without great trouble. The cost of limestone may have risen in Sichuan at the end of the 19th century as brick-and-mortar building became more common and cement production expanded: in Cremer's travels in Sichuan in 1905 he noted numerous lime kilns wherever he went.[100] But besides the cost of limestone another major disadvantage of its use is that a basic slag attacks the lining of the blast furnace, reducing its useful life. In the generally poor economic conditions of the time, operating blast furnaces without flux was a sensible way of cutting costs.

Water power continued in use rather longer, perhaps until around 1920, but later we have only reports of human labour being used for the blast.[101] Perhaps some electric or steam-powered blowing machines were also in use, but the overall impression is that of a transition from water power to labour power. This presumably reflects an economic development in which the price of capital rose while the cost of labour fell. Besides the obvious direct saving of capital for the building of water-wheels, the transition to human labour saved capital in another way as well. Water power could obviously be used only in certain locations. A labour-powered blast furnace, not being restricted in this way, could be located according to other considerations, such as land prices or proximity to raw materials, markets, or transportation, and some saving in capital costs, operating costs, or both would have resulted.

In the 1930s there were also changes in the technology of Sichuan's iron industry which were due to foreign influence. The 1936 survey describes a cementation steelmaking furnace in Weiyuan County 威遠縣 which clearly is of foreign design.[102] The cementation steelmaking process was a German invention of the late 16th century, and developed into the most important steelmaking process of the early 19th century.[103] The introduction of the Bessemer process provided cheaper means of making steel, and by 1900 the cementation process was essentially obsolete, though it continued in use in Sheffield and a few other places until as late as the 1950s.[104] It is a surprise and a puzzle to find this process in use in Sichuan in the 1930s. When was it introduced, and by whom?

Another surprise has already been mentioned, the distinction between 'older' and 'newer' internal shapes of blast furnaces mentioned in a report of 1940.[105] The

[100] Cremer (1913, *passim*).
[101] Notices of water power used in blast-furnace operation in Sichuan include: Széchenyi (1893, pp. 678–9) (see Box 2); DuClos (1898, p. 313); Cremer (1913, p. 58); Way (1916, p. 22).
[102] Luo Mian (1936, pp. 35–8).
[103] See Section 2(vi) below, pp. 66–9.
[104] Barraclough (1976a; 1984, vol. 1, pp. 121–2).
[105] See Figure 16 and p. 26.

'newer' form resembles that of some 19th-century European blast furnaces, curiously enough a form which in the mid-19th century was being replaced by more rounded forms like the 'older' form in Sichuan.[106] It is perhaps less certain that this 'newer' form in Sichuan was introduced from the West; if it was it is one of only very few examples I have seen of changes being made to traditional Chinese iron-production technologies through foreign influence.[107] The usual pattern of foreign involvement entailed the total replacement of existing technologies with foreign technologies, usually under foreign control.[108] Again: when was this influence, and through whom?

The first two technological developments listed above – concerning the flux and the blast – would seem to be the cumulative result of decisions made by numerous entrepreneurs adapting to changing economic conditions. In one sense these developments represent a technological degeneration, since they involve the abandonment of previous innovations; in another sense, however, they may be seen as progressive, for they make for a more efficient iron industry in the specific context in which it must function. In dealing with technological change it is always well to remind oneself of these two sides of the question of progress.

The latter two developments – concerning possible foreign influence – probably involved some form of government intervention. From the 1911 revolution to 1937 Sichuan was controlled by a number of mutually hostile 'warlords' (*junfa* 軍閥, regional militarist rulers).[109] After the 'War of the Two Lius' (Liu Wenhui 劉文輝 and Liu Xiang 劉湘)[110] of 1932, the most important iron-producing areas of the province were under the control of Liu Xiang. Though in general as bellicose and mediocre as any of the others, Liu Xiang did do a certain amount towards industrial development, and research into his 'Min Sheng Industrial Company' and 'West China Development Corporation' may well show that they were the mediators of foreign influence in the traditional iron industry of Sichuan.[111]

In 1937, with the start of full-scale hostilities with Japan, Sichuan took on a new importance. Chiang Kai-shek's Nanjing government moved here, as did the greater part of China's universities and scientific research institutes. During the war Joseph and Dorothy Needham were in Sichuan with the Sino-British Science Co-operation Office, and their *Science outpost*[112] provides a wonderful glimpse of the intense atmosphere in the by this time almost totally isolated province. Attempts to build modern steelworks had failed, and the traditional iron industry was now the only provider of iron and steel. Numerous studies were made of ways

[106] Percy (1864, pp. 350ff, esp. pp. 441, 475–91, 559).
[107] Other examples can be seen in Gottwald (1938); Craddock and Zhou (2003).
[108] See e.g. Brown (1978; 1979). Note also Dernberger (1975).
[109] See especially Kapp (1973); Bonavia (1995, pp. 140–53).
[110] Boorman (1967–71, vol. 2, pp. 417–19, 395–8).
[111] Kapp (1973, pp. 58, 152 nn. 85–6; 1974, pp. 147–53) cites some sources on these enterprises. Note also Luo Mian (1936, pp. 5–7); Xiong Fu (1981); Rawski (1989, pp. 82–3, 148, 159).
[112] Needham and Needham (1948).

to improve the traditional technology, and it would seem that some at least of these were successful.[113]

After the Second World War the traditional iron industry seems to have continued in full-scale operation, and efforts to develop its technology continued. For example, in the early 1950s experimental work commenced in Hechuan 合川 and Jiangbei 江北 Counties on ways to prolong the operating life of the Sichuan blast furnaces.[114] This type of research was no doubt of great value in the Great Leap Forward in Sichuan, though I have not found much information on this.[115]

(iii) Crucible Smelting in Shanxi

Shanxi seems fitted out by nature for the iron industry, with the world's largest deposit of coal, reasonably large reserves of iron ore and limestone, and not very much else in the way of raw materials for industry.[116] Coal mining and iron production were sideline occupations for a large part of the peasant population, but there seem also to have been large areas in which iron making was the *only* occupation. In Yincheng 蔭城, for example, a town with a population of perhaps 5000, people told a visitor in 1898, 'We eat iron.'[117]

Crucible smelting

The method used here for smelting iron was very different from what we have seen above. A mixture of crushed iron ore and coal was packed in crucibles, and the crucibles heated in a stall furnace with more coal. The coal in the crucible reduced the iron oxides in the ore.

The earliest published description of the method seems to be that of von Richthofen in Dayang 大陽, Shanxi, in 1870. It is worth translating in full for the light it also sheds on the general conditions of the iron industry in Shanxi. No illustrations accompany this description, but Figures 22–25, taken from later publications, provide some help.

[113] E.g. Wang Ziyou (1940); Zhu Yulun (1940); and many other articles in the journal *Kuangye banyue kan* 鑛冶半月刊 (Mining and Metallurgy Semimonthly) in the war years. Hu Boyuan (1946, pp. 810–11) gives information in tabular form on many of the ironworks established in Sichuan in this period.

Meanwhile, in the Shaanxi–Gansu–Ningxia Border Region Soviet research was also being carried out on the improvement of the local traditional iron-production techniques. Mao Zedong (1980, p. 160); I. Epstein in Needham and Needham (1948, pp. 202–3).

[114] Li Renkuan (1959). As noted above (Box 3, p. 27), a normal furnace campaign was on the order of 200 days before repairs became necessary. One blast furnace in Jiangbei County operated continuously from November 1954 to August 1958; one in Hechuan County was blown in in July 1955 and was still in blast at the beginning of 1959.

[115] But note Goodman (1986, pp. 91ff).

[116] Background material for Shanxi's economic geography includes Williamson (1870, pp. 151–69, 287–363); von Richthofen (1872, pp. 27ff, 94ff; 1877–1912, vol. 2, pp. 336–493); Willis et al. (1907, vol. 1, pp. 167–96; vol. 2); Nyström (1910; 1912); Corbin (1913); Anon. (1920; 1985a); Yang Dajin (1938, vol. 2, pp. 341–8); Qiao Zhiqiang (1978); Brandt (1994).

[117] Shockley (1904, p. 850).

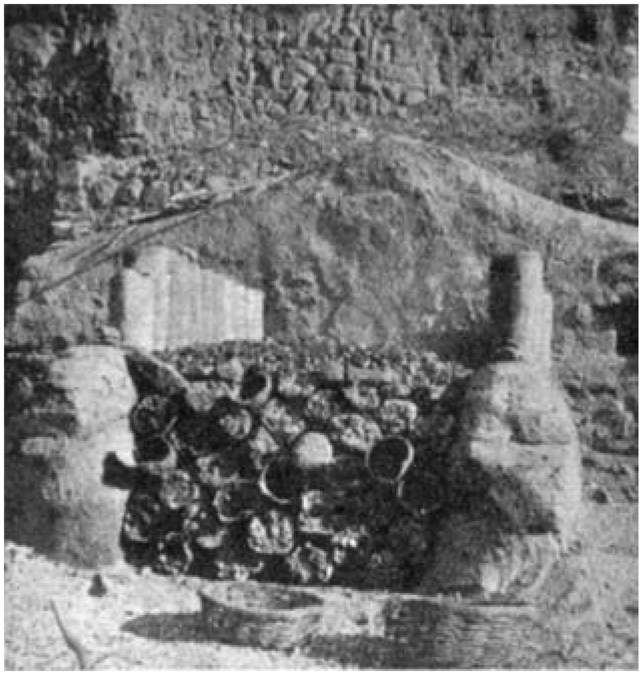


Figure 22 Stall furnace for crucible iron smelting in southern Shanxi, photograph reproduced from Kocher (1921, p. 10, fig. 1).

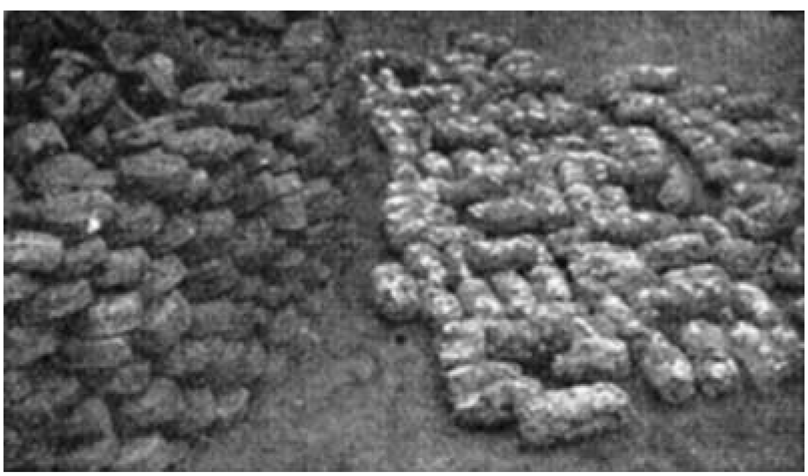


Figure 23 Lumps of cast iron and puddled wrought iron in southern Shanxi, photograph reproduced from Kocher (1921, p. 10, fig. 3).

Figure 24 Stall furnace for crucible iron smelting somewhere in Shanxi, photograph reproduced from Dickmann (1932, p. 154, fig. 9).

Figure 25 Crucible smelting of iron in progress in Gaoping 高平 County, Shanxi, photograph reproduced from Shockley (1904, fig. 1, facing p. 854).

Meeting innumerable animals and coolies on the pack road carrying anthracite, one expects to find a large-scale mine; but both coal mining and iron manufacture in this region have the character of all Chinese industry: rough, exceptionally diminutive, and nevertheless of an extraordinary perfection. One is astounded, arriving at these much-discussed places, to see merely hundreds of small establishments among which the work is distributed. One finds nothing which even remotely resembles a European blast furnace.

The iron smelter is situated on a slightly inclined floor, 2½ m long and 1½ m wide. On the two long sides are walls, 1¼ m high; the third side, towards which the floor ascends, is open; and on the fourth is a small and primitive hut for the bellows and two people who work it. The floor is covered with small pieces of anthracite, the size of a fist. On this are placed about 150 crucibles of refractory clay, [15] inches high [38 cm][118] and 6 inches wide [15 cm], which are filled with a mixture of small pieces of anthracite and crushed iron ore. All the spaces between crucibles are carefully filled out with anthracite, and a layer of the fuel is spread on top. Sometimes a second layer of 150 crucibles is laid over the first. Over this is laid more anthracite and on top a layer of shards of old crucibles. The whole heap is ignited, and air is blown in. When everything is burning and the heat is great, the blowing is stopped, since the natural draught is sufficient to maintain the heat.

If the intention is to make cast iron [*Roheisen*], the crucibles are taken out after a certain period of time and the contents cast as flat plates; the result appears to be a clean white steel-making pig iron.[119] If wrought iron is desired, the heap is allowed to burn out and cool off over a period of four days. The crucibles are then taken out and broken. In this case the iron is in the form of a hemisphere.

These two types of iron serve as the raw material for a wide variety of manufactures. Their further treatment of one sort or another for particular purposes is kept secret by the individual factories, and some of these have acquired a great reputation for the preparation of kettles, ploughs, or other equipment.

A third type of raw iron is also prepared by casting the molten metal in water to form drops. This type is added in various quantities to the other types in order to suit various purposes.

The best product is the wrought iron, which is far superior to that of Europe and possesses great malleability. The Chinese also excel in the casting of very thin objects, such as the iron pans [woks] used for cooking; this is an art which they understand everywhere, but Shanxi is its home.

It is of great interest to go around to the different establishments and see everywhere these simple methods used which have served since ancient times. It is clear that this great perfection must be ascribed not only to experience but also to the quality of the raw materials. Everything they need is supplied by the strata of productive coal formations which are only a few hundred feet thick. Of the very widespread iron ores only the purest and most easily smelted are used. Clay and refractory material are also found in great quantities. But the most important material is anthracite.[120]

118 It seems certain that von Richthofen meant English inches when he used the word *Zoll*. The text gives 5 inches, which is very unlikely to be correct. The versions in von Richthofen (1872, p. 30, and 1877–1912, p. 412) give 15 inches. Even with this correction these are by far the smallest iron-smelting crucibles reported anywhere in Shanxi.

119 *Stahleisen*, a pig iron suitable for open-hearth steelmaking, with low phosphorus and sulphur and fairly low silicon; cf. Anon. (1939, p. 782).

120 von Richthofen (1907, pp. 498–9; cf. 1872, p. 30).

Figure 26 Operation of a furnace in Shanxi for converting cast iron to wrought iron, photograph reproduced from Alley (1961a).

Numerous other sources also exist for the crucible smelting process as it was practised in Shanxi and elsewhere, and we find considerable variation in the details from place to place.[121] Typically the crucibles might be 15–20 cm in diameter and 50–100 cm high; the charge in each, 15–25 kg ore and 4–6 kg coal; the number of crucibles in the furnace from under 100 to over 300; the heating time 1–3 days; and the yield of iron from ore 20–40 per cent.[122] Natural draught alone was sometimes used, but more often, as here, a man-powered blast was used during part or all of the process. The iron produced in this way was normally in the form of a very slaggy bloom, with a carbon content in the range 1–3 per cent. This was either decarburised by any of a number of processes (e.g. Figure 26) to make wrought iron, or carburised in a cupola or crucible furnace to make cast iron.

As von Richthofen observed, the scale of enterprise in Shanxi in the 19th and 20th centuries was very small.[123] We may perhaps explain this by noting the tiny capital cost of a crucible iron smelter: 'A capital of thirty dollars would be sufficient to start

[121] The most important sources seem to be the following. In Western languages: Davidov (1872a; 1872b); von Richthofen (1872, pp. 30, 34; 1877–1912, vol. 2, p. 412; 1907, pp. 498ff); Henderson (1872, pp. 74–7, 85–6, 119–20); Henderson in Day (1875, Appendix, pp. 29–32); Shockley (1904); Nyström (1910, p. 398); Anon. (1910); Read (1921); Kocher (1921); Licent (1924, vol. 2, pp. 623–6); Tegengren (1923–24, pp. 323–7); Foster (1926); Wang Jingzun and Wang Yuelun (1930, English pp. 109–112, Chinese pp. 85–7); Dickmann (1932); Hara (1992). In Chinese: Yang Dajin (1938, vol. 2, pp. 344–5); Ding Wenjiang (1956, pp. 369–72); Kong Lingtan (1957); Yang Kuan (1960, pp. 95–9); Fan Baisheng (1985). In Japanese: Anon. (1920, pp. 596–7); Hara Zenshirō (1993). In compiling these sources I have benefited greatly from a correspondence some years ago with Dr Bennet Bronson.

[122] See e.g. the comparative table given by Tegengren (1923–24, p. 326).

[123] He was not correct in supposing that the same was true all over China without exception, as will be seen below.

this complete set of foundry and iron works, including the purchase of a stock of coal, ore and fire-clay. These substances are all close at hand, and cost only a trifle.'[124] It seems that almost anyone could start an ironworks, and that the technology used did not provide any great economies of scale.

Tegengren gives some economic data on the process as he observed it, also in Dayang, around 1920:[125]

Expenditure (for one heat).			
Raw materials:			
Anthracite	2000 catties	@ 1.3 cash	2600 cash
Ore	1500 catties	@ 0.6 cash	900 cash
Hei-T'u[a] and dust coal	400? catties	@ 1.0 cash	400?cash
Clay for 64 crucibles @ 5 kilos each–320 kilos		@ [0.5] cash[b]	160 cash
Labour:			
Wages for 500 catties of raw iron		@ 1.2 cash per catty	160 cash
Addition for sundry expenses, 2% of the total			100 cash
		Total	**4760 cash**
Receipts			
Sales at the smelter of 500 catties of raw iron		@ 10 cash per catty	**5000 cash**
		Approximate profit	**240 cash**

[a] 黑土, see below, p. 46.
[b] Tegengren has '5 cash', but this can only be a typographical error for '0.5 cash'.

We may note the prodigious consumption of fuel here, almost five times the weight of the iron produced: its cost represented more than half of the total cost, and a small reduction in coal consumption could have increased profits dramatically. We may wonder whether Tegengren's figures are typical for all crucible smelting.

The cost of the large amount of refractory clay needed for the crucibles would have been prohibitive in many parts of China, but in Shanxi it seems to have been insignificant. It was available in great quantity out of the same geological strata as the ore and the coal. A final point to be noted is that the fragmentation of the iron industry into small competing enterprises had driven profits down to only 4.8 per cent on the price of the product.

[124] von Richthofen (1872, p. 34).
[125] Tegengren (1923–24, p. 327). 'Catty' was formerly a commonly used translation for *jin* 斤, a measure of weight equal to about 0.6 kg.

Nature's greatest gift to Shanxi was its enormous coal reserve, but poor transportation made the export of coal uncompetitive,[126] and the province's most important export to other provinces was iron. From early times speciality products of iron and steel seem to have been the leading exports: the Tang poets Du Fu 杜甫 and Lu Lun 盧綸 both mentioned the famous scissors of Shanxi,[127] and for centuries a large proportion of the needles used in China came from here.

This speciality trade was hit very hard by foreign competition, as von Richthofen noted:

> The competition with foreign trade is another cause of the decadence of the wealth of [this province]. If we commence with the trifling article of needles, their manufacture in Shansi has almost been annihilated, by the importation of the much better and cheaper foreign article. The same will be true, before long, in regards to guns and steel ware; and there can be no doubt that the injurious effects of foreign competition have been seriously felt by the iron trade of Shansi in general. Being the only noteworthy article of export from that province, the diminished sales and reduced prices contribute to impoverish the inhabitants.[128]

He estimated the iron production of the entire province to be very roughly 160,000 tonnes per year. When Shockley visited Shanxi in 1898 he arrived at a rough estimate somewhat in excess of 50,000 tonnes per year, and went on:

> When von Richthofen was in Shansi, he estimated the production of iron at 160,000 tons per annum, which was considered an absurdly large estimate by critics who had never been in the province,[129] but I have no doubt he was well within the truth. The district magistrate at Tsê Chou[130] said that the iron made in that district now was only one-fourth of what it was thirty years ago, which was about the time that von Richthofen visited the province (1870–72). If the iron-trade has declined as much in the rest of the province as it has here, my estimate and von Richthofen's would not be so very different.[131]

The effect of the shortage of iron during World War I is perhaps seen in an estimate cited by Yang Kuan for 1916 of 70,000 tonnes per year for the whole province.[132] An estimate of 68,600 tonnes per year for the early 1920s is given by Wang Zhuquan 王竹泉.[133]

[126] In 1870, 'I repeat, that coal, which costs in Shanxi thirteen cents per ton at the mine, rises to four taels at a distance of thirty miles, and to over seven taels at a distance of sixty miles; also that, at Nan-yang-fu [南陽府] (Henan), coal from Hunan is used which has travelled eight hundred miles by water, and is sold at the same price with the coal mined at a distance of thirty miles from the city, but which is transported by land.' von Richthofen (1872, p. 37).

[127] *Du Gong bu shi ji*, ch. 4, p. 3a; Liu Jixian et al. (1982, p. 9); Liu Chutang (1989, p. 235); tr. von Zach (1952, p. 243).

[128] von Richthofen (1872, p. 38).

[129] See Henderson (1872, pp. 155–7) and the reply by von Richthofen (1872, p. 148).

[130] Zezhou 澤州, modern Jincheng 晉城, Shanxi.

[131] Shockley (1904, p. 871). It should be noted that F. R. Tegengren (1923–24, p. 320), after citing this evaluation, gives a careful criticism of von Richthofen's estimates and suggests that the true annual iron production of Shanxi in 1870 may have been closer to 125,000–130,000 tons.

[132] Yang Kuan (1960, p. 95); note also Tegengren (1923–24, pp. 320–1).

[133] In a report reprinted and translated in Tegengren (1923–24, Chinese pp. 305–13, English pp. 435–43). This production estimate is given on English p. 321.

The coming of the railroads improved the chances of the iron industry in some parts of the province. In Pingding County 平定縣, in 1870, von Richthofen estimated an iron production of about 54,000 tonnes per year. In 1898 Shockley's estimate was only 18,000 tonnes, and in the early 1920s Wang Zhuquan's estimate was 20,000 tonnes. By 1928 production in this county may have doubled rather suddenly, though there does not appear to have been much, if any, speciality production:

Annual pig iron production of Pingding County by traditional methods. The Office of Public Finance[134] of Pingding County estimates that, in times when transportation is in order, the pig iron exported on the Zheng–Tai 正太 [Shijiazhuang–Taiyuan] Railway amounts to about 1500 carloads per year. Assuming 20 tonnes per carload, this gives 30,000 tonnes. In addition more than 5,000 tonnes is either melted and marketed locally or transported by mule. Thus in times when transportation is in order production is around 40,000 tonnes per year.[135]

In addition to iron produced by traditional methods, a modern ironworks established in Pingding in 1926, 'when in good running order', was producing about 500 tonnes per month.[136] Thus the local modern sector was not yet, at this time, a serious competitor of the traditional sector.

An economic survey of selected counties of Shanxi carried out in 1950 showed that large parts of the province were still heavily dependent on iron production. In the county of Changzhi 長治, for example, of 179 villages, 53 were 'coal and iron villages'. Before the War, coal and iron production had accounted for about 60 per cent of the income of the population of these villages. In 1950 production had fallen to about 30 per cent of the pre-war level, but still there were 444 crucible smelting furnaces in operation, with about 20,000 people directly engaged in coal and iron production and over 50,000 directly or indirectly dependent on the industry for their livelihood.[137] Similar conditions were found in several other counties as well.

In 1870 our earliest witness, von Richthofen, gave great praise to the iron produced in Shanxi,[138] and it is odd to find that later its quality was usually reported as being quite poor. In 1911 T. T. Read published analyses of samples of iron from twelve different ironworks in Pingding: the sulphur content ranges from 0.13 to 0.61 per cent, and even the lowest of these figures is far higher than is desirable for most uses of iron.[139] By the time of the Great Leap Forward the process was considered unusable because of the high sulphur content of the product.[140] I think it is safe to say

[134] *Gong kuan ju* 公款局.
[135] Wang Jingzun and Wang Yuelun (1930, Chinese p. 86; cf. English p. 112).
[136] Wang Jingzun and Wang Yuelun (1930, English p. 112). In 1950 Pingding produced 2049 tonnes of iron (Anon., 1954b, p. 81).
[137] Anon. (1954b, pp. 10–11, 81–2).
[138] See above, pp. 38–42.
[139] Read (1911, p. 27). Nyström (1910, p. 398) also mentions the high sulphur content of Shanxi wrought iron. Note, however, an analysis done in 1915 which showed only 0.078 per cent sulphur in a sample of Shanxi wrought iron (Tegengren, 1923–24, p. 329).
[140] Yang Kuan (1960, p. 99).

that it would be almost impossible to make needles of this iron, and the same is likely to be true for scissors and other fine wrought products. It is likely that the quality of Shanxi iron had been much better in earlier times, but deteriorated as prices fell and it became necessary at the ironworks to reduce costs drastically.

It is not easy to know what exactly the differences may have been between the crucible smelting process as observed in the late 19th and 20th centuries and the earlier higher-quality process which I have posited here. One possibility, however, can be seen from experiments with essentially the same process in 1908 in Höganäs, Sweden: these showed that the sulphur content of the iron produced could be reduced to 0.01–0.03 per cent by the addition of a small amount of limestone ($CaCO_3$) to the crucible charge combined with careful temperature control at about 1200°C.[141] Limestone is available in large quantities in Shanxi,[142] and has been used in iron production in China at least since the Han period.[143]

Another possibility is the likely rôle played by a material known as 'black earth' (*hei tu* 黑土), which several observers were told was essential in the crucible charge in the Shanxi process.[144] This is a kind of decomposed coal produced by the weathering of the upper strata of the coal seams; an analysis given by Tegengren indicates that it has very low sulphur (0.21 per cent) and very high ash (32 per cent) as compared with ordinary coal. It contains about 9 per cent lime (CaO), and therefore could be expected, in sufficient quantities, to be effective in removing sulphur from the iron.

The numerical data which I have compiled here for iron production in Shanxi are the best we have for any region of China in the early 20th century, though they are clearly less reliable than the precise numbers given might suggest. Production fell drastically in the second half of the 19th century, and this fall hit especially hard in the manufacture of high-profit speciality products which require high-quality iron. With the rise in iron prices during World War I production increased again, and the coming of the Shijiazhuang–Taiyuan railroad opened new markets for some (unknown and probably short) time.

The economics of the iron market forced the ironmasters of Shanxi to adopt a poorer technology, which gave an inferior product; in the long run this meant the ruin of the Shanxi iron industry. In the Great Leap Forward, if only a method of controlling sulphur content had been known, the crucible smelting process would have been attractive for the purposes of the campaign, for it required low investment and was easy to learn; but in fact it was abandoned and traditional blast-furnace technologies were introduced in Shanxi from elsewhere in China.

141 Sieurin (1911, pp. 458–9). On the Höganäs process see also Anon. (1979d, pp. 316–25), and pp. 365–8 below.

142 An earlier remark by Williamson (1870, p. 296) suggests that limestone was considered a normal part of iron production in Shanxi. In Pingding, in 1866, 'Natives told us that lime, coal, coal-charcoal, and a clay they called *kal* . . . are all found in the immediate neighbourhood.'

143 P. 235 below.

144 P. 43 above; Shockley (1904, p. 852); Read (1921, p. 454); Tegengren (1923–24, pp. 323–4).

(iv) Large- and Small-Scale Ironworks in Guangdong

On the southern coast, in the mountainous subtropical province of Guangdong,[145] the traditional iron industry had the peculiarity that it was divided into two distinct sectors. Hundreds of small blast furnaces rather like those of the Dabieshan region produced iron in small quantities for consumption in their immediate vicinity, while a number of very large blast furnaces in the mountains produced large amounts of iron for a very wide market. Most of the iron produced by the large-scale sector was shipped on the great rivers of the province to one centre, the industrial city of Foshan 佛山 (Fatshan), about 20 km from Guangzhou (Canton), where it was fabricated into products which were traded throughout China and Southeast Asia and even further afield.

Our sources for the iron industry of Guangdong have a greater historical depth than for any other part of China, allowing us to see it with some clarity as far back as the late Ming period. On the other hand our knowledge of the actual technologies used by the two sectors of this industry is very limited; as usual, however, it is with the technologies that we must begin.

Small blast furnaces

Our *only* source for the technology of the small-scale sector is the gouache paintings reproduced here as Plates I–VIII. They are from an album painted by a Chinese artist in Guangzhou in the middle of the 19th century and acquired by the *Mission Lagrené*, a French diplomatic and commercial mission which spent about a year in Guangzhou in 1844–45.[146]

Before showing the blast furnace the album illustrates exploration for suitable iron ore, Plates I–II,[147] the digging of ore from a hillside, Plate III, and the calcining of the ore, Plate IV. The blast furnace is shown in Plate V: it appears to have a cast-iron base (no doubt lined with fireclay) and a ceramic shaft. The shaft was probably made by plastering fireclay on the inside of a basket plaited in the intended form, producing the appearance of wickerwork. Plate VI, labelled ‘removing the fire’, probably shows a worker getting rid of slag which has been tapped from the

[145] On the physical and human geography of Guangdong see *SCC*, vol. 5, part 13, pp. 55–6 *et passim*; Ye Xian’en and Chen Chunsheng (1990); Imbault-Huart (1899); Anon. (1917); Xu Junming (1956); Wu Yuwen (1985). On its economic history see Faure (1989); Zhu Jieqin (1985); Anon. (1987b); Situ Shangji (1986); Xu Junming and Guo Peizhong (1981); Lian Haowu (2004).

[146] This information was kindly supplied by Mme Madeleine Barbin, Conservateur de la Réserve, Bibliothèque Nationale, Paris. The history of the mission is described by Lavollée (1853, pp. 1–304), who also gives an extensive bibliography of books and articles by members of the mission (pp. 415–17). Brief notes on this album are given by Huard and Wong (1966, p. 219); Cordier (1909, p. 246); Courant (1902–10, p. 179).

On the Guangzhou export watercolours and gouaches in general see Daurand (1845, pp. 56–64); Feuillet de Conches (1856, pp. 256–60); Feuillet de Conches (1862, pp. 145–8); Lavollée (1853, pp. 361–4); Downing (1838); Crossman (1972, pp. 92–120; 1991); Clunas (1984).

[147] Plate I is also reproduced and discussed in *SCC*, vol. 5, part 13, pp. 207, 209, fig. 26.

furnace.[148] The tapping of iron from the furnace is shown in Plate VII: like the furnaces of the Dabieshan region,[149] the whole furnace is tilted in order to pour out the molten iron into a ladle. Finally Plate VIII shows the iron being poured into simple bar-moulds and the bars being cooled in water.

It is important to recognise that we do not know how well the artist knew the technical processes that he depicted. The windbox seen in Plates V and VII seems too small in comparison with the much larger ones used in the Dabieshan blast furnaces, which were about the same size. We might also wonder whether the tapping of the furnace was really done in such a difficult and dangerous way as that shown in Plate VII: compare the methods used in the Dabieshan region, shown in Figures 3–5.

At a guess, the operation of this blast furnace was probably rather like that of the Dabieshan blast furnace, operating continuously for a period from a few days to a week or two, producing several hundred kilograms of cast iron per day. We shall see below[150] that this was a very useful technology for the small-scale village ironworks which were to be found throughout the province of Guangdong.

Large blast furnaces

Our principal source for the large-scale ironworks of the province is a very interesting passage in the *Guang dong xin yu* 廣東新語, 'New discourses on Guangdong', a book of jottings written about 1680 by Qu Dajun 屈大均 (1630–96).[151] Chapter 15 concerns 'Products' (*huo* 貨), and one section of that chapter concerns 'Iron'. It is translated in Box 4. This text is clearly composed of information from several unrelated texts, and caution will be advisable as we use it in an attempt to understand the technology and economics of the traditional iron industry of Guangdong.

The passage begins with a discussion of a kind of iron ore. In the middle of this is the warning that an ore deposit, no matter how rich, is useless if there is not sufficient wood in the vicinity[152] (the only fuel used was charcoal), and in general the passage shows a constant awareness of the economics of iron production. A geologist, R. C. Armstrong, comments on the description of ore: the 'yellow water seeping out' is coloured by an iron hydroxide gel (FeOOH), which is common in surface waters

[148] Or perhaps, as G. Hollister-Short has suggested to me, the worker is pouring molten iron into water to granulate it. We have seen that granulation was sometimes used in Shanxi (p. 41 above).

[149] See p. 11 above.

[150] Pp. 57–8.

[151] On Qu Dajun see especially Hummel (1944, pp. 201–2); Ou Chu (1986); Li Mo (1997); Peng Shijiang (1997). There are several variants of parts of this passage in 18th-century Chinese texts, and some modern historians cite these in preference to the *Guang dong xin yu*, thus taking them as quotations from Qu Dajun's sources rather than from his text. See e.g. *Yue zhong jian wen*, ch. 21, pp. 244–6; *Yue dong wen jian lu*, ch. *xia* 下, p. 131; *Nan Yue bi ji* 南越筆記, ch. 5, pp. 3a–5a; Li Longqian (1981, pp. 361–2, 363, 367); Luo Yixing (1985, p. 82).

[152] A warning also given by Agricola in his *De re metallica* of 1556. Agricola (1912, p. 31).

Box 4 *Translation of a passage on iron smelting by Qu Dajun* 屈大均 *(1630–96) in* Guang dong xin yu 廣東新語, *'New discourses on the province of Guangdong' (1700 edn, ch. 15, pp. 7b–10a; cf. 1974 edn, pp. 408–10).*

There is no better iron than Guangdong iron. In the iron-producing mountains of Guangdong, wherever there is yellow water seeping out, one knows there is iron. Digging there, one will find a large body of iron ore in the form of an ox; this is the 'iron ox' [*tie niu* 鐵牛]. If one follows the path of the underground water [*mai lu* 脈路] and digs deeply, more iron will be obtained.[a]

However, of the mountains which produce iron, it is only on those which are forested that one can operate a furnace. If the mountain is bare, even if there is a great deal of iron it will be of no use. This is why 'iron mountains' are not easy to find.

Splitting a body of iron ore layer by layer, one finds that each [layer] has a tree-leaf pattern. This differs on the two sides. If the mountain has a certain type of tree, then that tree's leaf pattern will be found in its iron ore. Even if one digs as deep as several tens of *zhang* 丈 [several times 32 m], the same phenomenon is found. When it is extremely cold in south China [Lingnan 嶺南], the leaves do not [normally] fall from the trees; it is only on mountains which produce iron that the leaves fall, and these are absorbed by the essence of the iron [*tie zhi jing ying* 鐵之精英]. This is an example of the Way of 'metal conquering wood'.

The iron ore has a spirit, and to this the furnace-master must sacrifice devoutly before he dares to operate a furnace.

The furnace has the shape of a vase [*ping* 瓶] with its mouth upward. The breadth at the mouth is about a *zhang* 丈 [3.2 m]. The base is 3 *zhang* 5 *chi* 尺 [11.2 m] thick [*sic*!], and the height is half of that [5.6 m].[b] The thickness of the body is slightly more than 2 *chi* [64 cm]. It is built of ashes, sand, salt, and vinegar.[c] It is bound about with thick cane and braced with wood of the *tie li mu* 鐵力木 and the *zi jing mu* 紫荆木.[d] It is also built against a mountainside for greater solidity.

At the back of the furnace is an opening, and outside the opening is an earthen wall. The wall has two 'doors' [blower fans], 5–6 *chi* high [1.6–1.9 m] and 4 *chi* broad [1.3 m]. Four persons operate these 'doors', 'closing' and 'opening' [pushing and pulling] alternately in order to produce the force of the blast.

The two openings [the blasthole and the taphole] are lined with 'water stone' [*shui shi* 水石].[e] 'Water stone' is produced at Dajiang Mountain 大絳山 in Dongan 東安 District [modern Yunfu County 雲浮縣]. Its substance is not hard, and not being hard it does not 'receive the fire' [*shou huo* 受火]. Not receiving the fire, it can endure long without altering; hence the name 'water stone'.

Furnace operation begins in the autumn and ends in the spring. Because the weather is cold the iron contains a great deal of water; metal is the source of water, and water flourishes in the winter, so that molten iron [*tie shui* 鐵水] is engendered by cold.

When the iron ore is charged [*xia* 下] [into the furnace] it is mixed with 'hard charcoal' [*jian tan* 堅炭].[f] Usually a mechanical device [*ji che* 機車] is used to cast down [the furnace charge] from the mountain into the furnace.

The flames [from the furnace] light up the sky, and its dirty black smoke [*qi* 氣] does not disperse for several tens of *li* 里 [1 *li* = about 0.6 km].

When the iron ore has 'melted' [*rong* 溶] it flows out into a rectangular pool [*chi* 池] [i.e. pig mould] and solidifies into an iron slab. This is removed. Then the furnace is

(*Contd.*)

Box 4 *Continued*

'shaken' [*jiao* 攪] with large wooden poles, and the molten iron flows out to form another slab.[g]

In the twelve hours [24 modern hours] [of the day], one slab should be produced each hour, with a weight of about 10 *jun* 鈞 [180 kg]. If two slabs are produced per hour, this is called a 'doubled cycle' [*shuang gou* 雙鈎]; then the furnace is excessively vigorous [*wàng* 王 = 旺], and in danger of damage. One must anoint the furnace with the blood of a white dog; then no accident will occur.

Among the Five Metals, Iron is the one which corresponds to Water; it is called the Black Metal [*hei jin* 黑金],[h] and is formed by the Essence of Great Yin [*tai yin zhi jing* 太陰之精]. Its spirit is a woman. According to tradition, the wife of a certain Mr Lin 林, when her husband was in arrears in his official iron quota, threw herself into the furnace in order to make it produce more iron. Today those who operate the furnaces always sacrifice to her, calling her 'Madame Gushing-Iron' [*Yong tie fu ren* 湧鐵夫人]. Her story is bizarre in the extreme.

An ironworks generally has 300 families living around it, [providing services as follows:] furnace tenders, more than 200; miners, more than 300; water-carriers[i] and charcoal-producers, more than 200; pack animals, 200 oxen; freighters, 50 vessels. The expense [i.e. capital investment] of an ironworks totals not less than 10,000 *jin* 金.[j] If it produces more than 20 slabs per day it is profitable, while eight or nine slabs [per day] is unprofitable; this is a fundamental principle.

Of all the smelters it is the iron of Datangji Furnace in Luoding 羅定大塘基爐 which is best. All of it is 'first grade iron' [*kai tie* 鍇鐵], glossy and soft, which can be drawn into wire. When it is cast into woks [*huo* 鑊][k] it is also good and 'hard' [*jian* 堅]. It is more expensive than the first-quality [iron] of any of the other smelters.

After smelting at any of the smelters, all of the iron is shipped to the port city of Foshan 佛山, where the people are excellent founders. Of the woks which they produce, the largest are called '*tang wei* 糖圍' ['sugar pot'?], 'deep-seven', 'deep-six', 'ox-one', and 'ox-two'.[l] The smallest are called 'ox-three', 'ox-four', and 'ox-five'. If there are five to a bundle they are called 'five-*kou* 口', and if there are three to a bundle they are called 'three-*kou*'. Those without handles are called 'oxen' [*niu* 牛]. The best are called 'pure' [*qing* 清].

In former times those who cast [woks] with handles [*er* 耳] were not permitted to cast them without handles, and those who cast them without handles were not permitted to cast them with handles. Those who cast both were indicted.

After [a wok] is cast it is coated with yellow clay and pork fat [to prevent rust].

When [a wok] is struck with a light stick, if it [sounds] like wood then it is good. It sounds like wood because its substance is 'hard' [*jian* 堅]. Thus the woks of Foshan are expensive, because they are 'hard', and those of Shiwan 石灣 [in modern Boluo County 博羅縣, Guangdong] are cheap, because they are brittle.[m] When they are sold [as far away as] central China [*Jiang Chu jian* 江楚間], people can distinguish them by their thinness and smoothness; the foundrywork is refined, and the craftsmanship is accomplished. Foundry products are generally better in Foshan, while ceramic [products are better] in Shiwan.

In iron fining [*chao tie* 炒鐵], cast iron is kneaded [*tuan* 團] and charged into the furnace [i.e. the fining hearth].[n] It is fired until it glows red,[o] then taken out and put on the anvil. One person holds it with tongs and two or three hammer it. At the side ten or more youths [*tong zi* 童子] fan it [i.e. work the bellows for the blast in the fining hearth]. The youths always sing a shanty without stopping. After this [the iron] can be converted into wrought iron and made into thin plates [*ye* 鍱].

Box 4 *Continued*

[In Foshan?] there are several tens of iron-fining plants [employing] several thousand persons. Each plant has several tens of anvils and at each anvil there are more than ten persons.

This [the fining hearth] is the 'small furnace'. Furnaces are large or small according to whether the iron [produced] is cast or wrought. The treatment [*zhi* 治] of cast iron is a matter for a 'large furnace' [a blast furnace], while the treatment [*zhi* 治][p] of wrought iron [i.e. the conversion of cast iron to wrought iron] is a matter for a small furnace.

The excellence of the strength [*jian* 健][q] of steel lies in its quench-hardening [*cui* 淬].[r] Before it has been quench-hardened, its softness remains. In quench-hardening, the steel is first hammered [into the desired shape] at the forge, then removed from the fire and put into water. A great fire is needed to soften it, and pure water is needed to strengthen it and form pure steel. This is the refining of steel [*lian gang* 煉鋼].

Ganquan 甘泉[s] has said: Observe the casting of metal in a great furnace, and you will know the end and beginning of Heaven and Earth. When [the metal] is melted in the furnace, this is its birth [*sheng* 生]. When it leaves the furnace and solidifies, this is its accomplishment [*cheng* 成]. Melting is a matter of the watery beginning, and solidification is a matter of the earthy end. Men consider melting to be subjugation [*qu* 屈, lit., 'bending'], but do not realise that it is the beginning of birth; what could be more enduring [*shen* 信 = 伸, lit., 'straight']? Men consider solidification to be enduring [*shen*], but do not realise that it is the end of accomplishment; what could be more of a subjugation? Beginnings and ends alternate, subjugation and endurance interact,[t] but the metal never changes; this is an image of the Way.

[a] The importance of underground water in the search for ores is also mentioned by the 16th-century writers Biringuccio and Agricola (Biringuccio, 1942, p. 15; Agricola, 1912, p. 116).

[b] *Di hou san zhang wu chi, chong ban zhi* 底厚三丈五尺，崇半之.

[c] Presumably it is built of clay with these ingredients added.

[d] *Mesua ferrea* and *Madhuca subquincuncialis*, 'common mesua' and 'peanut madhuca'.

[e] *Shui shi* sometimes refers to pumice stone (Read and Pak, 1936, p. 44, no. 73), but this would be unlikely to have the required refractory properties. In the present case the word may mean diatomite (or 'diatomaceous earth'), 'a light-colored, lightweight, friable sedimentary rock composed of the siliceous shells of microscopic aquatic plants called diatoms' (Bates, 1969, p. 360). Because of its porosity it is used in modern industry as a heat insulator, and we have seen above (p. 11, fn. 18) that it was used for refractory 'taphole stones' in blast furnaces in the Dabieshan region. Perhaps fossils of one kind or another reveal its aquatic origin and justify the name 'water stone'.

[f] This does not refer to mineral coal. Charcoal varies greatly in its mechanical properties; in a tall blast furnace it was essential that the charcoal be hard and strong so that it could support the weight of a high column of furnace burden.

[g] The most common meanings of the word *jiao* are 'to shake' and 'to stir'. Its use here is difficult to explain if the furnace was as large as Qu Dajun states. The furnace could not be 'shaken', nor could the iron in it be 'stirred' with a wooden pole, nor would there have been any reason to stir it. On the other hand, the tapping of one of the small Guangdong furnaces (Plate VII) could easily be described as *jiao*. It seems therefore to be likely that Qu Dajun had his description of the physical construction of the furnace from a source concerned with the large-scale ironworks of Guangdong, while his source for the tapping was related to the small-scale works.

[h] Cf. p. 86 below.

[i] *Ji zhe* 汲者, perhaps to be understood more generally as 'fetchers and carriers'.

[j] In this type of context one *jin* usually means one *liang* 兩 (about 37 g) of silver, so that the sum indicated, if it is to be taken literally, amounts to 370 kg of silver.

[k] The Cantonese pronunciation of this word gives us the English word *wok* for the round-bottomed pan which is a fundamental implement in every Chinese kitchen. The more usual north Chinese word is *guo* 鍋 .

[l] *Shen-qi, shen-liu, niu-yi, niu-er* 深七、深六、牛一、牛二. *Shen* [illegible] = 深. The 1974 edition has another obscure character, 滚, for the second *shen*.

(*Contd.*)

Box 4 *Continued*

[m] The point of this passage is that the best woks will be of grey rather than white cast iron (see below, pp. 161–3). White cast iron is very hard and can ring like a bell, while grey cast iron is soft and contains microscopic flakes of graphite which deaden vibration. Both are brittle (for very different reasons), but white cast iron is considerably more brittle than grey. The term *jian* 堅 normally means 'hard', and is so translated here, but it might be better to take it as meaning 'strong' or 'robust' in a vague sense. In modern technical terms, the mechanical property which is relevant here is *toughness*.

[n] I suspect that the author has misunderstood his source here, for in the fining process an action very like 'kneading' of the cast iron takes place *in* the fining hearth rather than before it is charged. See pp. 16–18 above.

[o] We should expect the iron to be white hot rather than red hot when it is taken from the furnace.

[p] Perhaps the two occurrences of *zhi* 治 , 'to order, govern', in this sentence are scribal errors for *ye* 冶, 'to smelt', though in the second case this would be an incorrect use of the word.

[q] Here the relevant mechanical property is in fact *hardness*.

[r] See pp. 133–7 below.

[s] Possibly the philosopher and educator Zhan Ruoshui 湛若水 (1466–1560), whose literary name was Ganquan. He came from Zengcheng 增城 in Guangdong, and wrote a number of books which, judging from their titles, might well contain the passage quoted by Qu Dajun here; see Goodrich and Fang (1976, pp. 36–42). Or conceivably the person referred to might be Qu Dajun's son Qu Minghong 屈明洪, whose alternate name was Ganquan; see Hummel (1944, p. 202). The quotation from Ganquan probably continues to the end of the passage translated here.

[t] *Qu shen xiang gan* 屈信相感, a quotation from the *Xi ci* 繫辭 commentary of the *Book of Changes*. *Zhou yi*, ch. 8, p. 87c; Legge (1882, p. 389).

draining iron deposits. The 'iron ox' is probably hematite formed in place by remobilisation of iron by groundwater and deposition in large pods. The leaf pattern is fairly common for water-deposited minerals, and is generally called a dendritic pattern.[153]

Further on we find a description of the workforce of an ironworks: it includes more than 200 furnace tenders, 300 miners, and 200 'water-carriers' and charcoal producers; transportation is provided by 200 oxen and 50 river vessels. The blast furnace produces 2–4 tons of pig iron per day, and this is shipped down-river to Foshan. These figures are suspicious, for if we take them seriously we are forced to suppose that the cost of iron was enormous. Production alone, without transportation costs, seemingly required between 0.5 and 1 worker-year per ton of pig iron. Even the labour-intensive technology used in the Dabieshan region required far less labour than this,[154] and production at this level would not require 50 ships to transport the product to market. Obviously the passage refers to a large firm which operated numerous ironworks scattered over a large area. (Two charcoal blast furnaces would not normally be placed too close together, as this would mean a doubled load on forest resources with little or no gain in efficiency.)

The actual mining of the ore might have been done in the same general way as in the small-scale industry (Plate III). Calcining is not mentioned, but it seems a good bet that, since it was necessary in the small-scale industry (Plate IV), it was also practised in the large-scale industry. In the description of blast-furnace operation there

[153] Personal communication to P. Golas, 1996.

[154] Pp. 13, 17 above; Wagner (1985, p. 2).

are at least two aspects which we should expect to see mentioned but do not: the addition of flux in the charge, and the tapping of slag. Fluxes can sometimes be omitted in blast-furnace operation,[155] but there is no way at all to avoid the production of slag.

The text mentions that furnace operation begins in the autumn and ends in the spring, and explains that this is because the element Water is in the ascendant in the winter, so that melting is facilitated. In 18th-century Britain, before the invention of the hot blast in 1828, it was a widely remarked phenomenon that blast furnaces operated more efficiently in winter than in summer. The reason for the greater efficiency in winter was that the air contained *less* water.[156]

The description of the blast furnace itself mentions a base, 11.2 metres thick. We know from Han archaeology,[157] and from accounts from the Great Leap Forward,[158] that large blast furnaces required a substantial base which could withstand the high temperatures at the bottom of the furnace and prevent any moisture from penetrating into it. It was typically made by digging a deep hole in the ground which was filled up with alternating layers of loose stones and tamped clay. A thickness of 11.2 metres for this base is surely excessive, but there is no obvious alternative interpretation of the text. We should not try to make too much of it, but assume for the moment that it reflects some misunderstanding, either ours or the author's.

The height of the blast furnace is said to be half of the given thickness of the base, or 5.6 metres. This is more in line with what we otherwise know about large Chinese blast furnaces, though we might have expected it to be even higher. The blowing apparatus is not the more common double-acting piston bellows, but a type with two large hinged fans which are pushed and pulled alternately by four workers. A very good illustration of it can be seen in Figure 130,[159] which shows a Yuan-period cupola furnace (not a blast furnace) with its blowing apparatus. It is something of a surprise that the blast is labour-powered rather than water-powered, but it may be that geographical considerations made this difficult in the ironworks about which Qu Dajun had information.

The mention of a mechanical conveyance for the furnace charge is interesting. Probably this device carried the charge up to an appropriate height, then was arranged to 'cast it down' into the furnace mouth from a sufficient distance to the side so that the apparatus, perhaps made of wood, was safe from the flames shooting out of the furnace.

Qu Dajun states that the best iron in Guangdong comes from a place called Datangji 大塘基 in Luoding Department 羅定州 (modern Luoding County). In

155 Pp. 16, 21–38 above.
156 Percy (1864, p. 397).
157 See p. 232 below.
158 See e.g. Yang Kuan (1960, pp. 132, 136).
159 P. 324 below.

1978 and 1982 investigations were carried out here by the Guangdong Provincial Museum, and some useful information came to light.[160]

The ruin of a blast furnace, believed to be of the early Qing period, was investigated in 1978 in a village named Luxia 爐下, 'Below the Furnace'. It is built into the side of a mountain near a stream, and the ruin of a 'water-powered pounder' (*shui dui* 水碓), believed to have been used in ore dressing, lies half a kilometre upstream. Numerous old mine-pits, called *genglongtou* 埂壟頭 by local people, are found on the mountain, and there is still virgin forest not too far away. Large amounts of slag and charcoal turn up in the fields around the furnace site. The Luxia furnace has enough points in common with the description in *Guang dong xin yu*, including its time and place, that it is quite likely that Qu Dajun (or the author of his source) actually saw a furnace like this one.

The furnace in Luxia is built on a base of refractory bricks laid on a 'very thick' base of clay mixed with salt and sand. The height of its charging platform indicates that the furnace was 6–8 m tall; the height of the ruin is 2.71 m. The investigators give the diagram shown in Figure 27, which does not entirely match their verbal description. The walls of the furnace are 77 cm thick. A surprise here is that the furnace appears to have had an elliptical cross-section. Some elliptical blast furnaces are known from Han China,[161] and this form was also tried in 19th-century America, Britain, and Russia,[162] but the purpose in these cases was to distribute evenly the blast from four or more tuyères, which were placed on the long walls of the furnace. In this case, with only one tuyère, it is not at all clear what purpose was served by the elliptical shape.

There are numerous blast-furnace iron-smelting sites in Luoding County, usually in villages with the character *lu* 爐, 'furnace', in their names. There are two places with the name Datangji (mentioned by Qu Dajun), but there is no sign of iron production in the immediate vicinity of either, and we must suppose that one or both of these served as trans-shipment points for iron from the scattered ironworks of the area, which perhaps all belonged to the same firm. Both are on the Luojing River 羅鏡河. This flows into the Shuang shui 瀧水, which flows into the Xi jiang 西江 (West River), one of the major rivers of Guangdong, which flows into the sea near Guangzhou.

> In the past, commercial vessels could navigate the Luojing River as far as the wharves at Fenjie 分界; today it is no longer navigable because of stones and shallow water . . . [One of the places named Datangji is in Fenjie.] Here there is a great bay which is suitable as a harbour for commercial ships. According to several retired sailors, including Yang Ya 楊呀, Xie Wenda 謝文大, Chen Shengcai 陳生才, and Zhou Jin 周金, in the past there were normally 30 to 40 ships berthed in this bay. These ships carried pig iron, iron woks, mountain products, and other local products down the Luojing River, the Shuang shui, and the Xi jiang as far as Zhaoqing 肇慶 , whence the loads were carried further to Foshan,

[160] Cao Tengfei and Li Caiyao (1985); Cao Tengfei and Tan Dihua (1985, pp. 118–23).
[161] P. 234 below.
[162] Percy (1864, pp. 489–91).

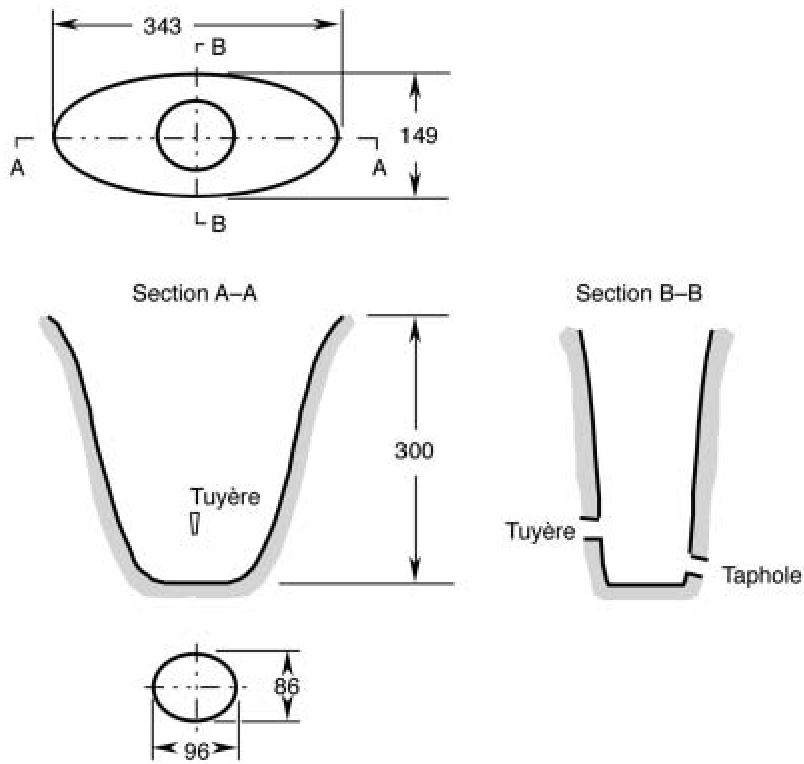


Figure 27 One possible reconstruction of an early Qing blast furnace investigated at Luxia Village in Luoding County, Guangdong, redrawn from Cao Tengfei and Li Caiyao (1985, p. 72, fig. 5). Dimensions are given in centimetres. The figure does not correspond to the description in the text of the article, according to which the entire north wall of the furnace above the taphole is missing, the remaining height of the south wall is 271 cm, and the original height was 6–8 m. The measurements shown here for the mouth of the furnace are those of the remaining upper part of the furnace as excavated.

Guangzhou, and other places. On the return trip they carried handicraft products from other areas as well as scrap iron . . . The older generation of sailors recalled the hard-working life of sailing on the Luojing River so vividly that we could see it before our eyes. Boatmen who served their apprenticeship under Yang Ya and the others are still working for the Luoding Wooden Sailing Ship Transport Company 羅定木帆船運輸社.[163]

It is a surprise to learn that iron was being produced somewhere in this vicinity within living memory, for we seem to have no other written sources indicating that iron was produced here since Qu Dajun's account of about 1680.

Six ruined furnaces were investigated in 1982, in villages named Tielu 鐵爐, Jiuludu 舊爐督, Jigonglu 雞公爐, Lezhalu 簕揸爐, Zaoshilu 鑿石爐, and Shuiyuanlu 水源爐. According to a retired schoolteacher in Tielu, Ye Qihua 葉其華, these were all owned by one man, named Mai Wenyuan 麥文元. Iron from all six

[163] Cao Tengfei and Li Caiyao (1985, pp. 70–1).

furnaces was transported to Tielu, where conversion to wrought iron took place. A fining or puddling hearth (*chaolu* 炒爐) was indeed found near the blast furnace at Tielu. We are not told what sources Ye Qihua had his story from, but no doubt he had access to local records, family documents, and the like. Perhaps he had also interviewed descendants of Mai Wenyuan. It is a pity that no dates are given for this entrepreneur, but presumably he lived in the early Qing period, when many sources indicate that the iron industry flourished here.

Other ruins of early Qing blast furnaces were noted by Yang Dajin in 1938 at Wushiling in Yunfu County 雲浮烏石嶺, some 65 km east of Luoding:

> The ore here was discovered very early: in the Qianlong period [1736–95] it was already being mined by the local people, and the remains of their diggings are numerous. Their products included iron woks, old-style cannons, large temple bells, and large incense burners. The iron-casting furnaces are still there; for example the ruins of Daping Furnace 大平爐 and Daan Furnace 大安爐. In form they somewhat resemble modern lime kilns. The fuel used in their operation was taken from nearby mountain forests. When this fuel was used up, furnace operation was stopped, for the difficulty of transportation made it extremely uneconomical to bring in fuel from elsewhere. Another reason for discontinuing mining here was geomantic superstition.[164]

The description of these furnaces as resembling modern lime kilns makes it likely that they were of the same form as the Luoding furnaces. It is generally believed that all or nearly all of the iron from the large blast furnaces was shipped to Foshan for further processing, but the range of products listed here indicates that the situation must have been more complex.

The debate of recent decades on 'embryonic capitalism'[165] in late Imperial China has included a large amount of research on the iron industry of Guangdong in the late Ming and Qing periods, and has given the impetus to some first-rate research on topics in Chinese economic history which for too long have been ignored. An amazing mass of source material has been uncovered, and numerous high-quality articles have been published.[166] Much of the source material is not easily available outside Guangdong, and the following discussion will be more dependent than usual on quotations in secondary sources.

[164] Yang Dajin (1938, vol. 2, p. 352).

[165] *Zibenzhuyi mengya* 資本主義萌芽, often translated literally as 'sprouts of capitalism'. 'Embryonic capitalism' in the Ming or Qing period, and the reasons why it did not develop into capitalism, is a very controversial subject among historians of modern China. For an introduction to the subject and the debate the most useful references seem to be Feuerwerker (1958; 1992); Liew (1988); Brook (1995); Tipton (1996); Brook and Blue (1999); Xu Dixin and Wu Chengming (2000); K. G. Deng (2000); Pomeranz (2001).

[166] Important publications on the iron industry of Guangdong include Anon. (1983a, pp. 493–6); Li Longqian (1981); Luo Hongxing (1983); Luo Yixing (1984); Peng Jianxin (1994); Deng Kaisong (1985); Tan Dihua (1987); Cao Tengfei and Tan Dihua (1985); Wang Hongjun and Liu Ruzhong (1980); Ye Xian'en (1987); Bao Yanbang (1997). In Western languages, see Hirth (1890); Eberstein (1974, pp. 23–60 *et passim*); Xu Dixin and Wu Chengming (2000, pp. 261–4).

Qu Dajun mentions two types of furnace, large and small, *da lu* 大爐 and *xiao lu* 小爐, and from his explanation it is clear that these are respectively blast furnaces and fining or puddling hearths.[167] A third type of furnace often mentioned in the sources is the *tu lu* 土爐, which presumably is to be taken as a 'local furnace', a furnace to serve local needs.[168] The *tu lu* were smaller than the *da lu* and were used in two ways: as blast furnaces, to smelt iron ore, and as cupola furnaces, to melt pig or scrap iron for casting.[169] It is likely that the small blast furnace in Plates V and VIII is precisely such a *tu lu*.

Both the *da lu* and the *tu lu* were blast furnaces which produced cast iron from ore, but they were supervised by different departments of the Qing government. The regulations are quoted in the premises of the judgement in a law case of 1821 on the illegal opening of an ironworks:

> There is a distinction between *da lu* and *tu lu*. The *da lu* cast[170] iron ingots. They are given licences by the Provincial Treasurer, who reports to the Provincial Governor and he to the Ministry. The furnace levy (*lu xiang* 爐餉) is collected by and goes into the account of the Provincial Treasury. The iron tax (*tie shui* 鐵稅) is collected by the Salt Controller and also transferred to the Provincial Treasury. The *tu lu* cast[171] farm tools, and are licensed by the Salt Controller, who reports to the Governor General and he to the Ministry. Both the furnace levy and the iron tax are collected by the Salt Controller and transferred to the Provincial Treasurer.[172]

Presumably the Regional Offices had the technical expertise necessary to oversee the large-scale ironworks with *da lu*, while the Salt Distribution Commission had a finer net of agents and was therefore better able to deal with the much more numerous, but administratively less important, *tu lu*. The 'furnace levy' probably had its origin in a tax in kind, but we see it in the Qing sources as an annual tax in silver paid without relation to actual production. We know very little about the 'iron tax',[173] but quite a bit about the furnace levies. Li Longqian has compiled from diverse sources a table of ironworks established in Guangdong in the Qing; his necessarily incomplete table lists 87 *da lu* and 33 *tu lu*.[174] The actual amounts of the furnace levies are available for 47 *da lu* and two *tu lu*. Of these most of the *da lu* levies

167 Box 4, pp. 49–52 above.

168 It could perhaps mean an 'earthen furnace', but these furnaces were all made of the same materials.

169 Deng Kaisong (1985, pp. 183–4); Li Longqian (1981, pp. 355, 364–6). On cupola furnaces see pp. 60–4 below. Cao Tengfei and Tan Dihua (1985, p. 118) are mistaken when they state that the *tu lu* was used for converting cast iron to wrought iron: they cite as evidence for the statement the passage translated immediately below from *Yue dong cheng an chu bian*, which clearly states that the *tu lu* was used for casting agricultural implements.

170 *Zhu shan* 鑄煽, probably 'to cast from a blast furnace'.

171 *Zhu zao* 鑄造, simply 'to cast'.

172 有大爐、土爐之分。大爐鑄煽鐵斤，由藩司給照詳明巡撫衙門咨部，爐 餉由藩司征收報撥，鐵稅運司征收轉解藩司報撥。土爐鑄運農具，由運司給照詳明總督衙門咨部，餉稅均由運司征收轉解藩司。*Yue dong cheng an chu bian*, ch. 24, p. 28b; also quoted, with a typographical error, by Cao Tengfei and Tan Dihua (1985, p. 118). The legal jargon of the passage is difficult, and I have been glad to have the advice of Charles Curwen. The law case is discussed in some detail by Li Longqian (1981, pp. 364–6).

173 According to Cao Tengfei and Tan Dihua (1985, pp. 127–8) the tax was in the early Qing 0.8 *liang* of silver per 10,000 *jin* of cast iron and 1.2 *liang* per 10,000 *jin* of wrought iron. Later this was changed to 1 *liang* per 10,000 *jin* of any kind of iron (37 grams silver per 6 tonnes iron).

174 Li Longqian (1985, pp. 372–9).

were 53 *liang* 兩 of silver, nearly all of the rest paying 50. The two *tu lu* levies were both only 5.3 *liang*.

Thus there were two distinct technologies for primary iron production in use in Guangdong in recent centuries, and the ironworks using them were recognised in law as forming two distinct sectors of the iron industry. Ironworks of the small-scale sector produced pig iron in small blast furnaces, and used the same furnaces to melt pig iron or scrap for casting products for local consumption. The large-scale sector was made up of large firms running numerous ironworks in the forested mountains of the province. In these ironworks large blast furnaces produced pig iron. Most of their production was shipped by river to the industrial town of Foshan, near Guangzhou, though as we have seen, some was cast or converted to wrought iron at the works for local consumption.

In Foshan some of the pig iron was converted to wrought iron, while the rest was used by foundries.[175] In either case the products were marketed far and wide: up and down the coast of China and all over Southeast Asia.[176]

In 1890 Friedrich Hirth called Foshan 'the city of iron and steel wares', and estimated its population as close to a million, 'mostly of the working class'.[177] We have no Western travellers' accounts of iron production here, for these industrial workers were considerably less tolerant of foreigners than the more commercially oriented people of Guangzhou. In 1847 a group of Englishmen and Americans visited Foshan and were attacked by an angry crowd which they claimed numbered twenty to thirty thousand. They were rescued by a company of Chinese soldiers ordered out by the city magistrate.[178]

A memorial by the Manchu official Omida 鄂彌達 in 1734 stated that there were at least 50 or 60 ironworks in mountainous regions of Guangdong, employing several tens of thousands of workers.[179] Another source, a century later, states that the annual production per furnace is 800,000–900,000 *jin* 斤.[180] Some modern historians multiply 60 furnaces by 900,000 *jin* and on this basis reach an estimate of annual production for the province of 54,000,000 *jin*, or about

[175] On Foshan and its iron industry see especially Luo Hongxing (1983), Luo Yixing (1984; 1985); Tan Dihua (1987); Anon. (1987a); Wang Hongjun and Liu Ruzhong (1980); Faure (1990); Xian Jianmin (1993); Huang Jianxin and Luo Yixing (1987); Jiang Zuyuan (1987a; 1987b); Imbault-Huart (1899, pp. 25–7).

[176] On the trade between Guangzhou and Southeast Asia see especially Bronson (1992); Viraphol (1977); Yu Siwei (1983). Bronson (1992, p. 94) gives statistics from Dutch colonial records for metal imports in Java in the years 1679–81, and these seem to show that the early Qing prohibition of the export of iron applied to wrought iron but not cast iron.

[177] Hirth (1890, p. 96).

[178] *Chinese Repository*, March 1847, **16**, 142–7. A rumour in the local English-language press had it that one Westerner had spent a day and a night in Foshan, disguised as Chinese (*Chinese Repository*, Feb. 1846, **15**, 64–5, quoting *Hongkong Register*). This may possibly have been the Swedish commercial attaché C. F. Liljevalch, who seems slightly better informed than other writers on the Guangdong iron industry, but even his report is too brief to be useful here (Liljevalch, 1848).

[179] Memorial by Omida 鄂彌達 (d. 1761), *Qing kai kuang cai zhu shu* 請開礦采鑄疏 , *Huang chao jing shi wen bian bu*, ch. 52, pp. 46a–47a, quoted *in extenso* in Anon. (1983a, pp. 32–3). Also quoted by Li Longqian (1981, p. 362) and Luo Yixing (1985, p. 84). Note also Deng Kaisong (1985).

[180] The 1835 edition of *Liang Guang yan fa zhi* 兩廣鹽法志 (which I have not seen), quoted by Luo Yixing (1985, p. 84).

32,000 tons.[181] (Clearly this method necessarily overestimates total production, and we should be justified in reducing it by at least half.) In 1735 Omida stated in another memorial that there were iron-smelting furnaces in every department and district (*zhou* 州 and *xian* 縣) of the province;[182] taken literally, this would imply well over 100 furnaces, and not all in mountainous regions. Obviously the 1734 memorial referred to *da lu* and the 1735 memorial to *tu lu*.

We have seen that the iron industry in Guangdong was largely overseen by the same government departments which dealt with the production and distribution of salt. A treatise of 1762 on the salt administration of Guangdong, *Liang Guang yan fa zhi* 兩廣鹽法志, includes a chapter on the iron industry which gives some interesting information. After a brief history going back to the pre-Qin period, it gives some statistics on production of iron in the Qing. The text is difficult, but it can be interpreted as giving total taxed production per year:

> From the first establishment of the Dynasty to the present there have been [years in which the tax on] 7,139,000 *jin* 斤, 6,839,000 *jin*, and 5,892,000 *jin* was collected [*zheng* 徵]; though the amount varies it is normally possible to obtain [the tax on] more than 6,000,000 *jin*. This is a constant. Thus the iron tax of Guangdong can be said to be plentiful.[183]

Six million *jin* is about 3600 tons. This seems distinctly on the low side, and may indicate that a good deal of the tax was evaded.[184] At the end of the chapter is a list of blast furnaces in Guangdong. Of these, 45 were in operation, 19 were temporarily out of operation, one was out of operation because of bankruptcy, and eight had been abandoned.

The decline of the Guangdong iron industry which began in the late 18th century has been documented by several Chinese historians.[185] One of many indications is that the 1835 edition of the *Liang Guang yan fa zhi* lists only 25 *da lu* in operation in 1799,[186] compared with the 45 listed in the 1762 edition. A memorial by the famous reformer Zhang Zhidong 張之洞 (1837–1909) in 1889 describes the traditional Guangdong iron industry as being in deep decline, and recommends various policy changes to make it more competitive with foreign imports.[187] By this time the large *da lu* were all gone, but the small *tu lu* continued to be used. In 1954 they were still in use in at least three counties of Guangdong, and had recently been reintroduced in several others.[188] Many more were built all over the province in connection with the Great Leap Forward of 1958.[189]

181 E.g. Luo Yixing (1985, pp. 84, 87).

182 Memorial by Omida 鄂彌達, quoted by Li Longqian (1981, p. 362).

183 我朝自定鼎以迄於今有徵 [7,139,000] 斤者有徵 [6,839,000] 斤者有徵 [5,892,000] 斤者雖參差不等大抵可得六百萬餘斤此其恆也是廣東一省之鐵稅可謂盛矣. *Liang Guang yan fa zhi*, ch. 24, p. 2a.

184 The figure is low if all of the 45 blast furnaces mentioned in the following were *da lu* producing several hundred tonnes per year each. The amounts stated cannot be the actual tax collected, since the tax was not in kind but in silver, and such tonnages of silver would be utterly unthinkable.

185 E.g. Luo Yixing (1985, pp. 90ff).

186 Quoted by Luo Yixing (1985, p. 90); cf. Li Longqian (1981, pp. 372–8).

187 Zhang Zhidong (1937, ch. 27, pp. 1a–4a). On Zhang Zhidong see Hummel (1944, pp. 27–32); Bays (1970).

188 They were still in use in Zijin 紫金, Pingyuan 平遠, and Xinyi 信宜, and were newly reintroduced in Liannan 連南, Lianjiang 廉江, and Huaxian 化縣. Xu Junming (1956, p. 104).

189 Peng Jianxin (1994).

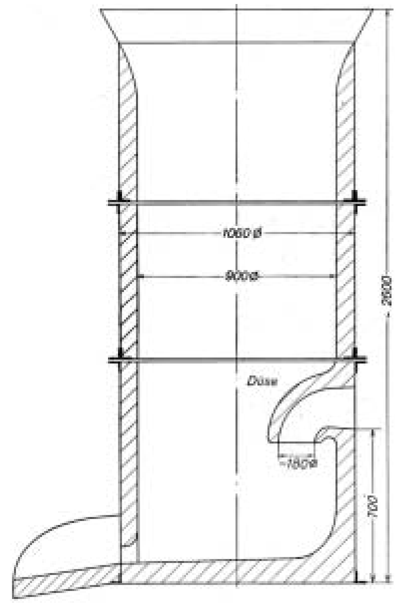


Figure 28 Diagram of a traditional Chinese cupola furnace, perhaps in Shanghai, reproduced from Gottwald (1938, p. 110, fig. 3). Dimensions are in millimetres; *Düse* means 'tuyère'.

(v) Traditional Chinese Iron-foundry Technology

The apparatus normally used for remelting most metals, in both China and the West, from ancient times until well into the 20th century, was the *cupola*, a shaft furnace which superficially resembles a small blast furnace.[190] How the word 'cupola' came to be applied to this type of furnace is uncertain, for there is no resemblance at all to a cupola dome.[191]

Some traditional Chinese cupola furnaces are shown in Figures 28–31. Fuel and iron are charged into the top, a blast of air is blown in through one or more tuyères near the bottom, and molten iron is tapped through the taphole at the bottom.[192]

An aspect which was common in small cupola furnaces is that they were built in sections to facilitate maintenance, as can be seen in Figures 28–29.[193] Some very small sectional cupola furnaces had no taphole; instead the bottom section was handled like a crucible. An admirably clear description of one of these, by a foreign traveller in Guangdong in 1898, is reproduced in Box 5. It is amazing that it was possible for the worker who poured iron into the moulds to pick up the bottom section of the

[190] See especially pp. 8–16, 47–8 above and Figures 3–5, Plates V, VII.

[191] See Ledebur (1885b, p. 124); Schneegans (1923); Johannsen (1953, pp. 302–4). R. F. Tylecote (1976, pp. 121–2) points out that *cupola* is the dimunitive form of Latin *cupa*, a cask, and that many early modern Western cupola furnaces resembled casks.

[192] Some very similar cupola furnaces in Thailand are described by Robert Thomsen (1970).

[193] See also Foster (1919).

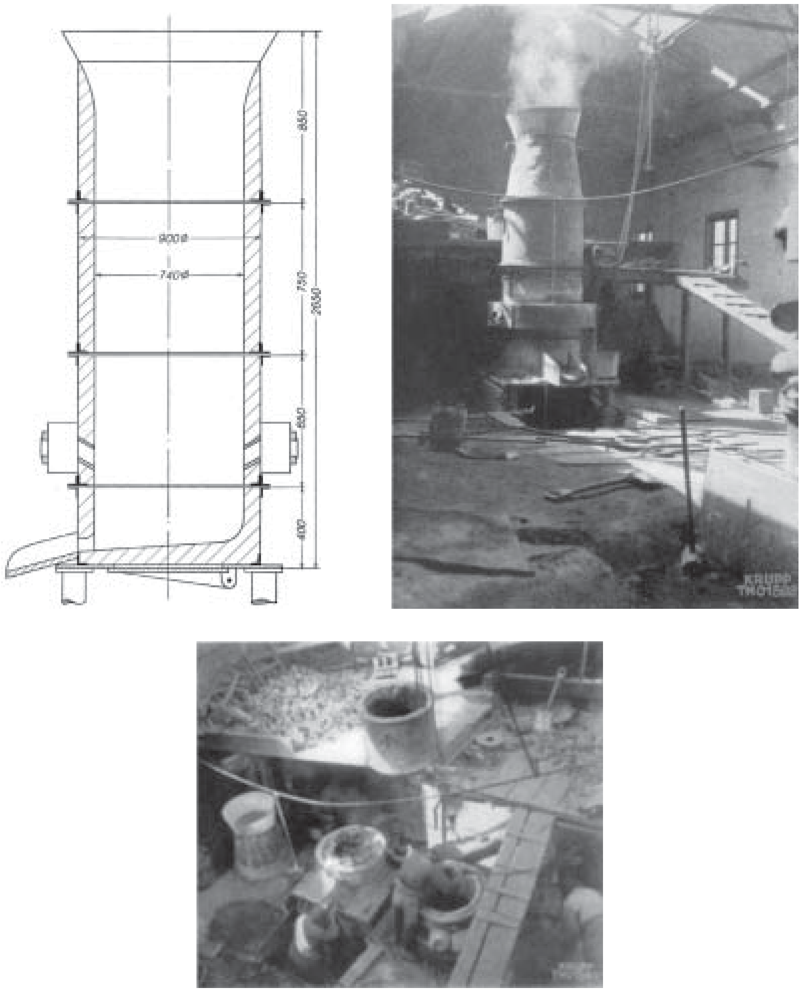


Figure 29 Diagram and photographs of a 'Chinese cupola furnace with European influence', perhaps in Shanghai, reproduced from Gottwald (1938, pp. 110–11, figs. 4–6). The photographs show the furnace respectively in operation and dismantled for maintenance. Dimensions are in millimetres. Compare Figure 28; European influence is seen in the use of multiple tuyères and the bottom drop-plate for maintenance.

furnace, containing 30 kg of molten iron at a temperature near 1200°C, 'literally hugging it to himself'. Figure 32 shows what may be the bottom of the same type of furnace in 1958, here being handled in a rather safer way, and the effiect of the heat can be seen on the faces of the workers.[194]

. . .

[194] It is interesting that Réaumur in the 18th century described a very similar furnace used by itinerant ironfounders in France (Sisco and Smith, 1956, pp. 276–81 + pl. 13). Otto Johannsen (1919, p. 1460) believes that Réaumur here refers to Gypsies [*Zigeuner*], and indeed there is considerable similarity to a Gypsy ironfounder's furnace in Scotland described by Simson (1865, pp. 234–5). A transmission of this type of furnace from China to Europe via wandering Gypsy ironfounders would not be an unreasonable hypothesis, though very difficult to prove.

Figure 30 Operation of a cupola furnace in Chengdu, Sichuan, photographed by Joseph Needham in 1943. Archives of the Needham Research Institute, Cambridge, SZE/2, nos. 24, 26, 27; see also Needham and Needham (1948, fig. 27, opposite p. 121).

Figure 31 A small cupola furnace photographed in the 1920s in De'an 德安, Jiangxi, reproduced from Hommel (1937, p. 27, fig. 39). Height 5 ft (150 cm), diameter 2½ ft (75 cm). In the background is a traditional Chinese windbox (*fengxiang* 風箱). Tapping is done by tilting the whole furnace.

Box 5 *Description of the operation of an iron foundry, probably somewhere near Guangzhou (Canton), in 1899, reproduced from Anon. (1899), where it is quoted from ' "The Celestial Empire" of November 21'.*

At Huangkiao we witnessed the operations of a Chinese iron foundry. The furnace was very simple in construction, being made of clay in three sections. The lowermost was what might be called the crucible, and was the receptacle for the molten metal, being about a cubic foot [28 litres] in capacity. The middle section was a ring of the same diameter as the lower section, and about eight inches [20 cm] in height. In this was a hole to receive the blast pipe, the blast being supplied by a native 'box' bellows[a] of the usual type. The upper section was another ring about a foot [30 cm] high. I was not fortunate enough to see the putting together of the furnace; when I saw it, the operation was begun, and a man was piling on the last of the charge – scrap cast iron and coke. One man was then pumping the blast; I waited till I saw the yellow flame begin to show above the piled up iron, which gradually sank down as that below melted. By and by two men pumped the blast. As the process went on, a still stronger blast was needed, so a third man helped at the bellows, and the pumping grew fast and furious, while one workman, wearing an old broad-brimmed straw hat to protect his head and face from the shower of sparks, stirred the glowing mass with an iron rod. In due time the melting was finished, the molten iron having fallen through to the bottom section of the furnace. The blast was stopped, the bellows disconnected, and the upper and middle sections of the furnace taken off and laid aside. The surface of the molten iron being skimmed of its slag, it was well covered with rice husk ashes. This protected the face of the man who next had to handle it from the intense heat that would otherwise have radiated from the molten iron. This man's duty was to clasp the crucible in his arms, literally hugging it to himself, and to fill the molds arranged around. In this he was assisted by a woman, who raked back the ashes where the iron was to run out. On this occasion plowshares were the result of the operation, the one charge being sufficient to cast about 20. Almost immediately following this man was another, who took the molds apart and removed their contents. No sooner were the molds empty, than the workmen set about repairing their inner surface with a black paste, ready for another casting. Upon inquiry I was told that about 50 catties [30 kg] of iron and 20 catties [12 kg] of fuel constituted one charge for the furnace, and that four meltings were effected in a day's work.

[a] *Feng xiang* 風箱 or double-action piston bellows: see SCC, vol. 4, part 2, pp. 136ff.

The 19th-century Chinese gouache painting reproduced in Plate X is something of a mystery, but my guess is that it shows a small cupola-like apparatus for melting iron. The crucible (of iron, undoubtedly lined with fireclay) is filled with a mixture of iron and coal or coke. Air is blown in at the top from the wooden windbox on the right, which is protected by a firewall. When the iron is molten it will be poured from the crucible into moulds.

Shaft furnaces like this one, in which the tuyère projects downward through the furnace mouth rather than through the furnace wall, are known elsewhere in the

Figure 32 'Tapping, Anhwei', photographed by Rewi Alley in 1958. Alley (1961b, no. 203, cf. nos. 286, 297).

world in modern times, though they are very rare.[195] We shall see in Section 4(iv) below that a similar arrangement may have been used in bronze and iron casting in ancient China.[196]

An even more minimalist arrangement for melting iron can be seen in Plate XI, which shows a Chinese wok-repairman. He melts iron in crucibles in the little stove at the left, and uses it to repair holes and breaks in woks. These street tinkers fascinated Western travellers in China, and we have several good descriptions of their work. One of these, by Joseph Balestier in 1850, is quoted in Box 6.[197] In this connection Balestier's anonymous editor remarked:

> Perhaps no device can be named more characteristic of oriental ingenuity – of the most mechanical people of the east – than this. It is one that could only have occurred where ages of experience in the treatment of the metals have elapsed. The idea of an ordinary artisan fusing *iron* with a handful of charcoal, and handling the glowing liquid as if it were but melted wax or tallow, would be considered by our founders as belonging rather to romance than reality.[198]

[195] Henrik Bjerresø (1971) describes such a furnace in use in Afghanistan, and perhaps Friedrich Kußmaul (1965, p. 69, fig. 21) shows another. David et al. (1989) describe an African bloomery-cum-blast-furnace which has its tuyère extending through the mouth down into the furnace.

[196] Pp. 147–50.

[197] Other good descriptions are by Van Braam Houckgeest (1797, pp. 275–6 + plate facing p. 281; 1798, pp. 78–9); William Lockhart in Percy (1864, pp. 747–9); Hommel (1937, pp. 31–2). Percy noted that Lockhart had presented a wok and the entire kit of a wok-repairman to 'the Museum in Jermyn Street, where they may now be seen'. Inquiries at the present Science Museum, London, have been unsuccessful in locating this material or any information about it.

[198] Balestier (1851, p. 406).

Box 6 *Joseph Balestier's description of the work of a Chinese wok-repairman, in the report of the US Patent Office for 1850 (Balestier, 1851). Compare Plate XI.*

I procured the accompanying cast iron pan, measuring 12 inches [30 cm] in diameter, by 4 inches [10 cm] deep. A crack of 3 inches [7.5 cm] was made in it in the first place, and in the second a piece was entirely broken off: giving rise to two distinct operations.

The operator commenced by breaking the edges of the fractures slightly with a hammer, so as to enlarge the fissures, after which the fractured parts were placed and held in their natural positions by means of wooden braces. The pan being ready, crucibles made of clay were laid in charcoal, and ignited in a small portable sheet iron furnace, with bellows working horizontally. As soon as the pieces of cast iron with which the crucibles were charged were fused, it was poured on a layer of partly charred husk of rough rice, or paddy, which was previously spread on a thickly doubled cloth, the object of which is to prevent the sudden cooling and hardening of the liquid metal. Whilst in this liquid state it was quickly conveyed with the right hand to the fractured part under the vessel, and forced up with a jerk into the enlarged fissure, whilst with the left hand a paper rubber was passed over the obtruding liquid, inside of the vessel, making a strong, substantial and neat operation.

You will thus remark that the art of the Chinese for re-uniting cracked or severed cast iron vessels, of all sizes, consists in cementing them with cast iron, whilst in the liquid state.

[The editor adds:]
The crucible, not much larger than a thimble, is made apparently of the same material as our common sand crucibles; except the shape, it could not be distinguished from one of them.

The amount of one fusion seems not to cover more than half an inch [1.25 cm] of the crack, and hence in the piece inserted, no less than nine distinct applications of the melted metal are seen – resembling on the inside so many ragged wafers touching each other, while on the outside, where the metallic plaster was applied, there are the same number of rude protuberances.

This was intended as praise, and the wok-repairman's art was indeed remarkable, but readers of the present book will find a hundred other processes which better exemplify the Chinese genius for working with metals.

(vi) Traditional Chinese Steelmaking Technology

Chinese fining processes, described in Sections 2(i) and 2(ii) above,[199] produce *shu tie* 熟鐵 , iron with carbon content generally in the range 0.1–0.3 per cent. In modern technical terminology this is 'mild steel' (*ruan gang* 軟鋼), but *shu tie* was used in the same applications as wrought iron (with close to zero carbon) in the pre-modern West, so I follow standard English practice and translate *shu tie* as 'wrought iron'.[200]

[199] Pp. 16–18, 30–4.
[200] On the traditional English terminology for ferrous products see Percy (1864, p. 102).

Edged weapons and tools require a higher carbon content than this, and therefore various processes have been used to make *gang* 鋼, 'steel', generally with carbon content in the range 0.5–1 per cent (in modern terminology, 'tool steel', *gongju gang* 工具鋼). Chinese traditional steelmaking processes have either added carbon to wrought iron by cementation or mixed wrought iron and cast iron to obtain a product with intermediate carbon content.

Chinese smiths in recent centuries seem not to have much used 'case-hardening', in which a finished weapon or tool of wrought iron is cemented to produce a hard layer of steel on a soft tough base.[201] Instead steel is produced separately, most often by specialised steelmakers, and the smith forge-welds this onto a wrought-iron base. This method no doubt saves fuel, and if the smith is competent the product is as good as or better than a case-hardened weapon or tool.[202] Two examples are shown in Figures 33 and 34.

Cementation

The term *cementation* covers a variety of ancient and modern processes in which iron in the solid state takes up carbon from an atmosphere rich in carbon monoxide. An example is *case-hardening*: a smith may pack a semi-finished knife in charcoal in a sealed container and heat it to a fairly high temperature (typically about 950°C) for a period of hours in order to produce a hard steel surface layer, a few millimetres thick. Carbon is taken up at the surface of the iron and diffiuses slowly into the interior. On an industrial scale essentially the same process was widely used in Europe in the 18th and 19th centuries to produce high-carbon steel bars for the cutlery trade. Large furnaces were used like one still standing at Derwentcote near Newcastle, England. In this furnace about 10 tonnes of wrought-iron bars were packed with charcoal in two sandstone chests. These were heated with a coal fire to about 1100°C for a week or more, after which the furnace was allowed to cool for about a week. The bars could then be removed and processed further.[203]

The basic reactions involved here are

$$CO_2 + C\ \text{(charcoal)} = 2CO$$
$$2CO = CO_2 + C\ \text{(in Fe)}$$

The conditions under which these reactions proceed to the right are shown in Figure 41.[204] In addition an *accelerator* is normally mixed into the charcoal packing: in modern practice barium carbonate ($BaCO_3$), in earlier times usually calcium

[201] But serious studies of traditional smithy practice are almost entirely lacking, so this statement may turn out to need modification. We may hope that Chinese archaeometallurgists soon start on such studies, for there are thousands of practising smiths to interview, and hundreds of thousands of artefacts to study.

[202] The Icelandic sagas include a number of stories in which a steel edge breaks off a weapon, showing that the smith was not up to his job (Drachmann, 1967, pp. 55–6; 1968, pp. 32–3).

[203] Barraclough (1976a, pp. 73, 75, pl. 9; 1976b, pp. 12, 22–9; 1984, vol. 1, pp. 34–47 *et passim*); see also Percy (1864, pp. 768–73).

[204] P. 92 below.

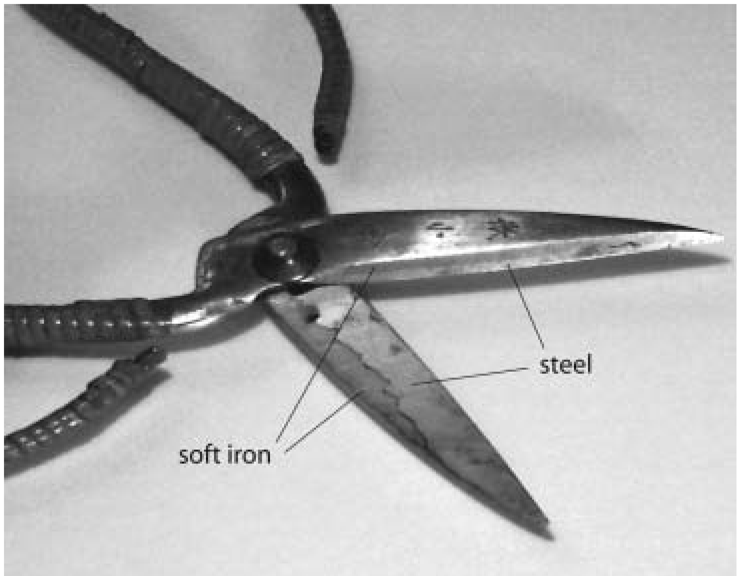


Figure 33 Scissors made by a Chinese smith in the 1960s or 1970s, purchased in San Francisco in 1975 (photo by DBW). The blade has an edge of steel, about 1 mm thick, forge-welded onto a wrought-iron base. The inscription Zhang Xiaoquan 張小全 is the brand name of Zhang Xiaoquan Scissors Factory, established in Hangzhou in 1663.

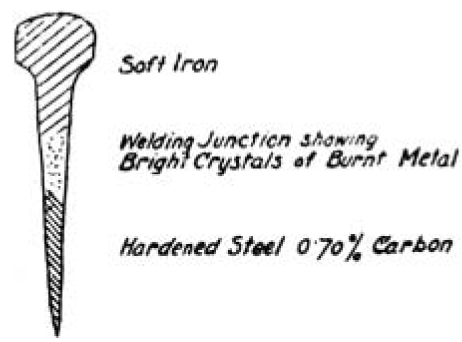


Figure 34 Diagram of a section through a Chinese razor, reproduced from Middleton (1913). A hard steel edge was forge-welded onto a soft iron back. The dimensions are not given, but the steel edge is likely to be 1–2 mm thick.

carbonate ($CaCO_3$) or sodium carbonate ($NaCO_3$). When heated the accelerator gives off carbon dioxide (e.g. $CaCO_3 = CaO + CO_2$); this replaces nitrogen in the packing atmosphere, increasing the partial pressures of both CO_2 and CO, permitting a faster uptake of carbon and also increasing the equilibrium carbon content at the surface of the iron.

In China, steelmaking by cementation is traditionally called *men* 燜. Like so many other Chinese metallurgical terms, this word comes from the kitchen: its original

Figure 35 Wall of old crucibles in Lanzhou, Gansu, photographed by Joseph Needham in 1943. Archives of the Needham Research Institute, Cambridge, NW/6, no. 26.

meaning is ‘to cook slowly in a sealed pot’. Not much is known about Chinese traditional methods of cementation steelmaking, but the historian Yang Kuan has some interesting information from a handbook published in connection with the Great Leap Forward.[205]

The furnaces are essentially the same as those used for crucible smelting (see e.g. Figures 22, 24, 25 above).[206] The cementation pots (crucibles) are ceramic (Figure 35) or iron. Low temperatures are used, not over 900°C, and the annealing time ranges from 9 to 24 hours. Such low temperatures and short times would give a carburised layer of only a millimetre or two, but the steel material used by smiths, judging from artefacts I have seen, seems to have been very thin (sometimes less than a millimetre), so this was an appropriate technique.

At some works charcoal alone is used for the packing, but a bewildering variety of accelerators are also seen. At a works in Lushan County 魯山縣, Henan, for example, to make steel from 60 kg of wrought iron, the packing is 6 kg charcoal, 3.6 kg powdered ox-bone, and 2.4 kg saltpetre (potassium nitrate, KNO_3). The bone supplies calcium carbonate. Saltpetre is a powerful oxidising agent;[207] it is difficult to understand what function, real or imagined, it might have here. Still other recipes include sodium carbonate, which functions like other metal carbonates, releasing

[205] Yang Kuan (1960, pp. 195–7), citing 冶金工業出版社編，土法煉鋼，第四輯。第一篇：怎樣炒鐵和燜鋼。第二篇：怎樣燜鋼並用燜鋼方法制滚珠軸承 .
[206] Note also Anon. (1958f; 1958j); Wu Guangya (1958).
[207] Note its use in a fining technique, p. 345, fn. 85 below.

carbon dioxide when heated. One recipe includes 'salt', presumably sodium chloride; what function might this serve?

At a works in Yidu County 宜都, Hubei, the packing material is 2.4 kg charcoal, 12 kg powdered ox-bone, and 3 kg sawdust. Here the bone supplies both calcium carbonate and the greater part of the necessary carbon. The sawdust, which is also seen in several other of the recipes, supplies carbon, but what other function might it serve?

Co-fusion

The co-fusion steelmaking processes, in which wrought iron and cast iron are mixed to produce an alloy with intermediate carbon content, have a long history in China, and will be dealt with in detail in Section 6(iii) below.[208] In recent centuries only one co-fusion process, called *Su-gang* 蘇鋼, seems to have been used, and it is rather different from the processes to be described there.[209]

The *Su-gang* steelworks known in the 20th century have all been in Sichuan. In 1936 local legend related that the process originated in the province of Jiangsu (whence the name, 'Jiangsu steel') in the early Qing period. The Qing government, fearing that sharp weapons made of this steel could be used in popular rebellion, forbade the process and began arresting the *Su-gang* workers. They fled in all directions: one, a man named Huang 黃, reached Sichuan and introduced the process there.[210] If there is any factual basis to this story at all, it might relate to the decline of the iron industry of Jiangnan 江南 in the Ming period, to be noted in Section 8(i) below.[211]

We have two detailed descriptions of the process, from 1936 and 1938, and they do not differ in any important way.[212] The 1938 description is translated in Box 7. Figures 36–38 show the furnace used. A very spongy bloom of wrought iron is heated to a very high temperature, and molten cast iron is dripped onto it. The worker turns the bloom and moves the melting cast-iron plate back and forth so as to assure that the steel is uniformly 'anointed' (*mo* 抹). Joseph Needham visited the same steelworks in 1958, and described his impressions as follows:[213]

In the summer of 1958 I had the good fortune to be able to spend an afternoon at a steelworks of traditional type making *Su-gang* at Beibei 北碚 near Chongqing.[214] Here cast pig iron (C 3.05%) is first converted in small wood-fired finery hearths (*chao tie lu* 炒鐵爐) to a low-carbon iron (*liao tie* 料鐵) not quite as pure as wrought iron (C about 0.4%). In the next

[208] Pp. 255–67.
[209] But note Geerts (1874, pp. 12–15); Anon. (1958f, p. 27).
[210] Luo Mian (1936, p. 26).
[211] Pp. 329–30.
[212] Luo Mian (1936, pp. 26–34); Zhou Zhihong (1955).
[213] This description is part of an undated typescript entitled 'The winning and working of martial metal', in the archives of the Needham Research Institute, Cambridge. I have converted the transcriptions to Pinyin and removed two unnecessary footnotes. Joseph Needham appears to have chosen four photographs from this visit to accompany the description, but I have been unable to locate these. What can be found in the archives is a number of photographs from the visit which he chose *not* to use. One of these is reproduced here as Figure 38.
[214] JN footnote: I am greatly indebted to Dr Liu Boyu who made this visit possible, as also to the director Mr Su Xianming, the union secretary Mr Luo Zongshu, and all the workers in the factory who gave us such a kindly welcome.

Box 7 *Description of* su gang 蘇鋼 *steelmaking by 'anointing'* (mo 抹) *wrought iron with molten cast iron at Beibei* 北碚 *in Chongqing, 1938. Translated from Zhou Zhihong (1955, pp. 26–7). See the diagram of the furnace, Figure 36, and note the photographs, Figures 37 and 38.*

First the furnace is filled with charcoal, and two bars of raw wrought iron are placed outside the furnace next to the furnace mouth. The cover is put in place and the blast is started, so that the charcoal burns with a red flame.

Then some charcoal is removed from the upper part of the furnace, the two pre-heated bars of raw wrought iron are placed inside, charcoal is added up to the furnace mouth, the cover is replaced, and charcoal is piled up on all sides of the furnace mouth.

Now the blower is operated energetically, and after 2 minutes the furnace interior is red hot. The cover is removed, and two plates of cast iron (rectangular, weighing 0.75 kg) are prepared. One is placed beside the furnace mouth and the other is inserted into the furnace with tongs. Energetic blower operation continues, and the temperature inside the furnace rises to about 1000°C.

After 3 minutes the cast-iron plate inserted in the furnace begins to melt, and sparks from the iron plate appear in the flames from the furnace mouth. At this time the temperature is about 1300°C.

The steel-anointing worker now takes over at the furnace. With his left hand he holds the cast-iron plate in a large pair of tongs, moving it left and right so that the drops of molten cast iron drip down uniformly over the raw wrought iron and there is an intense oxidising action [?!]. Meanwhile, in his right hand he holds a steel hook with which he constantly turns the raw wrought iron, so that all parts absorb as much of the molten cast iron as possible.

This is the most important step in the process, requiring practised skill as well as the ability to regulate the anointing according to the temperature-colour of the raw wrought iron bar. Most of the steel-anointing workers are able to regulate the speed of the blower judging from the colour of the furnace interior.

After 6 minutes the first cast-iron plate has been used up and the charcoal in the furnace has burned out. The furnace is then filled half-full of charcoal and the remaining cast-iron plate at the side of the furnace is brought to the furnace mouth, held as before with tongs, the cover is closed, and the blower is operated.

After 4 minutes the cast-iron plate begins to melt and the second anointing of iron is performed. When this plate is used up the process is finished and the blowing is stopped. The raw wrought iron bar is removed, hammered on an anvil to remove slag and make a steel billet, which is popularly called a *gang tuan* 鋼團 ['steel lump'].[a]

[a] Cf. pp. 256, 270, 322, 325, 343, 347.

shop, this iron, having been ~~formed~~ swaged into billets of markedly porous structure is heated strongly in coal-fired hearths where it is repeatedly subjected to the dripping of molten cast iron.[215] This can be seen through blue glasses melting like candle wax. The steel so formed is called *gang tuan* 鋼團 – a noteworthy use of a Song technical term[216] – and repeatedly forged into bars with a C content of about 0.9%. The hearths in which the sprinkling

[215] JN footnote: The *liao tie* billets are cut in two before being placed in the dripping hearths. Four of these halves are now treated at one time, but larger hearths now being built will take eight.

[216] See Section 7(iv), p. 321 below; also pp. 341, 346.

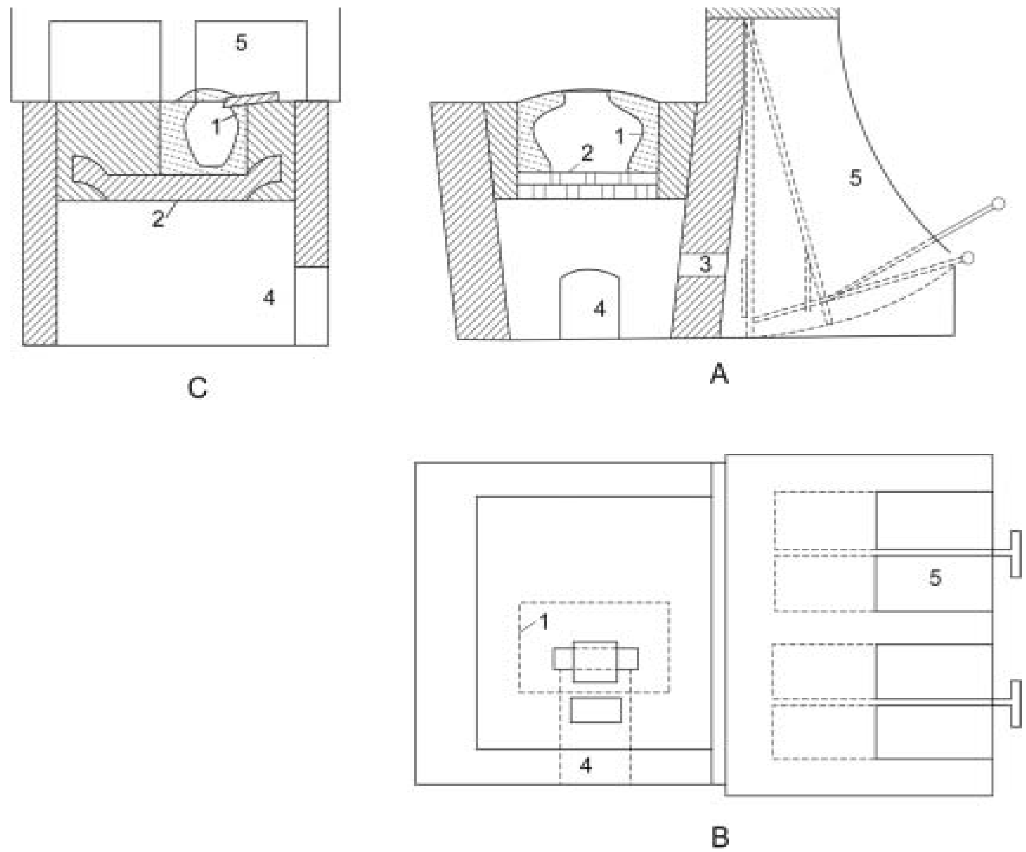


Figure 36 Diagram of a steel-anointing furnace (*mo gang lu* 抹鋼爐) at Beibei 北碚 in Chongqing, 1938. Redrawn from Zhou Zhihong (1955, p. 26, fig. 1).
A: front; B: top; C: side.
1. furnace chamber and furnace lining of sandy clay. **2.** grate. **3.** blast channel. **4.** opening for removal of ashes and slag. **5.** blowing apparatus.
'The furnace bottom consists of four wrought-iron bars laid in parallel to form a grate. This is covered on both sides with sandstone and clay, so that there are only three openings, ca. 2.5 cm wide, which must occasionally be bored out to allow the free passage of air and slag up and down.'

Figure 37 Photograph of a steel-anointing furnace (*mo gang lu* 抹鋼爐) in Sichuan, ca. 1936. Reproduced from Luo Mian (1936, p. 30, fig. 10).

Figure 38 Photograph by Joseph Needham of the operation of a steel-anointing furnace (*mo gang lu* 抹鋼爐) at Beibei 北碚 in Chongqing, 1958.

is done are known as *mo gang lu* 抹鋼爐 (steel-anointing furnaces), and the forges of the last stage are the *chou tiao lu* 抽條爐 (drawing-out furnaces). This factory, which has been working in an amphitheatre of hills overlooking the Jialing river [嘉陵江] and backed by Jinyunshan [縉雲山] for more than a hundred years, has always produced billet and bar steel, the method of dripping cast iron on to already formed wrought-iron tools not being practised in this part of Sichuan.[217] At the time of my visit, the future seemed to lie wholly with giant steel plants of modern type, but immediately afterwards there came the great movement for decentralisation of industry in China,[218] and for the revaluation of traditional techniques, so perhaps the Beibei plant is now safe for another hundred years.

He obtained three samples of the steel produced, and these are now in the collection of the Needham Research Institute. Samples cut from these were examined metallographically in 2005 by Alan Williams, and his report will in due time be placed on the web-site of the NRI.

The prediction at the end of the quotation above was not fulfilled: when Joseph Needham visited Chongqing again in 1972, he was told that the *Su-gang* process had been abandoned not long after his 1958 visit.[219]

Comparing the traditional Chinese cementation and co-fusion steelmaking methods, it is first important to note that they had different purposes. Cementation seems to have been used to produce thin edges of steel which smiths forge-welded onto soft iron backs, while co-fusion was used to produce larger billets of steel from which smiths could fabricate larger products. Cementation was a mass-production process, probably producing a relatively uniform product which was relatively cheap. Co-fusion steel seems more like a luxury product, requiring highly skilled labour and producing one billet at a time.

Costs are difficult to compare, for we do not have the necessary data. At a guess, labour costs per weight of steel were probably higher for co-fusion. Fuel costs in the two processes could have been about equal, with the low temperatures and long firing times of cementation balanced by high temperatures and short firing times in co-fusion. The fuel in cementation was mineral coal; co-fusion used charcoal fuel in the 1936 and 1938 descriptions, and mineral coal in 1958.

(vii) The Modern Fate of the Chinese Iron Industry

Sections 2(i) to 2(iv) above have gone into detail on what amount to four different iron industries. They used different technologies and they operated in very different geographic and economic conditions. I hope the reader has obtained some understanding of the technologies, together with a feeling for the ways in which techno-

217 A cementation method mentioned briefly in Song Yingxing's *Tian gong kai wu*, ch. 10, Zhong Guangyan (1978, p. 270); Sun and Sun (1966, p. 191).

218 The Great Leap Forward, pp. 79–81 below.

219 Archives of the Needham Research Institute, Cambridge, box marked 'China 72', notebook marked 工農, p. 81.

logical choices interact with more general factors in history. These interactions will show up especially clearly as we investigate what happened to Chinese iron production in the 19th and 20th centuries.

The iron industries of Sichuan, Shanxi, and Guangdong declined sharply in this period, while that of Dabieshan held its own and even prospered for a while. These developments become visible earliest in Guangdong, which was the first region to be affected by trade with the West, and we begin our investigation by looking at this trade.

Li Longqian lists four reasons for the decline of the Guangdong iron industry: intervention by the Qing state, domination by the guilds, a tendency to move capital out of industry into land, and the dumping of cheap commodities by foreign imperialists.[220] I shall not attempt to deal with the first two of these factors: a good deal of very detailed investigation would be necessary before I could speak with any confidence on the ways in which they affected the industry, and whether the net result was positive or negative. The third will be taken up briefly further below, but it is the fourth factor which I believe was the most important.

The terminology used by Li Longqian, 'dumping' by 'imperialists', will seem to many readers tendentious, but let us remember that Britain was explicitly imperialist in this period, and that the implicit threat of armed intervention gave the English East India Company a distinct advantage in its trade with China.[221] 'Dumping' suggests the deliberate sale of commodities below cost with the intention of ruining competitors; this specific intention would seem to be difficult to prove, but we shall see directly below that commodities often were sold below cost by European traders in China. Nevertheless the principal factor was simply that by the middle of the 19th century European ironworks were producing iron at a fraction of the cost of producing it in China. As will become obvious in later Sections, up to about 1700 China had the world's largest and most efficient iron industry, but about that time the British iron industry began the extraordinary sequence of technical improvements which brought the price of iron dramatically down and was a leading factor in the Industrial Revolution.

Western Competition

As early as 1750 a French ship landed some 30 tons of iron at Guangzhou. French, Dutch, and Swedish ships occasionally imported both iron and steel in the following decades, usually selling it at a loss. Some iron was landed by the English East India Company in 1801 and 1805, and in 1807 'a trial lot of iron bars' sold in Guangzhou at a better price than expected. From 1811 iron appears to have been one of the normal

[220] Li Longqian (1981, pp. 366–8). A more positive view of foreign trade is given by Ding Richu and Shen Zuwei (1992).

[221] On the European China trade in the 18th and 19th centuries see especially Greenberg (1951); Fairbank (1953); Dermigny (1964a; 1964b); Morse (1926–29); Chaudhuri (1985); Murphey (1972); Moulder (1977, pp. 98–127); Osterhammel (1989); Bowen (2002).

commodities imported by the EIC, and by 1834, the year of the abolition of the EIC's monopoly, foreign iron appears to have become very important on the Guangzhou market.[222]

The commercial agent C. F. Liljevalch (1796–1870), in a report to the Royal Swedish Chamber of Commerce in 1847, devotes ten pages to iron and steel in China, and gives some price details.[223] He states, 'after the most careful investigations', that the cost of producing Chinese bar iron and transporting it from the hinterland to the city of Canton (Guangzhou) cannot be less than 2¼ – 2¾ Mexican dollars per picul for second quality and 3¼ – 3¾ for first quality. The Mexican dollar (the most important medium of exchange in China's foreign trade at the time)[224] was worth 4s 4d (£0.22) sterling, and the picul was 133⅓ English pounds (61 kg). Liljevalch's 'careful investigations', and the resulting very precise cost figures, must be taken with a grain of salt, for he can hardly have had the opportunity to acquire the necessary technical and economic information for such an estimate. What is clear, however, is that the actual price of Chinese bar iron on the Chinese market in Guangzhou, which he must have known though he does not state it, was higher than these figures, which amount to £11 and £15 per ton respectively for the two grades. They may be compared with his figures for prices of European iron in Guangzhou:

wrought-iron hoops from imported cotton bales	$2 – 2½ per picul
English bar iron	$3¼ – 3½
English nail rod	$4½ – 4⅘
Swedish bar iron	$5

Thus foreign iron was already competitive with Chinese iron in Guangzhou. Liljevalch also states that the cost of shipping 10 tons of iron from England to Guangzhou, including freight, customs duties, etc., would be about £30. The price of bar iron in England in the 1840s was about £7 per ton;[225] a quick calculation shows that the import of English bar iron to Guangzhou could yield, as early as the 1840s, a profit as high as 50 per cent.

It is difficult to put this profit figure into a meaningful context, for statistics on net profit in the European China trade are rare and in any case rather artificial. Imports of cotton cloth to Guangzhou by the English East India Company, for example, usually were sold at what appears in the accounts as a *loss* – meaning only that the profit on the corresponding exports to England was less than what appears in the accounts.[226] The greatest problem for Europeans trading in China was 'laying

[222] Dermigny (1964a, pp. 197, 262–83, 367; 1964b, pp. 702–3) (18th century); Morse (1926–29, vol. 1, p. 292 [French import in 1750]), vol. 2, p. 357; vol. 3, pp. 1, 138 [trial lot in 1807], pp. 157, 174, 189, 205, 226, 242); Ball 1972, p. 3; Milburn (1813, pp. 482, 485; 1825, p. 458); Anon. (1834, pp. 463, 471).

[223] Liljevalch (1848, pp. 117–26).

[224] On the use of the Mexican dollar in China see especially Hao Yen-p'ing (1986).

[225] The price fluctuated wildly in this period, with a minimum of £4.75 in 1844 and a maximum of £9.75 in 1847. Here I have taken the mean of the figures for the years 1840–49 given in *Abstract of British historical statistics*, Mitchell (1971, pp. 492–3).

[226] Dermigny (1964b, pp. 720–2); Bowen (2002, p. 467).

down the dollar' – the Mexican silver dollar.[227] It was necessary to pay silver for tea and other exports, but carrying silver to China was the least profitable way of providing it. It was much more efficient to carry European products which could be sold for silver; but it was difficult to find imports for which there was sufficient demand in China, and many products were tried at one time or another. It was the opium trade which finally stopped and then reversed the flow of silver from Europe to China, but not all ships to China carried illegal cargoes. Every ship to China carried some sort of cargo, to help in laying down the dollar and also to serve as a ballast. The most common ballast cargo was pig lead, but as the number of ships to China increased, the market for lead was easily glutted.[228] Bar iron was a natural substitute, especially as further technical developments brought down even more the cost of iron production in the West.

At the same time, because of both technological and institutional developments, ocean freight rates also fell.[229] According to the Chinese Maritime Customs returns, China imported over 7000 tons of iron in 1867, the first year for which statistics are available.[230] Two years later, in 1869, about 27,000 tons were imported. In 1891 the figure was 112,000 tons. Some of this imported iron supplied increased demand as China took its first steps towards industrialisation, but a large part, especially in the early years, would have replaced production in the traditional sector. About half of the imported iron was scrap,[231] for example old horseshoes. Scrap wrought iron was probably a fine material for Chinese smiths, and it was extremely cheap in the West.

The Qing government did not normally attempt to regulate commerce and industry directly; this would have required officials to have a detailed knowledge of some very technical activities. Instead the state sold various kinds of monopoly or oligopoly rights to private individuals who then were held responsible for the ordered functioning of markets, the enforcement of the law, and the payment of taxes.[232] The most famous example of this means of regulation is the 'Thirteen Hongs' (*shi san hang* 十三行), the oligopoly which handled all foreign trade in Guangzhou.[233] Other examples are the salt gabelle and the Manchurian ginseng monopoly, and still another monopoly is the iron industry of Guangdong. It is not clear how this monopoly licensing system for the iron industry actually worked in detail, but it is fairly clear that state-granted monopolies of some sort did exist in the Guangdong iron industry.

It was a firm ideology, in fact an *idée fixe*, of the British traders in Guangzhou that all state regulation and all monopolies are pernicious. In 1842 the Treaty of Nanjing,

227 Morse (1922); Cheong (1965); Bowen (2002, p. 469).
228 Dermigny (1964a, p. 199); Morse (1922, pp. 233, 239).
229 Harley (1988).
230 Tegengren (1923–24, p. 400).
231 In 1899, the first year for which I have seen a breakdown of the import figures, scrap iron constituted 44 per cent of China's iron imports. Tegengren (1923–24, pp. 401–2); cf. Hosie (1901, p. 257). Hsiao Liang-lin's normally very useful digest of foreign trade statistics (1974) does not, unfortunately, include information on imports of scrap and ordinary grades of iron.
232 This use of monopolies is discussed briefly by Dermigny (1964b, p. 64).
233 See e.g. Cordier (1902).

the first of the unequal treaties forced upon China after its defeat in the first Opium War, contained a provision specifically banning the monopoly system.[234] Private trade monopolies on iron as well as other commodities were immediately formed, but the Qing state was forced to suppress these after complaints from British traders.[235]

With the Treaty of Nanjing the Qing state was denied its only means of regulating the iron industry, and at the same time four more ports were opened to foreign trade. From this point on, the decline of the iron industry became very rapid in Guangdong and began in other parts of the country. We have seen the results in Sichuan and Shanxi.[236]

In the above it has been possible to document the decline in these regions in some detail. There are also numerous other, more anecdotal, indications of decline caused by foreign trade, for example von Richthofen's description of Shanxi in 1870:

> The mining of coal, the manufacturing of iron, and the conveying of both to market employ a large number of men and animals. But notwithstanding its ample resources the country is poor. The profits are reduced to a minimum . . . Underground miners, who receive elsewhere 200 to 300 cash a day, must here content themselves with wages of 100 cash. Yet the owners of mines are poor people. There have evidently been better times in this region, as one is justified in concluding from the great number of houses built with luxury, and richly adorned with fine work of sculpture. It is possible that the introduction of foreign wrought iron, into those districts which are accessible by water from the Treaty ports, has greatly reduced the amount of sale and total production of Shansi iron, and that the desire to supply as many as possible of the former markets has tended to reduce the original price of the iron, and consequently the profits of the manufacturer.[237]

Geerts wrote of his observations in Japan in the late 19th century:

> Finally it may be noted that the manufacture of wrought iron in Japan has diminished considerably with the import to Japan of great quantities of iron in bars and plates, principally from England and Belgium. The convenient and diverse shapes of European wrought iron and their relatively moderate prices, together with the miserable state of the roads in the mining districts, are the causes which have made this metal an important article of foreign trade, in China as well as Japan, in spite of the abundance of excellent ores in both countries.[238]

Return on investment

While competition with cheap imported iron undoubtedly was the most important cause of the decline of the Chinese iron industry, other factors must also have been at work, for the decline of the Guangdong iron industry started in the 18th century, before significant amounts of iron began to be imported. An additional factor was probably that foreign trade brought new investment opportunities for Chinese

[234] Spence (1990, pp. 158–60).
[235] Fairbank (1953, pp. 306–7); Wakeman (1966, p. 97); Davis (1852, vol. 2, pp. 49–50, 90–2); Public Record Office, London, FO 228/51.
[236] Pp. 35–6, 45–6 above.
[237] von Richthofen (1872, p. 31).
[238] Geerts (1878–83, p. 540; cf. 1874, pp. 10–11).

entrepreneurs, and that these investments could give a higher return than ironworks could.[239] Luo Yixing has noted a number of cases in which ironworks were closed down because ore deposits were worked out.[240] These are likely to be signs of a shortage of investment capital, for searching for a new deposit and thereafter opening up a new mine was expensive, and would have been undertaken only if the expected return was competitive with other possible investments. Luo Yixing believes the principal cause of the decline of the Guangdong iron industry to be that the province actually had no more rich ore deposits left; this seems on its face to be unlikely, and the economic explanation of the decline appears to be more credible.[241]

China's first modern ironworks was established in 1891, in Hanyang, Hubei. In 1922 there were seven modern ironworks in operation. The vicissitudes of these enterprises are not part of the present story, however, for most of their production was sold to Japanese creditors at sub-market prices, while China continued to rely on the traditional sector and foreign imports for its own iron consumption.[242]

The effects of decline on technology

It is clear that competition with modern industry caused all of these regional industries to shrink, leaving fewer units and smaller total production; but the influence of this competition was not uniform over all ironworks. In fact it hit hardest precisely in the places where the most technically sophisticated and capital-intensive techniques were in use. The reasons are several. A prerequisite for a large highly capitalised works with a large production is a large market, and this implies good transportation facilities;[243] but the regions with good transportation facilities were also the first to be penetrated by foreign goods. Furthermore, in China, capital was much more mobile than labour. As the profits of the highly capitalised works declined because of falling prices, the investors could move their capital into other, more profitable, enterprises, for example tea and opium. On the other hand the labourers, facing a continuously falling standard of living, seldom had much choice but to continue producing iron. Furthermore, by 1900 at the latest, Chinese ironworks could no longer compete with foreign iron in quality, only in price.

The works that survived best were those in poor isolated regions like Dabieshan which produced for a purely local market and used labour-intensive low-capital methods. Their survival led to a curious phenomenon when World War I brought greatly increased prices for iron: the increased prices made the traditional methods viable again, but the best traditional methods had by this time been forgotten. The

[239] For example, Adshead (1984, pp. 110–11) notes a number of new investment opportunities brought to Sichuan in the early 20th century.

[240] Luo Yixing (1985, pp. 90–2).

[241] Note also *SCC*, vol. 5, part 13, p. 410.

[242] The story has been told by Tegengren (1923–24, pp. 365–97).

[243] Obviously what I mean by 'good transportation' must be taken in relation to the particular product involved. Transportation in Shanxi was by most measures dreadful, but the famous needles of Shanxi (p. 44 above) could have a very large market because transportation was not a large part of their price.

tiny blast furnaces of places like Dabieshan, which were appropriate for a small production for local markets, began to be used for mass production to supply a large part of southern Henan.[244] The inter-war depression in the West may also have had a positive effect on China's economy, and therefore on the traditional iron industry.[245]

The Great Leap Forward

The considerations discussed above have considerable relevance for the study of the campaign for iron production in the Great Leap Forward of 1958–59. The usual evaluation of that campaign, both in China and abroad, is that it was a total fiasco with no redeeming features.[246] Most contemporary accounts, even the wildly enthusiastic propaganda, tend to confirm this evaluation when they are read critically: there are very few signs that the thousands of 'backyard furnaces' actually produced any iron at all. Of the numerous photographs of traditional blast furnaces which can be seen in Chinese publications of the period, there are very few that show them actually in production. But according to a speech by Premier Zhou Enlai 周恩來 on 23 August 1959, in 1958 these primitive blast furnaces actually produced 4.16 million tonnes of usable pig iron (together with 4–5 million tonnes of pig iron of unusable quality).[247] That is, 30 per cent of the year's pig iron production (13.69 million tonnes of usable pig iron) was produced in these primitive blast furnaces which, in the opinion of most observers, were totally worthless. Many of the production statistics published in those years have later proved to have been greatly exaggerated: is this another example of the same?

It is more probable that the campaign actually was, to a certain extent, a success in those parts of the country where the traditional iron-production techniques had not been forgotten. Where production already existed for local purposes it could be expanded. This was normally the case only in places where transportation was bad. Here iron was produced using inefficient methods and was therefore expensive, and the added cost of transportation made it even more expensive in the places where it was to be used; but it is quite possible that iron production was nevertheless an economically rational use of labour in isolated poverty-stricken regions.[248] The great error of the campaign was the attempt to reintroduce the traditional techniques in places where they were long forgotten, and where there usually were better uses for labour as well.

It is rare that journalists, politicians, diplomats, or tourists travel in the poorest regions of China. Nearly all of those who reported on the Great Leap Forward,

[244] Note the remarks of Rawski (1989, p. 249) and Li Hu (1985) on the effect of World War I on Chinese industrialisation.

[245] Myers (1989).

[246] E.g. Chao (1964); MacFarquhar (1983); Liu Ta-chung and Yeh Kung-chia (1965, p. 115). More positive accounts are Sewell (1960); Nikolayev and Molodtsova (1960); Alley (1961a); Li Chenggui (2001).

[247] Anon. (1959c, p. 18); cf. Bowie and Fairbank (1962, p. 542); Hinton (1980, pp. 759, 762–3, 860). Note also the careful analysis of the industrial output statistics of the period by Subramanian Swamy (1973, pp. 41ff).

[248] Herman (1956) and Ishikawa (1972) discuss the economic factors involved. Herman also shows that numerous Asian governments at this time were beginning to recognise the potential value of traditional small-scale industries. The method applied by Putterman (1997) in his economic analysis of more recent developments could usefully be applied to the rural industries established in this period.

both Chinese and foreigners, kept to places where travel was reasonably comfortable. The only exception I am aware of is Rewi Alley, who retained his contact with China's poor and travelled where few others had any desire to go.[249] He also had a fine feeling for what makes a good picture, and many of his photographs show blast furnaces in production. He notes proudly several times that it was the poorest peasants who produced the best iron: no doubt he felt that there were moral reasons for this, but we may note that there may very well have been economic reasons as well.

The technical publications which came out of the Great Leap Forward have proved to be very useful sources in the foregoing study of Chinese traditional techniques. Because the campaign was such a fiasco, this material is seen by many as suspect; indeed, I have been advised that it is politically incorrect to use it at all. Therefore it seems necessary to defend the use I have made of it here.

Readers will see that all of the furnace types and processes discussed here are well known from much earlier sources, of the 19th and early 20th centuries; the Great Leap Forward material which I have used describes these same furnaces more precisely and in greater detail, because it was written by modern engineers for practical use. It is true that a great deal of nonsense was also published in the Great Leap years, but this is quite easy to recognise and ignore.

A useful example is a technical survey, published in December 1958, of production costs in a sample of 104 small ironworks in 12 provinces and municipalities.[250] The average cost of one tonne of pig iron was 250 *yuan* 元, with considerable variation, from 108 *yuan* at one works in Shanxi to 852 *yuan* at one in Liaoning. The article goes on to explain the discrepancy under four heads: (1) regularity of blast-furnace operation; (2) political leadership, mobilisation of the masses, and technical advance (i.e. efficient use of labour and fuel); (3) transportation costs; and (4) management costs.[251] The survey does not even mention the silly 'backyard furnaces' built in millions by peasants who knew nothing of iron production and wasted time and resources in futile attempts to make iron. The emphasis is on serious ironworks which used traditional technology, giving technical advice on how their production can be improved.

The real tragedy of the Great Leap Forward was the death of millions by starvation, caused by the breakdown of agriculture and distribution which was in large part a result of forced collectivisation;[252] the fiasco of the campaign for iron and steel

[249] Alley (1961a; 1961b). Rewi Alley was born in 1897, travelled to China in 1927, and lived there until his death in 1987. Charles Curwen writes of Rewi Alley: 'His experience of China, and his own character, led him – not surprisingly – to mistrust the rich, and he had a low opinion of the educated children of the rich and perhaps of intellectuals in general. He was prejudiced in favour of the poor and had a stubborn confidence in their natural ability and determination. This sentiment was confirmed by the quality of the young people, nearly all from poor often wartime refugee families, who were formed by the school, founded by the Chinese Industrial Cooperatives, of which he was director (and where I worked for about seven years). Later, in many different walks of life, they gained a reputation for their ability and their readiness to get their hands dirty.' (Letter to DBW, 30 March 1995.)

[250] Anon. (1958e).

[251] This last is quite interesting: it appears to cover what in other contexts would be called the profits of the ironmaster. The survey found that management costs varied between 5.3 and 30.2 per cent of total cost.

[252] See e.g. MacFarquhar (1997); Kung and Lin (2003); also Becker (1996). Ashton et al. (1984, p. 620) call this 'the worst famine in human history'.

production was in comparison a minor matter. The first major critic of the Leap, Marshal Peng Dehuai 彭德懷, was relatively mild in his criticism of this aspect. In a famous open letter of 14 July 1959 he stated:

> In the course of refining steel by the whole people, some small and indigenous blast furnaces which were not necessary were built, with the consequence that some resources (material and financial) and manpower were wasted. This is of course a relatively big loss. But a preliminary geological survey on a huge scale was carried out throughout the country, and many technical personnel were trained. The broad masses of cadres have tempered and improved themselves in this movement. Although a tuition fee was spent (in the amount of 2 billion *yuan*), even in this respect there have been losses and gains.[253]

(viii) Digression: Economies of Scale in Blast-Furnace Iron Production

In many places in this book I invoke as an explanatory factor the economies of scale which the use of the blast furnace makes possible. This is so important that it requires a detailed treatment, especially since it has been called into question.

It can be seen in Figure 10 that in an iron blast furnace, under normal operation, there is a 'zone of relatively constant temperature' near the top of the shaft, in which very little change occurs. It happens that the existence of this zone has great importance, for it acts as a buffer which shields the regions further down in the shaft from outside perturbances. This means that such a furnace is extremely stable in operation, and remains so even when it is scaled up to an enormous size.[254] Consequently the iron blast furnace is the largest machine used in modern industry, with volumes typically in the range 1500–3000 m^3, producing typically 2500–5000 tonnes per day and reaching as high as 10,000 t/day.

A general rule is that for maximum efficiency a blast furnace should be as large as the supply of its raw materials and labour, and the market for its production, will reliably allow.[255] No larger than that, for efficiency also requires that the furnace operate continually for years at a time; the cost of interruption of operation caused by labour or raw materials shortages, or by a failure of the demand for pig iron, will quickly eat up the intended economies of scale.

The principal technical reasons why a larger blast furnace is more efficient appear to be two. First, a larger volume of the whole furnace means less heat lost to the surroundings. Second, a reduction zone with a higher temperature and larger volume means faster reduction. Both factors lead to more efficient use of fuel. In addition, the larger furnace involves a smaller investment relative to production capacity, and requires a relatively smaller labour force.

With the technical explanation clear enough, and the empirical observation that modern industry prefers large blast furnaces to small ones, it is surprising to find two well-known archaeometallurgists, William Rostoker and Bennet Bronson, claiming

[253] Anon. (1968b, p. 9; Chinese text, p. 398); cf. Peng Dehuai (1984, pp. 513, 492, 499; 2002, pp. 290–1, 279, 282); MacFarquhar (1983, p. 214); Domes (1985, p. 91); Joseph (1984, pp. 62–119 *et passim*).
[254] Peacey and Davenport (1979, p. 40).
[255] See e.g. Sidney (1920); Jones (1933, pp. 219–44); Pratten and Dean (1965, pp. 65–7).

that the economies of scale in blast-furnace iron production are illusory.[256] They cite some data for Indian and Southeast Asian *bloomery* iron smelting, which are irrelevant. They make much of the fact that in Shanxi, in the 1920s, cast iron from the crucible smelting process sold for about the same price as imported blast-furnace cast iron. Again this is not a comparison of blast furnaces, but more striking still is the economic naïveté of the argument. In Shanxi, ironmasters and workers lived in utter poverty and produced iron because they had no other means of living, and obviously they could not sell this high-sulphur iron at a higher price than that of imported iron, produced by well-fed investors and workers in Britain and the USA The same argument applies to blast-furnace iron production in many other parts of China.

Rostoker and Bronson state that '[m]anagers of American steel corporations in the twentieth century have consistently preferred larger furnaces, but there is little good evidence that these produce significant savings in costs', citing as their only authority a survey of 20th-century American blast furnaces by Myles G. Boylan. But what Boylan actually said was this: 'In summary, the data indicate that while large blast furnaces were more efficient than smaller furnaces, their edge in efficiency was reduced when agglomerates of high quality were used (for example, pellets) in place of standard domestic ore.'[257] Ore agglomeration is an innovation of the late 20th-century, and has no relevance for Rostoker and Bronson's argument.

Thus Rostoker and Bronson, in an otherwise very useful textbook of archaeometallurgy, have on this issue merely introduced confusion into an issue which has been clear for centuries: larger blast furnaces are overall much more cost efficient than smaller ones.

[256] Rostoker and Bronson (1990, pp. 186–9).
[257] Boylan (1975, p. 176).

3 THE EARLIEST USE OF IRON IN CHINA

(i) The State of the Question

Studies of the written sources

Over the centuries there have been a number of studies of when iron was first used in China, but until recently the only basis for a discussion of the question was in written texts.[1] Perhaps the most important textual evidence is a passage in the *Mencius*, a text of the late −4th or early −3rd century,[2] in which it becomes clear that iron implements for tilling and metal pots for cooking were essential parts of peasant life; we shall consider it in Section 4(i) below.[3] Mentions of iron before this are rare, and in each case coupled with serious problems concerning the interpretation, authenticity, or dating of the text in question.[4] The *Yu gong* 禹貢 ('Tribute of Yu') chapter of the *Book of documents* lists iron (*tie* 鐵) and steel (*lou* 鏤) among the items of tribute sent by Liangzhou 梁州, modern Sichuan, to the Emperor Yu 禹 in the −22nd century;[5] but that text is not a reliable source for such ancient times, and cannot itself be dated with any precision. A poem in the *Book of odes*, probably to be dated before −600, uses the word *die* 驖 for a horse of some specific colour;[6] since this character is graphically and phonologically related to *tie* 鐵, 'iron', some writers have assumed that the horse is 'iron-coloured'.[7] Perhaps so, but if *die* can mean '*tie*-coloured horse', then *tie* can just as easily mean '*die*-coloured metal'.

The clearest apparent mention of iron in an early Chinese text is in the *Zuo zhuan*, referring to the year −512:

In the winter, Zhao Yang and Xun Yin of Jin led troops to build fortifications on the banks of the Ru. Thereupon they taxed the state of Jin one *gu* 鼓 of iron with which to cast penal vessels. [On these was] inscribed the 'Penal code' made by Fan Xuanzi.[8]

冬，晉趙鞅、荀寅帥師城汝濱，遂賦晉國一鼓鐵，以鑄刑鼎，著范宣子所為刑書焉.

[1] Modern studies include Zhu Xizu (1928); Fei Si (1935); Li Hengde (1951); Sekino Takeshi (1951); Ruan Hongyi (1955); Yu Yi (1959); Li Xueqin (1959); Yin Difei (1959); Guo Moruo (1973, pp. 202–7); Huang Zhanyue (1976); Yang Kuan (1982, pp. 17–24); Tang Jigen (1993); Bronson (1999); Zhao Huacheng (1996; 2000); Wang Bin (2000).

[2] D. C. Lau in Loewe (1993, pp. 331–5) ; cf. *SCC*, vol. 2, pp. 16–18.

[3] P. 116.

[4] The problems are discussed by e.g. Huang Zhanyue (1976); Tang Jigen (1993); Wagner (1993, pp. 52–60).

[5] Text and translation, Karlgren (1950a, pp. 15, 17); textual commentary, Karlgren (1948–49, pp. 154–5). Discussion, Huang Zhanyue (1976, p. 62); Wagner (1993, pp. 52–4).

[6] Ode no. 127, text and translation Karlgren (1950b, pp. 80–1); cf. Loewe (1993, pp. 415–23). Discussion Wagner (1993, pp. 54–6).

[7] Guo Moruo (1973, p. 32), in an essay originally written in 1952, quoted 'commentators' to this effect, but gave no reference. Later, in 1956, he changed 'commentators say' to 'it is said' (1973, p. 204).

[8] *Zuo zhuan*, Duke Zhao, 29th year, Yang Bojun (1981, p. 1504); cf. *SCC*, vol. 2, p. 522; Couvreur (1914, vol. 3, pp. 455, 456); Legge (1872, pp. 729, 732); Waley (1948); Wagner (1993, pp. 57–9).

Here follows an apocryphal quotation from Confucius: upon hearing of this action, he predicts that Jin soon will go to its ruin. If the ancient forms are abandoned, and the penal law is inscribed on vessels, the people will pay attention to the vessels and fail to honour men of rank.

Taken at face value, the passage appears to indicate that iron was being used to cast vessels as early as −512, and that it was a common enough commodity that it was practical to make it the object of some sort of tax or levy.

Much ink has been spilled over this passage. Huang Zhanyue calls it 'incomprehensible', and asserts that it is corrupt.[9] There is a +3rd-century quotation of the passage in which the character *zhong* 鍾, appears instead of *tie* 鐵, 'iron',[10] and he believes the crucial passage should be interpreted: 'Thereupon they taxed the state of Jin, unified the *gu* and *zhong* [i.e. standardised weights and measures], and cast penal vessels.' Yang Kuan in turn calls Huang Zhanyue's interpretation 'incomprehensible',[11] and cites a +2nd-century quotation of the passage to show that it is not corrupt.[12]

I believe both scholars miss the real point, which is a matter of source criticism rather than philology. Did the events narrated here, under either interpretation, actually take place? There seems to be general scholarly agreement that the *Zuo zhuan* was compiled in the −4th century from disparate earlier sources.[13] What was the *Zuo zhuan* author's source for the passage above, and can this source be trusted? The events narrated here are not mentioned elsewhere in the *Zuo zhuan*, or any other early source. Furthermore they appear to be mentioned only in order to introduce the precept, here attributed to Confucius, that a published penal code endangers the traditional social order. This is a fine example of the sort of moralising passage in the *Zuo zhuan* which the historian must always treat with caution, especially since there is a perfectly parallel story, with the same moral, earlier in the *Zuo zhuan*.[14] We must not expect such a story to be historically accurate. Adding to this consideration the possibility that the text is corrupt, and perhaps did not originally mention iron at all, the passage simply cannot be taken seriously as a source on the early use of iron in China.

The *Guo yu* 國語, in a passage probably dating to the early −4th century,[15] has a curious story which it may be appropriate to consider briefly here. Earlier in the text the statesman Guan Zhong 管仲 has advised Duke Huan of Qi 齊桓公 that,

[9] Huang Zhanyue (1976, p. 64).
[10] *Kong zi jia yu*, ch. 9, p. 24a.
[11] Yang Kuan (1982, pp. 21–3).
[12] Commentary by Fu Qian 服虔 (d. +190), quoted by Kong Yingda 孔穎達 (+574–648), *Zuo zhuan*, *SSJZS* edn, p. 2124.
[13] Anne Cheng in Loewe (1993, pp. 67–76); Creel (1970, p. 476).
[14] The state of Zheng 鄭 casts a penal law text (presumably in bronze) in −535. Shuxiang 叔向 of Jin writes a letter to Zichan 子產, Prime Minister of Zheng, reprimanding him for this break with ancient ways, but Zichan declines to accept his advice. A certain Shiwen Bo 士文伯 then predicts catastrophe by fire in Zheng. *Zuo zhuan*, Duke Zhao, 6th year, Yang Bojun (1981, pp. 1274–7); cf. *SCC*, vol. 2, p. 522; Couvreur (1914, 3, pp. 116–20); Legge (1872, pp. 609–10).
[15] Chang I-jen and others in Loewe (1993, pp. 263–8).

to keep his military preparations secret, he should establish a civil government and entrust military matters to it.

Duke Huan said: 'I have entrusted military affairs to the civil government, and now the state of Qi has a shortage of armour and weapons. What is to be done about this?'

Master Guan replied: 'Lighten [the punishments for] offences, and convert them to armour and weapons.'

Duke Huan said: 'How is this to be done?'

Master Guan replied: 'Ordain that serious crimes are to be redeemed with a suit of rhinoceros armour and one halberd, and minor crimes with a plaited leather shield and one halberd. Misdemeanours are to be punished with [a fine of] a quota of metal [*jin fen* 金分], and doubtful cases are to be pardoned. A case should be delayed for investigation for three [days] without allowing arguments or judgements; [by the time] the case is judged [the subject will have produced] one bundle of arrows. Good metal [*mei jin* 美金] should be cast into swords and halberd[-heads] and tested on dogs and horses, while poorer metal [*e jin* 惡金] should be cast into agricultural implements[16] and tested on earth.'

[Thereafter] armour and weapons were abundant.[17]

One often reads in Western works on early China that bronze was considered 'the lovely metal' and iron 'the ugly metal'. There is some archaeological evidence for suspecting that something of the sort may have been the case, as well as evidence that the situation may have been rather more complex.[18] It is important to note, however, that the only evidence for the statement is the passage above, where I have preferred to use the translations 'good' and 'poor' rather than 'beautiful' and 'ugly'. The passage does not actually mention iron, and, as Huang Zhanyue has pointed out, 'good metal' and 'poor metal' are, given the context, much more likely to refer to different types of bronze.[19] This seems to have been the view of the earliest commentator, Wei Zhao 韋昭 (d. +273),[20] and a parallel passage in the *Huai nan zi* 淮南子 suggests the same.[21]

Further, if the passage does refer to iron, it is by many centuries the earliest Chinese text in which iron is considered to be a kind of *jin* 金, 'metal'. We shall see directly below that the *Shuo wen jie zi* of +100 refers to iron as 'the black metal' (*hei jin* 黑金),[22] but before this there does not seem to be a clear reference. In fact, the −2nd-century text *Huai nan zi* has a reference to 'casting metal and forging iron to make edged weapons'.[23]

And so it goes with other mentions of iron in other ancient texts: either it is not clear that they really *are* mentions of iron, or it is not clear that the source is as ancient as is claimed. In many cases this does not much matter, for the text says nothing important. One thing that comes out of studies of the ancient texts, however, is the

16 *Chu, yi, jin, zhu* 鉏夷斤斸, four types of agricultural implement which are difficult to identify.

17 *Guo yu*, *SBCK* edn, ch. 6, p. 10b; 1978 edn, pp. 239–40; cf. Ōno Takashi (1975, pp. 335–6); parallel passage in *Guan zi*, ch. 8, sect. 20, pp. 13b–14a; cf. Rickett (1985, p. 334). There are various doubtful points in the translation which are not relevant to the present question.

18 Wagner (1993, pp. 181–2, 169–70).

19 Huang Zhanyue (1976, pp. 63–4).

20 He writes, *E cu ye* 惡麤也, '*E* means "coarse".'

21 *Huai nan zi*, *SBBY* edn, ch. 13, p. 18b; Zhao Zongyi (2003, p. 704); tr. Larre et al. (1993, pp. 186–7).

22 P. 86 below.

23 *Huai nan zi*, *SBBY* edn, ch. 13, p. 2a; Zhao Zongyi (2003, p. 655); tr. Larre et al. (1993, p. 162).

etymology of *tie* 鐵, the Chinese word for 'iron'. It appears to be related to a number of words meaning 'dark' or 'black'.

The Han dictionary *Shuo wen jie zi* defines *tie* as 'the black metal',[24] and an etymological association of iron with a dark or black colour is common world-wide. Some modern examples are: Japanese *kurogane* 黑金 ('black metal') for 'iron'; Russian *chernaya metallurgiya* ('black metallurgy') for 'ferrous metallurgy'; and of course English *blacksmith*. A wide-ranging compendium of etymologies for 'iron' and 'steel' in old- and new-world languages mentions words related to 'grey', 'dark blue', 'black', and 'dark' in numerous apparently unrelated cultures.[25]

The publications of Bernhard Karlgren on the history of the Chinese language make it fairly simple to investigate the etymological relations of a word like *tie*.[26] We consider first the Archaic pronunciation of *tie*, then look at other words to which it may be etymologically related.

1. *tie* 鐵, Arch. *t'iət* or *t'iet* or *t'iat*, 'iron'.[27]

By the known rules of cognate formation in Archaic Chinese, the following words are likely to be cognate with this:[28]

2. *ti* 銕, Arch. *d'iər,* 'iron'[29]
3. *die* 驖, Arch. *d'iət* or *d'iet* or *d'iat*, 'a horse of a certain colour',[30] mentioned above
4. *dai* 逮, Arch. *d'əd*, 'dark' (*GSR* 509c)
5. *di* 逮, Arch. *d'iəd*, 'dark' (*GSR* 509c)
6. *tai* 隸, Arch. *t'iəd*, 'dark' (*GSR* 509e)
7. *di* 墆, Arch. *d'iad*, 'to shade' (*GSR* 315d)
8. *tan* 炭, Arch. *t'ân*, 'charcoal' (*GSR* 151a)
9. *zhen* 袗, Arch. *t̂i̯ən*, 'black clothes'[31]

[24] *Shuo wen jie zi*, p. 293.

[25] Rex (1964, pp. 3a, 4a, 7a, 10a); note also Buck (1949, p. 613).

[26] Karlgren's work is not, of course, the last word on the subject. It has been criticised on methodological grounds (e.g. Serruys, 1960; Pulleyblank, 1962; 1985, p. 304), and alterations or refinements of various details have been proposed. There seems however to be general agreement among linguists that it constitutes a solid foundation for all future work on the subject. Most important for present purposes is that his rules for 'word families' function convincingly within his reconstruction of the pronunciation. I shall use Karlgren's system here, with almost no reference to the work of others, because only a trained linguist can safely explore the voluminous recent work on Chinese historical phonology.

[27] The reconstructed Ancient pronunciation (ca. +600) is *t'iet* (*GSR* 1256b); this could correspond to any one of the three Archaic forms (ca. –800) given here (Karlgren, 1954, pp. 285, 293, 307), but there is not sufflcient material to allow a determination of which is correct.

[28] Karlgren (1933, pp. 98–105) gives numerous examples of 'word families' (groups of words which are related both phonetically and semantically) which indicate that words with the following initials and finals may be cognate:

initials: *t-*, *t'-*, *d-*, *d'-*, *t̂-*, *t̂'-*, *d̂-*, *d̂'-*

finals: *-n*, *-t*, *-d*, *-r*

In addition Malmqvist (1962, p. 115) gives examples specifically related to alternations among final *-ər*, *-ət*, and *-əd*. These alternations seem to be the result of some grammatical inflection in Proto-Chinese.

[29] A synonym for *tie* mentioned in the *Shuo wen jie zi* (1963 edn, p. 293). Archaic pronunciation reconstructed by the method of Karlgren (1954).

[30] *GSR* 1256c, reconstructed as above; also modern *tie*, Arch. same as no. 1.

[31] Karlgren (1933, p. 89, no. 219); but cf. *GSR* 453f, where the only definition given is 'unlined garment'.

10. *zhen* 鬒、黰, Arch. *t̂i̯ĕn*, 'black hair' (*GSR* 375d, e)
11. *duan* 褖稅, Arch. *t'wân*, 'black dress' (*GSR* 171b, 324i)
12. *yuan* 緣, Arch. *di̯wan*, 'black dress' (*GSR* 171d)
13. *duan* 褍, Arch. *twân*, 'black straight robe' (*GSR* 168f).

It is therefore likely that *tie*, 'iron', is etymologically related to 'dark' or 'black'.

New light from archaeological material

The terms of the debate on China's earliest iron were changed irrevocably by excavations in 1950–52 in Hui County 輝縣, Henan.[32] Of 54 Warring States graves excavated here, seven yielded a total of 161 iron artefacts, including decorative objects, weapons, and implements. In 1953 there was another major find: the site of an iron foundry of the −3rd century in Xinglong County 興隆縣, Hebei,[33] where cast-iron moulds for iron implements were found. More surprises were to come as these and other iron artefacts were subjected to metallographic examination, and we shall go into these at length further below,[34] but the finding of large amounts of iron securely dated as early as the −4th century was remarkable enough in itself.

Guo Moruo responded to the new finds in an article entitled, 'In hope of more finds of ancient iron'.[35] Here he reiterated his view that the transition from 'slave society' to 'feudal society' occurred at the beginning of the −5th century, and suggested that more finds of iron artefacts would strengthen this hypothesis.

In the next few years excavations revealed more and more early iron artefacts. In 1957 the archaeologist Huang Zhanyue concluded the first systematic survey of these with a bitter complaint concerning, among other matters, the lack of rigour, or even total lack of basis, of many of the dates given for the artefacts he was interested in.[36] Such outspoken criticism of colleagues is rare in the Chinese scholarly literature, but it had its justification in this case. Much has since changed for the better, but it is still true that historians who wish to use Chinese archaeological material in their work must not blindly accept dates and other interpretations given by the excavators of material of interest, but find out how other Chinese archaeologists have received these claims, as well as looking critically themselves at the basis on which the claims are made.

. . .

[32] Excavation report, Anon. (1956); see also Watson (1957); An Zhimin (1990); Paul-David (1954); Wagner (1993, pp. 199–206); Zhang Xinbin (1994).
In 1952 the iron implements from Hui County were placed on display in the newly refurbished Museum of Chinese History in Beijing (cf. Wang Yu-chuan, 1953). A young Canadian delegate to the Asia and Pacific Peace Conference in October 1952, Finlay MacKenzie, sent Joseph Needham a set of sketches of these. He asked to remain anonymous, however, afraid that if the visit to Beijing were known he would not be able to obtain employment in Canada. The sketches are reproduced in *The development of iron and steel technology in China* (Needham, 1958, p. 66, pl. 2), credited to 'F. McK.' My attempts to make contact with Mr MacKenzie have been unsuccessful, but after fifty years it no longer seems necessary to keep his identity confidential.

[33] Excavation report Zheng Shaozong (1956); see also Anon. (1980a); Li Xueqin (1985, p. 327).

[34] Pp. 130–4, 137–40, 159–68.

[35] Orig. 1956, repr. Guo Moruo (1973, pp. 202–7).

[36] Huang Zhanyue (1957, p. 104).

With the publication of still more relevant archaeological material, many scholars have been attracted to the question of the origin of the use of iron in China. It was again Huang Zhanyue who, in an important article published in 1976, brought order to a confusion of claims and counter-claims.[37] Using rigorous philological criteria he rejected, one by one, all of the arguments based on written sources. Considering then the archaeological evidence, he rejected several arguments on such grounds as methodological confusion, incorrect dating, or inadequate reporting of excavation details. He concluded that the first use of iron in China was in the south, for the earliest iron artefacts so far found in China were from Changsha, Hunan (in the state of Chu 楚) and Luhe 六合, Jiangsu (in the state of Wu 吳).

When in the mid-1980s I wrote my own contribution to the problem, in two chapters of a book entitled *Iron and steel in ancient China*, the available archaeological material appeared to provide a moderately clear picture.[38] Several artefacts of *meteoritic* iron from the late Shang and early Western Zhou found in north China seemed irrelevant to later developments; and if one ignored claims that were not properly documented with archaeological and metallurgical details, it seemed that in China the *smelting* of iron from ore began, as Huang Zhanyue had suggested, in the south, sometime before the beginning of the −5th century. I felt, however, that I could narrow this further, to the state of Wu 吳.[39] From there it spread within a century to the other major southern state, Chu 楚, and within another century to the rest of the Zhou Empire, almost entirely replacing bronze as the metal of choice for most practical implements and weapons. Earlier iron artefacts of non-Chinese nomadic peoples north of the Zhou Empire (which I did not mention) appeared interesting but essentially irrelevant to the Chinese story: the rulers of the Zhou states had sufficient bronze for their purposes, and if they were aware of the new metal used by their northern neighbours they found it to be a poor substitute.

Even as that book was being printed, new publications of archaeological material were undermining its story. What is available as I write (January 2006) indicates that smelted iron definitely was in use in northwest China long before it was used in the south. A direct implication is that the technique of iron smelting came to northwest China from the West, for contacts with iron-using peoples on the periphery of the Zhou Empire were sufficiently intense that independent invention was hardly possible. Another surprising aspect of the new archaeological material is that it indicates that the early smiths may have used meteoritic and smelted iron interchangeably, so that the meteoritic iron artefacts have a significance which I had not earlier been willing to accept.

If iron-smelting technology came to China from the West, then the first iron smelting in China must have been done in bloomeries rather than, as a few writers,

[37] Huang Zhanyue (1976).
[38] Wagner (1993, pp. 51–146).
[39] In this I largely followed Huang Zhanyue. Since his article the new excavations of the Chu capital in Jiangling, Hubei, had discredited certain assumptions on which the dating of the Changsha material had been based; see Wagner (1987a; 1993, pp. 86–90); Zhou Shirong (1990); Yang Ding'ai et al. (2003, p. 31, n. 7). With the Changsha material essentially undatable, this put the use of iron in Chu at least a century later than in Wu. There do however seem to be some Chu iron artefacts from the late Spring and Autumn period, e.g. Yang Ding'ai et al. (2003, pp. 28–9); Sheng Dingguo and Deng Jianqiang (2003, p. 521). Some scholars continue to follow the older chronology for the Changsha graves, notably Han Rubin (e.g. 1998, p. 91); Anon. (2000b); and Wang Shimin (2003).

including myself, have assumed, in blast furnaces. The bloomery is a small-scale hearth or shaft furnace which produces wrought iron in the solid state. Technical aspects of bloomery iron smelting are described briefly in Box 8.[40]

Box 8 *Iron smelting in a bloomery furnace*

In a bloomery furnace wood or charcoal is burned, producing a temperature around 1200–1300°C and a furnace atmosphere rich in carbon monoxide (CO). Roasted iron ore, composed largely of iron oxides and silica (SiO_2), is added to this fire. Some of the iron oxide combines with the silica to produce fayalite (Fe_2SiO_4, i.e. $2FeO.SiO_2$), with a melting point of 1205°C. This is the primary component of the slag, most of which melts and flows to the bottom of the furnace. The rest of the iron oxide is reduced to metallic iron by the carbon monoxide. The resulting small pieces of iron, which are never molten, sinter together to make a sponge-like mass of iron and slag called the *bloom*. This is removed and hammered on an anvil to force out as much as possible of the slag. The reactions involved are:

$$C + O_2 = CO_2 \tag{1}$$
$$CO_2 + C = 2CO \tag{2}$$
$$2Fe_2O_3 + CO = 3Fe_3O_4 + CO_2 \tag{3}$$
$$Fe_3O_4 + CO = 3FeO + CO_2 \tag{4}$$
$$2FeO + SiO_2 = Fe_2SiO_4 \tag{5}$$
$$FeO + CO = Fe + CO_2 \tag{6}$$
$$2CO = CO_2 + \underline{C} \text{ (in solid solution in iron)} \tag{7}$$

The thermodynamic conditions for these reactions are shown in Figure 41. It can be seen that, under equilibrium conditions, there is only a narrow range of CO content in which FeO is reduced to Fe and Fe_2SiO_4 is not reduced (between curves C and B). In this range very little carbon can enter the iron (the curves between A and C). The bloomery operator does take care to control the CO content of the furnace atmosphere, but a bloomery operates very far from equilibrium conditions, and in fact it is quite possible to make steel, or even cast iron, in a bloomery. Nevertheless the operator generally avoids allowing too much carbon to enter the iron, for while steel is usually desirable, there is always the danger that so much carbon might enter the iron that it becomes cast iron, which is useless to a smith.

Modern metallurgists, attempting to reconstruct the bloomery smelting methods of the past, have found that modern technical knowledge is far from sufficient. The operation of such a bloomery requires long experience and a delicate feeling for the colours, sounds, and smells which appear. They have had a good deal of help from people in isolated parts of the world, especially parts of Africa, where bloomery furnaces have continued in use until modern times, but the forms of bloomery furnaces used in different parts of the world and in different periods have varied enormously, and the operation of one does not necessarily tell much about the operation of another.

Since there is as yet no information at all regarding what an ancient Chinese bloomery might have been like, I have chosen an arbitrary example, a 'peasant furnace' used in

(*Cont.*)

[40] Pp. 14–15. Out of the vast literature available on the archaeological, historical, theoretical, and experimental aspects of bloomery iron smelting, the best single reference is now Radomír Pleiner's magisterial *Iron in archaeology: the European bloomery smelters* (2000).

Box 8 *Continued*

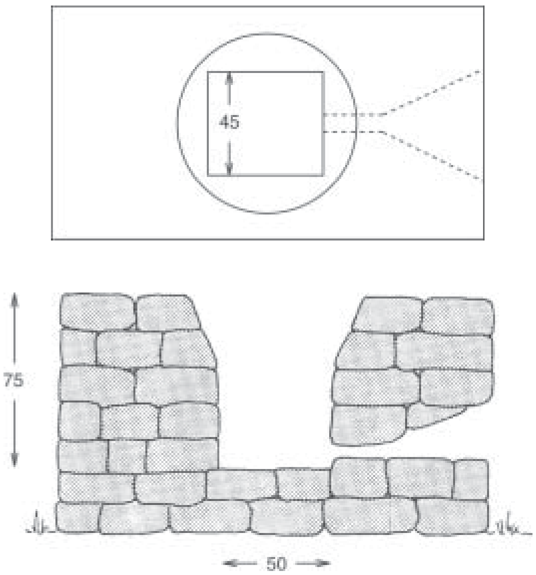


Figure 39 Diagram of a bloomery furnace used in Nornäs, Särna Parish, Sweden, in 1851, redrawn from Buchwald (1991, p. 271, fig. 3). Dimensions are in cm. *Upper:* top view. *Lower:* section. Figure 40 gives an impression of a similar furnace in operation.

central Sweden until the beginning of the 19th century. In 1851 four smelts, performed by men who remembered how it had been done in the past, were observed by professional metallurgists from the Swedish Ironmasters' Association (*Jernkontoret*). Their report was published in Swedish in 1946 and translated into English by J. A. W. Busch (1972). The following depends very heavily on a discussion by V. F. Buchwald (1991, pp. 271–3).

The furnace was filled with dry wood and ignited from below. After 30 minutes, after the wood was charred and had descended, a few shovelfuls of roasted and pulverised ore were added. Blast (in this case from a water-driven bellows) was blown in near the bottom, and this was increased as the process continued and more wood and ore were added. At a certain point charcoal began to be added instead of wood; it burned more quietly and allowed the furnace operator to see what was happening.

After 2–2½ hours the furnace burden had sunk down into the rectangular bottom of the furnace, and now the operator's skill came to the test. He worked with a hook, a pointed rod, and a spade, manipulating the remaining furnace contents to separate the metallic iron from the slag and gather it together into a compact bloom. During this operation the blast was carefully regulated to avoid oxidising the iron.

Finally the blast was stopped and the bloom, typically weighing 8 kg, was fished out with tongs and taken quickly to an anvil, where it was cloven with an axe but not further hammered. Later it would be reheated and hammered to squeeze out the slag, producing 4–5 kg of wrought iron.

This particular furnace had no taphole for slag. It was cleaned out from the top, then immediately charged for the next heat. The operations continued day and night for a week or more, until the stock of ore, wood, and charcoal were used up.

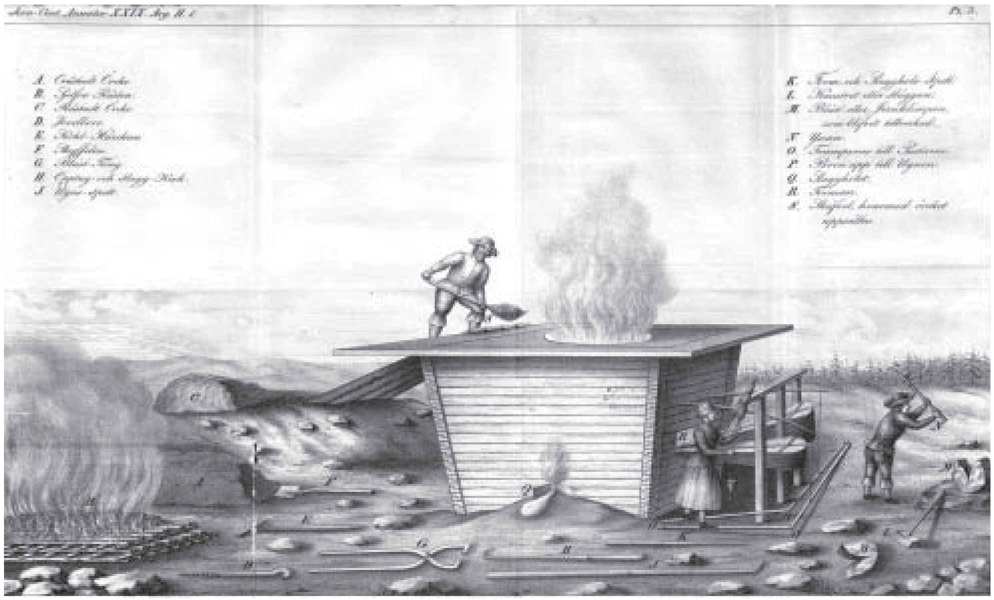


Figure 40 A family ironworks in Dalecarlia, central Sweden, early 18th century; drawing by Lars Schulze (1701–65) in a manuscript of 1732 now in the Royal Library, Stockholm. Reproduced here from the 1845 repr. of Schultze (1732, pl. 3); cf. Grabe (1922, p. 26, fig. 2); Percy (1864, pp. 320–1). The man is charging the furnace, the woman is working the bellows (with her feet, while spinning yarn with her hands), and the boy is cleaving a hot iron bloom with an axe.

(ii) Iron on the Periphery of the Zhou Empire

In Xinjiang, in the far northwest of modern China, some surprisingly early dates for iron have been published in recent years.[41] Iron is found in graves which for the most part show no sign at all of Chinese influence and which have surprisingly early radiocarbon dates. The most important early iron artefact type appears to be a small knife; a few examples are shown in Figure 43. Chen Ge gives a table of 35 radiocarbon dates (by three different laboratories) for graves in Xinjiang in which iron artefacts were found.[42] These can

[41] See especially Mei Jianjun (2000, pp. 15–24); Chen Kwang-tzuu and Hiebert (1995); Chen Ge (1989; also 1981; 1987; 1990); Cong Dexin and Chen Ge (1991); Sun Binggen and Chen Ge (1987; 1988); Zhang Ping et al. (1989); Zhang Yuzhong (1985); Debaine-Francfort (1989, esp. pp. 192, 194, 196–7, 198, 201, 206–7); Wu En (1993); Wang Binghua (1995); Zhang Yuzhong (2002, pp. 487–90); Qian Wei et al. (2000).

[42] Chen Ge (1989, pp. 426–7).

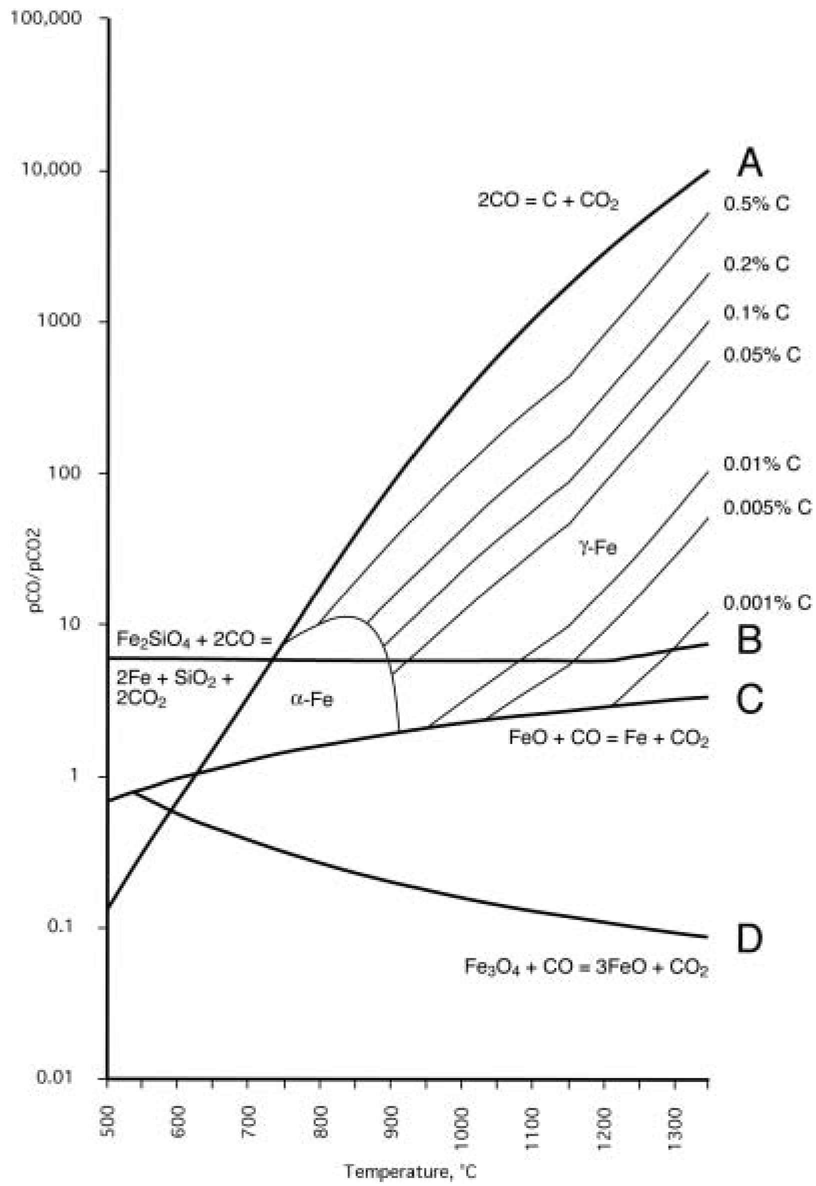


Figure 41 Equilibrium conditions for certain reactions which are important in bloomery smelting. The vertical axis gives the ratio of partial pressures of carbon monoxide (CO) and carbon dioxide (CO2) in the furnace atmosphere. When furnace conditions are above a particular line, the corresponding reaction goes to the right; if below, to the left. Curve A and the curves between A and C (except B) are calculated with the assumption that the atmosphere contains about cal 79 per cent nitrogen; this is more realistic than the customary assumption $pCO_2 + pCO = 1$. For the data and method used in calculating these curves see Wagner (1990, pp. 115–16); Rosenqvist (1974, chapters 3, 4, and 9); Richardson et al. (1948–52); Harris (1945); Groves (1949).

be summarised as follows:

earlier	1	
−1000–901	3	■■■
−900–801	6	■■■■■■
−800–701	7	■■■■■■■
−700–601	3	■■■
−600–501	5	■■■■■
−500–401	2	■■
−400–301	2	■■
−300–201	1	■
−200–101	2	■■
later	3	

There seems to be little room for doubt that iron was known here by the −8th century, but I would tend to be wary of the dates which are earlier than this, for they are difficult to fit in with what we know of iron in Siberia and China proper. They are best explained as the tail of the Gaussian distribution of radiocarbon dates of the −8th century. The region seems not to have had much contact with the Central Plain before the Han period.

There are also some early dates for iron in parts of Gansu, perhaps again pointing to a date in the −8th century for iron.[43] Here there are more signs of contact with the Central Plain.

How did the technology of iron smelting reach Xinjiang? In an earlier article I pointed to Scythic nomadic cultures in the steppelands as likely intermediaries.[44] The Scythians – *Saka* in Persian sources,[45] *Sai* 塞 (Archaic *sək* or *səg*)[46] in Chinese sources – dominated the steppelands of Inner Eurasia through the greater part of the −1st millennium, were extremely mobile, and were the carriers of many cultural influences between East and West.[47] There are definite signs of Scythian influence in Xinjiang very early on,[48] and iron metallurgy is taken as one of the diagnostic features of 'Scythic culture' by a number of authors.[49] However, firm dates for iron metallurgy in the eastern steppelands are not as early as for iron in Xinjiang. Iron may have been used very early at the western end of the distribution of Scythic cultures, but east of the Urals the earliest firmly dated Scythic iron

43 Pu Chaofu (1981); Pu Chaofu and Zhao Jianlong (1984); cf. Chen Ge (1989, p. 431).
44 Wagner (1999a).
45 Yablonsky (1995).
46 *GSR* 908a; Hulsewé (1979, pp. 104–5, fn. 210); Puri (1994).
47 'The "Scythic era", 1000–200 BCE', Christian (1998, ch. 6, pp. 123–62); Di Cosmo (2002, pp. 31–43); Marčenko and Vinogradov (1989); P'iankov (1994).
48 Mei Jianjun (2000, pp. 69–71); Wang Binghua (1987); Debaine-Francfort (1989, pp. 198–201); Ma Yong and Wang Binghua (1994); Chen and Hiebert (1995); Di Cosmo (1999, pp. 924–6).
49 Watson (1971, p. 109); Christian (1998, p. 127).

Figure 42 Map showing the major place-names mentioned in Section 3.


Amur
RUSSIAN MARITIME PROVINCE
HEILONGJIANG
Vladivostok
JILIN
INNER MONGOLIA
LIAONING
NORTH KOREA
JAPAN
Pinggu
Xinglong
BEIJING
TIANJIN
HEBEI
Gaocheng
SOUTH KOREA
Fukuoka
KYUSHU
SHANDONG
SHANXI
NINGXIA
Hui
JIANGSU
Luhe
Lingtai
Sanmenxia
Baoji
SHAANXI
HENAN
Xichuan
SHANGHAI
Fengxiang
ANHUI
Jingmen
HUBEI
ZHEJIANG
Jiangling
Changsha
JIANGXI
HUNAN
FUJIAN
TAIWAN
GUIZHOU
GUANGXI
GUANGDONG

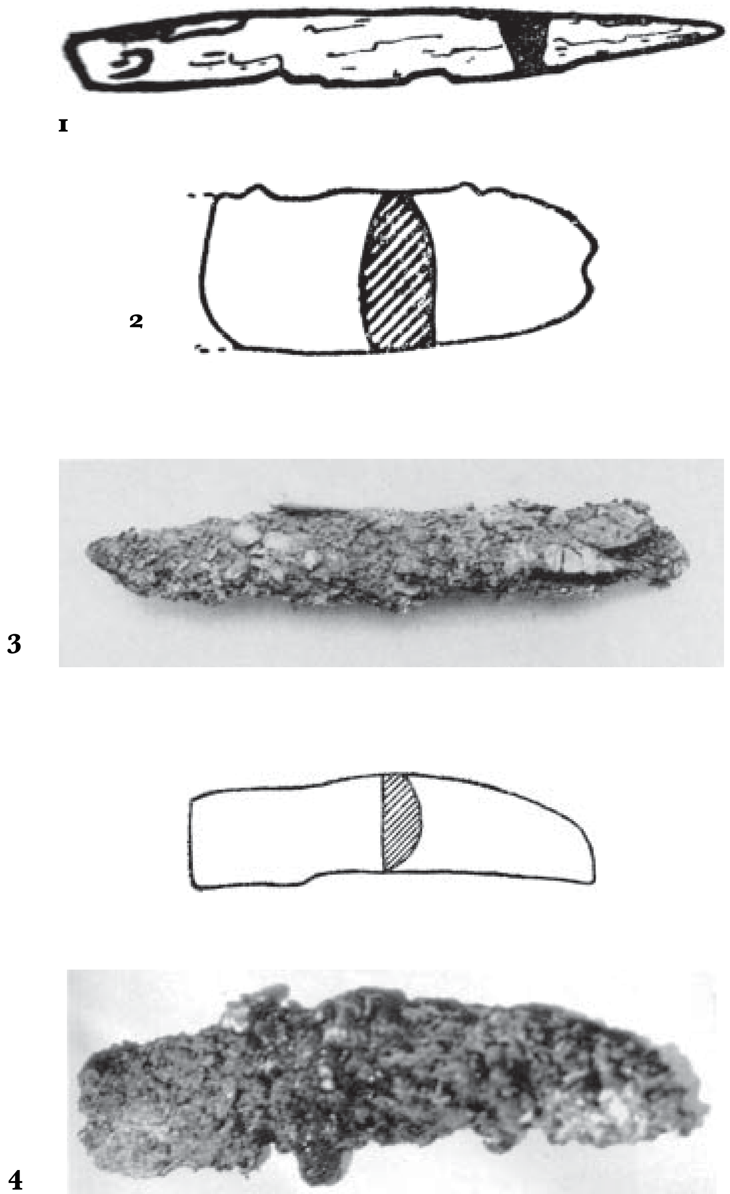


Figure 43 Photographs and sketches of iron knives from early graves in Xinjiang. **1.** From Cemetery no. 3 at Chawuhugoukou, Hejing County 和靜縣察吾乎溝口 (artefact no. M2:1). Length 16.5 cm, breadth 0.9 cm. Reproduced from Cong Dexin et al. (1990b, p. 887, fig. 8.3). **2.** From Cemetery no. 2 at Chawuhugoukou (artefact no. M14:11). Incomplete length 5 cm, breadth 2.1 cm. Reproduced from Cong Dexin et al. (1990a, p. 517, fig. 6.3). **3.** From a cemetery at Qunbake in Luntai County 輪臺縣群巴克 (artefact no. M3D:3). Incomplete length 12.2 cm, breadth 2 cm. Reproduced from Sun Binggen and Chen Ge (1988, pl. 5.7). **4.** From a period I grave in a cemetery at Yanbulake in Hami County 哈密縣焉不拉克 (artefact no. 31:5). Length 7.7 cm, breadth 2 cm. Reproduced from Anon. (1989, p. 348, fig. 26.10, pl. 13.7).

appears to come from kurgans (grave mounds) excavated in Tuva and dated to the −7th century.[50] A major study of ancient nomadic cultures of the Northern Zone of China by Wu En also places the earliest iron in the steppelands in the −7th century.[51]

Archaeological material available at this writing (April 2004) suggests that iron technology came to Xinjiang from the Chust culture of the Ferghana Valley, in modern Uzbekistan. Here iron appears at the beginning of the −1st millennium, and there is solid evidence of mutual influence between this culture and several cultures of southern Xinjiang.[52]

Farther east, in the Russian Maritime Province, some scholars believe that the use of iron was much earlier, perhaps as early as the −12th century. This claim seems to be based on a single radiocarbon date, and should therefore be treated with extreme caution until such a time as more solid evidence becomes available.[53]

It seems reasonable to conclude that the technology of iron smelting came to Xinjiang from further west. Given the present state of Inner Eurasian archaeology, however, further speculation concerning the precise route by which this transmission took place would probably be unwise. On the other hand, transmission to the Central Plain from Xinjiang through Gansu seems uncontroversial.

Early iron in Korea

There is some evidence that Korean iron technology may have come from the Scythians, and that this could have been as early as the −8th or −7th century. There is considerable controversy concerning the date of the first use of iron in Korea.[54] Sarah Taylor notes that the dates which have been proposed range from the −8th to the −3rd century.[55] Yoon Dong-Suk cites (and dismisses) Lee Byŏng-sŏn's statement that 'the early iron age along the Yalu River had begun as early as the −7th century'.[56] The early dates come from the North, and it appears that North Korean archaeology is

[50] Davis-Kimball et al. (1995, pp. 5–82, 276, 324); Kenk (1986, pp. 15–19, 75, 89, 99); Semenov and Kilunovskaya (1990); Chugunov et al. (2002; 2003); Čugunov et al. (2003). But note Grjaznov (1984, pp. 70–5); Hall (1997); and Di Cosmo (1999, p. 914), who give somewhat earlier dates for iron in Tuva.

[51] Wu En (2002, p. 443).

[52] Masson and Sarianidi (1972, pp. 164–5); Mei Jianjun (2000, pp. 67–70); Mei and Shell (2002); Mei and Li (2003, p. 114); Baratov (2001); Francfort (2001); Kohl (1984, pp. 189–91); Koshelenko (1988, p. 172); Askarov (1992, pp. 447–51); Zhou Jinling (1998); Shui Tao (1998; 1993, pp. 474–6). Note also Gorbunova (1986, pp. 18–21); Debaine-Francfort (2001).

[53] Chard (1974, p. 94) writes: 'Iron appears in the Vladivostok area in the eleventh to twelfth centuries B.C., coinciding with the development of the so-called Shell Mound or Sidemi culture.' Okladnikov (1965, pp. 184ff) discusses the Shell Mound culture in detail, but does not mention early iron artefacts. Murakami Yasuyuki (1991) mentions the iron artefacts of this culture, but does not take them seriously. See Chard (1961, p. 85, item 21, no. RUL-165); Di Cosmo (1999, p. 913; 2002, pp. 72–3); Derevianko (1965, pp. 138–9); Kuzmin et al. (1998, pp. 675, 682, 684); Wang Dehou (1999; 2003). I am grateful to Sarah M. Nelson and Charles T. Keally for several of these references.

[54] On iron in ancient Korea see Yoon (1984, pp. 35–46; 1990). Note also Taylor (1990, pp. 213–15); Barnes (1993, p. 214); Zhao Zhiwen (1996). There are also claims of very early iron in Manchuria, −8th century or even earlier, but I tend to be sceptical of the dates given (Di Cosmo, 2002, pp. 64–5).

[55] Taylor (1989, pp. 422, 427; cf. 1990, pp. 34–6, 42); Nelson (1993, pp. 172–4).

[56] Yi Pyŏng-sŏn (1967); cited Yoon (1986, p. 69).

not generally taken seriously in South Korea or in the West: 'The very early dates suggested by North Korean scholars (seventh or eighth centuries BC, i.e. before the first firmly dated iron production in China) seem motivated by nationalism as much as anything else, though it is often difficult to gain access to the data on which they base these claims.'[57] I must leave the discussion of the merits of North Korean archaeology in general, and of these claims in particular, to those who have access to the relevant publications, can read them, and have the necessary expertise to evaluate their reasoning. But it is very important to repeat that the first iron in Korea need not have come from China. Scytho-Siberian influences are known in South Korea, albeit at later dates than are relevant here (e.g. the Ipsil-ni 入室里 site, Kyŏngju, dated to the late –3rd century),[58] and we should expect to find the earliest such influences in the North. Yoon Dong-Suk cites with approval the statement that 'in the northeastern sector of the Peninsula, the early iron age culture had already started in or about the 4th century BC by not only Chinese influences but also Siberian, particularly along the Tuman River Basin'.[59]

The best evidence on the actual technology of iron smelting in early Korea seems to be the bloomeries used in later times in Japan; this technology is generally assumed to have been imported from Korea. Hashiguchi Tatsuya reproduces diagrams of two iron-production sites in Kyūshū 九州, but gives no explanation.[60] One of these, his figure 1, excavated in Fukuoka 福岡, is fascinating, for it appears to show an odd type of bloomery which might be an early ancestor of the traditional Japanese *tatara* 踏鞴 furnace.[61] It is dated +7th to +8th century, and if this is indeed a bloomery it may be the earliest so far excavated and published anywhere in East Asia. It shows that bloomeries were in use in early times in the Korea–Japan area. Its peculiar construction may have been developed in Korea or Japan in response to the technical problems caused by the use of ironsand ore; such problems have been observed in 18th-century American bloomeries and in 20th-century Chinese traditional 'dwarf' blast furnaces.[62]

(iii) Early Chinese Meteoritic and Smelted Iron

The earliest evidence of the use of iron in the region of Shang and Zhou culture is shown in Plates XII–XIV.[63] These are bronze axeheads of several kinds with cast-in edges of meteoritic iron, and all seem likely to be of the Shang or early Western Zhou period.[64] Until recently it seemed reasonable to ignore such artefacts as essentially

[57] Taylor (1989, p. 427; 1990, p. 34).
[58] Kim (1978, pp. 138–40).
[59] Tho Yu-ho (1960), cited by Yoon (1986, p. 69).
[60] Hashiguchi Tatsuya (1992, pp. 99–100).
[61] On which see e.g. Rostoker et al. (1989).
[62] Horne (1773); Wagner (1985, pp. 17, 38, 55, 57).
[63] Chen Ge (1989, p. 432, fn. 1) suggests that a Shang-period *yue*-axehead reported by Dai Zunde (1980, pp. 47, 48) might be of meteoritic iron, but in fact Dai Zunde describes it as being entirely of bronze.
[64] They are discussed further by Han Rubin (1998); note also Chêng Tê-k'un (1975, pp. 30–1).

irrelevant to the later development of iron smelting in China. Noel Barnard, writing in the early 1970s, put the argument as follows:

> Until the opportunity occurs to write at greater length on the subject I would simply observe here that the presence of meteoric iron in shaped form – particularly the FGA items (34.11) [Freer Gallery of Art, see Plate XII] with dovetail cutting of the iron blade – must indicate an alien source of origin. Such articles would have entered the Middle States' area as the result of occasional contacts with nomadic peoples far to the west and beyond the present boundaries of China. There is no evidence at all which would allow us to assume that these meteoric iron blades could have been worked by Chinese artisans in Shang and Western Chou times. On the contrary, one might now point to this early evidence of the metal iron in China and comment on the fact that its introduction (a) made absolutely no impact on current and later metallurgical technology (i.e. smithy work did not develop), and (b) had nothing to do with the Chinese discovery of cast-iron some five or six centuries later. The unusual articles were simply treated as a curiosity.[65]

There was at this time no evidence that smithy techniques were ever used by early Chinese bronze artisans. Professor Barnard believed that if the techniques needed to shape wrought iron had been known to the bronze artisans, we should see evidence of this in the bronzes of the time. On this point I am not convinced. The techniques of the blacksmith are very different from those of the bronzesmith. Bronze is brittle when hot, and therefore forging must be done cold. Any metal hardens under cold-forging; if it becomes too hard before shaping is finished it must be softened by 'annealing' – heating briefly to a red heat and cooling again. Wrought-iron alloys – including meteoritic iron – can be shaped by the same technique of cold-forging and annealing, but since they are plastic when hot it is more efficient to shape them by forging at a red or white heat. There is good metallographic evidence that the meteoritic iron parts of most or all of the artefacts shown in Plates XII–XIV were hot-forged; the evidence is summarised in the figure captions. This technique, whether learned from outside or independently invented, would have been useless in shaping bronze.

The bronze parts of these artefacts are clearly Chinese in style, and there are also many similar Shang artefacts with cast-in *jade* cutting edges, for example the spearhead shown in Plate XV.[66] There is still room for the supposition that the iron parts were imports from elsewhere, but very little reason for it. More likely there were Chinese smiths in the Shang and early Zhou who hot-forged meteoritic iron and produced small edges to be cast into bronze axeheads and other edged weapons. Meteoritic iron is usually fairly hard, and these bronze–iron weapons are likely to have been superior to weapons of bronze alone, but meteoritic iron is so rare that these must always have been uncommon luxury items. We do not know whether these smiths developed their techniques themselves or learned them from elsewhere. The probability of independent invention seems

[65] Barnard and Satō (1975, p. 85, fn. 5, cf. pp. 67–8, fn. 80); see also Barnard (1973).
[66] Wang Lin (1987); Xu Guangde and He Yuling (2004, pp. 17, 18, pl. 8.8).

high, but I have no information at all on the use of meteoritic iron in early Central Asia.[67]

Bronze–iron artefacts of the state of Guo with smelted and meteoritic iron

The earliest artefacts of smelted iron from a clearly Chinese context were found in 1990–91 in the royal tombs of the minor state of Guo 虢 in Sanmenxia, Henan, dated to the −9th or −8th century.[68] These are the three bronze–iron artefacts shown in Plates XVI–XVIII. Examination by Han Rubin and her group leaves no possibility of doubt that this iron is man-made.[69] It is very low in nickel and cobalt, which are always present in significant quantities in meteoritic iron, and metallographic examination of the badly corroded iron reveals inclusions whose form and composition are typical of slag inclusions in bloomery iron, but which would not be found in meteoritic iron.

The tombs are dated by the excavators to the period of the last two kings of Western Zhou, Kings Xuan 宣 and You 幽 (−827 to −771) on the basis of comparison of numerous bronzes with bronzes from well-dated tombs elsewhere in China.[70] In the past some Chinese authors have argued that all of the Guo tombs excavated in the Sanmenxia area must be dated later than −770,[71] while others have disagreed.[72] It is likely that the new excavations have laid this question to rest, but in any case, even if a much later date were supposed, these three artefacts would still be the earliest man-made iron artefacts so far found in a Chinese context.

Meteoritic iron was also found here. The three bronze–iron artefacts shown in Plates XIX–XXI are from the same tomb as that in Plate XVIII, which is of smelted iron, but the iron parts of the former have very high nickel contents, and therefore are almost surely of meteoritic iron.[73] High nickel content can occur in smelted iron, though it rarely does, and certainty on this question is possible only if metallographic examination shows the remains of a Widmanstätten structure, as in the

[67] Some meteoritic iron artefacts are known from the Afanasievo Culture in the Minusinsk Basin and the Altai region, apparently to be dated before −2000. These are mentioned very briefly by Okladnikov (1990, p. 80) and by Gryaznov (1969, pp. 27, 50, pl. 3) but neither gives any details or source references. It is interesting that Mei Jianjun (2000, pp. 58–9; 2004, pp. 176–7; Mei and Li, 2003, p. 114) finds evidence of contacts between this culture and early cultures in Xinjiang.

[68] The Guo tombs in Sanmenxia, discovered in 1956, have been excavated in a series of campaigns in 1956–57, 1990–92, and 1998–99. There is a considerable literature on these remarkable tombs: see especially Lin Shoujin (1959; 1961; 1978); Lin Shou-chin (1962); Guo Moruo (1959); Li Xueqin (1984, pp. 64–6; 1985, pp. 80–4); Anon. (1984b, pp. 283–5; 1991a, p. 343; 1999); Xu Yongsheng (1993); Cai Yunzhang (1994a; 1994b; 1996); Tang Shujun (1999); Wang Bin (2000); Zhang Yanxiu (2002; 2004); Yue Lianjian and Wang Longzheng (2003).

[69] Han Rubin et al. (1994; 1999, p. 570).

[70] Note also Jiang Tao et al. (1992); Anon. (1999, p. 528).

[71] E.g. Li Xueqin (1984, p. 65; 1985, p. 84); Guo Baojun (1981, p. 70); Ning Huizhen (2000). These authors argue on the basis of a single text, *Tai Kang ji* 太康記, now lost, of unknown date and authorship, quoted in *Shui jing zhu* (+6th century), ch. 18, p. 587.

[72] E.g. Anon. (1984b, p. 283; 1992, pp. 14, 17); Cai Yunzhang (1994a; 1994b); Zhang Yanxiu (2004); Li Jiuchang (2003).

[73] Han Rubin et al. (1999, p. 562).

meteoritic artefacts discussed earlier (Plates XII–XIV).[74] However, too little metallic iron was left in the badly corroded Guo artefacts to allow a meaningful metallographic examination. Therefore a slight element of doubt must remain, but since no high-nickel smelted iron of any period is known from China, it seems safe to conclude that these artefacts are indeed of meteoritic iron.

An interesting aspect is a possible connection westward, to the vicinity of Baoji, Shaanxi, where we shall see that other early iron artefacts have been found. Several sources indicate that there was a state named Guo near Baoji;[75] whether the Guo of the Sanmenxia graves was related to this Guo is less certain, but some art historians believe they can see elements of nomadic culture in the décor of some of the Guo bronzes.[76]

Finding meteoritic and smelted iron in the same context, seemingly wrought by the same artisans, is surprising; nearly as surprising as finding smelted iron at all at such an early date in China. More surprises are no doubt waiting for us, but it is clear that we must now look to the northwestern peripheral regions for the source of the earliest technology of iron smelting in China. Further evidence of this is afforded by a grave in Baoji, Shaanxi.

Gold–iron artefacts in a grave in Shaanxi

A grave in Baoji Municipality 寶雞市, Shaanxi, dated to the late Spring and Autumn period, contains some remarkable gold–iron artefacts, including three short-swords (Plates XXII–XXIV, XXVI), thirteen ring-headed knives (Plate XXV), two knives with gold ring-head, 'glass' (*liao* 料) back, and iron edge, and two other knives.[77] One of the short-swords has been examined by metallurgists, and was found to be of smelted rather than meteoritic iron.[78]

This is a typical Chinese small grave, a rectangular shaft, measuring 1.5 × 3.2 m at the mouth and 5.5 m deep, with 'second-level platforms' (*ercengtai* 二層臺) and with inner and outer wooden coffins (*guan* 棺 and *guo* 槨). The grave-goods, on the other hand, are highly unusual for a Chinese grave: there are no ceramic artefacts at all, there is a great deal of gold,[79] and there are many artefacts which are more typical of the steppe cultures.[80] It is difficult to date, but the date given by the excavators, corresponding to the –7th or –6th century, seems secure enough.[81]

74 Piaskowski (1982); Photos (1989).
75 See e.g. Ru Yu (1999); Anon. (1999, pp. 537–8).
76 E.g. Jenny F. So in Fong (1980, p. 252); note especially the mirror decorated with tigers and a horse, Lin Shoujin (1959, p. 27, fig. 21, pl. 40.2); Lin Shou-chin (1962, p. 11).
77 Excavation report, Tian Renxiao (1993). Studies, Li Xueqin (1993); Zhang Tian'en (1993); Chen Ping (1995).
78 Bai Chongbin (1994).
79 Gold was used very sparingly in Shang and Zhou China, but is very commonly found in Scythic cultures. See e.g. Qi Dongfang (1999); Bunker (1998).
80 Zhao Huacheng (1997).
81 Chen Ping (1995) discusses the sword and the tomb at great length and comes to roughly the same conclusion.

With iron-using cultures close by, and clear signs of cultural contact with them, it is quite possible that either the iron artefacts themselves, or the technology of their fabrication, came from outside. The ring-handled knives might in principle have been made in China or anywhere in the steppelands. The origin of this type of knife has long been a problem for archaeologists and art historians,[82] but the best guess at the moment is that its earliest development took place in western Siberia.[83] It was a simple and useful design, and spread quickly; it became one of the typical Shang bronze artefact types, and is also found throughout the steppelands. The short-swords, on the other hand, are more specifically Chinese; the decoration of their hilts is unusual, but similar sword-hilts have been found in China proper, and apparently nothing like them has been found outside China.[84] While the sword-blades could have been made anywhere, the hilts were surely made by Chinese craftsmen, and it is natural to suppose that the blades were also made locally.

A Qin tomb in Gansu

The bronze–iron short-sword shown in Plate XXVII comes from a tomb excavated in Lingtai County, Gansu.[85] Lingtai is only about 60 km north of the ancient capital of Qin in Fengxiang County, Shaanxi, and comparison of burial styles as well as artefact styles shows clearly that this is a Qin tomb. The excavators date it to the early Spring and Autumn period, i.e. the −8th century. Chen Ping argues for a slightly later date, in the reigns of Dukes De 德 and Xuan 宣 of Qin, −677 to −664.[86] He uses this tomb as one of the reference points in a systematic periodisation of Qin bronze vessels, and the bronzes in it seem to fit very well into his seriation.

A sample taken from the sword-blade by workers at the Beijing University of Iron and Steel Technology turned out to be totally corroded, and they felt that it was not possible to determine whether the iron was meteoritic or smelted.

The evidence presented thus far suggests that by the −8th century iron-smelting techniques, developed in the West, were being used in parts of Central Asia, and that these techniques diffused to the smiths of the Chinese states by way of various non-Chinese peoples in what is now Xinjiang. The Chinese smiths, now using smelted iron instead of meteoritic iron, continued to produce luxury articles such as swords and knives, with fittings of gold, jade, and bronze.

82 Important studies include Karlgren (1945, p. 128); Chen Zhenzhong (1985); Li Weiming (1988); Chernykh (1992, pp. 268–70); Wu En (1978); Liu Yiman (1993).

83 Chernykh (1992, p. 269), who however also notes that the Russian scholar who has carried out the most detailed investigation of the problem, N. L. Chlenova, suggests the opposite: that this type of knife originated in China.

84 Li Xueqin (1993); Zhang Tian'en (1993).

85 Excavation report Liu Dezhen and Zhu Jiantang (1981).

86 Chen Ping (1984a, p. 60).

The earliest of this class of iron artefacts are found in the northwest, but by the end of the –6th century a few examples are found quite far afield.[87] Perhaps the latest example, and the one found farthest afield, is a jade-hafted dagger discovered in what may have been a royal tomb in the northern part of Chu.[88] Almost nothing has been published about this interesting artefact, only a brief verbal description indicating that the blade has the shape of a willow leaf, with a rounded point. The total length is 22 cm, length of the cutting edge 12 cm, width 2.2 cm. It is entirely corroded, and no metallographic examination has been attempted. The excavators date the tomb to the end of the Spring and Autumn period, i.e. the beginning of the –5th century.

What part did these luxury edged weapons, of iron decorated with bronze, precious metals, and jade, play for the armies of early China? We lack the technical information needed for a careful answer to this question, but there is some reason to suggest that they may have had no great importance at all. One of the short-swords from Baoji, probably that shown in Plate XXVI, has a blade of pure iron, with zero carbon, rather than steel,[89] and this would not be expected to be a better metal for the purpose than bronze.[90] In Roman Europe, the historian Polybius described Gallic swords which were so soft that they bent in use, so that warriors had to fall back from battle to straighten them. These were undoubtedly of pure iron; metallographic examination of Celtic swords has revealed a number of examples.[91] The Gauls used this iron because it was available, not because it was better than bronze; this cannot be the explanation for the use of iron in the luxury products we have seen here.

Possible counter-evidence

Finds in Shaanxi and Shanxi present two possible exceptions to the pattern seen here, in which the early iron artefacts found in northwest China are all luxury wrought-iron products.

The tomb of a Duke of Qin, believed by many to be Duke Jing 景公, who died in –537, was excavated in Fengxiang County 鳳翔縣, Shaanxi, in the period 1978–86. In the fill of the tomb 'more than ten' iron digging implements were found. In a

[87] See e.g. Tang Jigen (1993, p. 558); von Falkenhausen (1994, pp. 104–5); Lian Haiping and Xiong Yingfei (1995). Note however that several of the artefacts listed by these authors are insufficiently documented and rather uncertainly dated. Note also a gold–iron sword of the Han period discovered in a grave in Inner Mongolia (Lu Shoulin et al., 2000).

[88] Tomb M10 at Xiasi in Xichuan county, Henan 淅川縣下寺, artefact no. M10:33. Excavation report Anon. (1991b, pp. 292, 347); see also Wagner (1993, pp. 90–1); Jian Fu (1994); Li Ling (1996); von Falkenhausen (1999).

[89] Bai Chongbin (1994). The author does not, unfortunately, give the artefact number, so we cannot be sure which sword was examined. Probably it was the one which in its present state is least presentable in a museum, and that is probably M2:3.

[90] But note Rehder (1992), who shows that work-hardening could have improved the hardness of such weapons, but that selective corrosion would probably remove any trace of this.

[91] Polybius, *Histories*, 2.30.8, 2.33.3; tr. Pédech (1970, pp. 73–4, 76); Paton (1922, pp. 317, 321, 323); cf. Walbank (1957, pp. 206, 209). Plutarch, *Camillus*, 41.5; tr. Flacelière et al. (1961, pp. 202–3); Perrin (1914, pp. 201, 203). Cf. Lang (1984, p. 64); Pleiner (1980, p. 411, n. 31). On the microstructures of Celtic swords, Thomsen (1975, p. 23); Pleiner (1980, pp. 393–4); Lang (1984); Tylecote (1987, p. 272). Pleiner (1993, pp. 157–69) introduces some much-needed nuances into the discussion of both the historical and the archaeological sources on the question of the battleworthiness of the Celtic swords.

published photograph one of these appears to be almost surely cast iron.[92] At the moment (January 2006) we are still dependent on journalistic accounts for all information about this tomb.[93] It is therefore not certain that the tomb really is as early as this, and more important, until a proper excavation report is published, it will not be clear whether these digging implements were found in undisturbed earth or in robber tunnels of later times. This would not be the first time that iron digging implements have been found in ancient robber tunnels.[94]

If, when the excavation report is published, it turns out that this tomb is indeed as old as some believe, and if the cast-iron digging implements are contemporary with the tomb, then the discussion that follows here will require radical revision, for I shall claim that the use of *cast* iron for practical implements began in south China, in a very different cultural context from that of Qin.

Excavations in 1980–89 at a very extensive site near Houma 侯馬, Shanxi, known as Tianma–Qucun[95] 天馬 – 曲村, have produced three early iron artefacts. Metallographic examination shows that two are of wrought iron, while one, artefact no. 84QJ7T12④:9, dated to the −8th century, is without doubt of cast iron.[96] It might be a bit later than the −8th century, but it is still very early.[97] But it is not clear that this indicates actual casting of iron products – it could be a waste product from a bloomery.

The excavation report, in its general discussion of the habitation sites, states that the cast-iron artefact was found at a habitation site designated J7, in a 5 × 5 m trench designated T12, in a stratum designated ④, but this and a brief note in the conclusion seem to be the only mentions of the artefact.[98] In the excavation report each trench has a separate discussion, with descriptions and diagrams of stratum relations and a discussion of the artefacts found; but the description of trench J7T12 does not mention the iron artefact.[99] Considering the importance of this find, it is disconcerting that the report does not give more information. This is especially so when the report states,

The report differs from all previous Chinese archaeological reports in that we intend to publish as much raw material as possible, especially those from the Western Zhou and

92 *Guangming ribao* 光明日報 ('Guangming Daily'), 15 May 1986, p. 4; reproduced in Wagner (1993, p. 93, fig. 2.41).
93 In English: Yi Xu (1986); Su Minsheng (1987); Han Wei (1987); Anon. (1986a; 1986b); *Xinhua News Agency News Bulletin* (Hong Kong), 3, 5, 12, and 23 May 1986. In Chinese: *Guangming ribao* 光明日報 ('Guangming Daily'), 28 April 1986, 1; 2 May 1986, 1; 3 May 1986, 1; 4 May 1986, 1; 15 May 1986, 4; 24 May 1986, 1; 13 July 1986, 3; 6 August 1986, 1; *Renmin ribao* 人民日報 ('People's Daily'), 3 May 1986, 3; 9 May 1986, 3; 25 May 1986, 3; 16 September 1986, 3. Discussion, Wang Hui (1989, pp. 20–1); Wagner (1993, pp. 91–4).
94 E.g. Anon. (1982a, pp. 73, 113).
95 The site is named for the villages of Tianma and Qucun in Quwo 曲沃 and Yicheng 翼城 Counties, Shanxi, respectively.
96 It has 4.5% C, < 0.1% Si, < 0.01% S, 0.55% P, and 0.25% Mn. Han Rubin (2000, pp. 1178, 1180, supp. pl. 7.7).
97 The stratum in which it was found, J7T12④, contains ceramic artefacts whose rim-shapes would tend to place them in the middle rather than the early Spring and Autumn period. Compare Zou Heng (2000, p. 117, figs. 100.2, 100.9, p. 63, figs. 38.8–9, p. 68, figs. 43.8–10).
98 Zou Heng (2000, pp. 59, 1132); Han Rubin (2000, p. 1178).
99 Zou Heng (2000, pp. 117–18). One of the other two iron artefacts, J7T44③:3, is mentioned briefly in the description of the trench in which it was found, p. 140.

Spring-and-Autumn periods. Whether they were habitation sites or tombs, all cultural sites and cultural remains will be published in full.[100]

The artefact was obviously not at first considered important at the time of its excavation in 1984.

Neither the excavation report nor the metallographic report gives any sort of description of the artefact. It is referred to only as 'a fragment of an iron object' (*tieqi canpian* 鐵器殘片), and even its size is not reported. Is this a fragment of a recognisable vessel or implement, or might it merely be a bit of high-carbon iron accidentally produced in a bloomery? Some writers believe that the presence of cast iron indicates that high temperatures have been *achieved*; in fact bloomery operation requires careful temperature control to *avoid* deleteriously high temperatures, which can result in the production of cast iron, which is useless until new techniques are developed.[101] Numerous cast-iron fragments have been found in excavations of early European bloomeries.[102]

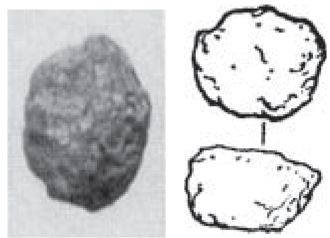
Habitation site J7 contains a number of production features such as ceramic kilns, bone workshops, and stone workshops; several ceramic moulds for casting bronze objects were also found here, indicating the probable presence of a bronze foundry.[103] It is therefore reasonable to look for iron-production furnaces here as well. The three early iron artefacts reported from Tianma–Qucun were found within a limited area in this habitation site, less than 20 metres from each other.[104] In this same area are three rather mysterious features identified as 'roasting ovens' (*shao zao* 燒灶).[105] Very little detail is given in the description of these, but it is quite possible that they in fact are the remains of bloomery furnaces.

We must therefore hope for closer investigation of these artefacts and features. If the cast-iron artefact is in fact a fragment of an object which has been cast, then iron casting has a much earlier history in China than has otherwise been suspected. And if the 'roasting furnaces' turn out to be bloomery furnaces, they are the first to be discovered in China.

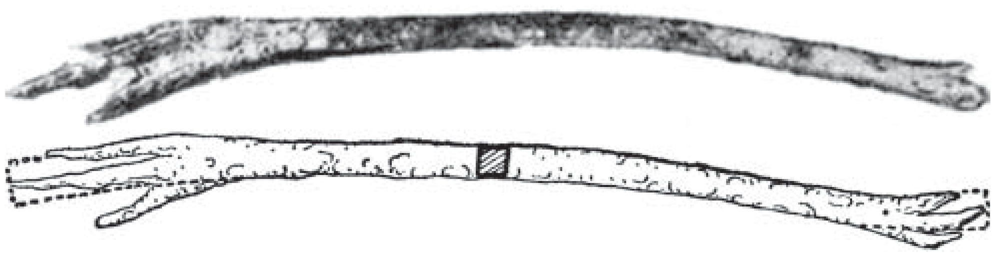
(iv) Iron Casting and the Blast Furnace

The new evidence reviewed above definitely shows that wrought bloomery iron was the first smelted iron to be used in China. This has been something of a surprise, for not many years ago the available evidence was consistent with the hypothesis that China started with *cast* iron, only later developing the techniques of the blacksmith.[106] But while the use of wrought iron and the bloomery started in the northwest, and was a borrowed Western technique, iron casting was a Chinese invention. It seems to have started in the south, in either Wu or Chu.

100 Zou Heng (2000, p. 1181).
101 See p. 113 below and Box 8, pp. 89–90.
102 Tylecote (1986, pp. 167–8; 1987, pp. 325–6); Pleiner (2000, pp. 247–50).
103 Zou Heng (2000, pp. 1133, 62).
104 Artefact nos. 84QJ7T12④:9, 84QJ7T14③:3, and 86QJ7T44③:3, in trenches T12, T14, and T44. Han Rubin (2000, p. 1179); Zou Heng (2000, foldout fig. 27, opposite p. 34).
105 J7T12Z1, J7T23Z2, and J7T1085Z3; Zou Heng (2000, pp. 44, 166).
106 Barnard and Satō (1975, p. 67); Wagner (1993, pp. 145–6).



44 Lump of cast iron (Grave no. 1, artefact no. 35), reproduced from Wang Zunguo et al. (1965, pl. 1.9) and Huang Zhanyue (1976, p. 67, fig. 2.4). Diameter 2–3 cm.



45 Rod of wrought iron (Grave no. 2, artefact no. 18), reproduced from Anon. (1974a, pl. 6.8) and Huang Zhanyue (1976, p. 67, fig. 2.5). Length 25.5 cm.

Figures 44–45 Iron artefacts from two graves at Chengqiao in Luhe County, Jiangsu 六合程橋, dated to the beginning of the −5th century. See Wagner (1993, pp. 60–80).

If we restrict our view to properly published and reliably dated archaeological material the earliest cast-iron artefacts have been found in south China. Perhaps the most famous is the lump of cast iron shown in Figure 44, from a grave dated to the early −5th century in Luhe 六合, Jiangsu, in the territory of the ancient state of Wu. Other iron artefacts from Wu which are either uncertainly dated or not properly published may turn out to be older.[107]

In the territory of the ancient state of Chu most of the evidence suggests a later date than this for the use of cast iron. The excavation of some 558 small and medium-sized graves at Yutaishan in Jiangling, Hubei 江陵雨臺山, near the site of Ying 郢, capital of Chu from −689 to −278, has provided a chronological series for many aspects of Chu material culture.[108] Here iron artefacts do not appear until the early −4th century, and this suggests an approximate date for the widespread use of iron in Chu – though not, necessarily, for its *first* use there. The actual site of the capital has not yielded iron artefacts which are definitely earlier than this.[109] There

[107] Wagner (1993, pp. 81–5).
[108] Excavation report Anon. (1984c); discussion Wagner (1993, pp. 85–6, 152–7). Note also a later excavation of 73 more graves at Yutaishan, Chen Fengxin (1990).
[109] Wagner (1993, p. 86).

have as yet been no metallographic examinations of these artefacts, but in photographs they appear all to be of cast iron.

We have already noted a luxury iron dagger, presumably wrought, found in a royal tomb in the northern part of Chu, dated to the end of the –6th century.[110] Practical iron implements, apparently cast, which may be equally old have been found at a Chu settlement site in Jingmen 荆門, Hubei, 75 km north of Jiangling.[111]

It is now difficult to maintain, as I did in my earlier book, that iron smelting itself was independently developed in south China,[112] but it still seems quite likely that both iron *casting* and the blast furnace were developed here.[113] And it still seems quite reasonable to connect this development with the use of bronze for agricultural implements in the state of Wu.

The written evidence shows that the population of Wu was seen in the north as 'barbarian', and archaeological evidence shows that their material culture was indeed in significant ways different from that of the north.[114] They seem in particular to have had very different customs regarding the burial of the dead. The forms of their graves, together with some curious ritual animal-horns found in Wu contexts, suggest a completely different spiritual culture. On the other hand they adopted some important elements of material culture from the north, among which was bronze technology.

Bronze production was, in the Chinese states of the north, concentrated in a few very large centres. Over the centuries a narrow range of smelting and casting techniques were intensively developed, and the bronze-casting techniques developed in the Shang and Zhou foundries produced castings which are among the finest the world has known, even in modern times.

It was this highly sophisticated technology which the 'barbarians' of Wu learned from their northern contacts. In a new cultural context this technology could be developed in new ways. New techniques were invented, and these techniques were applied to new uses, in particular to the production of agricultural implements.

Figures 46–49 show some of the bronze agricultural implements which have been found in Wu contexts, as well as one from a Chu context. Surprising numbers of these have been found, while comparatively few bronze implements, and none of the forms shown here, are known from the north. Especially interesting are the caps for digging implements shown in Figure 48, which are clearly the models for later iron implement-caps.

110 P. 103 above.
111 Li Zhaohua (1990, pp. 17–18, 22–3).
112 Wagner (1993, chs. 2–3).
113 Though we must always remember in this connection the possibility, mentioned above, that certain cast-iron digging implements found in the excavation of a Qin ducal tomb may be equally old (p. 103). If this turns out to be the case much of the present discussion will be invalidated.
114 On the ancient states of Wu and Yue see Wagner (1993, ch. 3). Note also Yao Fangmei (1994).

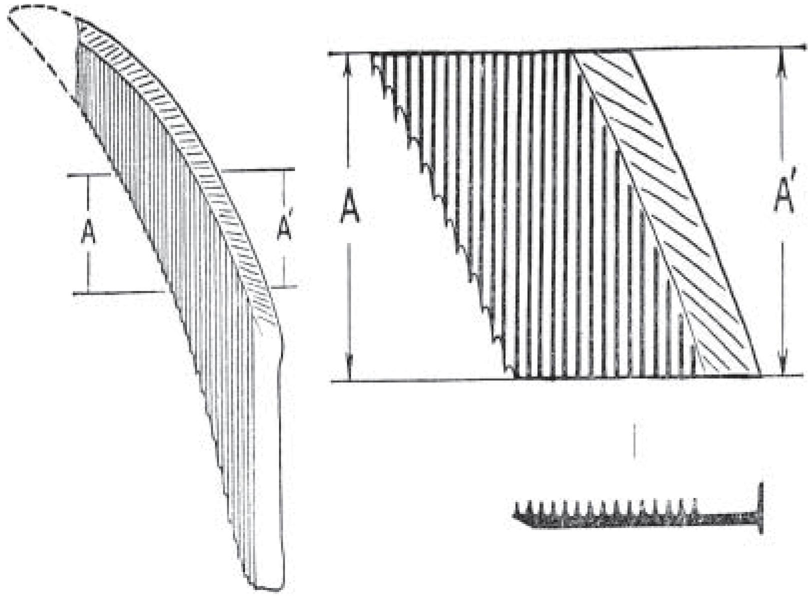


Figure 46 A sawtoothed sickle-blade, with magnified detail and cross-section, reproduced from Yun Xiang (1985, p. 260, fig. 4).

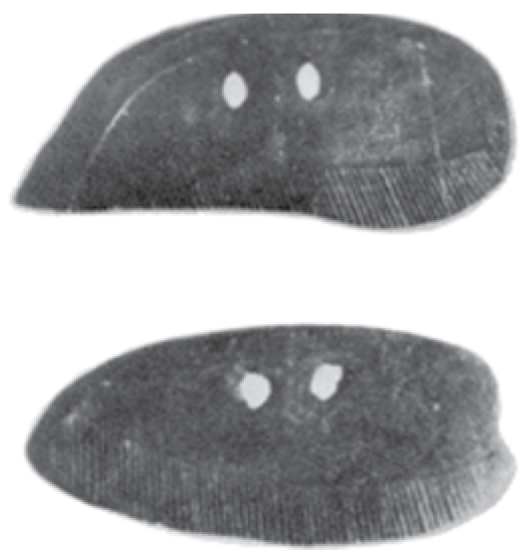


Figure 47 Two bronze toothed 'harvesting knives' (*zhi* 銍) from a hoard found in dredging operations at Fengmen 葑門 in Suzhou. Length 10.4–10.7 cm, breadth 4.5 cm. Liao Zhihao and Luo Baoyun (1982, p. 91, fig. 4.6); better reproduction of same photograph, back cover of *NYKG* 1982 (no. 2).

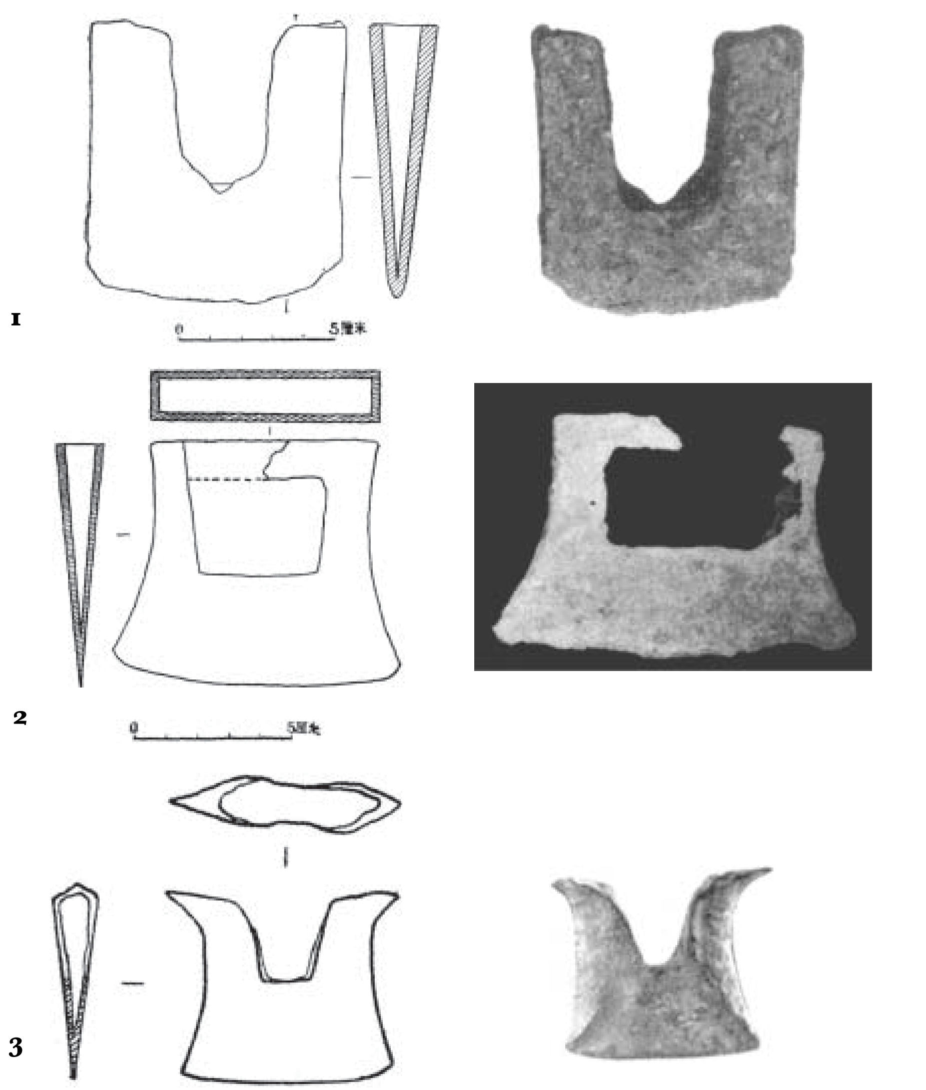


Figure 48 Bronze caps for digging implements. Provenances: **1.** From Tomb no. 2 at Chengqiao in Luhe, Jiangsu 六合程橋, dated early −5th century. Anon. (1974a, p. 119, fig. 5.2, pl. 6.2). On this tomb see Wagner (1993, pp. 60–80). **2.** From a tomb at Jiulidun in Shucheng, Anhui 舒城九里墩, dated by the excavators, on the basis of bronze inscriptions, to the late Spring and Autumn period. Length 7.8 cm, breadth of edge 9.4 cm. Yang Jiuxia (1982, p. 237, fig. 9.3, pl. 21.6). **3.** Found in a scrap metal heap in Nanchang 南昌, Jiangxi, in 1975. Length 5.8 cm, breadth of edge 6.2 cm. Li Jiahe et al. (1977, pp. 60, 61, figs. 5.1, 6.1); these authors date the artefact to the Shang period, but do not state the reason for this judgement. **4.** Discovered together with a large quantity of Eastern Zhou period pottery in Dinghai County on Zhoushan Island, Zhejiang 舟山定海縣. Length 8.5 cm, breadth of edge 8.1 cm. Wang Heping (1983; 1984). **5.** Found in the fill of Tomb no. M5 at Xi'eshan in Jiangling, Hubei 江陵溪峨山, dated by the excavators to the −4th century. Length 9.8 cm, breadth of edge 11 cm. Yang Ding'ai (1984, p. 522, fig. 10.8). **6.** From a hoard of bronze artefacts found by workers in 1963 at Yonglin in Yongjia County 永嘉縣, Zhejiang. Breadth of edge 9.7 cm. Xu Dingshui (1980, p. 16, pl. 3.4). **7–11.** From a hoard found in dredging operations at Fengmen 葑門 in Suzhou. Breadths respectively 9.2, 9, 7, 6.5, 13 cm. Liao Zhihao and Luo Baoyun (1982, p. 91, figs. 2, 4.1); Liao Zhihao (1982, p. 115, fig. 6).

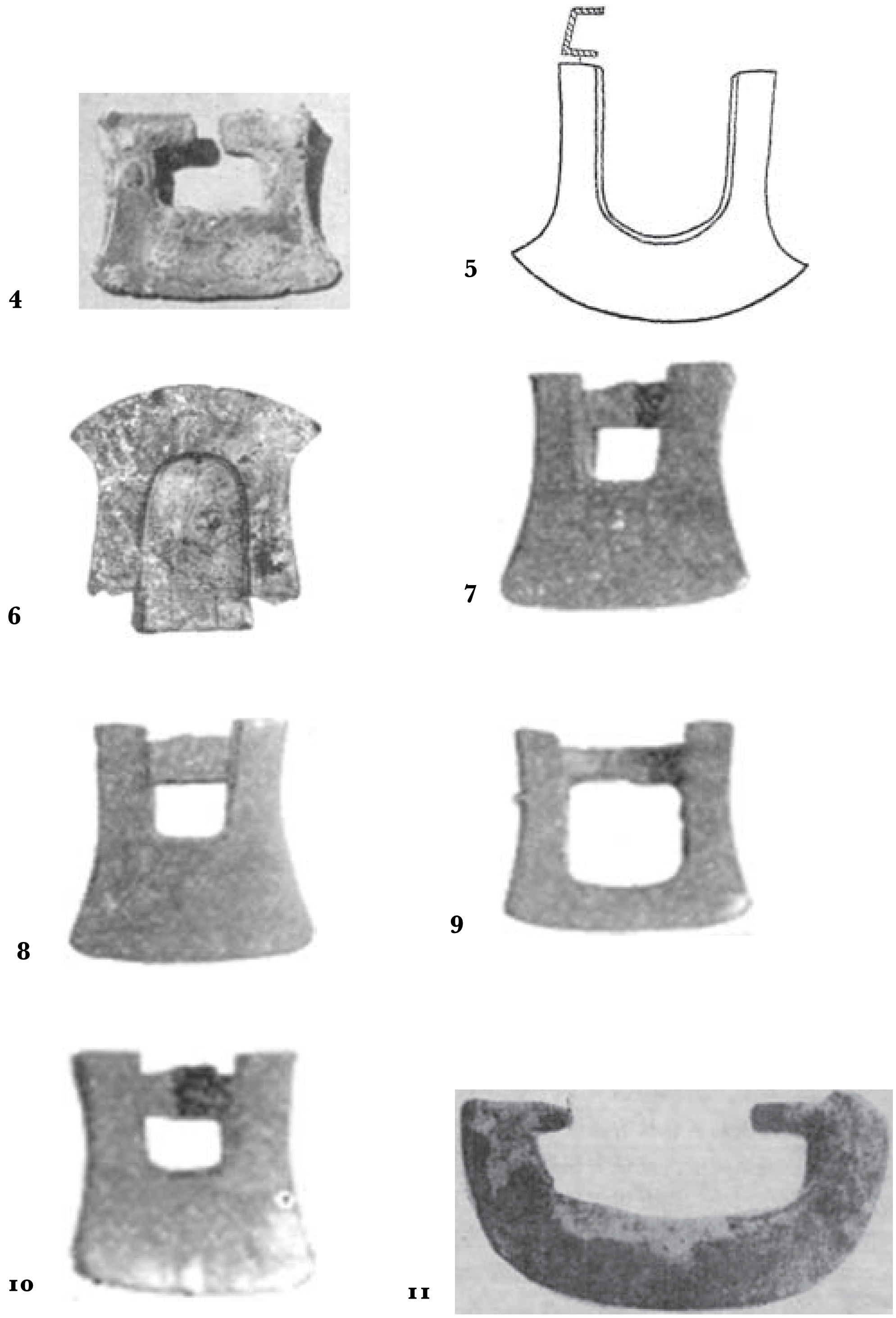


Figure 48 (*cont.*)

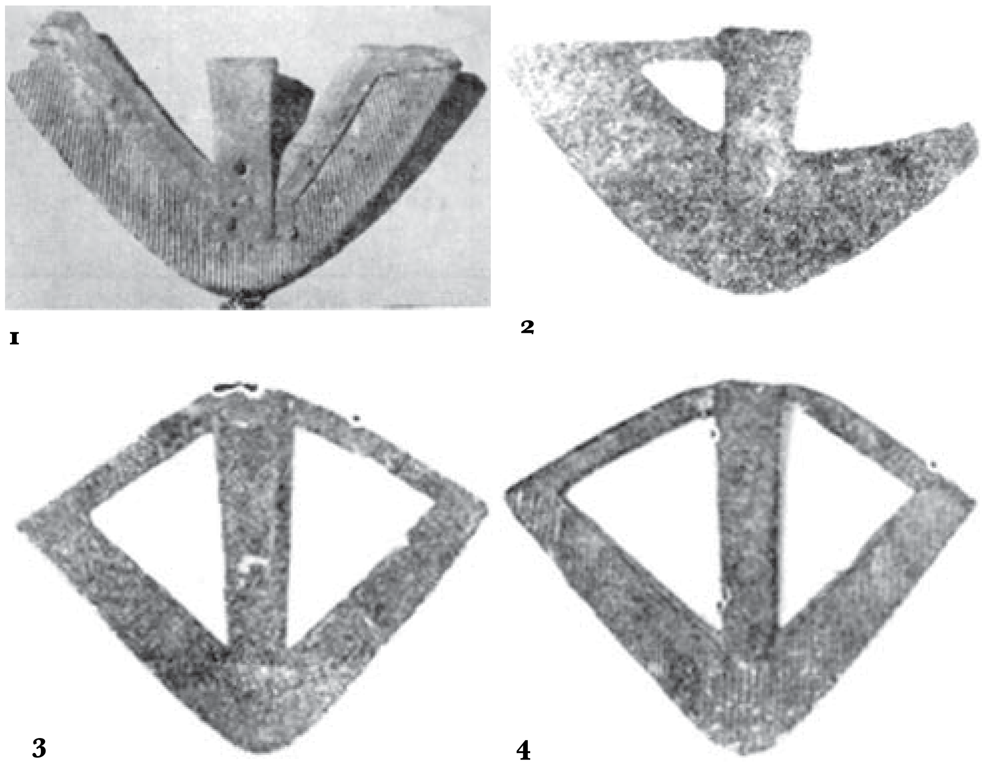


Figure 49 Bronze 'weeding hoes' (*nou* 鎒). Provenances: **1.** Discovered together with a large quantity of Eastern Zhou pottery in Dinghai County on Zhoushan Island, Zhejiang 舟山定海縣. Length 8.4 cm, breadth 17 cm, rectangular socket 2.4 × 1.9 cm (Wang Heping, 1983; 1984). **2.** From a hoard of miscellaneous bronze artefacts in a bronze *ding*-cauldron found at the New Suzhou Silk Weaving Mill near Suzhou, tentatively dated late Spring and Autumn or early Warring States. Length 10 cm, distance between corners 18 cm (Yang Xizhang, 1980, p. 20, fig. 12). **3–4.** From a hoard found in Guichi County 貴池縣, Anhui. (3) Length 11 cm, breadth between corners 15 cm, rectangular socket 1.8 × 1.5 cm. (4) Length 12.5 cm, breadth between corners 16 cm, rectangular socket 2 × 1.6 cm (Lu Maocun, 1980, p. 24, fig. 3.9–10; also 1984, p. 45).

In the Wu region copper deposits are small and scattered, and tin and lead deposits are rare; bronze agricultural implements must necessarily have been costly. As agriculture in the region developed and became dependent upon metal implements, it was necessary to find a cheaper metal. In one way or another it was discovered that iron could be cast; the problems involved in casting white cast iron could be solved, at least adequately for castings which need not be beautiful, because the Wu ironfounders had at their command the highly sophisticated bronze-casting techniques developed in the north.

This hypothesis is strengthened somewhat by the fact that the earliest cast-iron implements known, the implement-caps found in Chu graves of the −4th century and later,[115] have clear bronze prototypes found in the Wu region, for example

[115] Pp. 122–4 below.

those shown in Figure 48. An obvious weakness, on the other hand, is that no early iron implements of any kind excavated in the Wu region have yet been properly published.[116] A possible answer to this objection is that Wu archaeology is still in its infancy: most finds of metal artefacts have been made by non-archaeologists, who might easily fail to recognise a badly corroded piece of iron as a valuable artefact, or even as an artefact at all.[117] Nevertheless the possibility should be held open that the development described here occurred in Chu rather than Wu: it is here that the earliest cast-iron implements are found, and a few bronze agricultural implements have also been found in Chu contexts (e.g. Figure 48, no. 5).

My original suggestion was that the use in Wu of large copper-smelting furnaces led directly to the discovery of iron. In these furnaces iron ores were used as a flux to reduce the melting point of the silica gangue of the copper ore.[118] Much more iron ore than copper ore was used, and in normal operation the iron left the furnace harmlessly in the form of iron oxide (FeO) in the slag. Improper furnace operation could lead to the production of metallic iron, and experimentation could have led in one way or another to the development of the iron blast furnace.[119]

That hypothesis might still explain the development of *cast* iron, but it has always suffered from the fact that it gives no explanation for the appearance of *wrought* iron in Wu just as early as cast iron.[120] An example is shown in Figure 45. It now seems more likely that bloomery iron smelting was introduced in Wu from the north, and that the first iron casting involved the carburisation and melting of iron blooms in a cupola furnace of the sort used for melting bronze.[121] Precisely this is described in a German manuscript of 1454, and it is possible that iron casting began in Europe in this way.[122]

However cast iron was discovered, for most purposes it would not have been a good material. It would have been very low in silicon, and therefore be what is called *white* cast iron, which is difficult to cast and also very hard and brittle.[123] The only advantage would have been that it was cheaper than bronze. In the north the primary applications for bronze were weapons and symbolic objects of various kinds. Substitution of white cast iron for bronze in weaponry would have had disastrous effects, and casting difficulties would have made its use unlikely in fine ritual vessels.

[116] Two ‘iron artefacts’ are reported very briefly from Wu graves in Wu County 吳縣, Jiangsu, which are believed to be of Spring and Autumn period, but more details will be needed before this find can be evaluated. Zou Houben (1984).

[117] Cf. Wagner (1993, pp. 83–5).

[118] On fluxes see Box 1, p. 15 above.

[119] This begs a number of technical questions raised by my friend Paul Craddock (1994, p. 887). The fact to be emphasised is that iron *could* be produced in a blast furnace of the same size and shape as the ancient copper-smelting furnaces, as traditional Chinese blast furnaces of the 19th and 20th centuries demonstrate (see pp. 8–16, 47–8 above). The exact development route from copper to iron production would no doubt have been less straightforward than I suggested, but it would certainly have been possible. See however Merkel and Barrett (2000).

[120] Cf. Wagner (1993, p. 146).

[121] On cupola furnaces see pp. 60–4, 147–70, 237–9.

[122] Johannsen (1910; 1913).

[123] See pp. 161–3 below.

We shall see below that the blast furnace and the finery were in use in China by the –1st century. If we take it that the earliest iron smelting in the south used the bloomery, and that iron casting began with the melting of iron blooms in a cupola furnace to cast agricultural implements, then the development of the blast furnace is quite easy to explain. Bloomery smelting is a delicately balanced operation, and can easily produce cast iron by mistake, as various modern experimenters have discovered.[124] In the early West, until the advent of the iron cannon in medieval times,[125] no economically important use was known for cast iron, and the only intention in bloomery smelting was to produce wrought iron or steel. In some types of bloomery great skill was required to limit the carbon content of the iron produced.[126]

Lumps of cast iron produced in the bloomery would however melt just as easily in the cupola furnace as iron blooms (probably more easily), so that iron smelters who were engaged in producing iron for casting would have had no reason to care about the kind of iron they produced. Experience might easily have led, as many historians believe it later did in medieval Europe, to furnaces which produced both wrought-iron blooms and flowing cast iron in the same operation.[127] From there the development of the much more efficient blast furnace would have been more or less straightforward. With the development of the finery for decarburising cast iron to convert it into wrought iron, the production of bloomery iron would have become uncompetitive, and in time gone out of use.[128]

We do not know where and when this development might have taken place, nor do we know very much about the actual furnaces used for iron smelting in China before as late as the –1st century, so it would be unprofitable to speculate more here concerning details of the development of the blast furnace in China.

Studies of the origins of iron smelting in the West stress that iron was not in the beginning a better metal than bronze. Iron seems to have been known here as early as –3000, but first became an important metal about –1200. It was originally put to use for economic reasons, an increased demand or a decreased supply of either copper or tin. In time the smiths, working intensively with the new metal, learned more about its properties and possibilities. In particular, they discovered various ways of making *steel* by adding carbon into the iron. Once these discoveries had been made, developed, and widely diffused, iron became the material of choice for most weapons and implements.[129]

[124] E.g. Pleiner (2000, pp. 245–7); Crew (2004).
[125] *SCC*, vol. 5, part 7.
[126] E.g. Percy (1864, p. 326).
[127] P. 352 below.
[128] A possible scenario for the invention of the finery has been suggested by Bronson (1999, p. 191). Incorrect operation of a cupola furnace for remelting iron can lead to an excessively oxidising atmosphere, so that the molten iron in the furnace is decarburised and solidifies as a lump of wrought iron. This may have happened fairly often; the invention of the finery would then start with the discovery that this unwanted by-product could be useful.
[129] This account is largely based on Childe (1964); Snodgrass (1971; 1980); Maddin et al. (1977); Sørensen and Thomas (1989); Waldbaum (1999).

There is thus a certain parallel between the Western story and the story told here for China. In the beginning, in China, smelted iron may in about the –8th century have come into use as a cheap substitute for meteoritic iron in luxury weapons. As far as we know there were no great improvements in the techniques of the smith until in the south, perhaps in the –6th century, the founders of bronze agricultural implements discovered that they could cast iron and thus make a useful product from a metal more readily available than bronze. How the cast-iron implements compared with bronze ones in practical use is difficult to know. The extreme hardness of white cast iron would have made it extremely wear-resistant, but also liable to break. The answer to this question is however not as important as the fact that in this application iron was *economically* superior to bronze.

We shall see in Section 4 below that experience with the new material, cast iron, led to great improvements in its mechanical properties. In particular, the development of what we now call *malleable cast iron* made cast iron a better material than bronze and at least competitive with wrought iron or steel.

4 THE FLOURISHING IRON INDUSTRY OF THE −3RD AND −2ND CENTURIES

It is from the beginning of the −3rd century that we have evidence for a widespread use of iron throughout China. From the points of view of both the technology and the structure of the iron industry the −3rd and −2nd centuries form a coherent period which should be studied as a whole.

In political history a great deal was happening.[1] In −300 China was a collection of 'Warring States', but one of these, the state of Qin, had already begun the course of conquest which was to end in the unification of the states in the Qin Empire in −220. Qin's administration was of a new kind, sometimes said to be totalitarian, which depended on a corps of literate local administrators appointed by and responsible directly to the central government. The unification of the Empire was encouraged by numerous measures, both ritual and practical, of the Qin government, among them large-scale public works such as the First Emperor's Mausoleum, the Great Wall, long-distance roads, and central granaries.

Qin overextended itself and could not in the long run keep tight control over the population of its vast empire. Peasant uprisings led soon to the fall of Qin and the establishment of a new empire, that of the Han, in −206. The earliest Han emperors, consolidating the Empire, continued the Qin system in a moderated and less centralised form. It was not until the accession of Wu-di 武帝, 'The Martial Emperor', in −140 that a more activist policy was followed by the Han government. There was a new emphasis on military confrontation with the Xiongnu 匈奴 and other nomadic 'barbarians' as well as much greater expenditure on public works.

Of fundamental importance for our present interests is that in −117 Wu-di introduced a state monopoly on the salt and iron industries. The change in organisational structure that the monopoly brought to the iron industry may have led to important changes in its technology and geography; it certainly marks a change in the character of our sources (both written and archaeological), and it is with this date that the present Section will end. Section 5 will then consider the organisation and technology of the iron industry under the Han state monopoly.

There is no doubt that the period covered by this chapter was a time of great change: political, social, economic, philosophical. The expansion of agriculture in the period surely was related to the use of iron. Many scholars have also suggested that the rise of Qin was made possible by superiority in iron weaponry, and we shall have to consider below the merits of this proposal.[2] The expanded use of iron was

[1] See e.g. *SCC*, vol. 1, pp. 90–109; vol. 2, pp. 1–215; Li Xueqin (1985); Lewis (1990); Twitchett and Loewe (1986); Loewe (1974); Liu Pak-yuen (1983); Loewe and Shaughnessy (1999, pp. 587–1032).

[2] Pp. 146–7 below.

no doubt an integral part of all the changes of the period, but we shall find it difficult to distinguish cause from effect.

(i) The Widespread Use of Iron

Textual evidence

Towards the end of the −4th century the philosopher Meng zi 孟子 (Mencius) is told of the teachings of a certain Xu Xing 許行 of Chu, who holds that a good and wise ruler tills the land himself and cooks his own meals; not to do so is to inflict hardship on the people. As Mencius argues his own point of view, the following exchange occurs:[3]

> 'Does Master Xu cook with a [metal] pot [*fu* 釜] and an [earthenware] steamer [*zeng* 甑]? Does he till with iron [implements]?'
>
> 'Yes.'
>
> 'Does he make them himself?'
>
> 'No, he trades grain for them.'
>
> 'Trading grain for implements does not inflict hardship on the potters and founders. And when the potters and founders trade implements for grain, does this inflict hardship on the peasants? How can it be that Master Xu does not establish his own pottery and foundry? Why does he go about trading with the hundred craftsmen? Why does he bother?'
>
> 'The work of the hundred craftsmen certainly cannot be done while tilling.'

This story is told in the *Meng zi*, a book which was probably compiled by the philosopher's disciples in about −300.[4] At this early time it is doubtful that iron agricultural implements were common anywhere outside China; yet here they are taken for granted as a necessity. Another underlying assumption is that the production of iron implements is a specialised craft which the peasant would be foolish to take up himself.

Incidental mentions of iron are found in numerous pre-Han texts. The *Lü shi chun qiu* 呂氏春秋 notes that a lodestone calls iron to itself; this is an example of 'The Universal Permeation of Essences' (*jing tong* 精通).[5] The *Xun zi* 荀子, commenting on the defeat of Chu in a battle in −300, states that 'the hard iron spears of Wan 宛 [a city in Chu, near modern Nanyang 南陽, Henan] are as cruel as wasps and scorpions'; Chu's weakness was not in its weaponry but in its leadership.[6] *Han Fei zi* 韓非子 contrasts ancient and modern warfare: in the time of the ancient emperor Shun 舜, the barbarian Miao 苗 tribes submitted when he danced a war-dance with a shield and battle-axe. But in a recent battle with another barbarian tribe, the Gonggong

[3] *Meng zi*, ch. 5, pp. 8a–10b; cf. D. C. Lau (1970, p. 101); cf. *SCC*, vol. 2, pp. 120–1. On Xu Xing see Graham (1989, pp. 70–2).

[4] D. C. Lau in Loewe (1993, pp. 331–5); cf. *SCC*, vol. 2, pp. 16–18.

[5] *Lü shi chun qiu*, ch. 9, p. 9b; cf. Wilhelm (1928, p. 114); Knoblock and Riegel (2000, p. 218); *SCC*, vol. 2, pp. 36, 55; vol. 4, part 1, pp. 31, 232, 257.

[6] *Xun zi*, *SBCK* edn, ch. 10, pp. 15b–16b; Zhang Shitong (1974, p. 159); cf. B. Watson (1963, pp. 71–2); Knoblock (1988–94, pp. 229–30); *SCC*, vol. 2, pp. 19–20.

共工, 'the iron-tipped lances reached the enemy, and those without strong helmets and armour were injured'. Shields and (bronze) battle-axes were effective in ancient times, but now they have been superseded by iron weapons and armour.[7] And there are many more examples like these, indicating that iron was a common feature of daily life.

Archaeological material

While the written sources give a useful general impression of the use of iron in early China, archaeological evidence has the potential of taking us further, showing more precisely what iron implements and weapons were like and also giving useful information on how they were made. A number of published works give lists of iron artefacts found in pre-Han and Han contexts, and these show in a general way that by the −3rd century iron implements, weapons, and decorative objects were common throughout China. One of the first of these lists forms a part of Noel Barnard and Satō Tamotsu's massive *Metallurgical remains of ancient China*, which includes material excavated under controlled conditions between 1923 and 1971,[8] and publications by various authors have kept the subject up to date.[9]

The illustrations on the next few pages show some of the types of iron artefact which are known from the Warring States and Han periods (Figures 50–54). They include weapons, implements, and decorative objects, and their variety, together with the sheer number excavated in recent years, indicates again that iron was a very common material in this period. Methodological problems begin to show themselves, however, as we attempt to say something more precise about the when and the where of this use of iron. These problems were discussed in a most interesting debate in three issues of the American journal *Early China*, with articles entitled 'Where have all the swords gone?', 'Where all the swords have gone', and 'Did the swords exist?'[10] In the first article David Keightley discussed the common hypothesis that the Qin conquest of all China was made possible by a superiority in iron weaponry.[11] While there might be a good deal in the ancient literature to recommend this hypothesis, it was striking that in Noel Barnard's map of the distribution of finds of iron swords there is very little evidence of the use of iron swords in Qin. Keightley added a stricture which in any case will always be important in the study of such questions: 'the question of why Ch'in emerged victorious is, even in purely military terms, not easy to answer. It seems unlikely, however, that a purely materialist, technological explanation will suffice.'[12]

[7] *Han Fei zi, SBCK* edn, ch. 19, p. 2a; Chen Qiyou (1974, p. 1042); cf. B. Watson (1964, p. 100); W. K. Liao (1939, vol. 2, p. 279).

[8] Barnard and Satō (1975), 'Table of sites and remains', pp. 163–295, cols. 6, 11–14; Distribution maps 4, 4a–d, 6, 6c–d, 7d, 8d, 9, 9b–d, 10, 10c–d, 13, 16, 23.

[9] See e.g. Lei Congyun (1980a; 1980b); Chen Wenhua and Zhang Zhongkuan (1981–87); Ling Yeqin (1987, pp. 58–60); Miao Changxing et al. (1993); Ke Jun et al. (1993); Yang Jiping (2001); Xue Ruize (2001).

[10] Keightley (1976); Trousdale (1977); Barnard (1979). These articles were followed up later in another journal by Rostoker (1987a).

[11] Cf. *SCC*, vol. 2, pp. 215.

[12] Keightley (1976, p. 33).

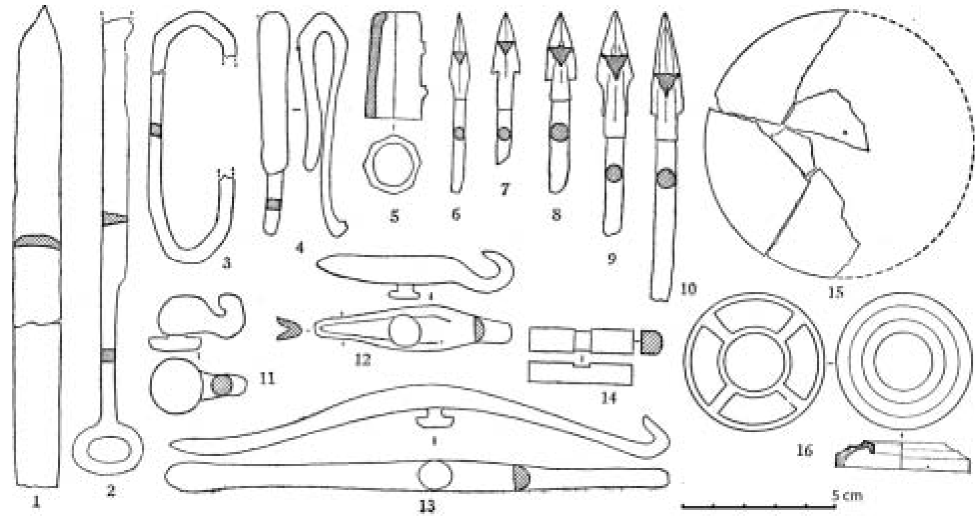


Figure 50 Artefacts from Grave no. M44 at the Xiadu site, reproduced from Liu Shishu (1975, fig. 3, p. 229). **1**. Iron dagger-blade (*bishou* 匕首). **2**. Iron ring-handled knife. **3**. Iron ring. **4**. Iron hook. **5**. Bronze bow-end (*jumo* 距末). (Also called *mi* 弭, Anon., 1957, plate 27.) **6–10**. Crossbow-bolts with iron shaft and bronze tip. **11**. Iron belt-hook. **12**. Bronze belt-hook. **13**. Bronze belt-hook. **14**. Bone ornament. **15**. Bronze disc. **16**. Bronze ring-like object.

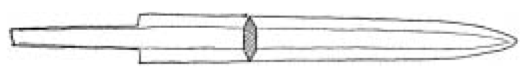


Figure 51 Bronze dagger-spear head (*pi* 鈹, originally identified as a sword) from Grave no. M44 at the Xiadu site, reproduced from Liu Shishu (1975, fig. 4, pp. 229, 235); cf. Wang Xueli (1985b, p. 61). Total length 31.5 cm, width of blade 3.3 cm.

An important, though somewhat ill-tempered, response by the art historian William Trousdale stated some basic considerations in the interpretation of the raw archaeological data shown on Barnard's distribution maps. These may be summed up by saying, first, that the relation between what is placed in the graves of the dead and what is used by the living is neither simple, nor constant in time and space, nor known; and second, that what is dug up (and published, I would add) is the result of complex choices in a modern economic and political context. On this last point he noted a remark by Keightley, that there seems to be a concentration of finds of iron swords along a line running from Hebei, through Henan, to Hunan, 'the battleground of Chan-kuo China'.[13] Trousdale sees this rather as the line of the Beijing–Guangzhou railway,[14] the building of which presumably brought much archaeological material to light.

[13] Keightley (1976, p. 33).
[14] Trousdale (1977, p. 66).

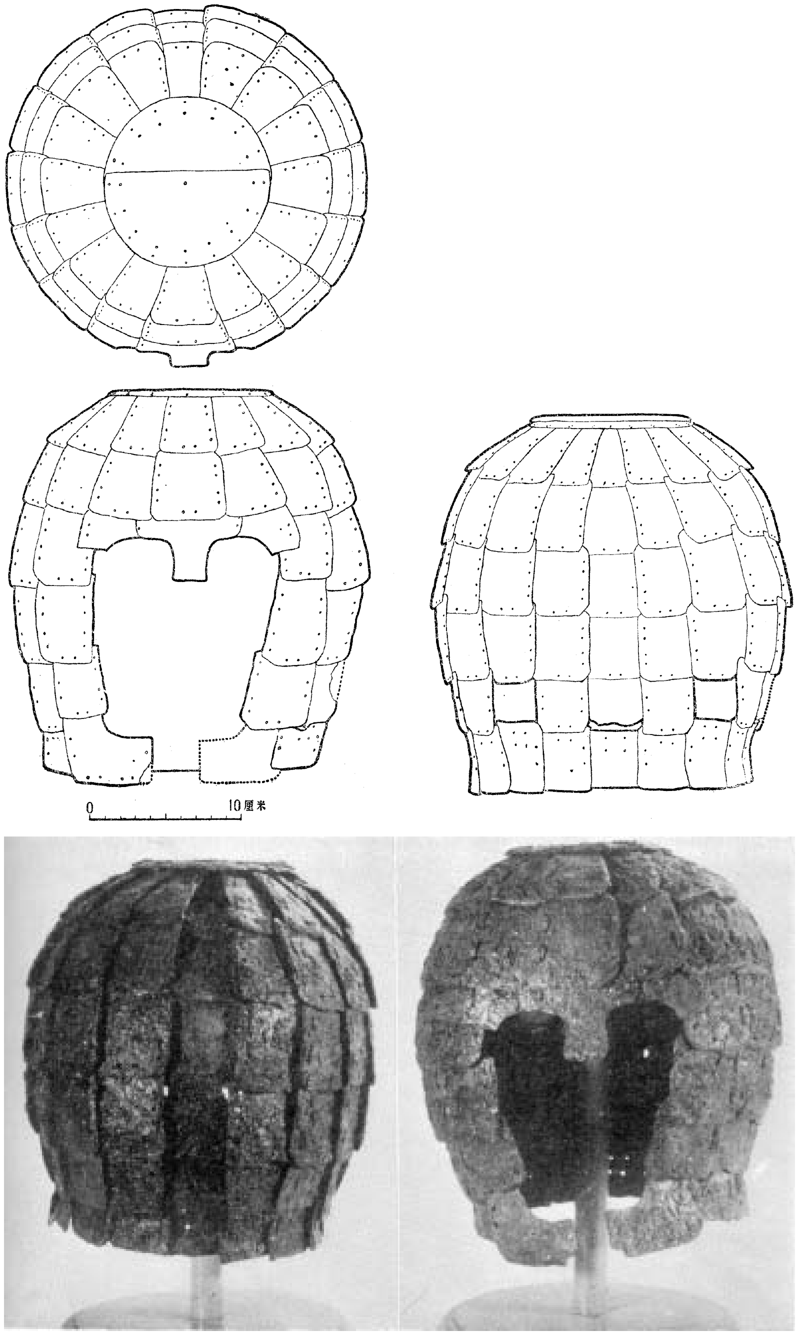


Figure 52 Iron helmet from Grave no. M44 at the Xiadu site, reproduced from Liu Shishu (1975, fig. 5, pp. 230–1, pl. 5.1–2). The helmet was originally composed of 89 separate plates, of which 86 were found, held together by cords or leather thongs. In the photograph the three missing plates have been restored. Slight traces remain of a cloth lining. The thickness of the plates is not stated; presumably it was 2–3 mm.

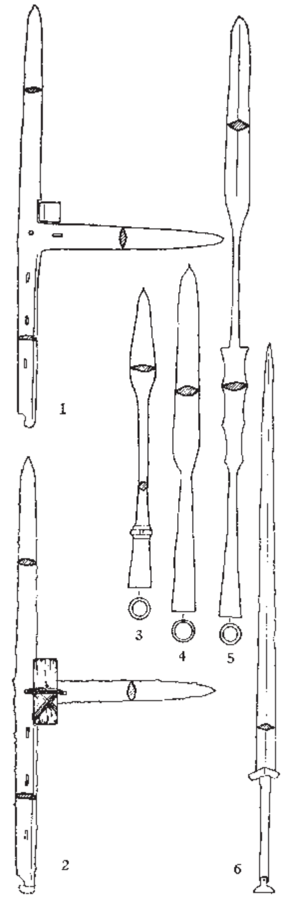


Figure 53 Iron artefacts from Grave no. M44 at the Xiadu site (Liu Shishu, 1975, fig. 6, p. 233). **1**. Halberd-head, length 46 cm. **2**. Halberd-head, length 45.2 cm. **3**. Spearhead, length 32.4 cm. **4**. Spearhead, length 37.5 cm. **5**. Spearhead, length 66 cm. **6**. Sword, length 99.5 cm.

Barnard, in the third article of the debate, pointed out that Trousdale's last point was somewhat shallow, for modern railways go where ancient roads went, and modern settlement patterns are not unrelated to ancient settlement patterns.[15] But the problem is more serious than Barnard was willing to admit at that time. An example which is relevant to our present concern is the history of the archaeology of the state of Chu: before the early 1980s, most of what was known of the material culture of Chu was from grave robbery and salvage excavations in the city of Changsha, Hunan, in the extreme south of the state, while the region of Chu's capital, in Jiangling, Hubei, was archaeologically almost unknown. This fact, which is related to modern patterns of trade and construction, produces one kind of distortion of the distribution maps. Another kind of distortion comes from

[15] Barnard (1979, p. 60).

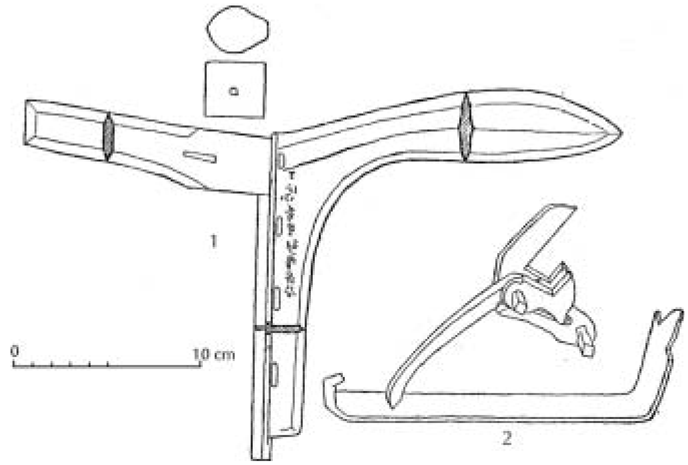


Figure 54 Bronze and bronze–iron artefacts from Grave no. M44 at the Xiadu site, reproduced from Liu Shishu (1975, fig. 10, p. 234). **1**. Dagger-axehead and associated ferrule (M44:73). **2**. Crossbow-lock, bronze with iron base-plate (M44:21).

the fact that virtually all of the pre-Han and early Han material excavated in Changsha has been dated too early, so that many aspects of material culture, including the use of iron weapons, seem to have their earliest occurrence there.[16] We shall see directly below that the more systematically excavated and dated archaeological material from Jiangling gives a rather different picture of this question.

Another question in the *Early China* debate concerned the relative effectiveness of iron and bronze swords. At that time it was widely believed that early Chinese iron was almost exclusively cast rather than wrought, and Trousdale remarked that, 'Unless Chinese cast iron had properties quite unimaginable at present, no soldier equipped with a cast iron sword is likely to have survived his initial encounter with a bronze-wielding adversary.' It happens to be true that ancient Chinese 'malleable cast iron' did have properties which are unimaginable to some art historians, as Barnard was quick to point out.[17] By now, however, the archaeological evidence which has accumulated makes it fairly certain that from early times swords were made from wrought iron or steel and virtually never of cast iron.[18]

Barnard also pointed out that Trousdale, in an earlier book, had himself shown less methodological rigour than he was now demanding of others, for he had written, 'it is significant to note that the archeological record suggests that during the late

[16] See p. 88, fn. 39 above.

[17] Trousdale (1977, p. 65); Barnard (1979, pp. 63–4). William Rostoker (1987a) also attempted to show experimentally that the very hard 'white cast iron' also could be used to make an adequate sword.

[18] A recent great surprise is a Chinese sword in the British Museum, believed to be from the Han period, which is of malleable cast iron (Wayman and Michaelson, 2006). This appears to be the only malleable cast-iron sword ever reported, from any period, anywhere in the world. Note added in proof: Scott and Ma (2006, p. 109) appear now to have found a second Han-period sword of malleable cast iron.

Chou, iron swords were most plentiful in the territories of Ch'in and its chief contender – the large state of Ch'u in South China'.[19] Barnard's more methodical consideration of the distribution of iron swords in controlled excavations contradicts the first part of this statement, about Qin; but what of Chu?

Iron artefacts in graves of Chu and Qin

I have suggested elsewhere that the intractable question of the relation of grave-goods to life can be partly by-passed by using comparisons of occurrences of iron artefacts with those of artefacts of other materials with comparable functions.[20] Focusing in such comparisons on excavations of large cemeteries gives series through time at particular places, partly helping with another problem, that of the biased distribution of excavations in modern times. We shall consider here cemeteries at the capitals of Qin and Chu.

The site of Ying 郢, the capital city of the state of Chu from −689 until the city's destruction in −278, is in Jiangling County 江陵縣, Hubei. Excavations at the site began in 1973, but the only excavation report available as yet is a two-part article published in 1982.[21]

It has been estimated that there are over 20 cemeteries in the vicinity, containing over 2000 graves each.[22] One of these, at Yutaishan 雨臺山, about 1 km northeast of the ancient city wall, has been the subject of an intensive archaeological study, in which 558 graves were excavated.[23] A chronology for 423 of these has been presented and argued in meticulous detail, and this work gives us for the first time a reliable sequence for the study of a great many aspects of Chu culture. The graves are divided into six periods, and this *relative* chronology seems very reliable. The *absolute* dates given for the six periods, running from the middle Spring and Autumn period to the destruction of the city in −278, are derived by comparison of artefacts with dated material from as far away as Luoyang and Changsha, and not all of the dates for the comparative material are uncontroversial. For present purposes, however, the dates given for the periods are probably reliable enough.[24]

Not many iron artefacts were found: none at all in periods 1–3 and 6, and only the following in periods 4–5:

Period 4, early part of middle Warring States (early to mid −4th century):
- 7 bronze *ding*-cauldrons 鼎 with cast-iron legs (e.g. Figure 55)
- 2 crossbow-bolts with bronze tips and iron shafts (e.g. Figure 56, no. 7)

[19] Trousdale (1975, p. 64); Barnard (1979, p. 62).
[20] Wagner (1993, pp. 240ff).
[21] Anon. (1982b); note also Höllmann (1986).
[22] Guo Dewei (1982, p. 157).
[23] Excavation report Anon. (1984c); discussion Wagner (1993, pp. 152–3). A later excavation of 73 more graves at Yutaishan (Chen Fengxin, 1990) seems to have yielded no iron artefacts at all.
[24] Wagner (1993, pp. 85–6, 245).

Figure 55 Bronze *ding*-cauldron with iron legs from a Chu grave of period 4 (early to mid −4th century) at Yutaishan in Jiangling, Hubei (artefact no. 323:2, Anon., 1984c, p. 72, pl. 31.2). Height 25 cm, belly diameter 23.2 cm, belly depth 12 cm.

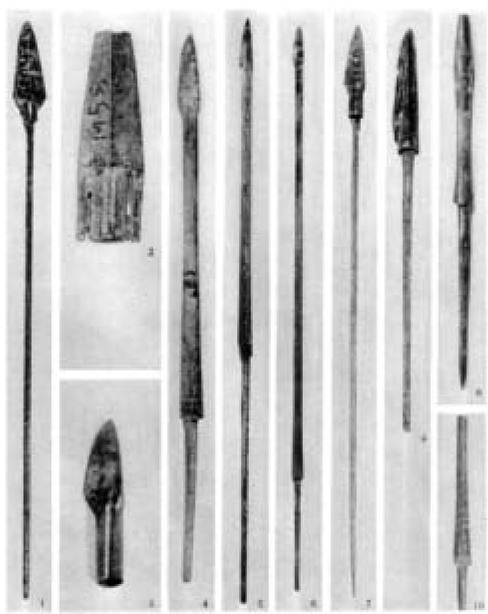


Figure 56 Crossbow-bolts from Chu graves at Yutaishan in Jiangling, Hubei (Anon., 1984c, pp. 83–5, fig. 65, pl. 43). All are of bronze except no. 7, which has a bronze tip and an iron shaft. **5**, **8**, **9**. Period 3 (mid −5th to early −4th century). **1**, **3**, **4**, **6**, **7**, **10**. Period 4 (early to mid −4th century). **2**. period 5 (mid to late −4th century).

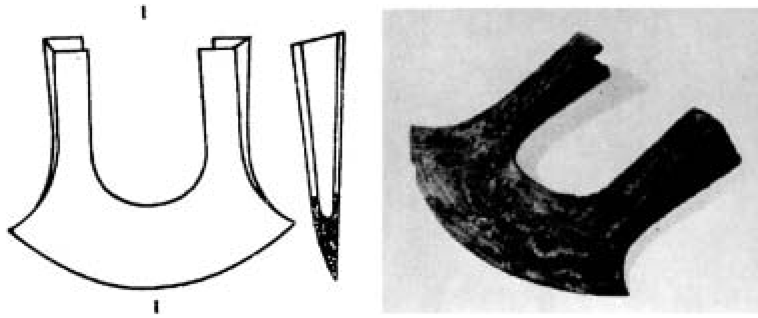


Figure 57 Iron U-shaped implement-cap from a grave of period 5 in the Chu cemetery at Yutaishan in Jiangling, Hubei (artefact no. 232:4, Anon., 1984c, p. 86, fig. 67.8, pl. 51.5). Breadth of working edge 11.2 cm.

Period 5, later part of middle Warring States (mid to late −4th century):
- 1 bronze *ding*-cauldron with cast-iron legs
- 1 cast-iron U-shaped implement-cap (Figure 57)
- 1 cast-iron axehead

The only iron *weapons* are the two crossbow-bolts with bronze tips and iron shafts, while bronze weapons are common. Totals of bronze weapons for all periods are:

- 172 swords
- 41 daggers
- 98 dagger-axe heads
- 183 bronze crossbow-bolts
- 7 halberd-heads
- 15 spearheads

Weapons occur in 40 per cent of the graves, and this suggests that nearly every man was buried with a weapon. Since virtually none of these is of iron, it is a moderately safe conclusion that iron weapons were very little used in Chu in the period covered by the Yutaishan material.

The picture is quite different when we look at several comparable cemeteries near the capitals of Qin. These comprise 46 graves near Fengxiang 鳳翔, Shaanxi,[25] and 160 graves near Xianyang 咸陽, Shaanxi, 125 km east of Fengxiang. Both places have been capitals of Qin: the site of Yong 雍, the capital from −677 to −383, is at Nangucheng 南古城, just south of Fengxiang, and the site of Xianyang, the capital from −350 until the fall of the Qin empire in −207, is near modern Xianyang.[26]

[25] Excavation reports Wu Zhenfeng and Shang Zhiru (1981); Sun Derun (1982); Jin Xueshan (1957). Discussion Wagner (1993, pp. 161–5).

[26] On the Qin capital sites see Li Xueqin (1985, pp. 229–33); Anon. (1984b, pp. 277–8, 383–5); Wang Xueli (1985a); and numerous excavation reports cited by these. A very thorough survey of excavations of Qin graves is given by Ye Xiaoyan (1982, esp. p. 65, fns. 1–30); see also Han Wei (1981), but note the reservations concerning this latter article expressed by Li Xueqin (1985, p. 223).

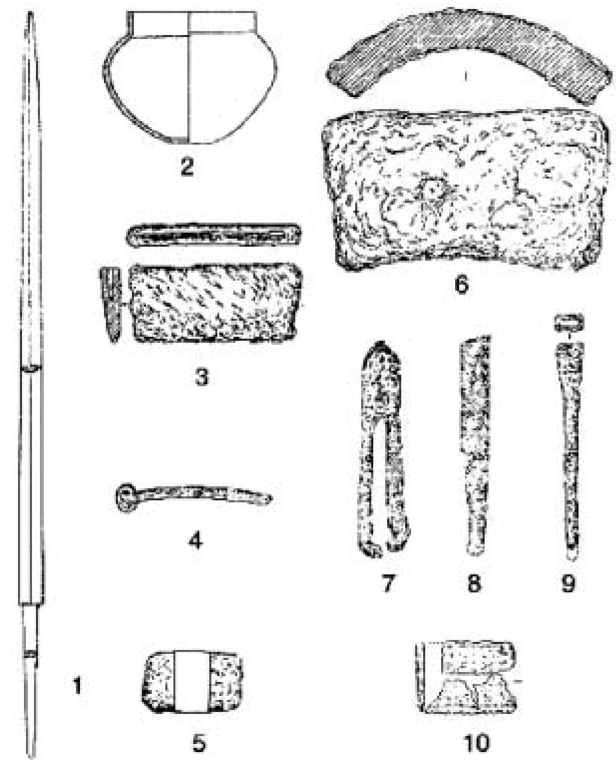


Figure 58 Iron artefacts from graves excavated at Gaozhuang in Fengxiang County, Shaanxi (Wu Zhenfeng and Shang Zhiru, 1981, p. 33, fig. 21). **1**. Sword (M21:1). Total length 105 cm, stem length 21 cm, breadth of blade 3.2 cm. **2**. *Fu*-pot 釜 (M32:2). Height 20 cm, mouth diameter 20 cm. **3**. Straight implement-cap (M6:1). Length 14 cm, breadth 6 cm, thickness 1.4 cm. **4**. Ring-handled knife (M39:16). Length 19.6 cm. **5**. Unidentified (M33:13). Rectangular, 2.8 × 1.7 cm, with square hole. **6**. Unidentified (M6:12). Length 8 cm, breadth 4.2 cm, thickness 1.2 cm. **7**. Pincette (M39:2). Length 6.2 cm. **8**. Drill-bit (M21:6). Fragmentary length 4.5 cm. **9**. Chisel (M21:5). Fragmentary length 25 cm. **10**. Fragment of a saw-blade (M21:4). Remaining length of cutting edge about 2.8 cm.

We can summarise the finds of iron artefacts in the three cemeteries as follows:

Period 1, late Spring and Autumn, 2 graves:
no iron artefacts.

Period 2, early Warring States, 16 graves:
1 belt-hook

Period 3, middle Warring States, 20 graves:
2 belt-hooks
5 rings
1 ring-handled knife

Periods 3–4, middle to late Warring States, 4 graves:
1 belt-hook

Figure 59 Iron belt-hooks from Warring States period graves at Banpo in Xi'an, Shaanxi (Jin Xueshan, 1957, p. 85, pl. 16).

Period 4, late Warring States, 146 graves:

1 ring-handled knife (Figure 58, no. 4)
1 pincette (Figure 58, no. 7)
3 belt-hooks
2 knives
1 coffin-nail
11 badly rusted and unidentifiable artefacts

Period 5, Qin imperial period (−221 to −206), 16 graves:

5 rings
6 ring-handled knives
5 straight implement-caps (e.g. Figure 58, no. 3)
5 swords (e.g. Figure 58, no. 1)
2 knives
6 *fu*-pots 釜 (e.g. Figure 58, no. 2)

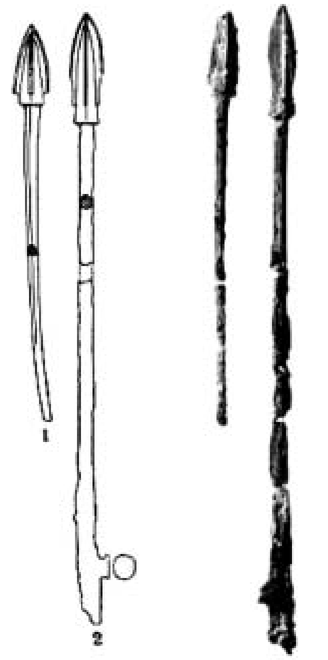


Figure 60 Crossbow-bolts from a late Warring States period grave at Banpo in Xi'an, Shaanxi (Jin Xueshan, 1957, p. 71, fig. 5, pl. 13.4–5). The person buried in the grave was probably killed by these. **1**. Bronze. Length 13.1 cm, tip length 2.8 cm, fragmentary shaft length 10.3 cm. **2**. Bronze tip, iron shaft. Length 20.7 cm, tip length 3.7 cm, fragmentary shaft length 17 cm.

22 belt-hooks (e.g. Figure 59)
1 plate
1 drill
1 bronze–iron crossbow-bolt (Figure 60, no. 2)
several miscellaneous iron artefacts

Thus iron was used in Qin from early times for a great many purposes, but here, as in Chu, we find very little in the way of iron weapons: among the 206 graves of all periods, three of the latest period contain iron swords and one of the next-latest period contains a bronze–iron crossbow-bolt. But now consider the occurrences of bronze weapons. In the 206 graves only the following bronze weapons were found:

2 dagger-axe heads
1 sword
1 spearhead
5 crossbow-bolts
1 crossbow-lock

Furthermore at least some, perhaps all, of the crossbow-bolts were simply the projectiles that had killed the people buried, rather than grave-goods in the usual sense.[27] Thus there was in Qin very little tendency to place weapons in the graves of the dead, and the dearth of iron weapons in the Qin archaeological material has no significance.

Though it is a commonly accepted idea that Chu and Qin were the most advanced ancient states in the use of iron weapons, this more systematic study of a sample of the archaeological material suggests a quite different conclusion. It is unlikely that iron weapons were used to any significant extent in Chu, and there is no evidence one way or the other for iron weapons in Qin.

Under this interpretation the archaeological evidence contradicts the evidence of written sources on iron weapons in Chu. The *Xun zi*, in a passage quoted earlier,[28] implies that Chu produced superior steel weapons in the city of Wan as early as −300. How are the two types of evidence to be reconciled? According to John H. Knoblock's closely argued chronology of the chapters of the *Xun zi*,[29] the chapter *Yi bing* 議兵, in which this passage occurs, was written in −259 or −258, long after the conquest of Chu by Qin (completed in −278). A possibility is that production of iron and steel weapons in Wan was indeed flourishing at this time, but that this was a recent development, encouraged by the new Qin government, and Xun Kuang was mistaken in the assumption that it went back as early as −300.

Other sources, to be discussed further below, indicate that the state of Qin, in the course of its conquest of the Six States, put great effort into developing the natural resources of the conquered areas. Wan is specifically mentioned as one of the places to which ironmaster families were forcibly moved from other parts of the empire in order to develop the local iron industry.[30] This would have been odd if there already was a flourishing weapons production in Wan; and the almost total lack of finds of iron and steel weapons at the Chu capital suggests that such production did not in fact exist before the Qin conquest of Chu.

(ii) The Arts of the Smith

There is virtually no written evidence on the techniques of iron production in early China, but this is a gap admirably filled by archaeology. One of the important sources on the arts of the smith is a metallographic study of weapons of soldiers of the state of Yan.

A mass grave of fallen soldiers

In 1965 a remarkable grave was discovered inside the walls of the ancient city of Xiadu 下都, the 'lower capital' of the minor northeastern state of Yan 燕, in Yi

[27] Jin Xueshan (1957, p. 71).
[28] P. 116 above.
[29] Knoblock (1983); but note Knoblock (1988–94, vol. 2, p. 338, fn. 93).
[30] P. 141 below.

County 易縣, Hebei, about 100 km southwest of Beijing.[31] The grave is a long narrow pit, 7.8 m N–S × 1.46–1.64 m E–W. It has a tamped-earth floor, 0.3 m thick; the corpses were placed on this floor, and the pit was then filled with solidly tamped earth. Twenty-two skeletons were found in the grave, mostly in the undisturbed southern part, and presumably there were more in the northern part. Many of the skeletons show clear signs of death by violence: some are headless, and others have arrowheads stuck into or between bones. The greater part of the artefacts found in the grave are weapons, and all in all it seems certain that this is a grave of soldiers.

The grave can be dated with some certainty, on the evidence of coins, to the early decades of the −3rd century. The excavators conclude from a review of artefact styles, as well as the inscription on a bronze dagger-axe head, that all of the weapons found were made in Yan, and that the dead were soldiers of Yan.[32]

The grave is oddly located, not in one of the cemeteries associated with the city site but in the midst of a complex of tamped-earth platforms which presumably were the foundations of palatial or ceremonial structures. The corpses are randomly thrown together; but since the grave otherwise seems to have been carefully prepared, including the tamped-earth floor, this must be taken as indicating, not haste, but a demonstrative contempt for the persons buried.

The excavators relate the grave to an ancient type of war memorial called a 'mound-spectacle', *jing guan* 京觀.[33] One of the texts cited in this regard is a passage in the *Zuo zhuan*: after the defeat of Jin 晉 by Chu in the Battle of Bi 邲 in −579, an adviser says to the Viscount of Chu:

> Should my lord not build a war-camp and gather in the corpses of Jin to make a *jing guan*? Your servant has heard that when enemies have been defeated they should be shown to posterity, so that great military deeds are not forgotten.[34]

The commentator Du Yu 杜預 (+222–284) explains: 'When corpses are piled up and covered with a mound of earth, this is called a *jing guan*.' It is impossible to know whether there originally was a mound over the mass grave at Yan Xiadu, but otherwise it seems to fit what we know of the *jing guan*: a monument commemorating the defeat and humiliation of an enemy. It cannot be identified with a known historical event, but if it is true that the dead were men of Yan then we may guess that they were the leaders of a revolt, or deserters from the Yan army, or something of the sort.

The importance of this grave lies in the fact that it gives us a large sample of the sort of equipment that soldiers carried in a particular place at a particular time, and

[31] On the city-site see, in English, Ferguson (1930); K. C. Chang (1977, pp. 335–9); Li Xueqin (1985, pp. 111–19); Shi Yongshi (1987). In Chinese the best brief description seems to be Wang Sufang and Shi Yongshi (1982); see also Anon. (1979a, pp. 42–3); Liu Wei (1981); Anon. (1984b, p. 273); and the many excavation reports cited in these publications. Excavation report on the grave, Liu Shishu (1975); detailed discussion Wagner (1993, pp. 176–82).

[32] Liu Shishu (1975, pp. 239–40).

[33] Liu Shishu (1975, p. 239). The translation 'mound-spectacle' is Karlgren's (1969–70, p. 87).

[34] *Zuo zhuan*, Duke Xuan, 12th year, *SBCK* edn, ch. 11, pp. 7b–8a; *SSJZS* edn, pp. 1882–3; Yang Bojun (1981, pp. 744–7); cf. Legge (1872, pp. 320–1); Couvreur (1914, vol. 1, pp. 635–7).

it is clear that here the material of choice for most weapons was iron. Some of the artefacts found are shown in Figures 50–54 above. There are 15 iron or steel swords and none of bronze; considering shafted weapons, there are one dagger-axe head and one dagger-spearhead (*pi* 鈹)[35] of bronze compared with 12 halberd-heads and 19 spearheads of iron or steel. It is very likely, as the excavators suggest, that the few bronze weapons were symbolic objects, not intended for serious fighting. They are reminiscent of the fine steel swords carried by officers in some modern armies, which hark back to imaginary good old days when weapons were beautiful and wars were fought by gentlemen.

A crossbow-lock is of bronze, and the reason for this is clearly technical: crossbow-locks are precision mechanisms which must be cast to close tolerances, and bronze is far superior to iron in this sort of work. The strength of iron is of no importance here, and the higher cost of bronze is not important. Nearly all of the crossbow-locks ever found anywhere in China are of bronze.[36]

Most (perhaps all) of the iron swords have bronze guards, and of 21 ferrules for shafted weapons, 10 are of bronze. These are again cases in which the superior casting properties of bronze may have played a rôle, but clearly the ferrules could just as well all have been made of iron. It is likely that symbolic or aesthetic considerations influenced the choice of bronze for these artefacts, since bronze surely would have been more costly. The same would have been the case with three bronze belt-hooks found in the grave.

Several artefacts from the grave have been subjected to metallographic examination, and this gives us a chance to see something of how Chinese smiths worked in this period.[37] Some of the weapons are of wrought iron with very low carbon, and thus correspond to the soft, easily bent Gallic swords which have been mentioned earlier,[38] but others are of quench-hardened steel and show a remarkably advanced technique. I shall concentrate here on a sword fragment, artefact no. M44:100, which has been examined in detail by the Historical Metallurgy Group of the Beijing University of Technology (formerly Beijing University of Iron and Steel Technology). First, however, it is necessary to explain a bit about the technical concepts involved.

In a previous book I have given an introduction to the metallography of iron and steel, then discussed the Chinese metallographic evidence in some detail.[39] I must refer the technically minded reader to that book; here I shall give only the briefest of explanations.

35 The excavation report's identification of this artefact as a sword is corrected by Wang Xueli (1985b, p. 61); see also Wagner (1993, p. 185).

36 Barnard and Satō (1975, pp. 116–17, 192–3, 286–7) list 123 crossbow-locks found up to 1966 in sites dated Han or before. Only two of these are of iron, and they are from sites dated Eastern Han.

37 Anon. (1975); Li Zhong (1975, p. 10); tr. Wagner (1993, pp. 461, 462–4).

38 P. 103.

39 Wagner (1993, chs. 6–7).

The basic techniques of the smith in forming an artefact are sometimes said to be no more than three: 'to draw, upset, and weld'. 'Drawing' is elongating or spreading a piece of iron, and 'upsetting' is shortening and thickening it. Both are done by heating the iron to a high temperature (typically 1200°C, a white heat) and hammering it; exactly how is best demonstrated by a smith.

Today the word 'welding' suggests a welder in a heavy mask with an oxyacetylene torch joining steel components together by locally melting both. That is 'fusion welding', which did not come into common use until the mid-20th century. The pre-modern term 'welding', now often 'forge-welding' or, in technical parlance, 'solid-state welding', refers to an utterly different technique. Two pieces of iron to be welded together are heated in the forge hearth to a very high temperature, typically in the range 1300–1400°C.[40] When they are well heated the two are taken from the hearth and hammered together on the anvil. If this is done correctly the two pieces are perfectly joined together and now form one piece of metal.[41]

When a smith has heated a piece of iron to welding temperature he may point out to visitors what seems to be a fluid on the surface of the iron, and say that the iron is now hot enough to weld, for it is molten on the surface. Actually it is not the iron which is molten but the slag, a mixture of FeO (iron oxide), SiO_2 (silica), and perhaps some other components. At the high temperatures employed it is unavoidable that some of the iron burns to FeO, which has a high melting point, 1369°C. If the slag is not liquid it will act as a barrier between the pieces of metal and the welding will not succeed. A mixture of FeO and SiO_2 can have a much lower melting point, as low as 1177°C,[42] so the smith may throw sand on the two surfaces to be welded together. The liquid slag layer also protects the iron from further oxidation and so facilitates welding. Some slag is inevitably trapped between the welded surfaces, but the smith works hard to keep this to a minimum.

Slag inclusions introduced in welding are not the only ones which will be found in the artefacts. Regardless of how pre-modern wrought iron was produced, whether in a bloomery or a finery,[43] there would virtually always be some slag inclusions in the raw material which the smith started with. Study of the form, distribution, and chemical composition of the inclusions, as they are seen in metallographic sections, can tell a great deal about how an artefact was made.

Figures 62 and 63 show micrographs of a polished cross-section of the sword fragment. It has been etched to show how the carbon content of the iron varies through the section. The white areas are ferrite (with about zero carbon) and the dark areas are pearlite (with about 0.8 per cent carbon). It can be seen that the carbon content varies considerably through the artefact; a simplified map of the sword's cross-section is given in Figure 61. As the Chinese metallurgists conclude, the sword was probably

[40] Shrager (1969, p. 38).
[41] The metallurgy of solid-state welding has been studied theoretically and experimentally by R. F. Tylecote (1968). As we should expect from one of the greatest of 20th-century archaeometallurgists, this book also includes a fascinating historical introduction (pp. 3–17).
[42] Muan and Osborn (1965, p. 62, fig. 45a).
[43] See respectively Box 8, pp. 89–90, and pp. 16–18 above.

Figure 61 Sketch of the microstructure of a sword fragment (artefact no. M44:100) from the Xiadu site in Yi County, Hebei, reproduced from Li Zhong (1975, fig. 2, p. 10). The four graphic codes are:

higher-carbon layer (0.5–0.6% C)

martensite

lower-carbon layer (0.15–0.20% C)

inclusion

(It is odd that no inclusions are actually shown in the diagram: perhaps the dark area within the martensite at the bottom is actually an inclusion.)

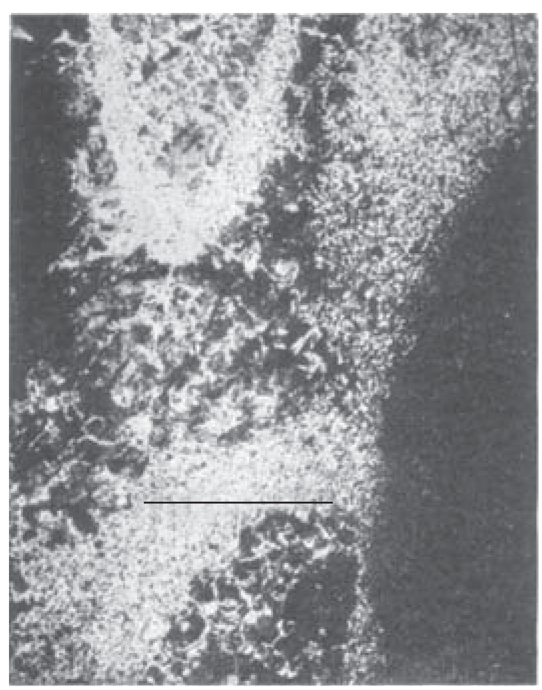


Figure 62 Micrograph of a sample from the sword fragment (artefact no. M44:100) from the Xiadu site, corresponding to approximately the middle of Figure 61. Reproduced from Li Zhong (1975, pl. 2.11). Etched (with nital?), × 50 (scale bar 0.5 mm). *Light:* lower-carbon areas, primarily ferrite. *Dark:* higher-carbon areas, primarily pearlite.

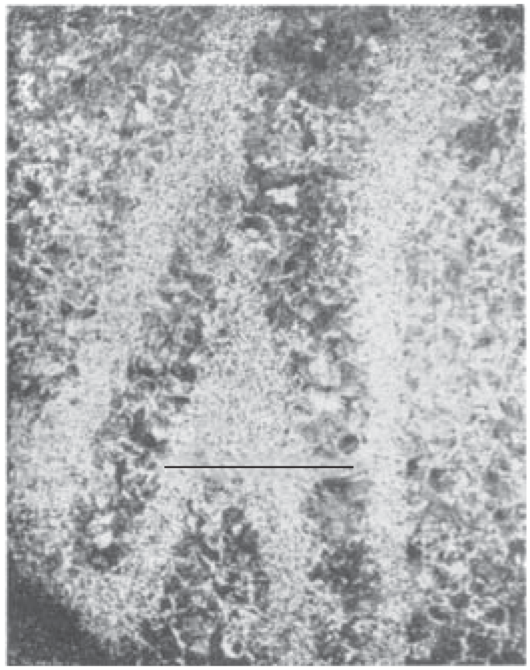


Figure 63 Micrograph of a sample from the sword fragment (artefact no. M44:100) from the Xiadu site, corresponding to the upper right of Figure 61. Reproduced from Li Zhong (1975, pl. 2.12, inverted). Etched (with nital?), × 50 (scale bar 0.5 mm). *Light:* lower-carbon areas, primarily ferrite. *Dark:* higher-carbon areas, primarily pearlite. In its original publication (Li Zhong, 1975, pl. 2.12) this figure was inverted; the mistake was corrected in the reprint, Ke Jun (1986, p. B12, pl. 8.8(2)). Cf. the text, Li Zhong (1975, p. 10), translation Wagner (1993, pp. 462–4).

made of a number of pieces of iron which were hammered out to thin plates and then surface-carburised so that they had a high carbon content at the surface and a much lower carbon content in the core. These were then folded and welded together in intricate ways to make the sword. Finally the smith heated the sword to a red heat and quench-hardened it in water.

The *quench-hardening* technique, in which a steel artefact is heated to a red heat and suddenly cooled in water, is certainly one of the most spectacular of the arts of the smith. From a moderately hard microstructure the smith obtains one which is extraordinarily hard and can take and hold a very sharp edge, but is also very brittle; it can shatter like glass, and is sometimes said to be ‘glass-hard’. The hardness and brittleness can be adjusted by reheating to a lower temperature (200–600°C). This process, applied to a quench-hardened iron artefact, is called *tempering*, and it results in a structure which is less hard but also less brittle.[44]

[44] The sudden cooling of austenite causes it to transform to a crystal structure called *martensite*. The theoretical explanation of the nature of martensite was worked out slowly, and with many missteps, in the course of the first half of the 20th century. C. S. Smith (1988) discusses 18th-century speculations on the subject; the later development of the theory can be studied in textbooks of various dates, but has attracted very little attention from historians of science. Sauveur (1920, pp. 308–14) reviewed the current theories and concluded that ‘new avenues of approach must be found if we are ever to obtain a correct answer to this apparent enigma’. See further Rosenholtz and Oesterle (1938, pp. 163–5). Shrager (1969, p. 141) retained an already obsolete theory when he wrote that ‘martensite is considered to be a supersaturated solution of carbon in ferrite’; the modern explanation, that martensite is a body-centred tetragonal crystal structure with carbon in solid solution, is given e.g. by Van Vlack (1964, pp. 289–94) and in more detail by Brick et al. (1977, pp. 126–65).

Before the evidence of this sword of the −3rd century it was believed, on the evidence of written sources, that quench-hardening in China was a Han innovation. Those sources remain interesting, as they show something of how early Chinese smiths and natural philosophers thought about this technique.

Quench-hardening in early Chinese thought

The earliest word for 'quench-hardening' in Chinese is *cui* 淬 (sometimes written 焠), and this character is still used in the modern technical term *cuihuo* 淬火 .[45] We find this very clearly in a 'Eulogy on the sage ruler obtaining wise servants' (*Sheng zhu de xian chen song* 聖主得賢臣頌), presented to the Emperor Xuan-di 宣帝 (r. −73 to −49) by Wang Bao 王褒:

> When a skilled metallurgical worker 'casts' [*zhu* 鑄][46] the material of a Gan Jiang 干將 [sword], quench-hardening [*cui* 淬、焠][47] its tip with pure water and grinding its edge with a whetstone from Yue 越, then in the water it can slice water-dragons, and on land it can cut rhinoceros hide as quickly as sweeping and sprinkling or drawing in mud.[48]

A few other, even earlier, texts can give us a chance to see how quench-hardening was interpreted in ancient China. In the story of Prince Dan of Yan 燕丹子 in the *Zhan guo ce* and the *Shi ji*, Prince Dan purchases a fine dagger and has an artisan quench-harden (*cui* 淬、焠)[49] it with a 'drug' (*yao* 藥), making it a supremely lethal weapon. When it was tested on human victims, 'when the blood had [barely] stained a thread [of their garments] there was not one who did not die instantaneously'.[50] Commentators generally assume that the dagger was merely dipped in a poison, but this would not require an 'artisan' (*gong* 工), and in any case the passage seems to indicate that the lethal quality of the dagger comes from its sharpness. The 'drug' in the story is more likely to have been used to improve the quench-hardening of the steel.

The properties of various liquids used for quench-hardening have been the subject of both myth and empirical research from early times in both East and West. In the Icelandic sagas, for example, we read of the dwarf smith Alfrig, who searched through nine kingdoms to find the right water to harden the sword Ekkisax; and of weapons which are hardened in poison or in blood.[51] In the 16th century the art

[45] What may be an earlier term for quench-hardening is *ling* 陵, in a passage in *Xun zi: bing ren bu dai ling er jing* 兵刃不待陵而勁 , 'the edges of their weapons are strong without *ling*' (ch. 12, Zhang Shitong, 1974, p. 125; cf. Knoblock, 1988–94, vol. 2, p. 178).

Wang Zhenduo (1948–51, part II, pp. 188–9) notes some modern dialect terms for the same: *jian huo* 濺火 ('to splash fire') in north China, *bing* 冰 ('to ice') in Sichuan, and *shang gang* 上鋼 ('to present the steel') in Yunnan.

[46] A misuse of the word, for the sword is clearly wrought rather than cast.

[47] The *Han shu* version has 焠 and the *Wen xuan* has 淬.

[48] *HS*, ch. 64b, p. 2823. Variant text in *WX*, ch. 47, p. 2089.

[49] The *Zhan guo* ce version has 淬 and the *Shi ji* version has 焠.

[50] *Zhan guo ce*, ch. 31, p. 1136; tr. Crump (1970, p. 558); *SJ*, ch. 86, p. 2533; tr. Watson (1969, p. 62); Bodde (1940, p. 32). The relevant passage is not in the version of the same story in *Yan Dan zi* (ch. *xia* 下, p. 14); tr. Franke (1957; 1969, p. 54).

[51] Drachmann (1967, pp. 12, 54).

historian Giorgio Vasari wrote of the use of goat's blood for quench-hardening. He also claimed that the Grand Duke Cosimo I of Tuscany, in 1555, prepared from certain unspecified herbs a liquid for the quenching of steel tools which made them sufficiently hard to carve porphyry.[52] A Tang text states that certain barbarians in Yunnan quench-harden steel in 'the blood of a white horse'.[53]

Various Chinese texts indicate that the waters of particular rivers are good for quench-hardening steel: two +3rd-century texts mention the Qingzhang River 清漳水 (in modern Shanxi)[54] and the Longquan River 龍泉水 (modern Anhui).[55] The story of Pu Yuan 蒲元, swordsmith to Zhuge Liang 諸葛亮 in the +3rd century, takes this kind of thinking much farther:

He 'cast' three thousand swords for Zhuge Liang in Ye Valley 斜谷 [in southern Shaanxi], 'melting' the metal and forming the objects in a highly unusual manner.[56] When the swords were finished, he reported to Zhuge Liang: 'The Han River 漢水 is sluggish and weak, and is not suitable for quench-hardening [*cui* 淬]. The Shu River 蜀江 [near Chengdu, in modern Sichuan] is bold and vigorous; it is called the Primeval Essence of Great Metal [*da jin zhi yuan jing* 大金之元精], and Heaven has blessed its region.' So people were sent to Chengdu to obtain water from the river and return. One arrived back before [the others]. [Pu Yuan] used [the water he brought] to quench-harden a sword and said: 'This is mixed with [water from] the Fu River 涪水, and is useless.' The person who had obtained the water steadfastly maintained that it was not mixed; but [Pu Yuan], after making signs in the water with the sword, said, 'It is mixed with eight *sheng* 升 of [Fu River] water! How can you deny that it is mixed?' The one who had obtained the water then kowtowed and confessed: 'In fact, I was carrying it while crossing at the Fu River Ford, and I fell and overturned the water. I was afraid, so I added eight *sheng* of water from the Fu.' Then everyone marvelled and called [Pu Yuan] extraordinary.[57]

The Elder Pliny in the +1st century also referred to certain localities whose water was good for quench-hardening,[58] and in 1880 a group of cutlers from Sheffield who emigrated to the United States took tanks of Sheffield water with them for the purpose.[59]

[52] Vasari (1907, pp. 30, 32, 112–13); cf. Beckmann (1846, vol. 2, p. 329). Some Arabic examples are given by Rāġib (1997, pp. 49–51).

[53] *Man shu*, ch. 7, p. 8a.

[54] *Dian lun* 典論, by Cao Pi 曹丕 (Emperor Wen 文 of Wei, r. +220–226), quoted in the Tang compendium *Yi wen lei ju*, ch. 60, p. 1081; see also *TPYL*, ch. 343, p. 6a. The version of the passage in *Chu xue ji* (ch. 10, p. 230) omits the mention of quench-hardening.

[55] *Tai kang di ji* 太康地記 (Geography of the Taikang reign, +280–289), quoted in the Suo-yin 索隱 commentary in *SJ*, ch. 69, p. 2252, n. 16; parallel passages, *SJ*, ch. 74, p. 2349, n. 2; *HS*, ch. 6, p. 163, n. 2. Note also a parallel passage which does not mention quench-hardening, quoted in *Shui jing zhu* (ch. 31, p. 1005).

[56] Here again we have an author using technical terms which he does not understand. Quench-hardening would not improve the quality of a cast-iron sword.

[57] *Pu Yuan bie zhuan* 蒲元別傳 (Unofficial biography of Pu Yuan), quoted in the Sui-period encyclopaedia *Bei tang shu chao* (ch. 123, pp. 2a–b); see also *Yi wen lei ju* (ch. 60, pp. 1083–4); *TPYL* (ch. 345, pp. 10a–b); *QSG* (Sanguo section, ch. 62, pp. 5b–6b). Another variant is partly quoted by Wang Zhenduo (1948–51, part II, p. 189) from the *Tai ping guang ji*; however he gives no indication of where the passage occurs in this very large compilation, and I have been unable to find it. In this variant the characters used for Pu Yuan's name are 普元, and Zhuge Liang is referred to by the alternate name Kong Ming 孔明.

[58] *Historia naturalis*, book 34, sect. 41, par. 144, text & tr. Bailey (1929–32, vol. 2, pp. 59, 187); cf. Percy (1864, p. 852). Pausanias in the +2nd century wrote that *copper* could be hardened by quenching in certain waters, but this is certainly incorrect. Jones (1918–35, vol. 1, p. 261); cf. Forbes (1950, p. 328).

[59] Anon. (1880). I am grateful to the late Kenneth C. Barraclough for this reference.

Quench-hardening is one of those processes which are influenced by so many variables that no artisan, modern or pre-modern, is able to keep the process under complete control. In such circumstances myths flourish, and these stories of the qualities of particular waters are surely myths rather than empirically derived facts. However, there *are* real empirical differences among different liquids used in quench-hardening, principally because they give different rates of cooling. Slow cooling minimises internal stresses and can generally be expected to give a tougher blade, but in some steels a very fast quench may be necessary to give a hardened layer of adequate thickness. In modern industry the most important liquids used are oil, water, and salt water, though a number of proprietary polymers which give specific cooling rates can also be added to the water.[60]

We see what is more likely to be an *empirical* knowledge of the qualities of different quenching liquids in a passage to be considered in detail in Section 6 below.[61] The smith Qiwu Huaiwen 綦毋懷文 in the +6th century is said to have used both animal urine and animal grease for quench-hardening, and the text uses two different words for this: *cui* 淬 for quenching in fat and *yu* 浴 for quenching in urine.[62]

The spectacular and counter-intuitive process of quench-hardening has fascinated poets and philosophers both East and West. Homer used it in a simile,[63] and it played a part in debates on the nature of matter from the 17th century onward.[64] How was the process seen in China? We may start with a passage from an astrological text entitled *Xing jing* 星經 (Star canon), of early Han date or possibly earlier.[65]

The five planets: A conjunction of the Fire Planet [Mars] with the Water Planet [Mercury] is a 'quench-hardening' [*cui* 焠]; an armed initiative will be greatly defeated.

A conjunction [of the Fire Planet] with the Metal Planet [Venus] is 'fusion' [*shuo* 鑠][66] and mourning; an initiative is inappropriate[67]

[60] There is no generally accepted explanation for the interesting fact that salt water quenches hot steel much faster than pure water does. Most proposed explanations concern the formation of a vapour layer at the surface of the steel which inhibits heat transfer: in salt-water quenching this layer either is not present or more quickly breaks up. See e.g. Shrager (1969, pp. 157, 165); Krauss (1989, p. 159). On the other hand, Thelning (1984, pp. 270–1) emphasises the fact that salt raises the temperature of greatest heat-extracting capacity of water from 300°C to about 500°C. I am grateful to Mike Wayman for help on this and many other technical questions.

[61] P. 256 below.

[62] *Bei Qi shu*, ch. 49, p. 679; *Bei shi*, ch. 89, p. 2940; *TPYL*, ch. 345, pp. 6b ff; cf. Lin Shoujin (1955); Yang Kuan (1956); Needham (1958, p. 26).

[63] Odysseus has plunged a burning wooden spike into the eye of the Kyklops: 'Just as a smith dips a great axe or adze in cold water, treating it so that it cries, for the strength of the iron comes of this, thus hissed his eye around the olive stake.' *Odyssey*, book 9, lines 391–4, tr. by Jørgen Larsen; cf. Fitzgerald (1961, p. 168).

[64] C. S. Smith (1988, pp. 72ff, 225ff; 1968a).

[65] Not to be confused with later works with similar titles. Yabuuchi (1969a, p. 50).

[66] The *Han shu* has two passages parallel to this one, one with 'fusion' and the other with 'mourning' (ch. 26, p. 1286, lines 2 and 5). The passage as we have it here may therefore be a conflation of two earlier traditions which were both available to the *Han shu* authors.

[67] Quoted in the *Zhengyi* 正義 commentary on *Shi ji* (ch. 27, p. 1321, n. 3). Parallel passages: *SJ* (*ibid.*); tr. Chavannes (1895–1905, 1969, vol. 3, p. 369); *HS* (ch. 26, pp. 1285–6); *Jin shu* (ch. 20, pp. 320–1); tr. Ho Peng Yoke (1966, pp. 320–1); *Sui shu* (ch. 20, pp. 558–9).

This fragment of the *Xing jing* appears to be an example of the work of certain lesser Han thinkers who built systems on the basis of free association, ignoring serious metaphysical questions. The intellectual value of such works in their own time cannot have been great, but for us they can give useful examples of Han-period free association. Quench-hardening is associated in the text with a union of Fire and Water, just as fusion is associated with the union of Fire and Metal. The same association is found in a Jin text, *Wu li lun* 物理論, 'On the principles of things', by Yang Quan 楊泉:

> In former times, the knives of Master Ruan 阮師 were prized throughout the Empire. He received his method of making knives from the Spirit of the Essence of Metal. In the seventh month, on a *Gengxin* 庚辛 day, he met the Metal Spirit at the Zhijian Gate 治監門. His person was radiant and shining. [Master Ruan] faced him and bowed twice; the spirit then took his hand and said, 'You, sir, would be worth teaching.' Ruan made him comfortable, presented food, and asked for instruction. The spirit taught him the equalising of Water and Fire [*shui huo zhi qi* 水火之齊], the forming of the Five Essences, and the use of the signs of Yin and Yang in the harmonising of hard and soft [*yong yin yang zhi hou qu jian ruan zhi he* 用陰陽之候取剛軟之和].
>
> He practised this art for three years, making 1770 knives, after which he became blind. His knives have a flat spine, a narrow blade, a straight edge, and a large ring.[68]

It is clear that 'equalising water and fire' refers to the quench-hardening of steel. Possibly 'harmonising hard and soft' refers to tempering after quenching, with the signs of Yin and Yang being the 'tempering colours' which a smith watches for in the tempering process.

Thus while early Western smiths seem to have believed that quench-hardening was a kind of *purification* of the steel, in early China they seem to have seen it as a *combining* of Water and Fire in the correct proportions within the steel. This conception was later elaborated by such writers as Fang Yizhi 方以智 and Song Yingxing 宋應星.[69]

Bloomery smelting versus fining

In recent years several archaeometallurgists have proposed that study of the microstructures of wrought-iron artefacts might indicate whether they were made of bloomery iron or from iron which has been fined from cast iron.[70] If a method could be found to answer this question with some certainty, we would be equipped to deal with broader questions concerning the introduction of the blast furnace and finery in early China and in medieval Europe.[71] No clear consensus has formed around any one method, or indeed on whether such a method is ever likely to be found, but research continues on the problem.

[68] Quoted in *TPYL* (ch. 345, pp. 8a–b); cf. *Bei tang shu chao* (ch. 123, p. 2b).

[69] *Wu li xiao shi*, ch. 7, pp. 27a–b; *TGKW*, ch. 10, p. 45; Zhong Guangyan (1978, p. 267); Sun and Sun (1966, p. 190); Li Chiao-ping et al. (1980, p. 276); Cullen (1990).

[70] Bloomery smelting has been discussed in Section 3 above, Box 8 (pp. 89–90); blast furnaces and fining have been discussed in considerable detail in Section 2.

[71] Western attempts include Piaskowski (1989); Rostoker and Dvorak (1990).

The Historical Metallurgy Group of the Beijing University of Iron and Steel Technology,[72] writing under the pseudonym Li Zhong 李眾, has proposed a method of distinguishing bloomery iron from fined iron which has been widely accepted in China.[73] One artefact, the sword fragment from Yan already discussed above,[74] is of central importance in their study. They believe it was made of bloomery iron.

The most important of the characteristics pointing in this direction pertains to the distribution of manganese in solid solution in the iron. The average manganese content is about 0.15 per cent, but there are irregularly distributed spots, a few μm across, with manganese content above 0.35 per cent. We should expect that if this iron had ever been molten the manganese would have been uniformly distributed; the obvious conclusion is that the iron was produced by a direct method, and that the non-uniform distribution of manganese in the iron reflects a non-uniform distribution in the original ore. This seems to be a very reasonable hypothesis; it cannot, however, be said to have been proved. No effort has been made (at least none has yet, to my knowledge, been reported in the Chinese archaeological literature) to determine whether such a segregation of manganese in solid solution occurs in artefacts which are known to have been made of bloomery or fined iron.

The authors then contend that the characteristics of the slag inclusions in wrought iron or steel also provide useful indications for distinguishing bloomery iron from fined iron. They compare the slag inclusions in two groups of iron artefacts:

- the sword fragment from Yan, together with several other iron artefacts from the same grave, and three iron artefacts from the tomb of Liu Sheng, dated −113 (e.g. Figure 64)
- a sabre dated +112 and a knife dated +299 (Figures 65, 66).

In comparing the slag inclusions in these two groups of artefacts it is first necessary to distinguish between (1) inclusions introduced by the smith in forge-welding and (2) inclusions which were introduced in the original production of the raw material. Considering only original inclusions and ignoring those introduced in forge-welding, the authors observe that in the first group of artefacts the inclusions tend to be larger and more irregularly distributed than in the second group; and that in the first group the inclusions consist largely of wüstite and fayalite (FeO and $2FeO \cdot SiO_2$) while in the second group they are primarily silicates containing very little FeO.[75] Finally, in the second group there tend to be more inclusions in lower-carbon zones than in higher-carbon zones.

72 Now Beijing University of Science and Technology.

73 Anon. (1975, p. 241; 1980c, vol. 1, p. 372); Li Zhong (1975, pp. 10–11). I have translated and discussed these reports in detail in Wagner (1993, pp. 292–4, 462–4, 471–2); what follows is a very brief summary. Note also Chen Jianli and Han Rubin (1999); Lu Dimin (1999).

74 P. 130.

75 Chinese archaeometallurgists often report a 'wüstite–fayalite eutectic' seen in slag inclusions in ancient artefacts. Prof. Robert Gordon of Yale University has suggested to me (in a letter of 26 July 1989) that what is seen in these cases may actually be primary wüstite dendrites in glass or fayalite.

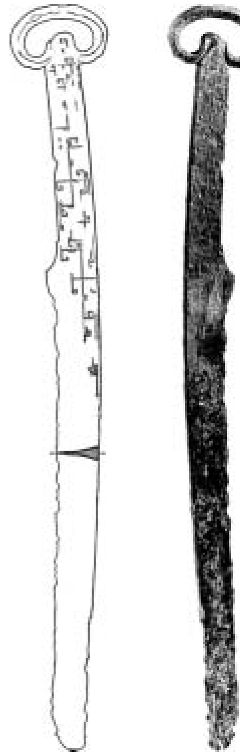


Figure 64 A gold-inlaid scribe's-knife from the tomb of Liu Sheng 劉勝 (d. −113) in Mancheng 滿城, Hebei (artefact no. 1:5197, Anon., 1980c, 1, pp. 105–7, fig. 72.1; 2, pl. 68.1). Total length 42.4 cm.

Figure 65 A ring-pommelled sabre discovered in Cangshan County 蒼山縣, Shandong (Chen Zijing and Liu Xinjian, 1974, pl. 5.1–3). Length 111.5 cm, breadth 3 cm, thickness 1 cm.

Figure 66 A knife from the tomb of Beautiful Lady Xu 徐美人 (d. +299) in Luoyang, Henan (artefact no. 8:2, Jiang Ruoshi and Guo Wenxuan, 1957, pp. 180–1, fig. 12.4). Length 22 cm.

The conclusion is then that the first group of artefacts was made from bloomery iron and the second from fined iron, and that the characteristics of slag inclusions listed above can reliably distinguish bloomery iron from fined iron. Since its publication in 1975 this conclusion has become a standard assumption in all Chinese studies of ancient iron artefacts, but no further work has been done to broaden its empirical basis.

The conclusion concerning the chemical analysis of the slag inclusions appears not to be valid. Inclusions in modern wrought iron, made by fining or puddling, are often composed of wüstite and fayalite.[76] The absence of such inclusions in several of the artefacts discussed above can be due to reduction of FeO in the inclusions to Fe by the carbon in the iron.[77]

Recent Western research on early iron technology has made slag and slag inclusions the object of intense study.[78] This is turning out to be a subject for workers who combine expertise in metallurgy, ceramics, and chemistry, and all of its results seem at the moment to be very tentative. The experts I have talked to seem all to be of the general opinion that the size and shape of slag inclusions in a wrought-iron artefact, taken alone, will tell more about the skill of the smith who made the artefact than about the process by which the iron was produced.[79]

(iii) Ironworks and Ironmasters

In the −3rd century there was a general development in favour of a large-scale iron industry, concentrated in a few large ironworks run by the wealthy families whom Joseph Needham called 'primitive "capitalists" or industrialists'.[80] There is not much archaeological material to help us in understanding these ironworks – what there is will be discussed further below – but we do have some important written sources.

Ironmasters

A view of the men who established and led some of these ironworks is given in the *Shi ji*. Sima Qian's great history is virtually our only source for political events of the Warring States period and the first century of the Han, but it clearly gives a very personal view and must be used with caution. In the chapter 'Biographies of the moneymakers', several wealthy ironmasters are mentioned, of whom three are mentioned in the following passage.

Now I shall tell briefly of how wise men of our day in all the rural areas have enriched themselves, so that future generations may learn from them.

The ancestors of the Zhuo 卓 family of Shu 蜀 [in the western part of modern Sichuan] were men of Zhao[81] 趙 who became rich with an ironworks. When Qin conquered Zhao [−228

[76] Examples can be seen in Barraclough and Kerr (1973); Gordon (1983, p. 97; 1988, p. 123); Trent and Smart (1984, p. 83, fig. 1); Rostoker and Dvorak (1988, p. 178, fig. 1).

[77] See Rostoker and Dvorak (1988).

[78] E.g. Morton and Wingrove (1969; 1972); Todd and Charles (1978); Gordon (1983; 1984); Todd (1984); McDonnell (1984); Kresten (1984); Blomgren and Tholander (1986); Tylecote (1987, pp. 291–324); Rostoker and Dvorak (1990); Williams (1991); Starley (1999).

[79] It is difficult to find this judgement committed to print, but see the brief remarks of Sperl (1986, p. 169) and Stech and Maddin (1986, p. 52, fn.).

[80] Needham (1958, p. 7).

[81] A state which included parts of modern Shanxi, Shaanxi, and Hebei.

to −222], Mr Zhuo was deported. [On the way] he was robbed, and he and his wife, pushing a handcart, arrived alone at the place of deportation. Those deportees who still had some money vied with each other in bribing the officials, seeking to be settled nearby; they were settled in Jiameng 葭萌 [near modern Guangyuan 廣元, Sichuan]. But Mr Zhuo said, 'This place is too narrow and barren. I have heard that under the marshland at the foot of Minshan 汶山 there is *dun chi* 蹲鴟 [bog iron?].[82] One can live all one's life without being hungry. Common craftsmen trade in the market.'[83] Therefore he asked to be deported to a distant place. He was sent to Linqiong 臨邛 [modern Qionglai 邛崍, Sichuan], and was very happy. At an iron mountain he smelted and cast, manipulated his calculating rods, dominated [the trade among] the people of Dian 滇 [in modern Yunnan] and Shu, and became so rich that he possessed a thousand [or eight hundred][84] slaves. In fields and lakes, and in the pleasures of the hunt, he equalled the rulers of men.

Cheng Zheng 程鄭 was another deportee from east of the mountains. He too engaged in iron production, and traded with the people who wear their hair in the mallet-shaped fashion [i.e. non-Chinese aboriginal peoples]. His wealth equalled that of Mr Zhuo, and they both lived in Linqiong.

The ancestors of the Kong 孔 family of Wan 宛 [modern Nanyang 南陽, Henan] were men of Liang 梁 [the capital of Wei 魏, near modern Linru 臨汝, Henan] who made their money by an ironworks. When Qin conquered Wei [in −225] the Kong family was deported to Nanyang 南陽 [Commandery, in which Wan was located]. They smelted and cast on a large scale and regulated ponds [for water-powered blast-furnace bellows?].[85] With a mounted retinue they visited the feudal lords, and therefore earned large profits in trade. They won a reputation for giving out gifts like leisured noblemen, but their profits were even greater [than their outlay for gifts], much greater than those of the more parsimonious [merchants], and the family became rich to the extent of several thousand in gold. Therefore all the traders of Nanyang follow the generous ways of the Kong family.[86]

Sima Qian was a great and complex writer, and his sympathies are not easily determined. In the 'Biographies of the moneymakers' his sympathies seem to lie with the wealthy commoners whom he describes. The chapter ends with a paean of praise which can be seen as a defence of this 'untitled nobility' against contemporary prejudices concerning *nouveaux riches* who pre-empted the traditional prerogatives of the aristocracy.[87] Nevertheless there are scattered remarks in other parts of the *Shi ji* which suggest that he in fact shared these prejudices.[88]

[82] On the possibility that this obscure term might refer to bog iron ore see Wagner (1993, p. 262).
[83] ? *Min gong yu shi yi gu* 民工於市易賈. The parallel passage in *HS* (ch. 91, p. 3690) changes this obscure sentence to 'common craftsmen make cloth and trade it' (*min gong zuo bu yi gu* 民工作布易賈) (cf. Swann, 1950, p. 452). On general philological principles the *lectio difficilior* of the *Shi ji* should be preferred, but its significance in context is obscure.
[84] The parallel passage in *HS* (ch. 91, p. 3690; tr. Swann, 1950, p. 453) gives the number of slaves as 800.
[85] See p. 239–42 below.
[86] *SJ* (ch. 129, pp. 3277–8); cf. B. Watson (1961, vol. 2, pp. 495–6); Swann (1950, pp. 452–4).
[87] That such prejudices already existed in very early times can be seen for example in the sumptuary laws against merchants enacted in −199 (*HS*, ch. 1b, p. 65; tr. Dubs, 1938–55, vol. 1, p. 120). The chapter of the *Han shu* parallel to the *Shi ji* chapter quoted above gives free rein to such prejudices, despite the fact that virtually its only source for the early period is precisely the *Shi ji* chapter: see for example the passage in which the Zhuo and Kong families are accused of 'lawlessness, excesses, and usurpation', *HS*, ch. 91, p. 3694; tr. Swann (1950, p. 461); L. S. Yang (1950, pp. 526–7).
[88] E.g. ch. 30, p. 1425; tr. B. Watson (1961, vol. 2, p. 87); p. 176 below.

It is possible to make a guess as to the source of the stories of Mr Zhuo and Cheng Zheng. In his biography of the poet Sima Xiangru 司馬相如 (−179 to −117), Sima Qian tells the story of a romance between him and Zhuo Wenjun 卓文君, the widowed daughter of a man named Zhuo Wangsun.[89] Zhuo Wangsun was a wealthy man of Linqiong Prefecture whose household included 800 slaves. His friend Cheng Zheng, another wealthy man, plays a minor rôle in the story. Sima Xiangru had been introduced to Zhuo Wangsun's household by his intimate friend Wang Ji 王吉, Prefect of Linqiong. The events leading up to the elopement seem to have taken place in or shortly after −144.[90] It seems likely that Sima Qian's source for the history of the Zhuo and Cheng families was some song or story which was primarily concerned with the love story of Sima Xiangru and Zhuo Wenjun. Perhaps it was written by the poet himself.[91]

The Qin policy of deporting wealthy and/or powerful families to distant regions, especially to the Sichuan area, is well documented. Ma Feibai lists no less than 47 incidental mentions of such deportations in various early sources (not counting multiple sources for a single event which probably are not independent).[92] He argues that this Qin policy served political, economic, and military purposes. When a powerful family was removed from a region, a power vacuum was left which could be filled by officials loyal to the Qin state. In the places where they were resettled their wealth and their technical and organisational skills contributed to economic development. Finally, the settlement of border regions by persons without local ties made these regions more secure against encroachment by non-Chinese peoples.

Another effect of this policy was a good deal of social tension in the places where the deportees were settled. The *Hua yang guo zhi* 華陽國志,'Treatise on the states south of Mount Hua', compiled by Chang Ju 常璩 in the +4th century, is a kind of gazetteer of the Sichuan area; it describes each prefecture, giving both geographical and historical anecdotes. The following passages tell a bit more about the Zhuo and Cheng families, in the context of a bitter attack on the newcomers who had been deported to Shu by Qin:

> But when King Huiwen 惠文王 and the First Emperor of Qin conquered the Six States, they deported the outstanding people to Shu and supplied them with our rich soil [which rightfully belonged to the conquered people of Shu]. Their families possessed the profits from salt and copper;[93] their households monopolised the mountains and rivers; their dwellings provided sufficiency and they dominated by their wealth.[94] Then craftsmen and merchants began riding about in fine carriages, and the powerful families donned the fine raiment of kings and lords. At their weddings the cuisine was like that of an Imperial sacrifice, and the

[89] *SJ* (ch. 117, pp. 2999–3074); tr. B. Watson (1961, vol. 2, pp. 297–342).
[90] The year that Prince Xiao of Liang died and Sima Xiangru returned from Liang to his family in Chengdu. *SJ*, ch. 58, p. 2086; ch. 117, p. 3000; tr. B. Watson (1961, vol. 1, p. 445, vol. 2, p. 297).
[91] Note also Schaab-Hanke (2002).
[92] Ma Feibai (1982, pp. 916–29).
[93] 'Copper' may be a scribal or other error for 'iron'. 'Salt and iron' were commonly associated in ancient China, while 'salt and copper' is very odd.
[94] ? *Ju ji ren zu yi fu xiang shang* 居給人足以富相尚.

bride was accompanied by a hundred carriages. At their funerals there was always a high mound and a tiled outer coffin; on the eve of the sacrifices a sheep and a pig were offered; the grave-clothes and the grave-gifts exceeded the Rites. Such were their excesses; and the cause of it all was the influence of Qin.

For example Zhuo Wangsun's family held slaves numbered in the thousands, Cheng Zheng had eight hundred retainers,[95] and when Master Xi 郗公 went bird hunting there was no one in the streets [because everyone went to watch].[96] Piping and drumming, singing and trumpeting, sounding bells hung up for display, their wealth matched that of the aristocratic houses and their glory exceeded that of Tian Wen 田文.[97] The 'Economics' (*Shi huo* 食貨) of the Han considered them 'notorious' (*cheng shou* 稱首).[98] All this happened because the soil was marshy, the ground was rich, and luxury was untimely.[99]

In Linqiong . . . is Gushishan 古石山 ['Old stone mountain'], where there are [pieces of] ore [bog iron?] as large as garlics. When it is fired it coalesces to form flowing iron,[100] which is very hard. For this reason an Iron Office has been established there. There is a temple to the Iron Ancestor. In the time of Emperor Wen of Han [−179 to −155] [the rights to] iron and copper were bestowed on the Gentleman-in-attendance Deng Tong 鄧通. He lent these to the commoner Zhuo Wangsun, taking [a price of] one thousand bolts of cloth per year. Therefore [Zhuo] Wangsun's wealth multiplied to the extent of hundreds of millions. Coins [minted by] Deng Tong also spread throughout the empire.

[Zhuo] Wangsun's daughter Wenjun could play the zither. At that time there was a certain Sima Changqing 司馬長卿 [the polite name of Sima Xiangru], who together with the Prefect of Linqiong, Wang Ji, visited the home of [Zhuo] Wangsun. [Zhuo] Wenjun thereafter eloped with [Sima] Changqing.[101]

There is a short biography of Deng Tong in the chapter 'Biographies of the Emperors' male favourites' of the *Shi ji*.[102] Here he is portrayed as an indolent incompetent who wormed his way into Emperor Wen's favour; a sexual relationship is strongly hinted at. The Emperor is said to have bestowed on him a 'copper mountain' in Yandao 嚴道, which is near Linqiong. He became rich by minting coins of this copper which

[95] Reading *ke* 客 for *ge* 各. For two other possible interpretations see respectively Liu Lin (1984, p. 226, n. 3) and Ren Naiqiang (1987, p. 150, n. 6).

[96] Master Xi is mentioned in similar terms in the *Shu du fu* 蜀都賦 (Rhapsody on the capital of Shu) of Zuo Si 左思 (+3rd century), in *WX* (ch. 4, pp. 186–7; tr. Knechtges, 1982–96, vol. 1, p. 363; von Zach, 1958, pp. 52–3). Ren Naiqiang (1987, pp. 150–1, n. 7) identifies Master Xi as a certain Xi Jian 郗儉, who was active in the period +168–188. As he also notes, however, Master Xi is mentioned in a much earlier *Shu du fu*, by Yang Xiong 楊雄 (−53 to −18). Ren Naiqiang attempts to prove that this *Shu du fu* is a late forgery, but his proof is not convincing. Whoever Master Xi may have been, he is likely to have been a contemporary of Zhuo Wangsun and Cheng Zheng.

[97] Better known as Lord Mengchang 孟嘗君.

[98] The reference here is presumably to the chapter *Shi huo zhi* 食貨志, 'Treatise on economics', of the *Han shu* (ch. 24, pp. 1117–86; tr. Swann, 1950, pp. 109–359). That chapter has some general remarks on the usurpation by *nouveaux riches* of the traditional privileges of the aristocracy (e.g. ch. 24a, p. 1137; tr. Swann, 1950, p. 181), but more details are given in the chapter 'Biographies of the money-makers' (ch. 91, pp. 3679–95; tr. Swann, 1950, pp. 414–64), which is largely copied from the corresponding chapter of the *Shi ji*. The relevant passage in the *Shi ji* has been quoted above. The specific mention of Lord Mengchang and his ilk as 'notorious' (*chengshou*) is however in the chapter 'Biographies of the wandering knights' (*HS*, ch. 92, p. 3697; tr. B. Watson, 1974, p. 224).

[99] *Hua yang guo zhi*, ch. 3, *SBCK* edn, pp. 8a–8b; Liu Lin (1984, p. 225); Ren Naiqiang (1987, p. 148).

[100] ? *He zhi cheng liu zhi tie* 合之成流支鐵.

[101] *Hua yang guo zhi*, ch. 3, *SBCK* edn, pp. 10b–11a; Liu Lin (1984, pp. 244–5); Ren Naiqiang (1987, p. 157).

[102] *SJ*, ch. 125, pp. 3192–3; tr. B. Watson (1961, vol. 2, pp. 463–4).

circulated throughout the empire. The story in the *Hua yang guo zhi*, that he received some sort of concession on copper and iron production somewhere near Linqiong, is much more credible than the more dramatic story of the gift of a 'copper mountain'. The source for the *Shi ji* biography of Deng Tong is likely to be some romantic rags-to-riches-to-rags account whose reliability must be considered thoroughly suspect.[103]

Qin ideology and practical policies appear to have favoured industrial development, especially in the iron industry. The modern experience of underdeveloped countries suggests that technological knowledge, which at least in principle can easily be imported, is less significant for industrial development than social and political conditions. The Qin policy of weakening the traditional landed aristocracy and strengthening the power of a centralised bureaucracy, whose power was based only on identification with the state, was no doubt conducive to a breakdown of traditional land-oriented values and to a new respectability for industry *vis-à-vis* agriculture. The sources quoted above tend to show in addition that the Qin rulers were well aware of the usefulness of the 'proto-industrialists', wealthy men who invested in industry rather than land and therefore helped to build up the political and military strength of the state. The story in the *Hua yang guo zhi* of Deng Tong suggests that state involvement in industry continued in one form or another in the early Han.

Ironworks

We get some idea of what these ironworks may have been like in the *Yan tie lun* 鹽鐵論, 'Discourses on salt and iron', written by Huan Kuan 桓寬 between −73 and −49:

> In the past [before the introduction of the state monopoly on salt and iron in −117], great and powerful families obtained control of the benefits of mountains and seas. They extracted iron ore to smelt and cast it, and they boiled the seas to make salt. One family might gather a multitude of over a thousand persons, nearly all of them common bandits. Travelling far from their homes and abandoning the graves of their ancestors, they became dependent on the great families. Being assembled in deep mountains and remote marshes, engaging in illicit enterprises and following the power of factions, their tendency to commit wrongs was a danger.[104]

The *Yan tie lun* is supposed to be a report on a conference on administrative and economic problems held in −81.[105] The passage above is part of a defence of the state monopoly on salt and iron production which was established in −117.

The polemical character of the passage is obvious, and needs no comment. Ignoring the polemics, the ironworks seem very like the 'iron plantations' of 18th-century

[103] On Deng Tong see Zhang Shanxi (1995); Loewe (2000, pp. 59–60). A memorial of about +516 mentions that Deng Tong's coins are still circulating (*Wei shu*, ch. 110, p. 2863).

[104] *YTL*, ch. 1, *SBCK* edn, p. 12a; cf. Wang Liqi (1958, p. 42; 1992, pp. 78–9); Satō (1970, pp. 31–2); Gale (1967, p. 35); Baudry-Weulersse et al. (1978, p. 74).

[105] On the conference and the book see below, pp. 185–6.

America and the *järnbruk* of northern Sweden.[106] An iron plantation or *järnbruk* was a largely self-sufficient community living at the centre of a large tract of forest. Some agriculture was practised, but nearly all activities in the community centred about the production of iron: forestry, charcoal production, ore gathering or mining, the operation of the blast furnace, etc. Their isolation was a natural consequence of their dependence on the forest for a large and reliable supply of charcoal to fuel the blast furnace. Labour relations could vary greatly. Slaves were used in Virginia, free labourers in Pennsylvania; and it seems that for the Pennsylvania iron plantations even the polemical parts of Sang Hongyang's description fit very well. In Sweden the *järnbruk* seem to have functioned rather like feudal manors.[107] The Swedish iron-masters (*brukspatroner*) are said to have been the first non-aristocratic upper class in Swedish society, a fact which must remind us of the *Shi ji*'s 'untitled nobility' of the iron industry.[108]

William Byrd visited two iron plantations in Virginia in 1732, and his narrative of the journey includes, interspersed with a good deal of charming gossip, some interesting information on their operation and organisation. A typical iron plantation produced about 800 tons of pig iron per year. 'Two miles square' (probably four square miles = 10 km^2) of forest were needed to supply the necessary charcoal, and about 120 slaves did the unskilled work. About ten skilled workers were required, 'a mine raiser, a collier [supervisor of charcoal production], a stocktaker, a clerk, a smith, a carpenter, a wheelwright, and several carters'. The blast furnace must be located on a suitable river for the water-powered bellows. 'All the land hereabouts seems paved with iron ore; so that there seems to be enough to feed a furnace for many ages.'[109] Today a typical blast furnace produces at least a million tons per year, and Virginia is considered to be without significant deposits of iron ore.

A point to be emphasised, because it seems so strange to modern readers, is that the limiting resource in pre-modern iron production is *wood*, not ore. The iron plantations were, from one point of view, a way of converting forest resources into a product which was more easily transported to markets than timber. For an annual production of a few hundred tons of pig iron, sufficient ore can be found almost anywhere in the world. Deep mining is rarely required: advantage can be taken of surface outcrops, ironsand in rivers, or bog iron. It is often more correct to speak of 'ore gathering' than of mining.

[106] Note also some ironworks in the Song period which may have been organised in a similar way, p. 301 below.

[107] Byrd (1966); Lewis (1974; 1933; 1938, pp. 29–48); Bergkvist and Olls (1971); Wertime (1961, pp. 111–13); Heckscher (1954, pp. 97–100). Peter Golas (1995, p. 428) believes that I have been overly speculative in suggesting this comparison with iron plantations and *järnbruk* (Wagner, 1993, pp. 257–9). It is true that the time gap is enormous, but I claim that this type of organisation is almost dictated by several factors common to the iron industries of −3rd-century China and 18th-century America and Sweden: charcoal blast-furnace technology, difficulty of transportation, and weakly developed markets. But we need serious studies of this question by American and Swedish economic historians.

[108] Heckscher (1954, pp. 98, 131–2; 1957, pp. 116, 145–6).

[109] Byrd (1966, pp. 348, 354, 360, 366).

The use of slave labour was not really economically suitable in iron production. On cotton plantations slaves could be overseen and controlled easily, and simple violence could keep them at work. On the iron plantations the work done by slaves, while largely unskilled, was more difficult to oversee and provided numerous opportunities for sabotage. Slaves had to be better treated; they were given monetary rewards and holidays in return for satisfactory work. The slaves used on iron plantations were usually rented rather than purchased, probably because the type of labour involved required young strong men, and there was little use for women, children, and old men.[110]

A problem for the iron plantations, whether they used free or slave labour, was the concentration of a hundred or more young strong uneducated men in an isolated settlement without families or local roots.[111] In the quotation from the *Yan tie lun* above, the workers are described as 'common bandits' who 'abandoned the graves of their ancestors'. The social, political, and perhaps even military problems caused by iron plantations in the Warring States period may well have been severe, and may have been among the reasons for the later establishment of the Han state monopoly.

The rise of the state of Qin

The history of the Warring States period is seen in the sources primarily as the story of Qin's rise from a minor state on the western periphery of Chinese culture to the conqueror of all China in −220. It is often suggested that the key to Qin's success lay in a technological superiority in weaponry, but real proof has never been forthcoming.[112] Qin's first major conquest was the southern state of Chu: if it is correct, as I have suggested above,[113] that iron weapons were not used here, then this may be an example of a technological superiority contributing to Qin's success. (Definite proof that Qin's iron weapons were in fact superior to Chu's bronze weapons is still needed.) But Qin's further conquests cannot be explained in this way, for the evidence seems to be incontrovertible that iron had almost entirely replaced bronze for weapons throughout north China by the early decades of the −3rd century. If the hypothesis is to be saved, we must look rather to a superiority in the *organisation* of the production of iron weapons.

Weapons were made by smiths of wrought iron and steel. The technique of the smith is to a significant extent the same throughout the world and throughout history, and everywhere there are master smiths and incompetent smiths. We should therefore not expect to find much difference between Qin and the rest of north China in

110 Lewis (1974); Dew (1974). In the American Civil War (1861–65), 'However bravely and creatively Confederate ordnance officers and manufacturers waged the battle of production, they lost the war for a slave society by demonstrating that a modern iron industry could not be based on slave labor' (Knowles, 2001, p. 2).
111 Cf. Bining (1933, pp. 127–9).
112 See p. 117 above.
113 P. 128.

the smiths' actual techniques of production of weapons, but should look instead to the production of the smith's raw material. We know little about pre-Han primary iron-production techniques, but it seems likely that there was not much variation from place to place in ancient China: in iron production the most important variation was not in its underlying technique, but perhaps in its organisation. Production of iron in a blast furnace is most efficient at a high level of production, and mass production requires a large market, good transportation, and a large and reliable labour force.[114] All these factors would be more easily forthcoming in the 'totalitarian' state of Qin than in the more 'feudal' states of north China. Qin's political practice and ideology made possible a reliable and efficient production of iron implements and weapons; this gave Qin an economic and military advantage over the other states; and this advantage made the Qin conquest possible. Had the technology of iron production been a different one throughout north China, some other political form might have given an analogous advantage to some other state or states, and Chinese history might have been very different.

We do not have the necessary material to discuss the technology of iron *smelting* in China before the −1st century. The ironworks of the Han monopoly will be discussed in detail in the next Section;[115] the slight material from the Warring States period suggests that at least some of the blast furnaces were as large as those of the later state ironworks, and used a similarly sophisticated design, with elliptical shafts of refractory brick tempered with a grog of powdered charcoal.[116] That is about all that can be said.

We can, however, describe the technology of the iron *foundries* of the period, where already-smelted iron was remelted and cast into the desired products. Foundries cause much less nuisance than smelters, and have more often been located in or near cities, close to their customers.

(iv) THE ARTS OF THE FOUNDRYMAN

Melting furnaces

The furnaces used in ancient times to melt bronze and iron are known only from fragments found in the excavation of foundry sites. Archaeologists have studied these intensively with a view to the reconstruction of the ancient furnaces, and work by Li Jinghua has brought new clarity to the subject.[117]

The forthcoming Section 36b of Science and *Civilisation in China*, on non-ferrous metallurgy, will no doubt discuss the early bronze-melting furnaces in detail. Here we can briefly note that many Shang artefacts which formerly were believed to be

[114] Section 2(viii) above, pp. 81–2.
[115] Pp. 229–45 below.
[116] Table 2, items 9, 21, 24, pp. 201–9 below.
[117] Li Jinghua (1992b, 1994b; 1994f).

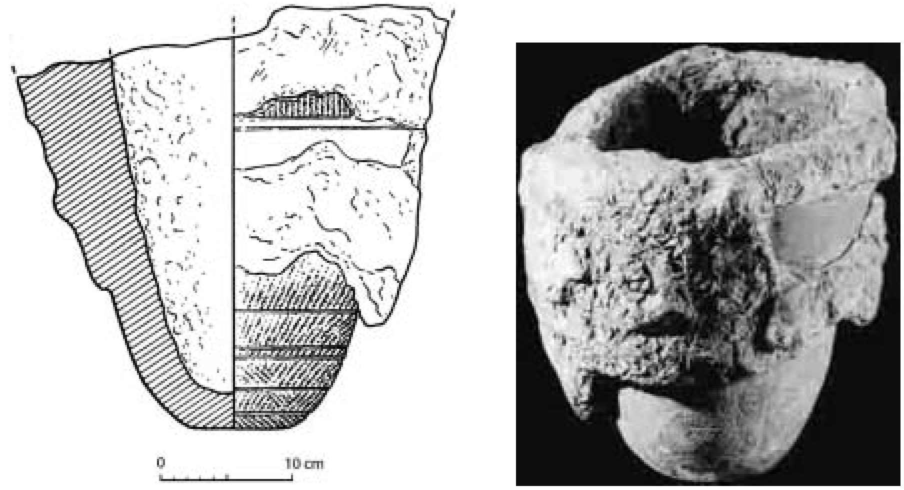


Figure 67 Photograph and sketch of a bronze-melting furnace from the Shang-period site in Zhengzhou, Henan (artefact no. C5.3T302B:83). Reproduced from Anon. (2001b, pl. 54.1, p. 339, fig. 209), where the artefact is referred to as a crucible (*ganguo* 坩堝).

fragments of 'crucibles' are now known to have been exposed to much higher temperatures on their inner surfaces than on the outside. They must therefore be fragments of a kind of cupola furnace,[118] but since there is no sign of holes in the sides it must be assumed that air was blown in from the top, and that molten bronze was poured out rather than being tapped through a taphole. Figure 67 shows a furnace of this type, and Figure 68 shows Li Jinghua's reconstruction of how it was used. It is a large ceramic *gang* 缸 pot for strength, plastered inside and out with straw-tempered clay for fire-resistance and insulation. A collar was placed on the mouth of this pot to extend its height. Charcoal and bronze metal were charged in and ignited, and air was blown in through one or more tuyères inserted into the furnace burden. When the metal was molten the collar was removed and the liquid metal poured into the mould (or into a ladle and thence into the mould). Li Jinghua believes that in early times air was blown by mouth through these tubes; perhaps so,[119] but one must suspect that a bellows of one sort or another was a very early invention.[120]

One of several later types of bronze-melting furnace is shown in Figure 69. This is in three sections. It has a single tuyère of straw-tempered clay, and is believed to have been blown with some type of bellows. A shaft furnace like this one, in which the tuyère projects downward through the furnace mouth rather than through the furnace wall, has been seen in Section 2(v) above.[121] This arrangement seems to simplify furnace construction, at the cost of a much higher consumption of tuyères,

[118] See Section 2(v) above, pp. 60–4.
[119] Note Rehder (1994).
[120] On some early types of blowing apparatus in China see *SCC*, vol. 4, part 2, pp. 135ff.
[121] Pp. 63–4.

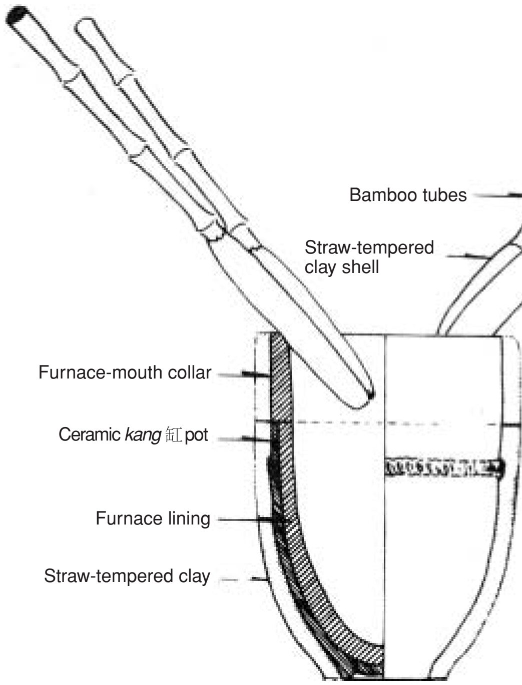


Figure 68 Diagram showing how a bronze-melting furnace like that in Figure 67 was used, reproduced from Li Jinghua (1994b, p. 145, fig. 72.2).

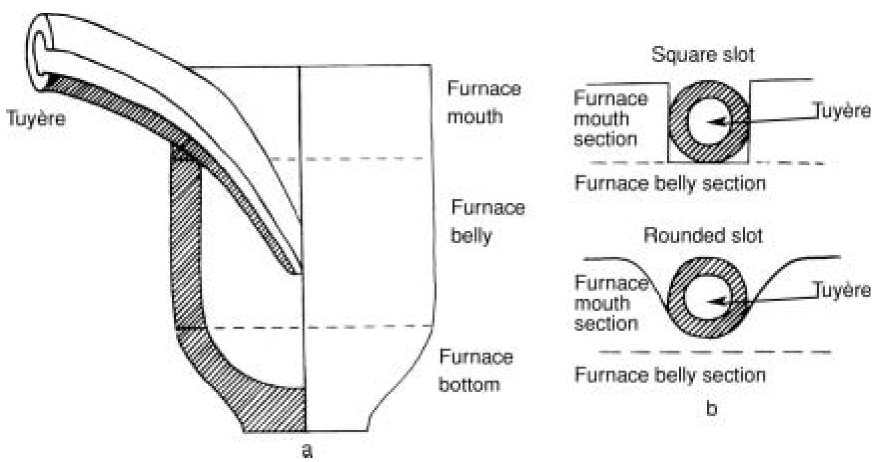


Figure 69 Reconstruction of a type of bronze-melting furnace found at many foundry sites of the Spring and Autumn period, reproduced from Li Jinghua (1994b, p. 147, fig. 74.1–2). **a**. The three sections of the furnace and the tuyère in place. **b**. Two ways in which the tuyère was fitted with the upper section.

which melt in the heat of the furnace. No doubt a flame blowing downward from the tuyère, rather than from the side and up, made for technical differences in furnace operation, but such differences are difficult to investigate without full-scale experimentation.[122]

Two large iron-foundry sites of the Warring States period have been studied by Li Jinghua.[123] He reconstructs several different types of melting furnace. The first is a small sectional furnace like the bronze-melting furnace of Figure 69, with diameter about 0.9 m and wall thickness 4–6 cm. In recent centuries furnaces very much like this one, though with the tuyère now inserted through a hole in the side of the middle section, were common in China.[124]

Small sectional furnaces like this one may never have gone out of use, but larger furnaces, more productive and undoubtedly more efficient, came into use well before the end of the Warring States period. Figure 70 shows one of these, a large shaft furnace which could not be tapped in the same way as the smaller ones. There must have been a taphole in this type of furnace, though it seems that no direct evidence of it has been found. The hole was kept plugged with clay until a certain amount of molten iron had gathered in the bottom. The plug was broken open to allow the iron to flow out, after which the taphole was replugged.[125] As in all of the iron-foundry furnaces reconstructed from this time, the tuyère was inserted downward through the mouth of the furnace. A more elaborate version of the same basic furnace design is shown in Figure 71. It was built of refractory bricks, reinforced with iron plates.

Moulds

The Chinese metallurgist was from the earliest times a sophisticated potter, and in the discussion above I have not attempted to deal with the complexities of the ceramic materials used for different parts of the furnaces. Most moulds too were of clay: sand-casting, in modern times the method of choice for most metal casting, was a later development.

[122] It is possible that the downward tuyère helped by pre-heating the blast air, but this is a controversial question. Schmidt and Avery (1983) contend that a tuyère extending (through the side of the furnace) some distance into a bloomery will pre-heat the blast sufficiently to improve the furnace's efficiency. Their article attracted a barrage of criticism (Rehder, 1986; Eggert, 1985; 1987; Killick, 1991; Miller and van der Merwe, 1994, pp. 23–4), and several extravagant technical and historical claims made by them have been definitely discredited. However, the particular question of interest here, *viz.*, whether the blast is in fact significantly pre-heated in this arrangement, seems still to be unresolved. It is extremely difficult to measure the temperature of a hot stream of air (because a thermocouple is heated much more by radiation from the surroundings than by the air itself); different theoretical approaches to the problem give radically different results, and it is very difficult to determine which approach is closest to being correct. Note the use of a somewhat similar heat-recycling arrangement in some Han cupola furnaces (pp. 237–9 below).

[123] See Table 2, items 6 and 23, in Section 5 below.

[124] See e.g. pp. 61, 63 above.

[125] According to a Han dictionary, *Ji jiu pian* (p. 36a), this action of plugging the taphole of a furnace was called *gu* 錮.

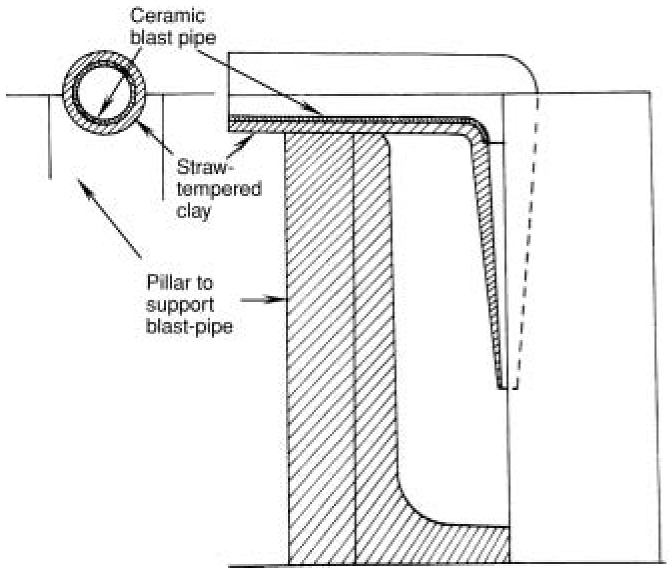


Figure 70 One type of iron-melting furnace of the Warring States period, as reconstructed by Li Jinghua from fragments excavated at an iron-foundry site at Gaocheng in Dengfeng County 登封縣告城, Henan. Inner diameter 1.14 cm. The furnace lining is 1–5 mm thick, of heavily sand-tempered clay, the wall itself about 15 cm thick, in two layers of straw-tempered clay. Reproduced and translated from Li Jinghua (1994b, p. 148, fig. 75).

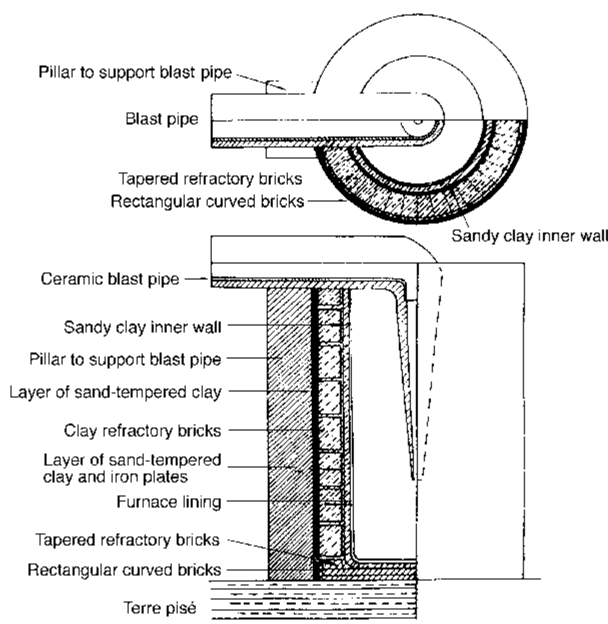


Figure 71 Reconstruction of another type of iron-melting furnace of the Warring States period, as recons-tructed by Li Jinghua from fragments found at an iron-foundry site at Gaocheng in Dengfeng County 登封縣告城, Henan. Reproduced and translated from Li Jinghua (1994b, p. 150, fig. 77). Dimensions not given.

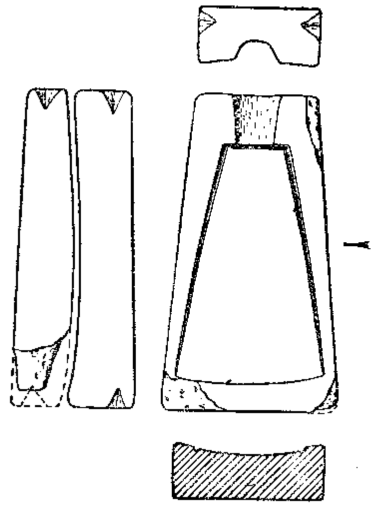


Figure 72 Two-section ceramic mould for an iron hoe-blade (?). From the Warring States ironworks site at Yangcheng in Dengfeng County 登封陽城, Henan, reproduced from Anon. (1977b, p. 62, fig. 22, artefact no. *caiji* 采集: 2).

The moulds for most early Chinese *bronze* casting were made by the piece-moulding technique. It should be discussed in Section 36b, on non-ferrous metallurgy, and will also be treated briefly here, in the discussion of later monumental castings.[126] Piece-moulding was no doubt sometimes used in the casting of iron objects in early times, but there seems at the moment to be no evidence of it. The usefulness of piece-moulding was greatest in the making of complex one-off castings, while for mass production other methods were developed. Probably these methods were pioneered by the founders of bronze coins, who needed to produce millions of identical small castings.[127]

Examples of simple moulds for iron implements are shown in Figures 72 and 73. A more complex example is in Figure 74. Two mould-sections like **a** are placed together, the core **b** is inserted into the top, and molten iron is poured into the gate formed by the cavity in the core, and a mattock-head like **c** results.

[126] Pp. 289–94. Until Section 36b is available, note that the classic works in English on ancient Chinese bronze-casting techniques are Karlbeck (1935); Barnard (1961); Barnard and Satō (1975); Gettens (1969); and Fitzgerald et al. (1989). Shaughnessy (1991, pp. 35–62) and Chase (1991) give useful brief summaries. Of the vast amount that has been published on the subject in Chinese, among the most important are the studies of Wan Jiabao (e.g. Li Ji and Wan Jiabao, 1964; 1966; 1968; 1970; 1972); Guo Baojun (1981); Hua Jueming (e.g. Hua Jueming et al., 1986, several articles; Hua Jueming, 1999); Li Jinghua (e.g. 1994a, several articles); Tan Derui (e.g. 1985; 1986a; 1986b; 1999); Ling Yeqin (1987); Su Rongyu et al. (1995). Most of this work concerns ritual vessels; when the excavation report on a −5th-century bronze foundry site in Houma 侯馬, Shanxi (Anon., 1993a) was published, it quite suddenly gave us a marvellously detailed view of the mass-production casting of bronze implements and weapons. Wen Tingkuan (1958c) describes the piece-moulding process as it is still practised in China today.

[127] On ancient Chinese coin-casting techniques see e.g. Zi Xi (1957); Han Shiyuan (1965); Li Gongdu (1977); Tang Wenxing (1983); Qian Jianfu (1986, pp. 184–227); E Xiang (1986); Wu Rongceng (1987); Tian Rong and Wang Dingruo (1992); Dang Shunmin (1994); Cai Quanfa and Ma Juncai (1995). See also An Jinhuai and Li Jinghua (1992); He Huilu and Zhang Youxin (1996); Li Debao (1994); Frick (1998, pp. 137–9).

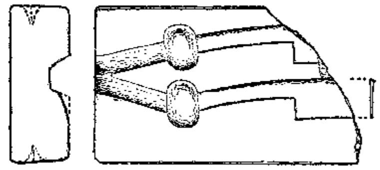


Figure 73 Section of a ceramic mould for two ring-handled knives. From the Warring States ironworks site at Yangcheng in Dengfeng County 登封陽城, Henan, reproduced from Anon. (1977b, p. 64, fig. 39, artefact no. *cai* 采:6).

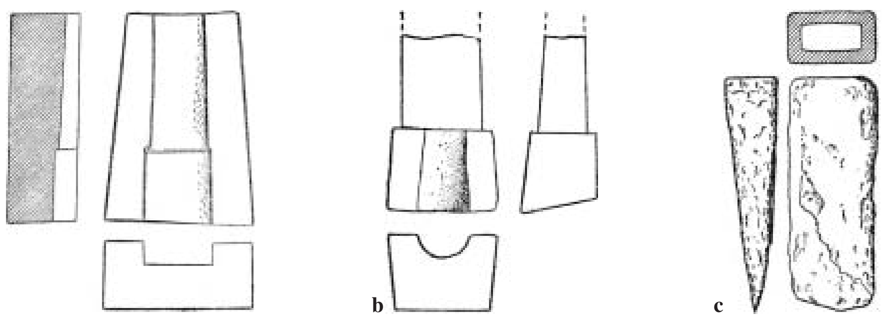


Figure 74 Artefacts from the Warring States ironworks site at Yangcheng in Dengfeng County 登封陽城, Henan, reproduced from Anon. (1977b, pp. 63, 59, figs. 25, 15, 26). Dimensions not given. **a**. Section of a ceramic mould for a mattock-head (artefact no. *cai* 采:22). **b**. Ceramic mould-core for a mattock-head (artefact no. *Gao-dong* 告東 T1: 38). **c**. Iron mattock-head (artefact no. *cai* 采:32).

Mould parts like the ones shown were probably fabricated in the same way as decorated bricks, by pressing wet clay into what might be called 'pattern-boxes',[128] then carefully removing, drying, and baking. The assembled mould would then be clamped together in some way (note the notches cut into the mould-sections), plastered with straw-tempered clay or mud, dried, and cast.[129] It is not clear whether the mould-parts could be used more than once; probably so. Pattern-boxes have not yet been found at Warring States ironworks sites, but pattern-boxes made of wood, stone, bronze, iron, or lead for making bronze-casting moulds are well known from coin-foundries of the Western Han period.[130] In the Chinese archaeological literature these are generally called *mu fan* 母范, 'mother-moulds' (sometimes *fan mu* 范母, 'mould-mothers'), but there is not general agreement on this terminology,[131] and often they are simply called *fan* 范、範, 'moulds'.

[128] 'Pattern-box', a literal translation of the term used by Li Jinghua, *mu he* 模盒, is quite appropriate in English as well. In early modern foundry terminology the 'pattern' is a device used to make the appropriate impression in a box of sand, and a 'core-box' is used in the way described here to make a mould-core.

[129] Li Jinghua (1985b, p. 51).

[130] See e.g. Zheng Jiaxiang (1959); Han Shiyuan (1965, esp. p. 247, figs. 9–10); Li Gongdu (1977, p. 37, figs. 4–5); Cai Yonghua (1978, pp. 122–3, 125, 126, figs. 1.3.4, 3.5, 3.7, 4); Tang Shifu (1981); Tang Wenxing (1983, p. 75, fig. 1); E Xiang (1986, p. 67, fig. 1); Qian Jianfu (1986, plates, figs. 55–7); Liu Dongya (1985, figs. 3–4, 8); Anon. (1977c, fig. 2); Cai Quanfa and Ma Juncai (1995, pp. 49–53, nos. 5–20); Yu Benai (1987); Li Shengyun and Yun Xuewen (1987); Zheng Ruifeng (1987); Zhang Xiufu (1987); Zhang Haiyun (1987); Jiang Ruoshi (1997).

[131] For example Cheng Xuehua (1959) calls the moulds *mu fan* 母范 and the pattern-boxes *zu fan* 祖范, 'grand-parent moulds'. Attempts to bring order into this terminological confusion include Tang Wenxing (1983); E Xiang (1986); Qian Zhuo (1993); Liu Chunsheng (1993).

Another moulding technique which probably originated with the coin-founders is *stack-moulding*, in which large numbers of identical moulds are arranged together, with a common casting gate, so that a very large number of castings can be made in a single pour, saving time, labour, metal, fuel, and refractory material. Figures 75, 76, and 77 show one example of a stack-mould, from a remarkable excavation in Wen County 溫縣, Henan. On the site of a Han foundry, a large kiln was excavated which turned out to be loaded with about 500 mould-stacks, fully fired and ready for casting. The large number found meant that a few could be used for direct experimental casting, and one result is shown in Figure 76c.

The design of moulds is a very complex affair. Today a good deal can be calculated, taking into account such quantitative variables as surface tension, viscosity, flow rates, heat conduction, cooling rates, and shrinkage,[132] but the placement of gates, runners, risers, vents, dross traps, and the rest was until recently a matter for the experience and judgement of the artisan.[133] To a considerable extent it still is. In the case of these stack-moulds Hua Jueming has applied the modern calculations and shown that the arrangement of runners is close to optimum,[134] assuming only that casting takes place with the mould pre-heated to about 600°C.

Figure 78 shows a reconstruction of the process by which some of these stack-moulds were fabricated. Single moulds like those of Figures 72 and 73 were undoubtedly made in much the same way.

Another approach to the mass production of castings can be seen in the use of cast-iron permanent moulds for casting iron implements. The ones shown in Figures 79, 80, 81, and 82 are from a Warring States iron-foundry site in Xinglong County 興隆縣, Hebei, in 1953; they have already been mentioned as the second of many surprises of the 1950s for the archaeology of iron in China.[135] Since then iron moulds have been found at numerous ironworks sites of the Warring States, Han, and Six Dynasties periods.[136]

There was a brief period of doubt about whether these moulds could really be for casting iron, or perhaps must be for bronze,[137] but the question was soon cleared up

132 See e.g. Ruddle (1956); Flemings (1974); Webster (1980).
133 See e.g. Palmer (1912); Laing and Rolfe (1960); or any of numerous other older manuals of foundry practice.
134 Hua Jue Ming (1983a); Hua Jueming (1983b); Anon. (1978a, pp. 27–34).
135 P. 87 above. The first news of these finds led Dr Walter Winton, Deputy Keeper at the Science Museum, London, to write to Joseph Needham and ask for his help in obtaining more information. With the friendly assistance of no less a personage than Guo Moruo, at that time Minister of Culture, plastic replicas were made in China and presented to the Museum, which unfortunately has never exhibited them. The lengthy correspondence on the production and shipping of the replicas is quite interesting; part of it is in the archives of the Needham Research Institute, part in the Museum archives.

I was allowed to study the replicas together with the late Susan Cackett, Dr Winton's successor, in 1986. I learned then that Dr Winton also did a most unusual experiment: he had a local foundry cast an iron replica of the plastic replica of one section of the mould for a hexagonal hoe-head (Figure 79), and used this mould-section as if it were an actual hoe-head in his garden for several months, thus proving that it was possible to use cast iron for such an implement at a time when this was widely believed to be impracticable or even impossible.
136 Li Jinghua (1985b, p. 2; 1994a, p. 108).
137 Alley (1955); Needham (1958, p. 6).

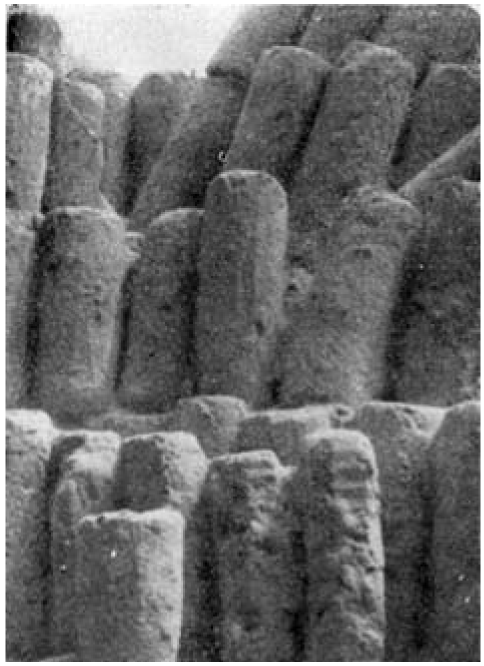


Figure 75 Stack-moulds under excavation in a kiln at the Han iron-foundry site in Wen County 溫縣, Henan, reproduced from Anon. (1978a, pl. 9, bottom left).

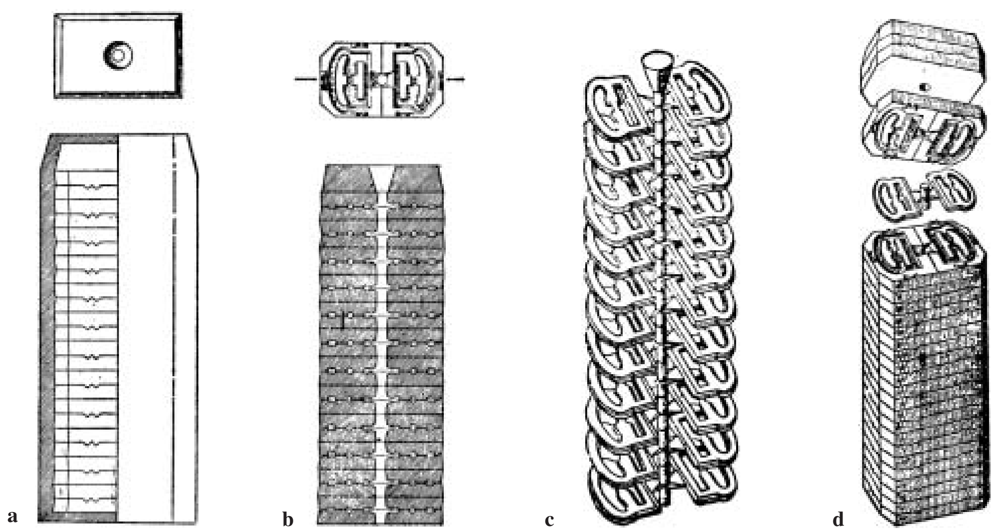


Figure 76 Sketches of a stack-mould for casting iron belt-buckles, one of those shown in Figure 75, reproduced from Anon. (1978a, p. 11, fig. 15). Cf. Figure 77. **a**. Mould prepared for casting, with outer plastering of straw-tempered clay. **b**. Vertical section through mould. **c**. The casting. **d**. Exploded view of casting in mould.

Figure 77 Photograph of an individual section of the stack-mould of Figure 76, reproduced from Anon. (1978a, pl. 6, bottom left).

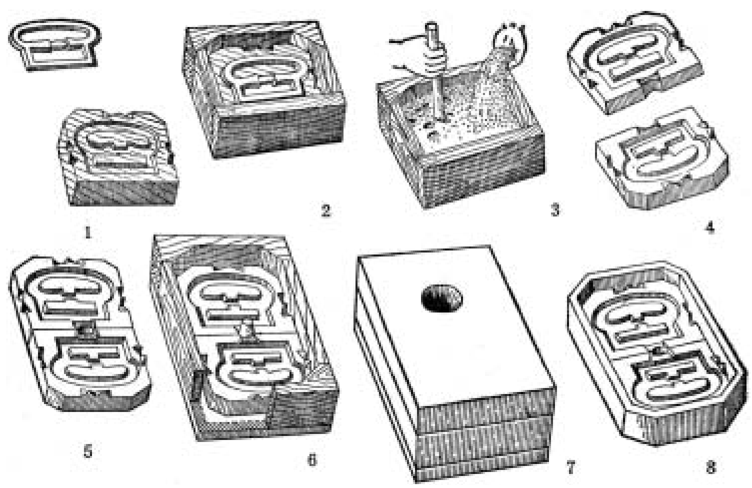


Figure 78 Reconstruction of the process of making the pattern-box for a mould section like that in Figure 77, reproduced from Anon. (1978a, p. 20, fig. 23). **1**. Model buckle and a wooden plate with depression to receive it. **2**. Box built around the wooden plate. **3**. Pressing clay into box. **4–5**. Two ceramic moulds made in this way. **6**. Box built around these two ceramic moulds, with model for runner added. **7**. Complete mould for casting metal pattern-box. **8**. Cast metal pattern-box. Clay will be pressed into this pattern-box as at stage 3 to form the mould section shown in Figure 77.

by working metallurgists. Metal moulds are quite often used in casting metals. Large numbers of bronze moulds for bronze are known from the ancient West,[138] and in China both bronze and iron moulds were commonly used in casting bronze coins.

[138] John Evans (1881, pp. 438–48) discusses prehistoric European bronze moulds, and lists about 40 examples. Coghlan (1952) describes in detail an Egyptian bronze mould for three arrowheads, possibly from the −8th or −7th century. E. Voce (in Coghlan et al., 1951, pp. 112–15) describes experimental casting of bronze in an ancient bronze mould.

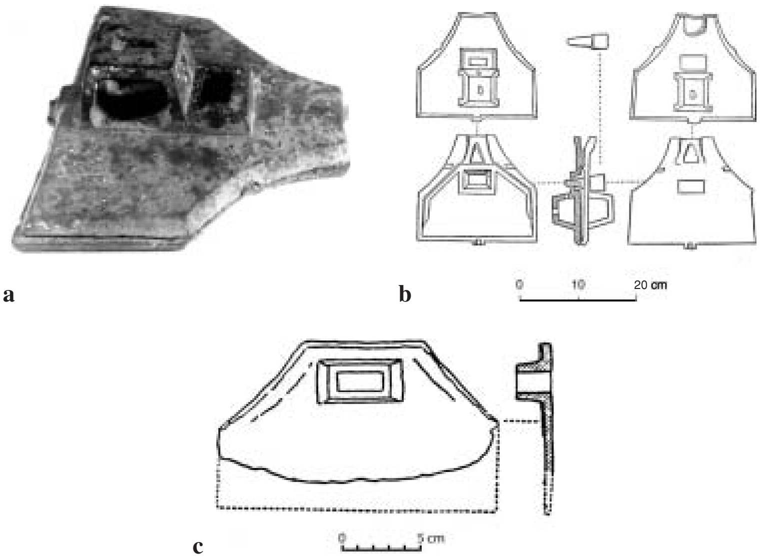


Figure 79 Three-section cast-iron mould for casting an iron hexagonal hoe-head, from the Warring States iron-foundry site in Xinglong County 興隆縣, Hebei. **a**. Photograph of the assembled mould. **b**. Sketch of the parts of the mould. **c**. Sketch of a hexagonal hoe-head from the same site. Sketches reproduced from Zheng Shaozong (1956, pp. 31, 35, figs. 2, 9); photograph supplied to Joseph Needham by the Chinese Ministry of Culture through Rewi Alley.

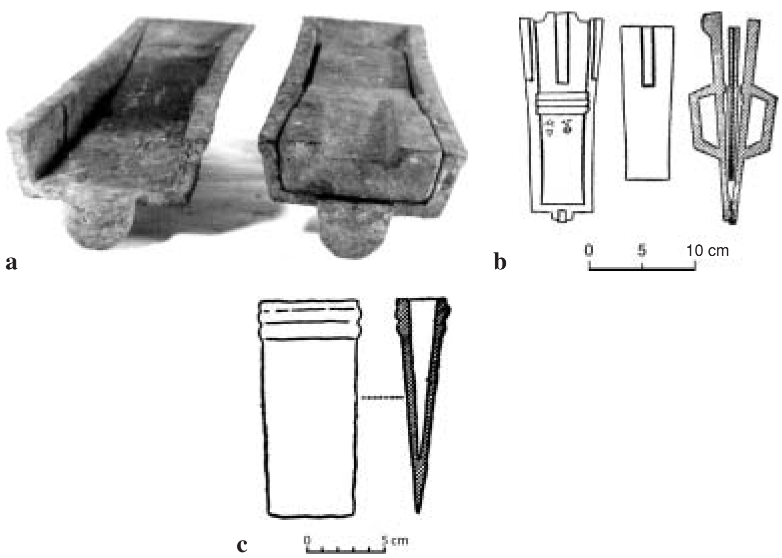


Figure 80 Three-section cast-iron mould for casting an iron axehead, from the Warring States iron-foundry site in Xinglong County 興隆縣, Hebei. **a**. Photograph of the assembled mould. **b**. Sketch of the parts of the mould. **c**. Sketch of an axehead from the same site. Sketches reproduced from Zheng Shaozong (1956, pp. 33, 35, figs. 5, 9); photograph supplied to Joseph Needham by the Chinese Ministry of Culture through Rewi Alley.

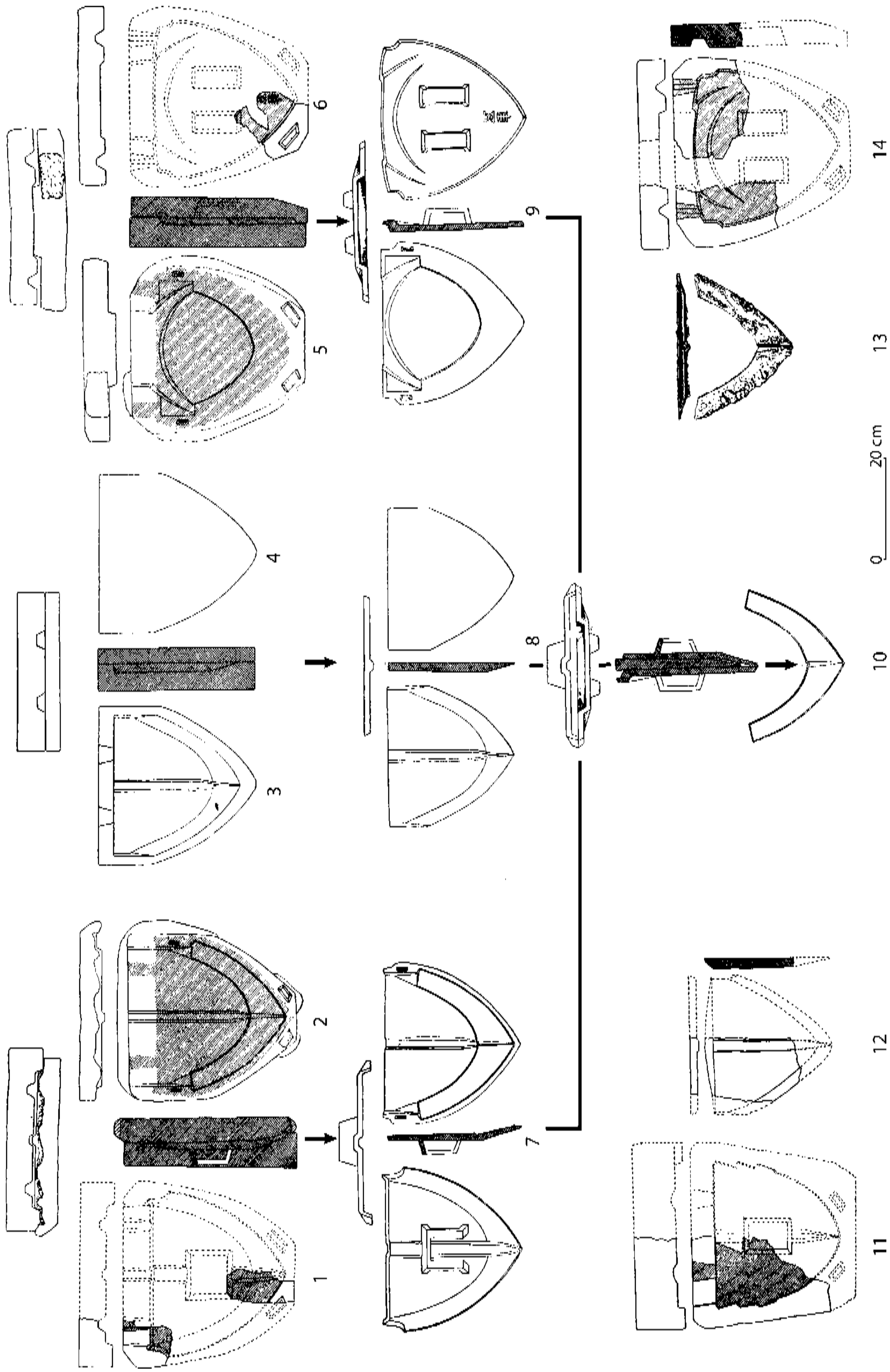


Figure 81 *caption page 159*

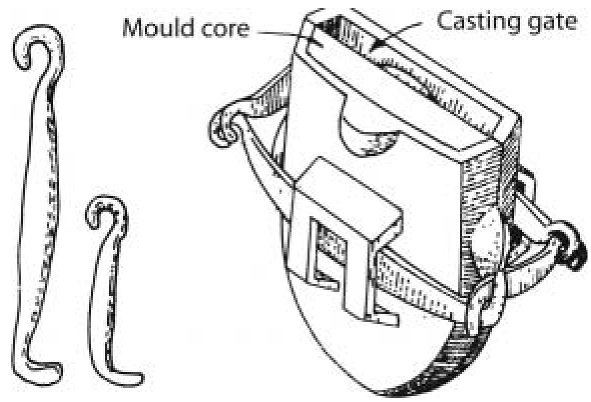


Figure 82 Arrangement of the iron mould for pouring (Figure 81, nos. 7–9), reproduced from Li Jinghua (1985a, p. 11, fig. 12; better reproduction, 1994a, p. 116, fig. 58).

(v) Malleable Cast Iron

We normally assume that wrought iron and steel are better materials for implements than cast iron. To a great extent this is quite true, and it is likely that most Chinese peasants would have preferred wrought- to cast-iron implements, if they could have got them. In fact, however, cast iron is not as inferior as it often is made out to be. It is brittle, but in many applications (cooking pots for example) this is not a major problem. In other applications, good design can minimise the effect of the brittleness: an example is the ploughshare shown in Figure 83, in which the edge, the part most subject to damage, is protected by a small V-shaped cap. This can be replaced quickly and cheaply when damaged and thereafter recycled.

Furthermore, a remarkable Chinese invention of the −4th or −3rd century made cast iron a much better material than would otherwise be expected. Subjecting a casting to a lengthy heat treatment can significantly improve its mechanical properties.

Figure 81 *see page 158* Sketch of the whole process of casting the parts of an iron mould for a V-shaped ploughshare cap, using artefacts from the ironworks site at Wafangzhuang in Nanyang 南陽瓦房莊, Henan, reproduced from Li Jinghua (1965, foldout fig. 6; also 1991, p. 34, fig. 29). Shaded areas are the working faces of the ceramic moulds, as indicated either by refractory facing or by casting traces. Nos. 1, 2, 5, 6, 11–14 are based on actual artefacts. Nos. 10 and 13 show the final cast implement. See also Figure 82. **1–2**. Two parts of ceramic mould for upper part of iron mould (no. 7) (resp. artefact nos. T49:2, T49:1; cf. no. 11). **3–4**. Two parts of ceramic mould for iron mould-core (no. 8) (plaster reconstructions). **5–6**. Two parts of ceramic mould for lower iron mould (no. 9) (resp. artefact nos. T49:3, T49:4; cf. no. 14). **7**. Upper part of iron mould (plaster reconstruction). **8**. Iron mould-core, outer and inner sides (plaster reconstruction, cf. no. 12). **9**. Lower part of iron mould (plaster reconstruction). **10**. V-shaped ploughshare-cap (plaster reconstruction, cf. no. 13). **11**. Part of ceramic mould for upper part of iron mould (artefact no. T10:10; cf. no. 1). **12**. Iron mould-core (artefact no. T39:9; cf. no. 8). **13**. V-shaped ploughshare-cap (surface find, no. 4:1; cf. no. 10). **14**. Part of ceramic mould for lower iron mould (artefact no. T49:5; cf. no. 6).

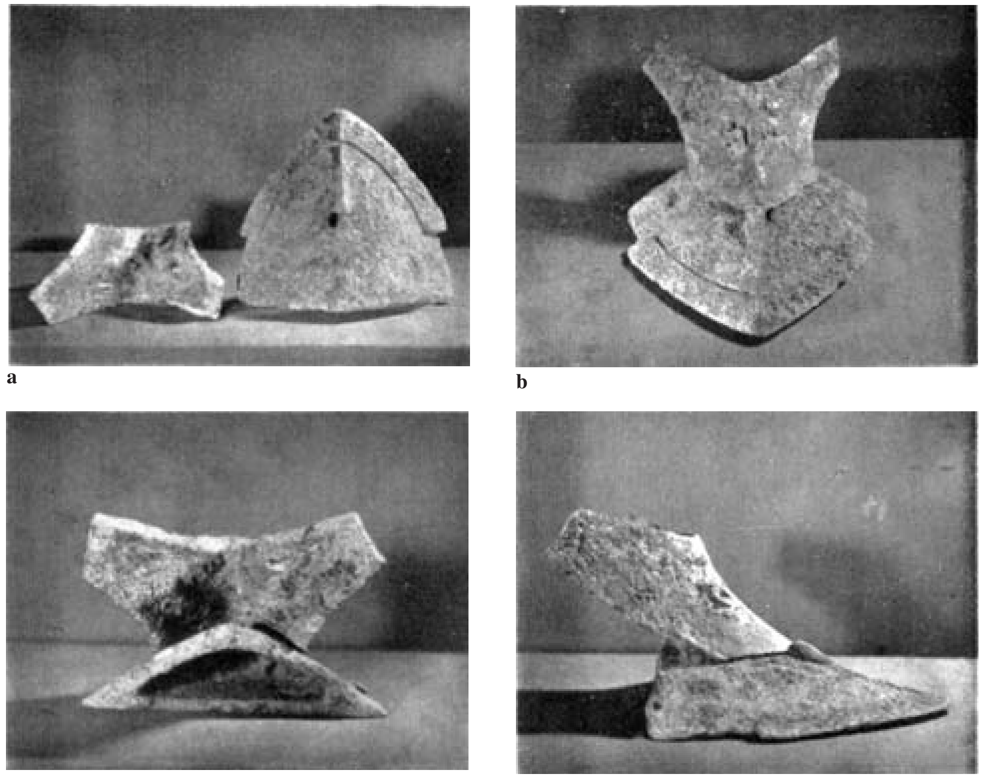


Figure 83 Mouldboard, ploughshare, and V-shaped cap found at Wangxiangcun in Liquan County 禮泉縣王相村, Shaanxi (Li Changqing and He Hannan, 1966, p. 20, pl. 3.3–6). **a**. The three artefacts. The cap is rusted fast to the ploughshare. Ploughshare 23.3 × 28 × 8.6 cm, mouldboard 22 × 23 cm. On the underside of the mouldboard are two lugs for tying with cord and a peg which fits precisely into the hole in the ploughshare. **b–d**. Three views of the artefacts when fitted together.

The result is called in English *malleable cast iron*.[139] In modern practice the heat treatment is typically for a period of a day or two at a temperature in the range 900–1000°C. The purpose may be a tougher casting, or one with a soft and easily machined surface, or a combination of both. The way the process works cannot be discussed in detail here, but a brief description will be given directly below. The

[139] 'Malleable cast-iron' products are seldom actually malleable, so the term is not really appropriate, but it is the only term available in English. The German *Temperguss* and the Chinese *renxing zhutie* 任性鑄鐵 ('tough cast iron') are better, but in these languages one also sees the English term translated: *schmiedbares Gusseisen, keduan zhutie* 可鍛鑄鐵. In the early 20th century the Chinese terms *rou zhutie* 柔鑄鐵 ('soft cast iron') and *ma tie* 瑪鐵 ('*ma*[lleable] iron') also had some currency (Anon., 1923; Hua Jueming, 1982, p. 2).

The term 'malleable cast iron' seems to come from early nineteenth-century marketing. At that time 'malleable iron' was a common term for wrought iron; 'malleable iron' and 'cast iron' thus denoted the two important classes of mass-produced iron products, with steel in a class by itself. 'Malleable cast iron' was therefore an eye-catching phrase, for at first sight it appeared to embody a contradiction in terms.

In modern technical writing one often sees 'malleable cast iron' abbreviated to 'malleable iron'; this term is ambiguous, and will be avoided here.

important matter to note here is that malleable cast iron was widely used in China as early as the −4th century. It was used both for implements and for decorative objects. For some time the *latest* malleable cast-iron objects known in China were from the +4th century, and Chinese historians believed that the technique dropped out of use and was forgotten by the Tang period,[140] but later studies have revealed several artefacts of malleable cast iron from as late as the +9th century,[141] and there is also good evidence that in both China and Japan a traditional technique for producing malleable cast iron was used to some extent as late as the 18th and 19th centuries.[142] The modern process was reintroduced from the West in the early 20th century.[143]

White and grey cast iron

Iron with low carbon content (under about 2 per cent) has excellent mechanical properties, but cannot be cast except at extremely high temperatures; so that wrought iron and steel rarely have been melted or cast before modern times. With higher carbon content the melting point of iron falls, and with about 4 per cent carbon it can be melted and cast using a technology which does not differ greatly from that used in ancient times for melting and casting bronze.[144] It is this high-carbon iron which is called *cast iron*.

Iron which contains so much carbon is brittle, but it may be so for either of two very different reasons, a fact which long confused natural philosophers like Réaumur studying the metallurgy of iron. When iron has been melted and poured into a mould it solidifies as either *white* or *grey* cast iron. These terms come from the colour of the fracture surface when the iron is broken; the colours are different because the microstructures are different. As early as 1722 Réaumur gave a very clear description of the two types: *White cast iron* is extremely hard and cannot be filed or chiselled. Since nearly all iron castings must be finished after they are taken from the mould, white cast iron is a useful material for only a limited range of applications. *Grey cast iron* is soft, and can be filed and chiselled, but the process is difficult to control, and the tool nearly always removes too much material. Grey cast iron can thus (in 1722, in Europe) be used only for coarse castings such as cooking pots and cannons. Both white and grey cast iron are brittle, and can break like glass when hit with a hammer.[145] Réaumur seems never to have considered the possibility of casting implements of any kind of cast iron.

The technical explanation of the properties of white and grey cast iron came later, with better microscopes and an understanding of the rôle of carbon as an alloying element in iron. The carbon in white cast iron is in chemical combination

[140] E.g. Hua Jueming (1982, pp. 17–19).
[141] Du Fuyun (1991, pp. 275–6, table 2, item nos. 14, 17, 28, 29, 34, 36, 37).
[142] See pp. 357–60 below.
[143] See e.g. Anon. (1923).
[144] See the iron–carbon equilibrium diagram in Figure 110 below, p. 259.
[145] Réaumur (1722, pp. 390–405); tr. Sisco and Smith (1956, pp. 260–70).

with iron in cementite (iron carbide, Fe_3C). A white cast iron with 4 per cent carbon is 60 per cent cementite. Cementite is extremely hard, harder than quartz, and this is why white cast iron is hard and brittle.

In grey cast iron the carbon is in the form of microscopic graphite flakes, and it is these which cause a fractured surface to appear grey. Graphite is very light (2.2 g/cm^3 vs 7.9 g/cm^3 for iron), and a grey cast iron with 4 per cent carbon by weight contains up to 13 per cent graphite by volume. Graphite comes close to being the softest mineral known, and in comparison with iron has no strength at all. The microscopic flakes act therefore as internal cracks in the iron. It is these cracks which make grey cast iron brittle, and they also cause the iron to spall when it is filed or chiselled.

Réaumur, using the concepts of the chemistry of his time, explained the difference between white and grey cast iron as being due to differences in their content of 'earthy matter' (*matières terrestres*); but it confused the issue for him that the thickness of the casting also plays a rôle. As he notes, thin castings have a greater tendency to solidify white than thick castings.

We know today that solidification of cast iron as white or grey depends on the interaction of two factors, the chemical composition of the iron (especially the silicon content) and the cooling rate in the mould. High silicon content and slow cooling rate encourage solidification as grey cast iron, while low silicon content and fast cooling rate encourage solidification as white cast iron. What Réaumur interpreted as 'earthy matter' in his observations was various silicon–iron–oxygen compounds in slag; and thin castings cool more quickly in the mould than thicker castings.[146]

Grey cast iron is by far the most widely used form of cast iron in modern industry. Its low cost, excellent casting properties, and reasonably good mechanical properties make it the material of choice for a wide variety of applications. In modern industry grey cast iron generally has about 2 per cent silicon. The cast iron used in early China always had an extremely low silicon content,[147] typically around 0.2 per cent, and such iron usually solidifies white. To cause it to solidify as grey cast iron requires elaborate techniques to assure that it cools extremely slowly in the mould. It is therefore not surprising that grey cast iron was seldom used in ancient China. A cast-iron mould from the Mianchi scrap-heap is the most interesting of these, for we also know its chemical composition.[148] It has only 2.31 per cent carbon and 0.21 per cent silicon, yet it is grey cast. In the micrograph of Figure 84 the graphite flakes can be seen as grey lines. This artefact was probably cast in a pre-heated massive ceramic mould and allowed to cool very slowly.[149]

[146] Cf. Sisco and Smith (1956, p. 261, fn.).
[147] Wagner (1993, pp. 348, 450–6).
[148] On the Mianchi scrap-heap see p. 250–1 below.
[149] An example of this technique can be seen in a 19th-century description (Anon., 1884a; Wagner, 1999b) of the casting of woks in 'Sam-tiu-chuk, one of the principal towns of the sparsely populated and mountainous district of Kwei-shin' (modern Huiyang County 惠陽縣, Guangdong). Massive ceramic moulds were heated in a special oven to 'a bright red or almost white heat'; the iron was then poured, after which the oven was closed and allowed to cool over a period of two days. The chemical analysis of the iron is not given, but it may be presumed that it had either very low silicon or very high sulphur, so that a grey microstructure could be obtained only by extremely slow cooling. That the castings did indeed solidify grey is indicated by the fact that casting runners could be sawed off; this would be virtually impossible with white cast iron.

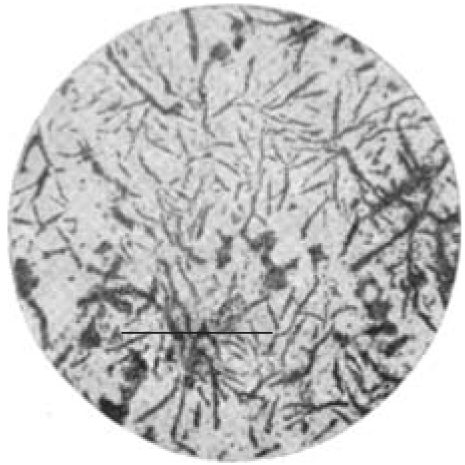


Figure 84 Microstructure of a ploughshare-cap mould from an ancient scrap-heap excavated in Mianchi County 澠池縣, Henan (artefact no. 420, Anon., 1976, p. 54, fig. 4). Etched with nital, × 100 (scale bar 200 μm). Ferrite + flake graphite.

White cast iron has been used in modern times in a number of applications in which abrasion resistance and high compression strength are important. Examples are railway-carriage wheels, the wearing parts of crushing machines, bearings, sprockets, ploughshares, and mouldboards.[150] It is much more important, however, in the production of malleable cast iron, to be discussed below. In a pre-modern context white cast iron could have been useful in a much wider range of applications, as William Rostoker has demonstrated.[151]

Ancient Chinese white-cast-iron artefacts include axle-collars, mattock-caps, and moulds. Axle-collars and mattock-caps are subject in use to considerable abrasion, and white cast iron may be a very good material for these, though many ancient Chinese mattock-heads have been found to be of malleable cast iron. A ploughshare and another axle-collar were found to be 'mottled', i.e. white cast iron with some graphite flakes in the structure. Since these artefacts require extreme abrasion resistance it is possible that it would have been better to have a pure white structure here.[152] For the iron moulds a grey structure would probably have been more appropriate than white, because of the great strains which a mould undergoes when molten iron is poured into it.

150 Massari (1938, pp. 217, 233).

151 Rostoker (1987a). An additional point to be noticed is that white cast iron with very low silicon and phosphorus was, in early modern times, called 'tough pig'. According to Morton and Wingrove (1971, p. 25), 'these irons were sufficiently tough in the cast condition to permit their use in hammers and anvils, hence the name . . .' If this is correct then the low-silicon low-phosphorus white cast irons of ancient China were even better for implements than Rostoker has shown, for it is likely that he used a modern alloy with 1% Si or more. I know of no quantitative studies on the influence of silicon on the mechanical properties of white cast iron, but Zhao and Langer (1982, pp. 289–90) have shown that other alloying elements can have a very significant effect. In one experiment the addition of 0.3% Mischmetall raised the impact toughness of a specific white-cast-iron alloy from 14,000 to 30,000 J/m^2.

152 On the other hand several V-shaped caps for ploughshares are of malleable cast iron. Apparently these protected the brittle ploughshare with a tougher part, which however wore away quickly and needed to be replaced frequently.

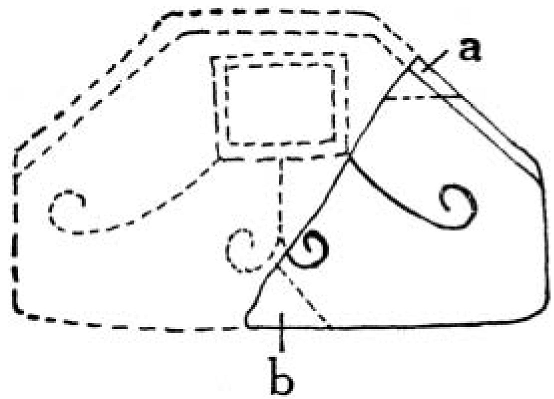


Figure 85 Hexagonal hoe-head fragment from an ancient copper-mine site at Tonglüshan in Daye County 大冶縣銅綠山, Hubei (Ye Jun, 1975, p. 25, fig. 13). Thickness 0.22 cm at cutting edge, 0.3 cm at farther side.

Malleable cast iron

Annealing (heat treating) a white-cast-iron object at a high temperature for a period of days can significantly improve its properties, producing what is called *malleable cast iron*. Two quite different processes operate to bring about this effect, *decarburisation* and *graphitisation*.[153]

If the furnace atmosphere during the anneal is slightly oxidising, the carbon in the iron is burned away at the surface. In the course of a few days all or most of the carbon in the casting can diffuse to the surface and be burned away, leaving a decarburised iron casting whose carbon content corresponds to that of steel or even wrought iron. An example is the hoe-head shown in Figure 85. The micrographs of Figures 86–87 show that it was cast as white cast iron, then decarburised in this way.[154]

The iron may also 'graphitise', that is, the cementite (iron carbide, Fe_3C) in the iron can decompose and precipitate as graphite ($Fe_3C \rightarrow 3Fe + C$). It happens that the microscopic graphite 'nodules' precipitated in this process have a much more rounded shape than the flakes in grey cast iron, and graphitised white cast iron is therefore much more tough than grey cast iron.[155] An example is shown in Figures 88–89.

153 For a more detailed treatment see Wagner (1987b; 1989; 1993, pp. 335–404).

154 Wagner (1989, pp. 15–20; 1993, pp. 356–9, 480–1).

155 The stress concentration at a crack is determined by the effective radius of its tip; this is why glaziers sometimes drill a small hole at the tip of a beginning crack in a window. In the same way the more rounded forms of graphite in malleable cast iron cause much less stress concentration (and therefore less brittleness) than the flakes of graphite in grey cast iron. J. E. Gordon (1978, pp. 65–71 *et passim*) has given a useful introduction to these difficult matters.

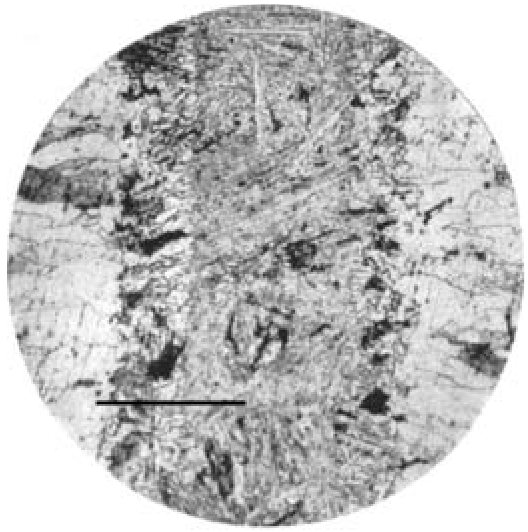


Figure 86 Microstructure of the hoe-head fragment of Figure 85 (Ye Jun, 1975, p. 25, fig. 14; better reproduction Li Zhong, 1975, pl. 1.5; cf. Hua Jueming, 1982, pl. 1.1). Point a in figure 85, etched with 4% nital, × 40 (scale bar 0.5 mm). Cf. Figure 87. Surface decarburisation at a temperature between 723°C and 910°C has given a structure with a layer of ferrite (with zero carbon) at the surface, a layer under this of pearlite (approx. 0.8% carbon), and an unchanged core of ledeburite (approx. 4.3% carbon).

Figure 87 Microstructure of the hoe-head fragment of Figure 85 (Ye Jun, 1975, p. 25, fig. 15). Central band in Figure 86, etched with 4% nital, × 100 (scale bar 200 μm).

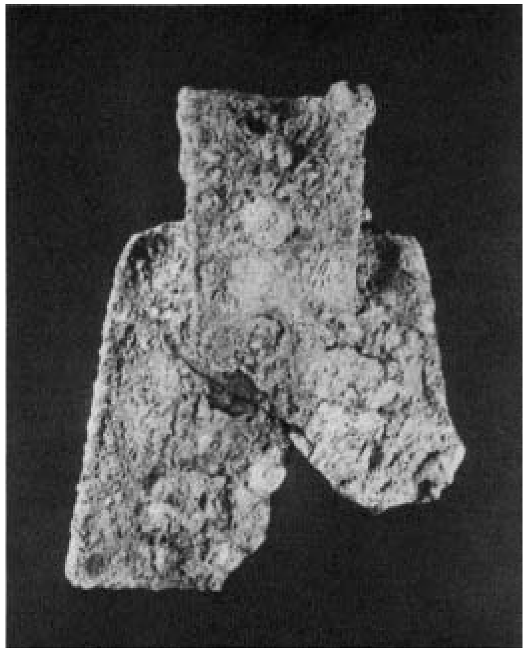


Figure 88 A spade-head, one of seven found in an accumulation outside the entrance to the tomb of Dou Wan 竇綰, consort of Liu Sheng 劉勝 (d. −113), in Mancheng 滿城, Hebei (artefact no. 2:001, Anon., 1980c, pp. 280–1, pl. 196.3). Length 14.2 cm, width at shoulders 8.8 cm, socket 4.6 × 1.6 cm.

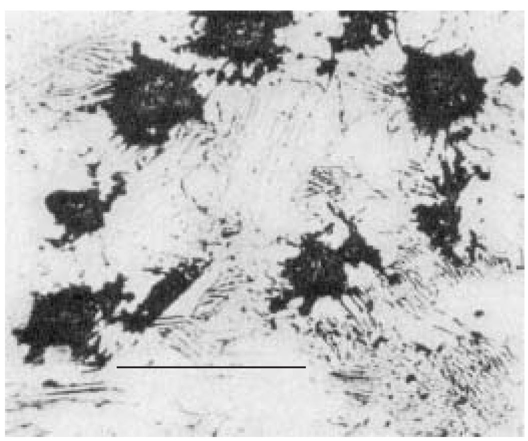


Figure 89 Microstructure of a spade-head from the tomb of Dou Wan (artefact no. 2:003, probably similar to Figure 88, Anon., 1980c, p. 370, pl. 252.4). Etched (with nital?), × 250 (scale bar 100 μm). Ferrite, pearlite, and compact nodular graphite.

In the production of malleable cast iron in industry today, usually only graphitisation takes place. Until recently, however, the annealing was carried out in such a way that both graphitisation and decarburisation took place, with one or the other dominant. If the primary effect of the heat treatment is to decarburise the casting, the product is called *whiteheart* malleable cast iron; if the primary effect is graphitisation, it is called *blackheart* malleable cast iron.[156]

The invention of malleable cast iron has usually been attributed to Prince Rupert (Rupprecht von der Pfalz, 1619–82), who patented the process in Britain in 1670.[157] The first systematic study of it was published in 1722 by René Antoine Ferchault de Réaumur (1683–1757),[158] but the technique first became industrially important in the 19th century, in Britain. The period of greatest relative importance of malleable cast iron may have been about the end of the 19th century, after which the falling cost of steel and the rising cost of fuel made it a less attractive alternative; but malleable cast iron is still very important in industry today.[159]

The discovery that this modern process had been used in China in the −3rd century was another of the surprises in the archaeology of iron which came in the 1950s. Before this time there had been few metallographic studies of ancient Chinese cast iron.[160] In 1956 Joseph Needham organised a project for the examination of 48 samples taken from iron artefacts in the Royal Ontario Museum, Toronto.[161] Reading the examination report with hindsight, it seems certain that several of the artefacts were of malleable cast iron, but this was not recognised at the time, partly because the samples were too small to provide the kind of definite evidence that would have been needed for such a radical conclusion.

The first metallographic investigation of iron artefacts from controlled excavations in China was that of Sun Tinglie.[162] From the iron artefacts unearthed in the

[156] The names come from the appearance of the fracture in older practice; see e.g. the illustrations given by Gilbert (1954) and Moore (1960).

[157] Prince Rupert's original patent was granted on 6 May 1670, but apparently was never published, and seems now to be lost. It is quoted in Patent no. 164 for 1671, with all technical details omitted. Patent no. 161 for 1670 transfers the rights to this patent from Prince Rupert to 'Hartgill Baron Edmund Hampden and Thomas Stringer'; but Patent no. 164 for 1671 assigns the same rights to the King, Charles II. Patent no. 165 for 1671 is a grant to Prince Rupert and two representatives of the Crown of the right to administer oaths of secrecy to workmen employed in the application of the original patent. These three patents were published at the Great Seal Patent Office, Holborn, 1857; I am grateful to Dr Michael Salt for tracking them down for me. On other early English patents see Lohse (1910, p. 102); Vogel (1917–20; 1980, pp. 1101–2); Schubert (1957, pp. 270–1).

[158] Réaumur (1722); tr. Sisco and Smith (1956).

[159] The history of malleable cast iron in the West has not yet been written. Voye (1914), Vogel (1917–20), Maurmann (1923), and Schüz and Stotz (1930, pp. 1–48) give some useful historical notes, mostly on developments in Germany. Deprez (1930) and Davis (1898) discuss early developments in Belgium and the United States respectively. Note also Lansing (1951).

[160] Perhaps the only important one was that of Pinel et al. (1938), in which none of the artefacts considered happened to be malleable cast iron.

[161] The examinations were carried out by Dr J. G. Pearce at the British Cast Iron Research Association in Birmingham. His report is in the archives of the Needham Research Institute, and will in the future be made available on the Institute's web-site. Correspondence with Dr H. Morrogh of the BCIRA in 1982 indicates that the samples used in this project are now irretrievably lost.

[162] Sun Tinglie (1956); Wagner (1993, pp. 355–6).

Hui County excavations he chose six which appeared to be of cast iron. The results seem to have come as a shock. The structures turned out to be extremely non-uniform. He believed that a cast artefact must have a uniform structure, and therefore found it necessary to assume that these had not been cast, but wrought from bloomery iron. He suggested an extremely complex reconstruction of how the artefacts, which seemed so obviously to have been cast, could have been made by a smith.[163]

Sun Tinglie's report was very soon corrected by other workers,[164] and further metallographic studies of ancient artefacts made it clear that malleable cast iron was the preferred material for a large variety of implements in ancient China. Today a great many metallographic examinations of ancient Chinese malleable cast-iron artefacts have made it possible to study the ancient techniques in considerable detail.[165]

In Western industry, before about 60 years ago, the heat treatment of castings to produce malleable cast iron was normally as follows.[166] The castings were sealed, together with a packing material, in 'annealing pots' (or 'saggars'). The packing could be a chemically neutral material such as sand or crushed slag, in which case its only purpose was to provide mechanical support for the castings. It might on the other hand be an oxidising material, such as iron oxide, assuring a slightly oxidising atmosphere in the annealing pot to decarburise the iron. Many tons of castings were packed in annealing pots, and the pots stacked up in a large annealing furnace, which usually was fired with cheap coal, sometimes with gas.

It was realised very early that the use of these heavy pots, together with the packing material, was wasteful of both labour and fuel, and that a good deal could be saved if the pots were eliminated. It was known that the annealing of castings directly exposed to the furnace combustion gases could be useful, though it did involve some 'scaling' (surface oxidation) of the castings,[167] but annealing without pots was seldom practised until World War II, when the 'gaseous process' was developed in parallel efforts in Germany and Britain.[168] Its use led to a great saving in time and fuel, as is shown for example by a survey of malleable foundries in the USA using both processes.[169] The foundries still using annealing pots reported total annealing times of 68–201 hours, those using the gaseous process 12–52 hours.

In excavations of ancient Chinese ironworks kilns are often found, and while some of these clearly were used for firing ceramic moulds, they may also have been

[163] This attempt at reconstruction is described in detail by William Watson (1971, pp. 83–4).

[164] Yang Kuan (1960, pp. 31–2) cites comments by Lin Shoujin 林壽晉 and Zhou Zeyue 周則岳 in publications which are inaccessible to me.

[165] See e.g. Wagner (1989; 1993, ch. 7).

[166] Among many early descriptions of the process the following are especially interesting: Strickland (1826); Terhune (1873); Rott (1881); James (1900); Akerlind (1907); Erbreich (1915); Turner (1918); Touceda (1922); Schwartz (1922); Guédras (1927–28); Schüz and Stotz (1930); Rehder (1945).

[167] James (1900).

[168] Anon. (1906); McMillan (1938; 1950); Hancock (1946; 1954); Schulte (1949). Bernstein (1954) describes a similar process which used an electric furnace.

[169] Hernandez (1967).

used for annealing iron castings. Chinese potters were capable of very close control of both temperature and atmosphere in their kilns,[170] so that something like the 'gaseous process' could have been used here. Artefacts which might have been used as 'annealing pots' do not seem to have been found, but a reverberatory furnace excavated at the Tieshenggou ironworks site seems to have been used to anneal castings packed in iron oxide in a large sandstone chest.[171]

Other techniques are known which could also have been used in ancient China, for example a traditional Japanese method of decarburising cast-iron tea-kettles by embedding the casting in burning charcoal.[172] In Britain malleable cast-iron nails seem sometimes to have been made by casting a nail and then taking it red-hot from the mould and holding it in a blast of air. The combustion of the carbon in the iron, as well as some of the iron itself, could keep it at the necessary temperature.[173]

The evidence of texts, ironworks excavations, and artefact finds indicates that iron was mass-produced on a very large scale in the −3rd century and after. It is not clear how many peasants used iron implements, but they were certainly a considerable proportion of the population. This surely had profound social and economic implications, though it is a bit difficult to pinpoint what these might have been.

The rapid increase in the use of iron in China was made possible by the use of cast iron. Matters were different at the other end of the Old World, in Roman Europe, where virtually all iron was wrought. Implements, made one at a time by smiths, were more expensive in labour than the Chinese cast-iron implements; and each smith had to undergo a long apprenticeship, so that the production of wrought-iron implements could expand only slowly. Again we have no way of estimating how many European peasants used iron implements rather than wood and stone, but it seems likely that the proportion was much smaller than in China.

Through most of the range of its applications the advantage of cast iron is economic: it is a material with adequate properties for the job to be done that is significantly cheaper than other materials which, were it not for their cost, would be better. The use of cast iron in early China meant that a large proportion of the peasant population could use iron implements. Later, perhaps by the Tang period, the number of smiths in China had increased to the point that many peasants were able to use wrought iron and steel implements, though cast iron continued to be used right up to modern times. No doubt wrought iron was a better material for these implements, but they also provided another sort of advantage which may have been more important. A village smith would have been better able to make implements

170 Rose Kerr et al., *SCC,* vol. 5, part 12, pp. 283–378, esp. pp. 296–301.

171 Table 2, item 8, in Section 5 below.

172 See Box 14, p. 361; Gowland (1914, pp. 52–4). The use of some similar technique might explain the curious mention by Joseph Priestley (1786, p. 358) of the annealing in Birmingham of cast-iron nails in charcoal. But C. S. Smith (1968a, pp. 268–70, n.) believes that Priestley was simply mistaken, and that the nails were in fact annealed in iron oxide.

173 Phillips (1837); Needham (1958, pp. 39–40). This may also be the explanation of the microstructures described by Epstein (1981).

which suited local requirements, while the use of cast-iron implements in the Han and before made the peasants dependent on trade with a distant mass-production centre, where it was more difficult to supply the exact needs of each customer.

The sudden expansion of the iron industry, and the resulting dependence of a large part of the peasant population on distant ironworks, where 'powerful families' assembled multitudes of 'common bandits' in 'deep mountains and remote marshes',[174] was politically dangerous for the rulers of the states of ancient China. Several of the states attempted to establish control over the iron industry, and at least one, Qin, had some success in this. After the establishment of the Han these attempts continued, and led in time to the establishment in −117 of a total state monopoly of iron production. This remarkable measure, its causes and its consequences, will be the subject of the next Section.

[174] P. 144 above.

5 THE HAN STATE MONOPOLY OF THE IRON INDUSTRY

The activist reign of 'the Martial Emperor', Wu-di 武帝 (−140 to −87), saw major changes in the government of the Chinese state, its relations with foreign powers, and its economy, including the rôle of the government in the economy.[1] In −120, two wealthy industrialists were appointed Assistants to the Minister of Agriculture (*Da nong cheng* 大農丞) and placed in charge of the salt and iron industries. These were Dongguo Xianyang 東國咸陽 and Kong Jin 孔僅, who had made their fortunes in salt and iron respectively. Together with Sang Hongyang 桑弘羊, a member of a wealthy merchant family of Luoyang, they investigated matters of government revenue, and in −117 (or possibly −119)[2] they submitted a proposal for a state monopoly of the salt and iron industries.[3]

The proposal was accepted, the monopoly was established, and thus began an immense upheaval in the Chinese iron industry which was long the subject of bitter contention. It has remained a matter of controversy through the centuries, as can be seen in discussions of it by Wang Anshi in connection with the New Policies of +1069[4] and in 1935 by Thomas T. Read in an attack on Roosevelt's New Deal.[5]

In the following discussion of the history of the monopoly we shall consider especially the reasons for the establishment of the monopoly and for the intense opposition which it provoked.

Several of the large ironworks of the monopoly have been excavated, and will be discussed at the end of this Section.[6] It has already been noted in the previous Section that these excavations provide virtually the only information we have on iron-smelting technology in early China.

[1] On the reign of Wu-di see *SCC*, vol. 1, pp. 106ff. Other useful discussions include Chavannes (1895–1905, 1969, vol. 1, pp. lxii–cviii); Loewe (1974; 1985); Twitchett and Loewe (1986, pp. 152–79); Dubs (1938–55, vol. 2, pp. 7–25).

[2] Swann (1950, p. 63) and Wu Hui (1981, p. 157, n. 8) review the sources and conclude, respectively, that the date was −117 or −119. The argument which Wu Hui considers to be strongest is that there would have been no reason to wait three years between appointment and action. I disagree: the establishment of the monopoly required extensive preparation, which could easily have taken three years. The basic sources on the question are *HS*, chs. 24b, 19b, pp. 1164–6, 1167–8, 777; *SJ*, ch. 30, pp. 1428–9; *Zi zhi tong jian*, ch. 19, p. 639; tr. Swann (1950, pp. 97, 271–2, 275, 285); Watson (1993b, vol. 2, pp. 69–71).

[3] *SJ*, ch. 30, p. 1428; *HS*, ch. 24b, p. 1164; tr. Watson (1993b, vol. 2, p. 70); Swann (1950, pp. 271–2, 275–7).

[4] Qi Xia (1987–88, vol. 2, p. 580).

[5] Read (1935). Read was an American mining engineer who spent several years in China, and was one of the best of the early writers on the history of Chinese ferrous metallurgy.

[6] Pp. 229–45.

(i) Outline History of the Monopoly

Background

In the Warring States period there is a fair amount of evidence that the individual states had administrative entities which dealt with bronze production. Numerous bronze inscriptions include the names and titles of officers in charge of metallurgical activities, for example a bronze sword of the state of Zhao 趙 with the inscription:[7]

In the tenth year, the Minister of State, Lord of Yang'an; the Master Craftsman of the Arsenal of the Right, Cha Hu; and the Smelting Officer [*ye li* 冶吏], Pao, . . .

十年相邦陽安君邦右庫工師吏筡胡冶吏疱敎劑

For direct state involvement in the *iron* industry there are various kinds of archaeological evidence, which Xu Xueshu has surveyed.[8] One example is that, at the site of the capital of the ancient state of Qi in Linzi, Shandong:[9] of four iron-foundry sites excavated, two are inside the palace precincts, a good indication, as Xu Xueshu argues,[10] that these were under royal administration. At the same site two early Western Han official seals were found, with the texts 'Aide to the Qi Iron Office' (*Qi tie guan cheng* 齊鐵官丞) and 'Seal of the Qi Iron Extractor' (*Qi cai tie yin* 齊采鐵印). These are from contexts which are certainly earlier than the establishment of the Han monopoly in –117, and Xu Xueshu therefore argues that they indicate the continuation of an administrative apparatus dealing with iron production, from the Warring States state of Qi, in the Han kingdom of Qi.[11]

Evidence for state involvement in the iron industry of the state of Yan is seen in an inscription on several iron moulds from the iron-foundry site in Xinglong County, Hebei.[12] The inscription is now generally read *You lin* 右㐭, and interpreted as 'Granary [*lin* 廩] of the right',[13] though several other interpretations have been suggested.[14] Since the moulds are all for agricultural implements it seems likely that this is the name of an administrative organ concerned with agriculture, and that the foundry was attached to it for the purpose of supplying iron implements for agriculture.[15]

7 Zhang Xueyan (1982); Huang Shengzhang (1983). These authors cite many other similar examples; see also Huang Maolin (1973); Li Jinghua (1985c); Huang Shengzhang (1989).

8 Xu Xueshu (1990).

9 See Table 2, item 39.

10 Xu Xueshu (1990, p. 38).

11 Note also Wang Zhongshu (1982, p. 124; 1984, p. 67); Zhang Chuanxi (1985b, p. 230). We may note in passing another possibility: that these seals represent an early Han continuation of Qin administrative organs rather than a continuation of organs of pre-Qin Qi.

12 Already mentioned above, p. 87.

13 Li Xueqin (1956); Wu Zhenwu (1984, pp. 83–4); Shi Yongshi (1985, p. 120).

14 Shi Shuqing and Yang Zongrong (1954, p. 113); Guo Moruo (1973, p. 205); Huang Maolin (1973, pp. 375–6); Wagner (1993, p. 261).

15 Xu Xueshu (1990, pp. 37–8).

The most substantial evidence for state involvement in the iron industry relates to the state of Qin.[16] Such texts as the stories of the Zhuo, Cheng, and Kong families, already discussed,[17] suggest that Qin may have had an 'industrial development policy' under which industrialists were deported to places where their wealth, together with their technical and organisational skills, could contribute to economic growth. From this type of source it might appear that the state's involvement in the iron industry was entirely indirect, much as in a modern capitalist state. Actual production and distribution may have been in the hands of private persons whose primary concern was their own enrichment, while state policies were designed to encourage them to work in ways which were beneficial to the state. Other sources indicate that this picture is either incorrect or incomplete. Officials of Qin were also directly involved in at least some of the technical processes of iron manufacture.

A couple of sources which tend in this direction have long been known. In his autobiography Sima Qian mentions that his great-great-grandfather Sima Chang 司馬昌 was 'an official in charge of iron' in Qin.[18] In a memorial of about −100, quoted in the *Han shu*, Dong Zhongshu 董仲舒 mentions that Qin 'monopolised the profits of rivers and marshes, and controlled the abundance of mountains and forests'. A comment by Ru Chun 如淳 (+3rd century) explains: 'Qin sold salt and iron expensively, and the common people were distressed.'[19] According to the *Hua yang guo zhi*, an 'officer in charge of the salt and iron market' was appointed by the Qin official Zhang Ruo 張若 in Chengdu 成都(modern Chengdu, Sichuan) in −312, after the Qin conquest of the region.[20]

More definite evidence is given by passages in the Qin legal texts of the −3rd century discovered in a tomb in Hubei in 1975. A number of these laws concern iron production, for example the following:

If mineral production [*cai shan* 采山] is twice assessed as substandard, the bailiff is penalised one *jia* 甲 and his assistant one *dun* 盾.[21] If they are assessed as substandard for three consecutive years, the bailiff is penalised two *jia* and dismissed from office. If they are assessed as substandard but no extra expense is caused, there is no punishment. In the collection of the annual quota, if it is lost before an assessment can be made, or the quantity is deficient, the

[16] The evidence in transmitted texts is conveniently collected by Xu Fu (1955, pp. 270–1) and by Ma Feibai (1982, pp. 487–8, 493). More general accounts are Zhang Chuanxi (1985b).

[17] Above, pp. 140–1.

[18] *Qin zhu tie guan* 秦主鐵官 (*SJ*, ch. 130, p. 3286; tr. Watson, 1958, p. 43). The parallel passage in the *Han shu* (ch. 62, p. 2708) has 'Iron Officer of the King of Qin', *Qin wang tie guan* 秦王鐵官; the graphic difference between the characters *wang* 王 and *zhu* 主 is slight, and either might be a scribal error for the other.

[19] *HS*, ch. 24a, p. 2137, and n. 6, p. 2138. But note Swann (1950, p. 181), where the passage is interpreted differently.

[20] *Hua yang guo zhi*, ch. 3, *SBCK* edn, p. 4b; Liu Lin (1984, p. 196); Ren Naiqiang (1987, p. 178). Liu Lin interprets the phrase *yan tie shi guan* 鹽鐵市官 as 'officers for salt, iron, and markets'.

[21] The words *jia* and *dun* normally mean 'armour' and 'shield' respectively, and commentators therefore interpret these two punishments as fines of a suit of armour or a shield (e.g. Shi Zizheng, 1984; Hulsewé, 1985, p. 18). However, this sort of fine in kind is otherwise either rare or entirely lacking in the Qin legal texts; furthermore the number of *jia* or *dun* specified as a penalty is always either one or two. Therefore I suspect that in this context the words may refer to some sort of fetters, to be worn for some period on the legs and arms respectively.

bureau chief is penalised one *dun*. If [the work of] the Grand Provisioner, the Treasury of the Right, the Treasury of the Left, the Iron Extractors of the Right, or the Iron Extractors of the Left is assessed as substandard, the [respective] bailiff is penalised one *dun*.[22]

It is amazing to have this kind of detail on Qin administration in the –3rd century, instead of the broad and vague view given by the transmitted texts. Ongoing research in China, Japan, and the West is building a much clearer picture of the workings of the Qin government on the basis of excavated texts like this one.[23] In the particular case of the iron industry, however, the details are tantalising, for we cannot put them into a broader picture. There can no longer be any doubt, however, that the Qin administration was deeply involved in the technical details of the production of iron.

Li Jin, in a monumental study of Qin law, suggests that most industry was under a state administration whose basic principles were: (1) standardisation of products; (2) establishment of labour quotas; (3) standardisation of raw material inputs; (4) standardisation of product quality; (5) specialisation of personnel; (6) standardisation of rewards and penalties.[24] His work brings us closer to an understanding of the Qin administration of the iron industry, but we still lack answers to basic questions. Where were the blast furnaces? Who ran them? Who made their charcoal and dug their ore? Where were the foundries and fineries? Through which hands did a ploughshare pass on its way from foundry to ploughman? Were the works actually run by officials on a day-to-day basis, or were they merely supervised by the officials mentioned in the quotation above? How can the principles outlined here be reconciled with the stories of rich industrialists in the *Shi ji*?[25]

There are some indications that Han continued the Qin system of industrial administration, for example a statement by the philosopher Dong Zhongshu 董仲舒.[26] Whether this is correct or not, the administration of the salt and iron industries was at the beginning of the Han under the office of the Privy Treasurer (*shao fu* 少府), who was responsible for the general well-being of the Emperor and his household, and kept his privy purse. The non-agricultural natural resources of the Empire were considered the Emperor's personal property and responsibility, and the income from their exploitation was for his personal use.

Whatever this system was, it was in some way relaxed in the reign of Wen-di 文帝 (–180 to –157). According to the *Yan tie lun*, 'In the time of Wen-di, the people were permitted to cast coins, smelt iron, and boil salt', and this led to excesses by such persons as the King of Wu 吳王 and Deng Tong 鄧通.[27] We have met Deng Tong, and the 'copper mountain' given to him by Wen-di, in a previous Section.[28] The

22 Anon (1978f, p. 138); cf. Hulsewé (1985, p. 112).
23 E.g. Yu Haoliang (1980); Li Jin (1985); Hulsewé (1985). See also Yang Jianhong (1989).
24 Li Jin (1985, pp. 432–5).
25 Translated and discussed above, pp. 140–1. In thinking about such questions it is important to remember that the system need not have been the same throughout the Qin Empire, and that orders from the central administration could not always be enforced in peripheral regions.
26 *HS*, ch. 24a, p. 1137; cf. Swann (1950, pp. 182–3); L. S. Yang (1950, pp. 553–5).
27 *YTL*, ch. 4, Wang Liqi (1958, p. 30; 1992, p. 57); cf. Gale (1967, p. 28); Baudry-Weulersse et al. (1978, p. 68).
28 P. 143 above.

King of Wu 吳王 (Liu Bi 劉濞, d. −154) was a nephew of the first Emperor of Han; in −195 he was enfeoffed with a large region of southeast China, and in −154 he led the unsuccessful Revolt of the Seven Kingdoms. According to the *Shi ji* he had gathered 'fugitives' from all over the Empire to exploit the copper and salt of his kingdom, and the wealth thus created enabled him to reduce taxes and win the loyalty of his people.[29] The relaxation mentioned is presumably a change recorded for −158, when, among several measures intended to relieve suffering from drought and locusts, 'the mountains and marshes were relinquished' (*shi shan ze* 弛山澤).[30]

The establishment of the monopoly

It was against the background of the earlier institutions outlined above that the state monopoly of the salt and iron industries was established in −117. What direct information we have about the events leading up to it comes entirely from the *Shi ji*; the *Han shu* largely copies what that book has to say. In writing the *Shi ji*, Sima Qian clearly had certain purposes, and it will be important to keep these before us as we consider what he actually says about the events.

Most of the story is in the chapter 'Treatise on the balanced standard' (*Ping zhun shu* 平準書), which concerns coinage and state finance.[31] A principal theme of this chapter is the decline from good times of prosperity and social tranquillity in the early years of the Han to hard times in the author's own lifetime, seen partly as an inevitable swing in a historical cycle, partly as a direct result of activist government policies. 'When the present Emperor [Wu-di 武帝, r. −140 to −87] had been on the throne a few years, the Han had flourished for 70-odd years and there was peace and prosperity for all, though some people were beginning to amass huge fortunes. When things reach their greatest growth they begin to decline: such changes are inevitable.'[32] Great expense was entailed in dealing with the barbarian peoples of the east, southeast, south, southwest, north, and northeast. This led to the appointment to official posts of persons who made contributions to the state finances, so that the administration fell into disorder – this breakdown of the state administration because of appointments on criteria other than merit is a recurring theme. At one point, Sima Qian claims, one could become a Court Gentlemen (*lang* 郎) merely by presenting a sheep.[33]

About −130 began the appointment of 'officials whose task is to make a profit' (*xing li zhi chen* 興利之臣)[34] A later commentator adds: 'Such persons as Sang

[29] *SJ*, chs. 106, 118, 129, pp. 2822, 2823, 2825, 2836, 3087, 3267; tr. Watson (1993b, vol. 1, pp. 404, 405, 406, 421–2, vol. 2, pp. 336–7, 444). Cf. *HS*, ch. 35, pp. 1904–5, 1918; Loewe (2000, pp. 334–7).

[30] *SJ*, chs. 10, p. 432; Chavannes (1895–1905, 1969, vol. 2, p. 485); Watson (1993b, vol. 1, p. 305); *HS*, ch. 4, p. 131; Dubs (1938–55, vol. 1, p. 266). Chavannes and Dubs both state that the passage refers to a relaxation of restrictions on hunting and fishing, but in fact 'mountains and marshes' was a standard way of referring to the iron and salt industries.

[31] *SJ*, ch. 30, pp. 1417–43; Watson (1993b, vol. 2, pp. 61–85). Much of this material is repeated in *HS*, chs. 24a–b; tr. Swann (1950).

[32] *SJ*, ch. 30, p. 1420; Watson (1993b, vol. 2, p. 63); cf. *HS*, ch. 24a, p. 1136; Swann (1950, p. 177).

[33] *SJ*, ch. 30, pp. 1422; Watson (1993b, vol. 2, p. 65); cf. *HS*, ch. 24b, p. 1158; Swann (1950, p. 250).

[34] *SJ*, ch. 30, p. 1421; Watson (1993b, vol. 2, p. 64); cf. *HS*, ch. 24b, p. 1157; Swann (1950, p. 246).

Hongyang and Kong Jin';[35] it may be, however, that Sima Qian was specifically referring here to a man named Zheng Dangshi 鄭當時, who was appointed Minister of Agriculture (*da nong ling* 大農令) at this time.[36] Not much is known about him,[37] but it was he who later appointed the men who established the monopoly. One of Zheng Dangshi's first acts in his new position was to propose the construction of a canal connecting the capital, Chang'an (modern Xi'an, Shaanxi), to the Yellow River, in order to expedite the transportation of tax grain from the eastern provinces.[38] This was the kind of measure for improving state finances that Sima Qian generally deplored, though in this case he seems to have approved of it.

Sima Qian mentions with explicit distaste that great fortunes were being made in salt and iron, and he tells of these industries coming under the purview of the Ministry of Agriculture in the context of increasing pressure on the finances of the state. The move clearly provides an example of the wrong sort of people becoming officials. At the beginning of the Han, the descendants of tradesmen had been barred from official positions;[39] now some of the highest positions in the land were held by such people:

> At this point [ca. –120], Dongguo Xianyang 東國咸陽 and Kong Jin 孔僅 were appointed Assistants in the Ministry of Agriculture [*da nong cheng* 大農丞] and given charge of matters involving salt and iron. Sang Hongyang 桑弘羊 served as Palace Attendant with duties involving calculations.[40]
>
> Dongguo Xianyang was a great salt-boiler of Qi 齊 [modern Shandong], and Kong Jin[41] was a great smelter of Nanyang 南陽 [modern Nanyang, Henan]. Each had accumulated a fortune of a thousand in gold, and therefore they were recommended by Zheng Dangshi. Sang Hongyang was a scion of a merchant family of Luoyang 雒陽 [modern Luoyang, Henan]. Because he could do mental arithmetic [*xin ji* 心計] he had been made a Palace Attendant at the age of 13. Thus the three men, in discussing matters of profit, were able to 'split an autumn hair'.[42]

Some modern readers will feel that these were the men who had the necessary expertise to administer a large industry, while others will feel that the Emperor was setting the fox to guard the henhouse. We shall see that both opinions were held in the Han period, but Sima Qian clearly held the second.

35 Wei Zhao 韋昭 (+3rd century), in *SJ*, ch. 30, p. 1421, n. 6.

36 Ma Yuancai (1934, p. 19) determines that the date of Zheng Dangshi's appointment was –130. See *HS*, ch. 19b, p. 770.

37 He has short biographies in *SJ* (ch. 120, pp. 3111–13); tr. Watson (1993b, vol. 2, pp. 315–18); and *HS* (ch. 50, pp. 2323–6). See also Loewe (2000, pp. 721–2).

38 *SJ*, chs. 29, 30, pp. 1409–10, 1424–5; Watson (1993b, vol. 2, pp. 55–6, 67); *HS*, ch. 24b, p. 1161; Swann (1950, pp. 260–1). The *Zi zhi tong jian* (ch. 18, p. 597) places this event in the year –129.

39 *SJ*, ch. 30, p. 1418; Watson (1993b, vol. 2, p. 62); *HS*, ch. 24b, p. 1153; Swann (1950, pp. 231–2).

40 *Sang Hongyang yi jisuan yong shi shi zhong* 桑弘羊以計算用事侍中. The parallel passage in the *HS* (ch. 24b, p. 1164) has merely that 'Sang Hongyang was an Imperial favourite' (*Sang Hongyang guixing* 桑弘羊貴幸). Ban Gu may have made this emendation because Sang Hongyang had already been a Palace Attendant since the age of 13, i.e. since –140, the first year of the reign of Wu-di. On these persons see Loewe (2000, pp. 75, 210, 462–4).

41 As Zhang Chuanxi (1985b, p. 232) notes, Kong Jin was presumably a member of the Kong family of iron-masters described by Sima Qian in his 'Biographies of the money-makers'; see pp. 140–1 above.

42 *SJ*, ch. 30, p. 1428; *HS*, ch. 24b, p. 1164; cf. Watson (1993b, vol. 2, pp. 69–70); Swann (1950, pp. 271–2).

In −117 the proposal for a state monopoly on salt and iron was presented to the throne:

The Minister of Agriculture [Zheng Dangshi] presented the memorial of the Assistants for Salt and Iron [*yan tie cheng* 鹽鐵丞] Kong Jin and Dongguo Xianyang:

'The mountains and seas are the storehouse of Heaven and Earth, and ought to belong to the Privy Treasury. Your Majesty has not been selfish, and has allowed it to be transferred to the Ministry of Agriculture in order to supplement the poll tax [*fu* 賦].[43]

'We propose that commoners be recruited to boil salt using government equipment, providing for their own expenses. The government should provide *lao* 牢-cauldrons.[44]

'As to those shiftless persons who get their sustenance without working,[45] and wish to arrogate to themselves the products of mountains and seas and become wealthy, profiting by the labour of the common people, there have been numerous accusations of "obstructing affairs" [of the state, *ju shi* 沮事].[46]

'Anyone who dares privately to cast iron implements or to boil salt should [be sentenced to] wear a fetter on his left foot, and his equipment should be confiscated.[47]

'In those commanderies which do not produce iron, "minor iron offices" [*xiao tie guan* 小鐵官] should be established, which may conveniently be administered by the prefectures.'

[The proposal was accepted and] Kong Jin and Dongguo Xianyang were sent by relay carriage to organise the salt and iron [industries] of the Empire. They established offices and appointed the wealthiest of the former salt and iron industrialists to staff them. The ways to official position became even more varied, proper evaluation was not carried out, and many [appointees] were merchants.[48]

The original memorial was surely much longer than the bit quoted here in the *Shi ji*, giving more historical background and many more details of the administration of the proposed monopoly.[49] We can see at any rate that salt-boiling was to be done by moneyed persons under some sort of government licence. The link between the salt and iron industries is explicitly the iron vessels used in salt boiling. Perhaps the casting of these vessels was, as in later times, often done at the salt works,[50] so that a monopoly

[43] Variant in *YTL*: 'In ancient times the famous mountains and great marshes were not given as fiefs for subordinates to monopolise the profits. The profits of mountains and seas and the accumulations of the great marshes are the storehouse of Heaven and Earth. Your Majesty has not been selfish, but has allowed these to be transferred to the Ministry of Agriculture in order to succour the common people.'

[44] Perhaps a particular type or size of salt-boiling cauldron, as suggested, e.g., by Hua Jueming (1997, pp. 94–5); but cf. Chen Zhi (1980, pp. 110–11), who 'suspects' that *lao* might mean 'strong, solid'.

[45] The *Suo yin* 索隱 commentary (+8th century) explains this as referring to the feudal lords, and this interpretation fits what we know of the attitude of Kong Jin and Dongguo Xianyang. On the other hand Wang Liqi (1992, p. 83, n. 10) adduces text parallels which suggest that the phrase refers to wealthy merchants.

[46] On this phrase note Wang Liqi (1992, p. 84, n. 14).

[47] The parallel passage in the *Yan tie lun* has at this point a passage which may be a part of the original memorial: 'Iron implements and edged weapons are the great essentials of the Empire; they are not suitable matters for the common run of men.'

[48] *SJ*, ch. 30, p. 1429; cf. Watson (1993b, vol. 2, pp. 70–1); Chavannes (1895–1905, 1969, vol. 3, 570–1). Parallel texts: *HS*, ch. 24b, pp. 1165–6; cf. Swann (1950, pp. 275–8). *YTL*, ch. 6 and 9, Wang Liqi (1958, pp. 42, 64; 1992, pp. 78, 120); Gale (1967, pp. 34–5, 55); Baudry-Weulersse et al. (1978, pp. 74, 77).

[49] As noted in nn. 43, 47, and 48 above, the *Yan tie lun* includes what appear to be quotations from the same memorial. A possibility worth exploring is that other passages in that book come from the lost parts of the memorial.

[50] Note e.g. the description of ironfounding given in a Yuan-period text on salt production, *Ao bo tu* 熬波圖, p. 324 below; Yoshida (1993, pp. 140–5).

of iron production could not have been effective if salt production were not also included. The vessels were to be supplied by the government, but no details are given as to the production of these;[51] however we know from other sources, primarily archaeological, that under the monopoly the Han government had the direct administration of the iron smelters and foundries.[52]

Iron production is a complex technical activity, and the ironworks could be effectively administered only by technically competent persons. As the quotation above makes clear, ironmasters were brought into the government as officials, much to the chagrin of traditionalists.

Criticism and disputation

Other state interventions in the economy were made around this same time. Considering the profound effect which these interventions must have had on daily life throughout the Empire, we know remarkably little about them. The system of 'equable transportation' (*jun shu* 均輸), intended to eliminate price variation both over time and from place to place, was established in about −110.[53] There were also a monopoly on fermented liquors, −98,[54] and a variety of measures concerning coinage.[55]

From the beginning the new measures were severely criticised. The criticism came, not from the industrialists,[56] but from traditional agricultural interests. A wealthy farmer named Bu Shi 卜式 in −110 complained that with the 'equable marketing' system 'Sang Hongyang has put the officers of the government in stalls in the market', and elsewhere he claimed that the quality of the iron monopoly's production was inferior[57] – a complaint which would be heard again. In −100 the philosopher Dong Zhongshu 董仲舒, in a memorial whose basic thrust was in favour of agriculture, demanded that 'salt and iron be returned to the people'.[58]

[51] Chen Zhi (1980, pp. 110–11) discusses two large Han iron vessels with inscriptions indicating that they were cast by state foundries.

[52] See below, pp. 192–221.

[53] *SJ*, ch. 30, p. 1432; tr. Chavannes (1895–1905, 1969, vol. 3, p. 598); Watson (1993b, vol. 1, p. 75). *HS*, ch. 24b, pp. 1168, 1174; tr. Swann (1950, pp. 65, 286, 314–15).

A passage in an early Han legal text excavated in 1983 from a grave at Zhangjiashan in Jiangling County 江陵張家山, Hubei, lists the titles of several officers involved in regulating 'equable transportation', but gives no immediate help in understanding the system. The most important fact about this text is that it comes from a grave dated to the early –2nd century (shortly after –186), and therefore indicates that the *jun shu* system was a part of Han administration long before we see it in the histories, in –110. Anon. (1985d; 1985e, p. 9; 2001a, pp. 25, 163–4); Du Shiran (1988, p. 203).

[54] *HS*, ch. 6, p. 204; tr. Dubs (1938–55, vol. 2, p. 107). Various commentators quoted by Yan Shigu indicate that this was a true monopoly of both production and sale.

[55] E.g. *SJ*, ch. 30, pp. 1433, 1434–5; Chavannes (1895–1905, 1969, vol. 3, pp. 580, 584–5); Watson (1993b, vol. 1, pp. 75, 76, 77). Cf. Swann (1950, pp. 377–84).

[56] Cf. Loewe (1974, p. 20).

[57] *SJ*, ch. 30, pp. 1442, 1440; tr. Chavannes (1895–1905, 1969, vol. 3, pp. 600, 595); Watson (1993b, vol. 2, pp. 83, 81). *HS*, ch. 24b, pp. 1175, 1173; tr. Swann (1950, pp. 319, 311). On Bu Shi see Loewe (2000, pp. 16–17).

[58] *HS*, ch. 24a, p. 1137; tr. Swann (1950, p. 183). On Dong Zhongshu see *SCC*, vol. 2, e.g. pp. 378–9.

Dissatisfaction with state interventions in the economy apparently became general enough to require some show of concern by the government, and in –81 a Grand Inquest was held. At this time the Emperor, Zhao-di 昭帝, was a child, and power was held by the General and Emperor-maker Huo Guang 霍光.[59]

[In the sixth year of the *Shiyuan* 始元 period], in the second month, a decree commanded the officers to inquire of Worthies and Scholars recommended by the provincial authorities concerning the causes of the people's suffering. They proposed the abolition of the salt and iron monopolies.[60]

'Worthies' (*xian liang* 賢良) were persons recommended to the central government by local authorities for possible official appointments, while 'Scholars' (*wen xue* 文學) were persons approved for their literary competence by the central government. The two categories represented between them the provincial elite in opposition to the central administration.[61]

Out of this inquiry came the abolition of the liquor monopoly, but only a minor adjustment of the salt and iron monopoly: the Iron Offices in the region 'within the passes' (the capital region) were closed.[62] But it became the subject of a remarkable book, *Yan tie lun* 鹽鐵論, 'Discourses on salt and iron', which purports to give a complete account of what was actually said in the debate. It gives in dialogue form a very clear picture of many controversies of the day, ranging from metaphysics to practical politics. I have already had occasion to quote from it.[63] One chapter is translated in Box 9,[64] and the book will be discussed further in the following Section.

Sang Hongyang appears to have been the prime mover in the economic initiatives of this time. Huo Guang appointed him to the high post of Imperial Counsellor (*yu shi da fu* 御史大夫) on taking power in –87. He came through the discussions of –81 with his policies largely intact, but there appears to have been more of a direct power struggle here than at first meets the eye, for in –80 he was implicated in a

[59] Wu-di on his deathbed had ordered that his youngest son should succeed him, with Huo Guang as regent. There had been no witnesses to this order other than persons who gained from it. Later on, when Zhao-di died before reaching his majority, Huo Guang first placed one Emperor on the throne, then immediately deposed him and replaced him with another, Xuan-ti 宣帝. Very different views of Huo Guang's character are expressed by Dubs (1938–55, vol. 2, pp. 143–4), Loewe (1974, e.g. p. 118), and Liu Pak-yuen (1983, e.g. p. 105). While Dubs concludes that Wu-di was 'an excellent judge of character' and Huo Guang 'the ideal person for the position – quiet, steady, careful and reliable', Liu Pak-yuen considers Huo Guang 'dishonest and unfaithful'. Loewe calls him 'a composed and calculating man of affairs', and tends towards the opinion of Dubs, but seems to avoid making an explicit judgement on whether the story of Wu-di's deathbed edict was true or false. Most of the story can be read in Huo Guang's biography, *HS*, ch. 68, pp. 2931–67; tr. Watson (1974, pp. 121–57); all of the relevant sources are translated into Swedish by Jongchell (1930).

[60] *HS*, ch. 7, p. 223; tr. Dubs (1938–55, vol. 2, p. 175).

[61] Cf. Bielenstein (1980, pp. 133, 94).

[62] The abolition of the liquor monopoly is in *HS*, ch. 7, p. 224; tr. Dubs (1938–55, vol. 2, pp. 161–2). The adjustment to the salt and iron monopolies is mentioned only in *Yan tie lun*, ch. 41, Wang Liqi (1958, p. 276; 1992, pp. 463–4).

[63] Above, p. 144.

[64] Pp. 180–2 below.

Box 9 *Translation of* Yan tie lun, *ch. 36, Wang Liqi (1958, pp. 251–3; 1992, pp. 428–30); cf. Baudry-Weulersse et al. (1978, pp. 193–6); Satō Taketoshi (1970, pp. 184–7); Sabine Ludwig in Schefold et al. (2002, pp. 178–92).*

Flood and drought

The Imperial Counsellor: Yu 禹 and Tang 湯 were enlightened rulers, Houji 后稷 and Yiyin 伊尹 were wise counsellors, and yet in their times too there were both floods and droughts. Floods and droughts are produced by Heaven; famine and plenty are due to the motions of Yin and Yang, and are beyond human forces. Thus when the number of Counter-Jupiter[a] is in Yang there is drought, and when it is in Yin there are floods. In six years there is one year of hunger, and in twelve years there is one famine.[b] The paths of Heaven are fixed, and surely the faults of the administration alone cannot cause these things.

A Worthy: In ancient times, when there was virtue in government, Yin and Yang were in harmony, the motions of the stars were regular, and wind and rain were seasonable. If behaviour is regulated within, then fame resounds without; if good is done to those below, then auspicious signs will respond in Heaven.

The Duke of Zhou cultivated himself and there was Great Peace under Heaven. There were no premature deaths in the kingdom, and no lean years. In that time the rain was never violent, nor did the wind howl in the trees. It rained only once every ten days, and always at night. Crops ripened on all the land, whether hilly or high or low. As the *Book of Odes* has it, '[the sky] is densely covered, and the rain[-clouds] rise amply'.[c] Here you fail to consider the true causes of things, but claim that they are due to the motions of Yin and Yang; this is unheard-of.

Mencius said: 'Outside the city walls there are people dying of hunger, and you do not think to nourish them; dogs and swine eat the food of men, and you do not think to be frugal. When he who should be father and mother to the people, seeing them die of hunger, claims it is the fault of a hard year rather than his own, how is this different from taking a knife and killing them, saying, "it is the knife's fault, not mine"!'[d] The task of our time is to eliminate the hardships of hunger and cold. Abolish the salt and iron [offices], remove powerful and wealthy persons from office, divide up the land, emphasise the fundamental vocation, cultivate mulberry and hemp, and make full use of the potency of the earth. If demands are few and expenses are sparing, the people will of themselves have abundance. Then flood and drought will not distress them, and hard years will not trouble them.

The Imperial Counsellor: A debater appreciates expressions which are succinct and clear and suitable for the ears of the mass of people. He does not resort to elegant writing, dense verbiage, and many words, hindering the administration's civilising project, but [uses] the language of the household.

Tao Zhu 陶朱[e] supported himself by a variety of activities, some of them in the fundamental occupations and some in the ancillary occupations. A family shares out many separate tasks in providing for its livelihood. At the present time the State casts implements for the farmers. This means that the people apply themselves to the fundamental occupation and do not concern themselves with ancillary occupations, so

Box 9 *Continued*

hunger and cold do not trouble them. What is the harm of the salt and iron [offices], that they should be abolished?

A Worthy: Agriculture is the great occupation of the Empire, and iron tools are the great implements of the people. When the efficacy of the implements is favourable, then the strength required is small and the results are many, and 'the farmer loves his task and endeavours to produce results'.[f] But if these implements are not provided, then the fields wither, the grain does not grow, strength is used in vain,[g] and the results obtained are halved. On the practicality or lack of it of the implements depends a tenfold difference in results. The iron implements cast by the State are mostly 'large implements';[h] they fill quotas rather than provide the necessities of the people. When the people's implements are dull and worn, straw is not properly cut; then the farmer's work is severe, the results are small, and as a result the common people suffer.

The Imperial Counsellor: Conscript and convict labourers and master craftsmen work daily for the State in the public interest. Their raw materials are supplied in abundance and their equipment is complete. When ordinary people gather together [to make iron], their time is too short and they are fatigued by the work; the strength of the iron is not 'melted and refined' [? *tie li bu xiao lian* 鐵力不銷鍊], and the hard and the soft are not harmonised [? *jian rou bu he* 堅柔不和]. For this reason the administration proposed that possession be taken of the salt and iron industries, so that usage would be unified and prices equalised, to the benefit of the common people and the public and private [interests]. Even the rule of Yu 虞 and the Xia 夏 was not simpler than this. The local officers instruct [the workers], the craftsmen do their work effectively,[i] hard and soft are harmonised, and the implements are practicable. What suffering does this cause the people, and why should the farmers be distressed?

A Worthy: [A fig for your] conscript and convict labourers and master craftsmen![j] Earlier, when foundrywork and salt-boiling were permitted to the people on the payment of a self-assessed tax, salt and grain were sold together. Implements were practical and suitable for use. Today the iron implements produced by the State are mostly crude and coarse. Expense is not spared, the conscript and convict labourers are driven, but their hard work is not used effectively.

When the members of a household united, and father and son pooled their labour, each sought to make excellent implements. Inferior implements were not sold.[k] At busy times for agricultural activity the implements were transported to the fields for distribution. People traded with each other, exchanging money and products, grain, and new and old [implements].[l] Sometimes they sold on credit, so that they did not abandon their vocation. The agricultural implements were supplied, and everyone got what he needed. Corvée was used sparingly. The State used convict labourers and amnestied labourers[m] to repair roads and bridges,[n] and conscripted labourers were not troubled.

Now that [the State has] taken possession of the sources and monopolised the trade, implements are hard and brittle and there is no choosing between good and bad. The responsible officers are often not at their posts, so that the implements are difficult to obtain, [but] ordinary people cannot stockpile several, for if several are stockpiled

(*Cont.*)

Box 9 *Continued*

they rust [?].[o] They must relinquish the most opportune days and travel far to buy implements, so that they must postpone the times of celebration. Salt and iron are sold at high prices, so that the common people are troubled. Some of the poorest must till with wooden implements and weed with their hands, harrow with earth [? *tu you* 土耰] and eat tasteless food.

When the Iron Offices are unable to sell their implements, they sometimes illegally make forced sales to the people. When the convict labourers do not meet their quotas, [the people] are often ordered to assist them. The labour levies are without limit, and the corvée is equally a hardship, so that the common people are distressed.

In ancient times, in a district with a thousand households, or a family with a hundred chariots,[p] there were potters and smelters, craftsmen and merchants, so that the requirements of the four classes of people were all filled by exchange. The farmers were supplied with implements without leaving the fields, the craftsmen were supplied with [lumber][q] without logging, and the potters and smelters were supplied with grain without tilling the fields. Each of the common people got what he needed without the lord's intervention. Thus the kings attended to the basic occupation and did not exert themselves in the ancillary occupations. They eschewed display, eliminated affectation, filled the people with the Rites, and manifested simplicity. Thus the common people attended to the basic occupation and did not involve themselves in the ancillary occupations.

[a] *Tai sui zhi shu* 太歲之數 . See *SCC*, vol. 3, p. 402.

[b] Wang Liqi points out parallels to this curious theory in *Huai nan zi* and in the *Shi ji*. Hu Huojin (1999) reviews some of the ancient sources on the theory, and proposes the surprising hypothesis that it may have been inspired by observed climatic regularities: Jupiter's period is 11.86 years, and this is close enough to the period of the sunspot cycle (about. 11 years), which is known to have an effect on climate.

[c] *Shi jing*, no. 212, text and tr. Karlgren (1950b, p. 167). The poem celebrates a rich harvest, and in its last verse attributes this felicity to the lord's faithful performance of the appropriate rites.

[d] The passage is a paraphrase of *Meng zi*, ch. 1, Yang Bojun (1960, p. 5); Lau (1970, p. 52).

[e] Tao Zhu, whose original name was Fan Li 范蠡, was the prototype of the successful businessman. He has a brief biography in the *Shi ji* (ch. 129, pp. 3256–7; tr. Watson, 1993b, vol. 2, pp. 436–8; cf. *HS*, ch. 91, p. 3683; tr. Swann, 1950, pp. 424–6). Tao Zhu was associated with a man named Jiran 計然, who proposed a theory very like that given above concerning a fixed cycle of good and bad years.

[f] *Le shi quan gong* 樂事勸功, a quotation from *Li ji*, ch. 12, p. 1338c; cf. Legge (1967, p. 230).

[g] ? *Xian* 鮮.

[h] *Da qi* 大器, see pp. 224, 225–8.

[i] An allusion to Confucius: 'The hundred craftsmen dwell in their workshops, so that they may do their work effectively'; *Lun yu*, ch. 19, p. 2532a, cf. Waley (1938, p. 225); Lau (1979, p. 154); *YTL*, ch. 3, Gale (1967, p. 23), Wang Liqi (1992, pp. 43, 53 n. 53, 433 n. 23).

[j] Probably something is missing in the text here.

[k] Taking *ji* 集 to be a scribal error for *shou* 售; cf. Wang Liqi (1992, p. 434 n. 27).

[l] Note the misprint in Wang Liqi's edition (1992, p. 430, line 6), *bi* 幣 for *bi* 弊.

[m] *Fu zuo* 復作, cf. Dubs (1938–55, vol. 2, p. 200, fn. 1.4).

[n] Chen Zhi (1980, pp. 260–1) lists several Han stone inscriptions which indicate that convict labourers were used in the construction and maintenance of roads and bridges.

[o] *Duo chu ze zhen sheng* 多儲則鎭生. The sentence makes little sense as it stands, and Wang Liqi (1992, p. 435, n. 35) suggests that *zhen sheng* 鎭生 may mean *sheng* 鉎, 'rust'.

[p] A fief of the lowest rank.

[q] Something is clearly missing in the text here. Wang Liqi (1992, p. 436, n. 43), following a suggestion of Guo Moruo, adds the characters *cai mu* 材木.

treasonous plot against Huo Guang and executed.[65] For the historian this is a great pity: as a traitor Sang Hongyang could hardly be given a biography in the official-history, the *Han shu*. Such a biography would surely have told us a great deal about his economic measures.

The views of the real ruler, Huo Guang, on economic policy are not made clear in our sources, but whatever these were, Sang Hongyang's fate had no effect on the policies he had promoted. According to the 'Treatise on economics' of the *Han shu*, from this time until the time of Wang Mang there were no major changes, except that the Salt and Iron Offices were abolished in –44 and reinstated in –41.[66] The abolition reflected a new ideological and policy orientation,[67] but the reinstatement is more difficult to explain. The *Han shu* suggests that the reason for the reinstatement was a need for money, but more may have been involved than this. A major industry cannot be privatised at a stroke without consequences for the entire economy: quite probably serious problems became apparent within a short time, and the government found it necessary to return to former arrangements.

The reforms of Wang Mang

The economic reforms of the reign of the usurper Wang Mang 王莽 (+9 to +23) are difficult to understand. The sources are inadequate.[68] If we had more information, from less hostile sources than the *Han shu*, some kind of economic rationality might appear behind them. The picture painted by the *Han shu* is of a chaotic series of measures, obviously unrealistic and self-contradictory. The Empire was ridden by famine and rebellion, events were out of control, traditional methods were inadequate, and radical measures were impossible to enforce.[69]

At any rate both salt and iron were among the 'Six Controls' (*liu guan* 六筦) established by Wang Mang in +10. These seem to have been very similar to the earlier measures of Wu-di's reign, but in +12 severe penalties, up to capital punishment, were prescribed for violators. Increases in statutory punishments are a sure sign that law violations are taking place and enforcement is unsuccessful. In +22 one of the controls, that of the 'mountains and marshes', was temporarily lifted, with the intention that it should be reinstated in +49. Later in the same year an edict was

[65] The plot was to murder Huo Guang, then depose Zhao-di and replace him with an older son of Wu-di who had been passed over in Wu-di's deathbed edict. Most of the story is in *HS*, chs. 7, 63, and 68; see the translations by Dubs (1938–55, vol. 2, pp. 164–6); Watson (1974, pp. 54–65, 126–8); Jongchell (1930, pp. 60–78). See also Loewe (2000, pp. 463–4). Why Sang Hongyang should have involved himself in such a plot is never really made clear, though a kind of explanation is attempted in *HS*, ch. 24b, p. 1176; tr. Swann (1950, p. 321).

[66] *HS*, ch. 24b, p. 1176; Swann (1950, p. 321).

[67] See e.g. Loewe (1985, pp. 242–3).

[68] Cf. Bielenstein (1954, pp. 84–5; 1959, pp. 13–14).

[69] See e.g. the remarkably divergent discussions of Hu Shih (1928); Dubs (1938–55, vol. 3, pp. 506–36); Swann (1950, pp. 69–70, 343 n. 708); Bielenstein (1954, pp. 82–7); Loewe (1974, pp. 286–306); Thomsen (1988). I find it difficult to accept Bielenstein's assertion that the bizarre measures attributed in the sources to Wang Mang were no more radical than those of many other Emperors.

prepared which would have rescinded all of Wang Mang's economic measures, but it was never issued; Wang Mang was killed soon after, in +23.[70]

The Eastern Han period

The –1st century seems to have seen a gradual deterioration of the powers of the central government in favour of powerful families throughout the Empire, and Wang Mang's reforms should probably be seen as a last-ditch attempt to reassert central authority. After Wang Mang's fall and the Restoration of the Han in +25, a reorganisation took place which in effect endorsed the central government's loss of power.

In particular the Salt and Iron Offices, which in the beginning had been under the direct administration of the Ministry of Agriculture, were transferred to the administration of the respective commanderies and prefectures. The office of the 'Commandant of the Imperial Gardens' (*shui heng du wei* 水衡都尉), which from –116 had had a major rôle in the monopolies, probably organising convict and conscript labour, was reduced from a major administrative instance to a minor office having a few seasonal tasks.[71] Judging from the sparse sources available, it seems that there was no longer a monopoly on iron production, but that wherever iron production was on a large scale the local government was directly involved in its administration. There are signs that at least some local Iron Offices still actually produced iron, rather than simply supervising private ironworks.[72]

One attempt was made to change these arrangements. In about +85 Zhang Lin 張林 proposed several economic measures, including government production of salt and iron. The proposal caused great controversy, and was first rejected, then accepted, over the strong protests of a group led by Zhu Hui 朱暉. These monopolies were however abolished again only three years later, in +88, in a 'deathbed edict' of the Emperor Zhang-di 章帝 announced by his 10-year-old successor, He-di 和帝.[73] It is not at all clear what actually happened here, but it is reminiscent of the attempt to *abolish* the monopolies more than a century earlier, in –44, which also lasted only three years. The administration of a large-scale, highly technical industry cannot be radically changed without the most careful preparation – the sort of preparation which seems to have taken place before the establishment of the original monopoly in –117.

[70] *HS*, ch. 99b, pp. 4118, 4150, 4175–6, 4179, 4191; tr. Dubs (1938–55, vol. 3, pp. 300, 369–70, 428, 434–5 [cf. 535], 466).

[71] On the *Shui heng du wei*: *SJ*, ch. 30, p. 1436; tr. Watson (1993b, vol. 2, p. 78); *HS*, ch. 24b, p. 1170; tr. Swann (1950, p. 297). Reorganisation of the salt and iron administration: *HHS*, treatise 26, pp. 3590, 3600; treatise 28, p. 3625; cf. Bielenstein (1979, p. 25); also Yü (1967, pp. 19–21), who interprets the sources differently.

[72] The sources are conveniently gathered together by Su Chengjian (1947, pp. 84–8).

[73] *HHS*, ch. 36, pp. 1225–6; ch. 43, pp. 1460–1; ch. 4, pp. 167–8; *Jin shu*, ch. 26, p. 793; L. S. Yang (1946, pp. 176–7; 1961, pp. 188–9); Zhang Chuanxi (1985b, p. 242). A different interpretation is given by Yü (1967, pp. 20–1) and Bielenstein (1979, pp. 16, 25, 153–4).

(ii) Discourses on Salt and Iron

Our most important source for the workings of the iron monopoly is Huan Kuan's *Yan tie lun*, and it will be useful to look at the book in some detail.[74] It is easy to agree with Guo Moruo's characterisation of it as 'a work of fiction in dialogue form on a historical theme', drawing on essays written in connection with the great debate on salt and iron in –81 but also bringing in much additional material.[75] This view is based especially on a brief note in the *Han shu*:[76]

> The 'discussions of salt and iron' [*yan tie zhi yi* 鹽鐵之議] began in the *Shiyuan* 始元 period [–86 to –81], when Scholars and Worthies were summoned and asked about how disorder was to be dealt with. They all replied by proposing that the [offices] in the Commanderies and Kingdoms for salt and iron, the liquor monopoly, and equable transportation should be abolished. [The government] should serve the fundamental activity [agriculture], restrain the ancillary activities [commerce and industry], and not compete with the empire for profit; only then could civilising instruction be successful.
>
> The Imperial Counsellor [*yu shi da fu* 御史大夫] [Sang] Hongyang believed that these [offices] were the means of pacifying the frontier regions and controlling the barbarians; this was the great task of the state, and could not be abandoned.
>
> At the time there was much questioning and criticism, and many written discussions. During the reign of Xuan-di 宣帝 [–73 to –49], Huan Kuan 桓寬 (from Ru'nan 汝南, with the courtesy name Cigong 次公) had edited the Gongyang version of the *Chun qiu* 公羊春秋 and had been appointed a Court Gentleman [*lang* 郎] [for this achievement]. He reached the post of Vice Governor [*tai shou cheng* 太守丞] of Lujiang 廬江; his erudition was wide-ranging and he was proficient in the composition of documents.
>
> He enlarged upon the discussions of salt and iron, added additional topics, and brought their criticisms to a conclusion, writing several myriads of words with the purpose of investigating how to deal with disorder and establishing a school of thought of his own.

One example of Huan Kuan's compilation technique is his use of the memorial proposing the monopoly, translated above.[77] He has Sang Hongyang saying exactly the same words in the debate, so that he refers to the *former* Emperor, Wu-di, as 'your majesty' (*bi xia* 陛下).[78] Another example is a large number of unattributed quotations from *Guan zi*.[79]

[74] The standard edition is that of Wang Liqi (1958). His revised edition (1992) has a much-enlarged and very useful commentary, but contains so many typographical errors that it cannot replace the 1958 edition. Here I always cite both editions. The most important study is Loewe (1974, esp. pp. 91–112); see also Loewe (1985; 2000, p. 163). The English translation of 28 of the 60 chapters, by Esson M. Gale (1967), is scholarly and reliable. The French translation (Baudry-Weulersse et al., 1978) was placed by its publisher in the hands of a journalist, who reduced it by a third (without indicating where the cuts were made) and revised the language (see p. 42). He succeeded in making the translation much more enjoyable to read than Gale's, whose language is very stilted, but reduced considerably its value for scholarly purposes. Fourteen selected chapters have also been translated by Sabine Ludwig in Schefold et al. (2002, pp. 107–83).

[75] Guo Moruo (1957, introduction p. 4).

[76] *HS*, ch. 66, p. 2903.

[77] P. 177.

[78] Michael Loewe (1993, pp. 478–9) notes that Zhang Zhixiang's 張之象 edition of +1554 has Xuan-di 宣帝 (the posthumous name of the Emperor who reigned from –73 to –49) here in place of *bi xia*.

[79] See e.g. Kroll (1978, p. 14).

One motivation for Huan Kuan to write this work may have been a later debate, which led to the brief abolition of the monopoly in the period –44 to –41.[80] The abolition was a result of a general attack on the rôle of government around this time, in which statesmen such as Gong Yu 貢禹 (–123 to –43) went so far as to demand the abolition of all forms of money and a return to natural economy.[81] Gong Yu seems even to have opposed the use of iron at all, rather than merely its manufacture by the state.[82]

Interestingly enough there seems to be no source outside the *Yan tie lun* which clearly states that the debate of –81 involved an actual meeting, with the opposing sides arguing face to face. The statement quoted above seems, in fact, to suggest that the 'debate' was conducted by exchange of written texts. However that may be, Huan Kuan describes a dramatic confrontation in which 60-odd provincial Scholars and Worthies engage in a dialogue with the Imperial Counsellor, Sang Hongyang (occasionally assisted by others from the government side), in the presence of the Emperor (Zhao-di, at this time in his 14th year) and Huo Guang. The tone of the debate is surprising, with the debaters freely trading insults: 'bigoted Confucians' versus 'decadent toadies'.[83]

The state and the forces of nature

In Box 9 I have translated one chapter of the *Yan tie lun*, and this can give readers a view of the style of the book. I chose this chapter because it contains one of the few concrete discussions of the actual functioning of the monopolies, but it is also an example of the way in which the government's critics directly related government policy to the quality of harvests. The belief that the behaviour of rulers can influence nature is common in many cultures, and surely had very ancient roots in China, though it was Dong Zhongshu who first gave it a systematic formulation.[84] In the decades up to the time of the debates of –81 there seems to have been a series of bad harvests, and for this many blamed Wu-di's policies. Bu Shi in –110 suggested that rain might come if Sang Hongyang were boiled alive.[85] A passage in the biography of an associate of Huo Guang, Du Yannian 杜延年, explicitly connects beliefs about the weather with the holding of the debate on salt and iron:

The nation had inherited the extravagance and military expeditions of the Emperor Wu-di, and [Du Yannian] said several times to General Huo Guang: 'The harvest has failed year

[80] See p. 183 above. This motivation is suggested by Loewe (1985, pp. 255–6).
[81] Gong Yu's memorials are quoted in his biography, *HS*, ch. 72, pp. 3069–80. The specific attack on monetary economy is on p. 3075 and is abridged in ch. 24b, p. 1176; tr. Swann (1950, p. 322). See also Loewe (1985, pp. 263–4 *et passim*).
[82] *HS*, ch. 72, p. 3075.
[83] *Ju ru* 拘儒, *gou he zhi tu* 苟合之徒; ch. 6, 24, Wang Liqi (1958, pp. 44, 172; 1992, pp. 80, 299); tr. Gale (1967, p. 38); Baudry-Weulersse et al. (1978, pp. 76, 148).
[84] *SCC*, vol. 2, pp. 278ff.
[85] *SJ*, ch. 129, p. 1435; tr. Watson (1993b, vol. 2, p. 83); *HS*, ch. 24b, p. 1174; tr. Swann (1950, p. 1174).

after year, and the displaced persons have not yet all returned. It would be appropriate to practise the government of the time of Wen-di 文帝 [r. –179 to –157], giving an example of frugality and modesty, following the will of Heaven and satisfying the feelings of the people. Then the harvests would reciprocate.' Huo Guang accepted this: he promoted Worthies [*xian liang* 賢良] and he held discussions on the abolition of the monopoly on fermented liquors and of the salt and iron [offices]. All this was at the initiative of Du Yannian.[86]

The passage translated in Box 9 begins with a discussion of the causes of good and bad harvests, with the government side claiming that these are an essentially mechanical result of the cycles of Heaven while the critics claim that they are Heaven's response to the behaviour of the government. This part is a continuation of a discussion in the previous chapter, but it has a special function here. Further on in the chapter the government side will claim that the monopolies work well, in what amounts to a mechanical way, while the critics will claim that everything was better before the establishment of the monopolies. Huan Kuan implicitly invites his readers to compare these statements with the two sides' unbelievable claims about the weather: that there is exactly one year of hunger in six and one famine year in twelve, or that in the time of the ancient sage kings it rained exactly once every ten days, and then only at night!

The scale of industrial production

Next in the chapter is the critics' conclusion that hunger and cold will be eliminated if the salt and iron monopoly is abolished, if wealthy persons (such as Sang Hongyang himself)[87] are eliminated from office, and if agriculture is restored to its proper place in the government's priorities. After a digression on the value of plain speaking, the government side uses a somewhat confusing analogy involving the activities of the businessman Tao Zhu 陶朱 to argue that industry is among the proper concerns of the state. Furthermore, when the state supplies his implements, the farmer is free to concentrate on the fundamental occupation, agriculture, and shun such ancillary occupations as iron smelting.

The doctrine that agriculture is the root (*ben* 本), and all other occupations merely branches (*mo* 末), is of course common ground in this debate, as indeed in most Chinese social thought. The difference between the two sides lies in what they believe will advance agriculture, and now we enter the meat of the argument. The critics claim that the implements produced by the state are inferior, produced to meet quotas rather than to provide for real needs. This complaint is repeated several times in the *Yan tie lun*, as well as elsewhere in Han literature,[88] and must be taken

[86] *HS*, ch. 60, p. 2664; cf. Jongchell (1930, p. 165). The statement of Huo Guang's accomplishments is an abbreviated reference to the encomium at the conclusion of the chapter on Zhao-di in *HS*, ch. 7, p. 233; tr. Dubs (1938–55, vol. 2, p. 175).

[87] The Imperial Counsellor (Sang Hongyang) speaks of his own great wealth in ch. 17, Wang Liqi (1958, p. 121; 1992, pp. 219–20); tr. Gale (1967, pp. 106–7); Baudry-Weulersse et al. (1978, p. 119).

[88] Pp. 224–8 below.

seriously. Since it is seen only in polemical contexts, however, we cannot know how serious the problem actually was.[89]

The Imperial Counsellor answers this complaint by claiming that the state uses better techniques than are feasible for private producers, who lack the advantages of specialisation: they are poorly equipped, do not have sufficient time, and omit certain technical processes. (These are unfortunately referred to in terms which today are incomprehensible.) A Worthy answers that small-scale family enterprises produced better implements, because of pride of workmanship and because they were closer to the users. It is interesting to see this explicit discussion twenty centuries ago on a dilemma which is still highly relevant today: large-scale enterprise can assure stable production of large quantities of goods, while small-scale enterprise can assure quality and workers' pride.[90]

Earlier we have seen another passage from the *Yan tie lun* in which the government side claimed that the iron industry before the monopoly was dominated by large-scale producers in the mountains. Dong Zhongshu, a critic of the government, said much the same in a memorial.[91] Here we have, on the contrary, both sides agreeing that production before the monopoly was by small-scale household producers. It is quite reasonable to suppose that both statements are correct: as in Guangdong in recent centuries,[92] no doubt there were two sectors of the iron industry, one consisting of small units producing for local needs, the other of large units producing for trade over long distances.

There is a good deal more in Box 9 that throws light on the workings of the monopoly, and this material will be discussed in Sections (iii) and (iv) below. We shall continue here with some aspects of the thought of the *Yan tie lun* which come out in other parts of the book.

The blessings of wealth

The government side argues several times that the monopolies serve to prevent private persons from amassing undue concentrations of wealth.[93] The critics reply by pointing out the enormous wealth acquired by those in charge of the state ironworks, and describe graphically the opulence in which they live. The government side does not deny this, but argues that wealth is a natural concomitant of responsible

[89] It is certainly incorrect to conclude, as Nishijima Sadao 西島定生 does without nuance in the *Cambridge History of China*, that 'iron implements manufactured under the state iron monopoly were too large for practical use' (Twitchett and Loewe, 1986, p. 563). A single statement in a polemical context is in any case insufficient basis for such a sweeping statement; in addition the archaeological evidence makes it clear that a wide variety of implements, large and small, were manufactured by the state ironworks (e.g. Li Jinghua, 1974).

[90] Consider for example two admirable books by modern economists who take almost opposite positions on this question: *The new industrial state*, by J. K. Galbraith (1967), and *Small is beautiful*, by E. F. Schumacher (1973). See also Sabel and Zeitlin (1985; 1997).

[91] *HS*, ch. 24a, p. 1137; Swann (1950, p. 181).

[92] Pp. 47–59 above.

[93] E.g. in the passages quoted on pp. 140–1, 144.

office, and taunts the Scholars for their poor clothing.[94] Throughout the book the government side tends to take wealth as the primary indicator of achievement, while the critics defend cultural values as superior to economic values.[95]

The body politic

A major aspect of the thought of the government side of the debate is the use of mathematics in proper government, in what we might, risking anachronism, call *managing the economy*.[96] This comes out very clearly in chapter 14, entitled *Qing zhong* 輕重, literally 'Light and heavy', a term which is sometimes loosely translated 'economics', but in any case has to do with equilibria or priorities. Gale translates it as 'the ratio of production' and explains it as the balance between agriculture on the one hand and industry and trade on the other.[97]

An assistant to the Imperial Counsellor [*yu shi* 御史] advanced and said: . . . When Guan Zhong 管仲 served Duke Huan 桓公 [of Qi 齊, in the –7th century], building upon the achievements of the former rulers and manipulating the 'ratio of production', he subdued the powerful state of Chu in the south and established hegemony over the feudal lords.

Today His Excellency the Imperial Counsellor practises the policies of Tai-gong 太公 [the founder of Qi], Duke Huan, and Guan Zhong. He has unified salt and iron [production] and disseminated [*tong* 通] the benefits of mountains and rivers, so that the myriad things have increased [i.e. the production of goods has developed]. For this reason the State's revenues are sufficient, the people are not distressed, the fundamental and ancillary [occupations] combine their profits, and both high and low are provided for. These accomplishments are the result of calculation and planning, not merely of the tilling and sericulture of the farmers.[98]

Answering this statement, a Scholar jeers at Sang Hongyang's famous ability to do mental calculations, and argues that only Benevolence and Righteousness can truly enrich the realm. The assistant to the Imperial Counsellor replies:

His Excellency the Imperial Counsellor, manipulating the calculating rods, has provided for the expenses of the State. He has monopolised the profits of both salt and iron in order to bring the rich merchants under control. Allowing the purchase of office and redemption of punishments reduces what is excessive and supplies what is deficient, thus equalising the black-haired people [the population of the Empire]. Therefore despite armed campaigns to the east and west there is sufficient revenue without increases in taxation.

Matters of subtraction and addition are for the wise [*xian* 賢], not for the common run of men.[99]

94 Ch. 9, Wang Liqi (1958, pp. 64–6; 1992, pp. 120–2); tr. Gale (1967, pp. 54–8); Baudry-Weulersse et al. (1978, pp. 77–80).

95 E.g. ch. 16, Wang Liqi (1958, p. 116; 1992, p. 209); tr. Gale (1967, pp. 103–4); Baudry-Weulersse et al. (1978, pp. 116–17).

96 Note the important strictures of Loewe (1985, pp. 237–9) on the use of such modern concepts in discussing the Han period.

97 Gale (1967, p. 12 n. 2, p. 85 n. 1). Of course the term is also the title of several chapters of the *Guan zi* 管子 book, on which see *SCC*, vol. 2, p. 36.

98 Ch. 14, Wang Liqi (1958, p. 98; 1992, p. 178); cf. Gale (1967, pp. 85–6); Baudry-Weulersse et al. (1978, p. 99).

99 Ch. 14, Wang Liqi (1958, p. 99; 1992, p. 179); cf. Gale (1967, pp. 87–8); Baudry-Weulersse et al. (1978, p. 101).

All this about adjusting equilibria leads the critics to compare the government's handling of the body politic with the medical treatments of the ancient physician Bian Que 扁鵲, pointing out that such adjustments are only possible when the source of the malady is known:

A Scholar: Bian Que was able, by feeling the pulses [of a patient], to discover the source of the illness. Then if Yang *qi* 氣 was excessive he reduced it and adjusted the Yin; if cold *qi* was excessive, he reduced it and adjusted the Yang. In this way he harmonised the channels of the *qi*, so that there was no place for pathological *qi*.

But an incompetent physician does not know the patterns of the channels or the distinctions of blood and *qi*. He sticks in his needles at random and has no effect on the illness, merely injuring flesh and skin. You wish to reduce what is excessive and supply what is deficient, but the rich become richer and the poor become poorer.[100]

The medical analogy is then taken up by the government side, likening the trade in goods through the Empire to the flow of blood and *qi* in the body:

An assistant to the Imperial Counsellor: . . . In the capacity of Commandant-in-Chief of the Granaries [*zhi su du wei* 治粟都尉], His Excellency the Imperial Counsellor manages the affairs of the Ministry of Agriculture. 'Cauterising and needling the blockages', he opens up the hundred channels of profit, so that the myriad goods are disseminated and the State is prosperous. At this time there are campaigns in all directions against the forces of disorder; the expenses for materiel and the rewards for military merit amount to billions, and they are all supplied by the Ministry of Agriculture. This is made possible by the powers of Bian Que and the well-being of the salt and iron [industries].[101]

The argument continues, but we may leave it here. It is apparent that the government side sees society as a coherent unit, united by trade, whose functions can be optimised by appropriate interventions from the centre. In this particular chapter the critics do not appear to disagree with this view, but are more concerned to argue that the actual interventions of the government have been ineffective or incompetent. Perhaps this is because the government at this point is expressing Huan Kuan's own view. In the chapter translated in Box 9, on the other hand, we find the critics opposed in principle to government intervention, in fact taking a line rather close to the Taoism of the *Lao zi* and *Zhuang zi*.[102]

Calculation

Presumably the concern on the government side for calculation owed something to the mercantile background of Sang Hongyang and other important ministers of the

[100] Ch. 14, Wang Liqi (1958, pp. 99–100; 1992, p. 179); cf. Gale (1967, p. 88); Baudry-Weulersse et al. (1978, p. 101).

[101] Ch. 14, Wang Liqi (1958, p. 100; 1992, p. 180); cf. Gale (1967, pp. 89–90); Baudry-Weulersse et al. (1978, pp. 102–3). The latter translation includes the magnificent phrase *le flot vivifiant du profit*; which undoubtedly is an excellent expression of the government side's attitude, but unfortunately corresponds to nothing in the text.

[102] *SCC*, vol. 2, e.g. pp. 68–70.

time, and included the keeping of accounts. The passages quoted above, however, suggest that something more complex was involved as well. While the historical sources do not give us a view of what sorts of calculations were actually involved, it is interesting to see that a Han mathematical text, the *Jiu zhang suan shu* 九章算術, contains a chapter entitled *Jun shu* 均輸, 'Equable transportation', the name of one of the contentious economic measures of Wu-di's time.[103] The first problem in the chapter is as follows:[104]

In the equable transportation of grain,
Prefecture A has 10,000 households and a journey of 8 days;
Prefecture B has 9,500 households and a journey of 10 days;
Prefecture C has 12,350 households and a journey of 13 days;
Prefecture D has 12,200 households and a journey of 20 days.
All [journeys] being to the place of [tax] transportation. The total liability of the four prefectures is the transportation of a tax of 250,000 *hu* 斛 in 10,000 carts. It is desired that this should be apportioned according to the distance travelled and the number of households. How much grain and how many carts does each supply?
Answer:
Prefecture A, 83,100 *hu* of grain, 3324 carts;
Prefecture B, 63,175 *hu* of grain, 2527 carts;
Prefecture C, 63,175 *hu* of grain, 2527 carts;
Prefecture D, 40,550 *hu* of grain, 1622 carts.

The calculated tax liabilities are proportional to the number of households divided by the number of days of the journey. The chapter continues with further problems in proportional distribution. The relation of the *Jiu zhang suan shu* chapter to actual practices of the state is not at all clear, but if we assume that there is any relation at all then the calculations referred to in the *Yan tie lun* are considerably more complex than straightforward accounting.

It should be clear from the above discussion that the greatest danger for the student of the *Yan tie lun* is the astonishing impression of modernity which it gives. The editor of the French translation says the book is as much French as it is Chinese,[105] and several historians of the Han have allowed their conclusions in matters of economic and intellectual history to be influenced by attitudes to political problems of their own time and place. Future progress in the study of the *Yan tie lun* will depend very much on historians' ability to look, as Kroll attempts to do,[106] beyond the superficially familiar and focus on those features which make it exotic, and specifically a book of the Han.

103 P. 178 above.
104 *Jiu zhang suan shu*, ch. 6, Guo Shuchun (1990, p. 315); cf. Vogel (1968, pp. 54–5); Chemla and Guo (2004, pp. 485–8). The text goes on to give the details of how the given answer is calculated. There is an interesting problem regarding the method of rounding the result of a division, but we cannot let it detain us here.
105 Baudry-Weulersse et al. (1978, p. 9).
106 Kroll (1978).

(iii) The Administration of the Iron Monopoly

There is surprisingly little information available in the basic Han sources on how the monopolies and other economic interventions were administered, though rather more on iron than on the salt and liquor monopolies or the 'equable transportation' system. The sources have been compiled and studied by a number of authors,[107] and can be eked out with some important archaeological information.

The Iron Offices

We have seen in the *Shi ji* account that 'Iron Offices' and 'Salt Offices' (*tie guan* 鐵官, *yan guan* 鹽官) were established throughout the Empire, and that 'the wealthiest of the former salt and iron industrialists' were appointed to staff them.[108] The 'Treatise on administrative geography' (*Di li zhi* 地理志) of the *Han shu* gives the locations of 48 of these, apparently those which existed in the year +2.[109] These are included in Table 1.

After the reorganisation of the Han government in +25, there continued to be offices for both salt and iron, but these were now under the administration of local authorities rather than the central government: 'If a commandery or prefecture produced large quantities of salt, a Salt Office was established to administer the salt tax; if it produced large quantities of iron, an Iron Office was established to administer production (*gu zhu* 鼓鑄).'[110] It would seem from this that, while the Salt Offices had a purely financial function, the Iron Offices were still involved (to an unknown extent) in the actual technical details of iron production. The 'Treatise on administrative geography' of the *Hou Han shu* lists 36 localities which 'have iron',[111] apparently in +140, and it seems reasonable to assume that these were the locations of Iron Offices.[112] They are also included in Table 1.

Table 1 attempts to bring together the most important information available on the individual Iron Offices.[113] Its principal source is the two 'Treatises on administrative geography', but it also includes the locations of several Iron Offices which are known only from other sources, written or archaeological. The approximate locations of these places are shown in Figure 90.

Many Han iron artefacts have cast-in inscriptions designating the Iron Office under which they were produced; some examples are shown in Figure 91. These have been studied by Li Jinghua, and his results are given in Table 1, column 7. As he points out, the inscriptions must have been assigned by a central authority, since they follow a consistent pattern in their abbreviations of place-names: a pattern

[107] E.g. Chen Zhi (1980, pp. 102–13); Li Jinghua (2000).
[108] P. 177 above.
[109] Cf. Bielenstein (1980, pp. 94–5).
[110] *HHS*, Treatises, ch. 28, p. 3625. The commentary cites Hu Guang 胡廣 (+91–172), who explains that *gu* 鼓 means to operate the mechanism which provides the blast of air needed in metal production; the word is often seen with this meaning in Han texts. On Hu Guang see Beck (1990, index).
[111] *You tie* 有鐵 or, in four instances, *chu tie* 出鐵, 'produces iron' (or perhaps 'exports iron').
[112] Cf. Bielenstein (1979, p. 155).
[113] Much more detail is given by Yang Yuan (1978).

Table 1 *Locations of Iron Offices (*tie guan 鐵官*) according to the* Han shu *(ch. 28), the* Hou Han shu *(Treatise section, chs. 19–23), and some other early sources, together with notes on their inscriptions where known.*

No.	Name of Han Commandery or Kingdom, as given in *Han shu*	Name of Prefecture, as given in *Han shu*	Modern location	Page in *Han shu*, ch. 28	Page in *Hou Han shu*, Treatises, chs. 19–23	Iron Office mark used in inscriptions (Li Jinghua, 1974; 1994c, pp. 161–2; 1999; 2000; Ushiomi Hiroshi, 1996)	Reference to excavated ironworks in Table 2
1	Ba Commandery 巴郡	Dangqu 宕渠	Northeast of Qu County 渠縣, Sichuan		3507		
2	Beidi Commandery 北地郡	Yiju 弋居	East of Ning County 寧縣,Gansu		3520		
3	Changshan Commandery 常山郡 (*HHS*: Changshan Kingdom 國)	Duxiang 都鄉	West of Jingxing County 井陘縣, Hebei	1576	3434		
		Puwu 蒲吾	Southeast of Pingshan County 平山縣, Hebei	1576			
4	Chengyang Kingdom 城陽國	Ju 莒 (*HHS*: In Langye Kingdom 瑯邪國)	Ju County 莒縣, Shandong	1635	3459		
5	Chu Kingdom 楚國	Pengcheng 彭城 (*HHS*: In Pengcheng Kingdom 彭城國)	Xuzhou 徐州, Jiangsu	1638	3460	*Lü* 呂	31
6	Donghai Commandery 東海郡	Qu 朐	South of Donghai County 東海縣, Jiangsu	1588	3458		
		Xiapi 下邳 (*HHS*: In Xiapi Kingdom 下邳國)	Northwest of Suqian County 宿遷縣, Jiangsu	1588[a]	3461		
7	Donglai Commandery 東萊郡	Dongmou 東牟	Mouping County 牟平縣, Shandong	1585		*Lai yi*[b] 萊一	
8	Dongping Kingdom 東平國		East of Dongping County 東平縣, Shandong	1637			
9	Guangling Kingdom 廣陵國 (*HHS:* Commandery 郡)		Northeast of Yangzhou Municipality 揚州市, Jiangsu	1638			
10	Guiyang Commandery 桂陽郡	Leiyang 耒陽	Leiyang County 耒陽縣, Hunan		3483[c]		

(*Cont.*)

Table 1 (*cont.*)

No.	Name of Han Commandery or Kingdom, as given in *Han shu*	Name of Prefecture, as given in *Han shu*	Modern location	Page in *Han shu*, ch. 28	Page in *Hou Han shu*, Treatises, chs. 19–23	Iron Office mark used in inscriptions (Li Jinghua, 1974; 1994c, pp. 161–2; 1999; 2000; Ushiomi Hiroshi, 1996)	Reference to excavated ironworks in Table 2
11	Hanzhong Commandery 漢中郡	Mianyang 沔陽	East of Mian County 勉縣, Shaanxi	1596	3506		
12	Hedong Commandery 河東郡	Anyi 安邑	Northeast of Yuncheng 運城, Shanxi	1550	3397	*Dong er* 東二 *Dong san*[d] 東三 *Da he wu*[e] 大河五	43
		Jiang 降	Southwest of Houma Municipality 侯馬市, Shanxi	1550		*Jiang* 降	
		Pingyang 平陽	Southwest of Linfen County 臨汾縣, Shanxi	1550	3397		
		Pishi 皮氏	Hejin County 河津縣, Shanxi	1550	3398		
13	Henan Commandery 河南郡		Luoyang Municipality, Henan	1555		*He yi* 河一 *He*[f] *er* 河二 *He san* 河三	27, 20, 8, 12
14	Henei Commandery 河內郡	Longlü 隆慮 (*HHS*: Linlü 林慮)	Lin County 林縣, Henan	1554	3395	*Nei yi* 內一 (*Wang xiao* 王小 *Wang da* 王大)[g]	18, 9, 13, 22
15	Hongnong Commandery[h] 弘農郡		North of Lingbao County縣 寶縣, Henan	1549		*Hong yi* 弘一 *Hong er* 弘二	25, 11, 16,
		Mianchi 澠池	Mianchi County 澠池縣, Henan			*Mian* 澠 *Xin an* 新安	
		Yiyang 宜陽縣	Yiyang County, Henan	1549		*Yi* 宜	
16	Jiaodong Kingdom 膠東國	Yuzhi 郁秩 (*HHS*: Jiaodong Marquisate 膠東侯國 in Beihai Kingdom 北海國)	Pingdu County 平度縣, Shandong	1635	3474		
17	Ji'nan Commandery 濟南郡	Dongpingling 東平陵	East of Ji'nan Municipality 濟南市, Shandong	1581	3471	*Ji . . .*[i] 濟口	37
		Licheng 歷城	Ji'nan Municipality 濟南市, Shandong	1581	3472		

18	Jingzhaoyin 京兆尹	Lantian[j] 藍田	West of Lantian County, Shaanxi			*Tian* 田	
		Zheng 鄭	Northeast of Weinan County 渭南縣, Shaanxi	1544			
19	Langye Commandery 瑯邪郡 (*HHS*: Kingdom 國)		Zhucheng County 諸城縣, Shandong	1585			
20	Liaodong Commandery 遼東郡	Pingguo 平郭	Gai County 蓋縣, Liaoning	1626	3529		
21	Linhuai Commandery 臨淮郡	Tangyi 堂邑 (*HHS*: In Guangling Commandery 廣陵郡)	Northwest of Luhe County 六合縣, Jiangsu	1590	3461	*Huai yi* 淮	29
		Yandu 鹽瀆 (*HHS*: In Guangling Commandery 廣陵郡)	Yancheng County 鹽城縣, Jiangsu	1589	3461		
22	Longxi Commandery 隴西郡		Lintao County 臨洮縣, Gansu	1610			
23	Lu Kingdom 魯國	Lu 魯	Qufu County 曲阜縣, Shandong	1637	3429		40
24	Lujiang Commandery 廬江	Huan 睆	Anqing Municipality 安慶市, Anhui	1569	3487	*Jiang*[k] 江	
25	Nanyang Commandery 南陽郡		Nanyang Municipality 南陽市, Henan	1563		*Yang yi* 陽一, *Yang er* 陽二	28, 15, 17, 21
		Biyang[l] 比陽	West of Biyang County 泌陽縣, Henan			*Bi yang* 比陽	
26	Pei Commandery 沛郡 (*HHS*: Pei Kingdom 國)	Pei 沛	East of Pei County 沛縣, Jiangsu	1572			
27	Qi Commandery 齊郡 (*HHS*: Kingdom 國)	Linzi 臨淄 (*HHS*: 菑)	North of Linzi 臨淄, Shandong	1583			39
28	Qiansheng Commandery 千乘郡 (*HHS*: Lean Kingdom 樂安國)	Qiansheng 千乘	West of Boxing County 博興縣, Shandong	1580			
29	Qianwei Commandery 犍為郡	Nan'an 南安	Leshan County 樂山縣, Sichuan	1599			
		Wuyang 武陽	East of Pengshan County 彭山縣, Sichuan	1599			
30	Ru'nan Commandery 汝南郡	Xiping 西平	Xiping County 西平縣, Henan	1562	3424		19, 24
31	Shanyang Commandery 山陽郡		Northwest of Jinxiang County 金鄉縣, Shandong	1570[m]		*Shan yang er*, 山陽二, *Ju ye er*[n] 鉅野二	
32	Shu Commandery 蜀郡	Linqiong 臨邛	Qionglai County 邛崍縣, Sichuan	1598	3509	*Shu jun Cheng du* 蜀郡成都	

(*Cont.*)

Table 1 (*cont.*)

No.	Name of Han Commandery or Kingdom, as given in *Han shu*	Name of Prefecture, as given in *Han shu*	Modern location	Page in *Han shu*, ch. 28	Page in *Hou Han shu*, Treatises, chs. 19–23	Iron Office mark used in inscriptions (Li Jinghua, 1974; 1994c, pp. 161–2; 1999; 2000; Ushiomi Hiroshi, 1996)	Reference to excavated ironworks in Table 2
33	Taishan Commandery 泰山郡	Ying 嬴	Laiwu County 萊蕪縣, Shandong	1582	3453	*Shan*[o] 山 *Da shan er*[p] 大山二	42, 38
34	Taiyuan Commandery 太原郡	Daling 大陵	Wenshui County 文水縣, Shanxi	1552	3523	*Ling* 陵	
35	Wei Commandery 魏郡	Wuan 武安	Southwest of Wuan County 武安, Hebei	1574	3432		
36	Yingchuan Commandery 潁川郡	Yangcheng 陽城	Gaocheng District 告成鄉 in Dengfeng County 登封縣, Henan	1560[q]	3422	*Chuan* 川 *Yangcheng* 陽城	6, 26
37	Yizhou Commandery 益州	Buwei 不韋 (*HHS*: In Yongchang Commandery 永昌郡)	North of Baoshan County 保山縣, Yunnan		3514		
		Dianchi 滇池	East of Jinning County 晉寧縣, Yunnan		3513		
38	Youbeiping Commandery 右北平郡	Xiyang 夕陽	West of Ningcheng County 寧城縣, Liaoning	1624			32
39	Youfufeng 右扶風	Qi 漆	Bin County 彬縣, Shaanxi	1547	3406		34
		Yong 雍	South of Fengxiang County 鳳翔縣, Shaanxi	1547	3406		
40	Yuexi Commandery 越嶲郡	Huiwu 會無	Huili County 會理縣, Sichuan		3511		
		Taideng 臺登	East of Mianning County 冕寧縣, Sichuan		3511		
41	Yuyang Commandery 漁陽郡	Quanzhou 泉州	Southeast of Wuqing County 武清縣, Tianjin		3528		
		Yuyang 漁陽	Southwest of Miyun County 密雲縣, Beijing	1623	3528[r]	*Yu* 漁	

42	Zhao Kingdom[s] 趙國		Handan Municipality 邯鄲市, Hebei				
43	Zhongshan Kingdom 中山國	Beiping 北平	North of Mancheng 滿城 , Hebei	1632	3434	*Zhongshan* 中山	
44	Zhuo Commandery 涿郡	Gu'an[t] 故安	East of Yi County 易縣, Hebei		([u])		
45	Zuopingyi 左馮翊	Xiayang 夏陽	South of Hancheng 韓城 , Shaanxi	1545		*Xia yang* 夏陽	35

[a] Note also the mention of this Commandery's Iron Office in the Yinwan texts, pp. 210–15.
[b] Liu Xiaoyan (1997).
[c] Note also *HHS*, ch. 76, p. 2459; cf. Bielenstein (1979, pp. 154, 155).
[d] Note also Li Jinghua (1997a, pp. 87–8).
[e] Li Jinghua (2001b).
[f] See also Tang Wei (2003).
[g] Li Jinghua (1999b) suggests that these two inscriptions may relate to a place called Yewang 野王 in Henei Commandery. *HS*, ch. 28b, pp. 1664–5.
[h] The information given in the *Han shu* on Iron Offices in Hongnong Commandery is somewhat confused. Under the name of the commandery it states: 'Has an Iron Office, in Mianchi' (*you tie guan zai Mianchi* 有鐵官在澠池), and under the name of Yiyang Prefecture it states: 'Has an Iron Office in Mianchi' (*zai Mianchi you tie guan ye* 在澠池有鐵官也); but under Mianchi itself there is no mention of iron.
[i] Probably either *Ji yi* 濟一 or *Ji er* 濟二 (Li Jinghua, 1998).
[j] Li Jinghua (1994c, p. 163) argues that the inscription *tian* 田 on an iron mouldboard discovered in Xianyang County 咸陽縣, Shaanxi, indicates that there must have been an Iron Office in Lantian Prefecture: there are only two place-names in the *Han shu* 'Treatise on administrative geography' which include the character *tian*, this one and Guangtian 廣田 Prefecture in Xihe Commandery 西河郡 (west of modern Linfen County 臨汾縣 , Shanxi). An early text entitled *San Qin ji* 三秦記 states that iron ore (*tie shi* 鐵石) was produced in Lantian Prefecture; this and its proximity to the place where the mouldboard was found suggest that Lantian is the more likely location of the Iron Office whose mark was the character *tian*.
[k] Ushiomi Hiroshi (1996, p. 97).
[l] The inscription *bi yang* 比陽 on an iron ploughshare from Biyang 泌陽 County, Henan, indicates that there was a Han Iron Office in Biyang 比陽 Prefecture (Li Jinghua, 1994c, p. 165 n. 60) .
[m] Cf. *HS*, ch. 10, p. 323; Dubs (1938–55, vol. 2, pp. 406–7).
[n] Under Wang Mang the name used for Shanyang Commandery was Juye 鉅野.
[o] Ushiomi Hiroshi (1996, p. 97).
[p] Zheng Tongxiu and Yuan Ming (1997, pp. 175, 177, fig. 23.4, 182); Zheng Tongxiu (1998, p. 69).
[q] Note also *HS*, ch. 10, p. 314; cf. Dubs (1938–55, vol. 2, p. 391) . Here an Iron Office of Yingchuan Commandery is mentioned; this would account for the inscription *Chuan*.
[r] Note also *HHS*, ch. 12, p. 503.
[s] An Iron Office in Zhao Kingdom is mentioned in *HS*, ch. 59, p. 2643.
[t] An Iron Office was 're-established' in Gu'an Prefecture in +103, according to *Hou Han shu*, ch. 4, p. 191. This appears to be the only mention of an Iron Office in Gu'an in extant Han sources.
[u] *HHS*, ch. 4, p. 191.

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Figure 90 Map showing the approximate locations of Iron Offices in the Han period, together with modern provinces. See Table 1.

Figure 91 Rubbings of cast-in inscriptions on Han-period iron implements, reproduced from Li Jinghua (1974, p. 62, fig. 1). **1**. *He yi* 河一, on an iron mould found at the Guxingzhen Han ironworks site (Table 2, item 8). **2**. *He er* 河二, on an iron V-shaped ploughshare-cap found in Long County 隴縣, Shaanxi (Li Changqing and He Hannan, 1966, p. 21, fig. 6, pl. 4.2). **3**. *He san* 河三, on a ploughshare-cap found at the Tieshenggou Han ironworks site (artefact no. T5:48; Anon., 1962, pp. 33, 31, fig. 21.5; Zhao Qingyun et al., 1985, p. 173, fig. 11.9, cf. also figs. 8.10, 11.22; Table 2, item 8). **4**. *Yang yi* 陽一, on a ceramic mould for a ploughshare-cap found at the Wafangzhuang Han foundry site (artefact no. T49 括 :28; Li Jinghua, 1991, pp. 39, 40, figs. 33.4, 34.4; Table 2, item 17). **5**. *Yang er* 陽二, on a spade-cap of unknown provenance (Luo Zhenyu, 1931, ch. 15, p. 12b). **6**. *Dong er* 東二, on a spade-head found in Long County 隴縣, Shaanxi (Li Changqing and He Hannan, 1966, p. 22, fig. 9). **7**. *Dong san* 東三 , on a ceramic mould for a toothed wheel, of unknown provenance (Zi Xi, 1957, p. 45). **8**. *Yi* 宜 , on a spade-head of unknown provenance (Rong Geng, 1931, ch. 4, p. 26a). **9**. *Juye er* 巨野二, on a ceramic mould found at a foundry site in Teng County 滕縣 , Shandong (Li Buqing, 1960, fig. 2). **10**. *Zhongshan* 中山, on a spade-head of unknown provenance (Rong Geng, 1931, ch. 4, p. 26). **11**. *Shanyang er* 山陽二 , on a ceramic mould found at a foundry site in Teng County 滕縣 , Shandong (Li Buqing, 1960, fig. 1). **12**. *Tian* 田, on a mouldboard found in Xianyang County 咸陽縣, Shaanxi (Li Changqing and He Hannan, 1966, p. 21, fig. 8). **13**. *Juye er* 巨野二, on a ceramic mould found at a foundry site in Teng County 滕縣, Shandong (Li Buqing, 1960, fig. 2). **14**. *Chuan* 川, on a ploughshare found in Xianyang County 咸陽縣, Shaanxi (Li Changqing and He Hannan, 1966, p. 21, fig. 7). **15**. *Shu jun Cheng du* 蜀郡成都 , on a U-shaped spade-cap found in Ludian County 魯甸縣, Yunnan (Li Jiarui, 1962, p. 33, fig. 1). **16**. *Huai yi* 淮一, on a U-shaped spade-cap found in Xiushui County 修水縣, Jiangxi (Xue Yao and Cheng Yinglin, 1965, p. 266, fig. 3).

which is also seen in Han pottery inscriptions.[114] The inscription *ju ye er* 鉅野二 (see Table 1, item 31) has special importance, for Juye was a place-name used only in the period of Wang Mang. This seems to prove that at least some Iron Offices continued their operation under his rule.[115]

[114] For this point Li Jinghua refers to Yu Weichao (1963). Note also Yao Shengmin (1984).

[115] Note also a bronze seal in the Henan Museum which may be that of an official in charge of an Iron Office under Wang Mang (Chen Xiaojie, 2001).

Where the *Han shu* lists an Iron Office at commandery level, for example Henan Commandery, it apparently had the administration of several ironworks, each with its own mark. In the case of Henan Commandery there were three, *He yi* 河一 , *He er* 河二 , and *He san* 河三 , i.e. He[-nan] numbers 1, 2, and 3 (Figure 91, nos. 1–3). It happens that we know two of these ironworks from excavations: number 1 was at Guxingzhen 古滎鎮 in Zhengzhou, Henan, and number 3 was at Tieshenggou 鐵生溝 in Gong County 鞏縣 , Henan; both are described briefly in Table 2 (nos. 27, 8). Inscriptions on artefacts, including moulds, found in the excavations make these two identifications quite definite. Number 2 may have been one of the other two ironworks excavated in the region of the Han commandery of Henan, in modern Ruzhou and Linru Counties, Henan province (nos. 20, 12 in Table 2).

The archaeology of the Iron Offices

Table 2 gathers together all of the published excavations of ironworks sites from the Han and before.[116] The list includes two types of ironworks: some had blast furnaces, and smelted iron from ore, while others were merely foundries, engaged in producing castings from iron smelted elsewhere. It is apparent that nearly all of the blast-furnace sites are from the period of the Han state monopoly; this fact needs an explanation, for as we have seen in Section 4 above, textual sources indicate that there were a great many large ironworks in China earlier than this, in the –3rd and –2nd centuries.

One possible explanation is the obvious one, that the introduction of the monopoly resulted in a great expansion of the iron industry, with the ironworks more widely distributed and with each operating on a larger scale. These factors would make the state ironworks more likely, in modern times, to be found, and to be investigated, than the earlier ironworks. If a very large ironworks operated on the site of an earlier smaller one, the traces of the earlier works could easily have been obliterated.

Besides this possibility, however, there are two geographical explanations to be considered. One is that more than half of the excavations are located in a few counties in Henan, and that these include all of the excavations which have been properly published in detail. China's most active archaeologist of iron, Dr Li Jinghua 李京華 , works in Zhengzhou, at the Henan Provincial Institute of Cultural Relics 河南省文物研究所 , and his influence is a large part of the reason for this bias towards Henan; but many of the excavations pre-date his work, and we must suppose that the people of Henan, for one reason or another, have been more interested in the archaeology of iron than those of other parts of China.[117] The story of the

[116] Zhang Zhenglang (1951, p. 21) states that in nearly every location of a Han Iron Office the local gazetteer notes the existence of traces of ancient iron production. I have not attempted to use this type of material here, nor, I think, has any other who has studied the Han iron industry.

[117] A large part of the other excavations listed in Table 2 appear to be amateur or semi-professional excavations conducted as part of the general propaganda effort of the Great Leap Forward in 1958–60. The publications tend to be very brief, usually only a page or two in length, and vague as to the technical details.

Table 2 *Archaeological evidence of Han and pre-Han ironworks.*

No.	Place	Date	Description	Han Iron Office, item in Table 1
1	**Beijing**	Han	Outside a Han city wall some 1 km E of Qinghezhen 清河鎮 in Beijing Municipality, 'remains of iron smelting' were found. In the vicinity 40+ iron artefacts were found in 1954. Su Tianjun (1959); Chen Zhi (1980, pp. 109–10); Anon. (1990b, pp. 97–8).	
2	**Fujian** Fuzhou	Warring States	The base of a furnace, some mould fragments, and some slag were found inside the site of a Warring States – Han city at Xindian 新店 in Fuzhou, Fujian. The excavators believe that the furnace is a bloomery, but there is not in fact enough remaining to make any determination of its function. The presence of moulds suggests that it is more likely to be a foundry furnace. Ou Tansheng (2001).	
3	**Gansu** Edsin	Han	The Sino-Swedish expedition to northwest China, led by Sven Hedin, found many large and small heaps of 'slag', often near watch-towers of the Great Wall (Sommarström, 1956–8, index, sub 'slag'). Some of these appear to be associated with bronze foundries, but at least one, in the Khara-khoto region, Edsin Banner 餓濟納旗, Gansu, is associated with iron casting. Sommarström (1956–58, p. 174) .	
4	**Hebei** Pingshan	Warring States	Bronze- and iron-foundry site at the site of the ancient city of Lingshou 靈壽, capital of Zhongshan 中山, in Pingshan County 平山縣, Hebei. The only information so far published about it concerns a large number of ceramic moulds for iron implements found here. Chen Yingqi and Li Enjia (1986); cf. Chen Yingqi (1995).	
5	**Hebei** Xinglong	Warring States	Foundry site in Xinglong County, Hebei, associated with the state of Yan. Finds include iron moulds for implements, a few potsherds, charcoal, ore, and slag. (No sign was found of ceramic moulds.) Inscriptions on the moulds are believed to indicate with some certainty that this was a Yan state foundry. Shi Shuqing and Yang Zongrong (1954, p. 113); Anon. (1954a, pls. 48–51); Cheng Chen-to (1954); Zheng Zhenduo (1954, p. 42, pl. 13); Zhang Zigao and Yang Gen (1973); Wu Zhenwu (1984); Yang Gen and Ling Yeqin (1962); Zheng Shaozong (1956).	
6	**Henan** Dengfeng	Warring States – Han	An ironworks site between the inner and outer walls of the ancient city of Yangcheng 陽城 at Gaochengzhen in Dengfeng County 登封縣告城鎮, Henan. There are both Warring States and Han strata. In the Warring States stratum many furnace-wall fragments were found, including some curved pieces from which a diameter of 1.44 m can be inferred. It is believed that these represent a foundry furnace rather than a smelting furnace. The fragments included some which were made of refractory clay mixed with fragments of scrap cast iron. Other finds include tuyères, charcoal, ceramic moulds, fragments of iron implements, roof-tiles, and potsherds.	36

(*Cont.*)

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
			In the Han stratum, part of the base of a furnace was found. The furnace was circular, with inner diameter 1.15 m, outside diameter 1.65 m. It was built of refractory bricks, the spaces between bricks filled with clay and fragments of scrap iron. This furnace is also identified as a foundry furnace. Anon. (1977b, pp. 57–60); Han Rubin (1994); An Jinhuai and Li Jinghua (1992); Li Jinghua (1997b, pp. 26–31); Zhou Shuanglin et al. (1999).	
7	**Henan** Fangcheng	Han	Li Jinghua and Chen Changshan (1995, p. 10) state that there is a Han ironworks site in Fangcheng County 方城縣, Henan.	
8	**Henan** Gongxian	–2nd – early +1st century	Ironworks site at Tieshenggou in Gong County 鞏縣鐵生溝, Henan. Within 300 m of the site are two Han-period mine workings. Pieces of ore found on the site are hematite and limonite; two samples analysed had 76% and 66% Fe_2O_3 respectively. At the site several large pieces of sintered iron (bear material), some as large as 8–9 tonnes, were found and removed in connection with local iron production in the Great Leap Forward. One, of 7 tons, remains on the site, and several more were excavated. These are a mixture of slag and iron with highly variable iron content. The site is estimated to measure some 180 × 120 m. In all 19 test trenches, averaging 100 m², were excavated (i.e. about 9% of the site). Major features excavated include the bases of 8 blast furnaces, 1 fining hearth, 1 smithy hearth, and one reverberatory furnace (perhaps for decarburising annealing), 16 kilns (for firing ceramic moulds and possibly for annealing), and 4 buildings. The slag heaps are estimated at 6000 m³ in all. Artefacts found include fuel, mould fragments, and about 200 iron implements, most of them cast (either products of the ironworks or scrap). The date is deduced from finds of coins and potsherds. Jin Huai (1959); Zhao Guobi (1960); Anon. (1962); Zhao Qingyun et al. (1985); Qiu Lianghui (1980); Anon. (1974b).	13
9	**Henan** Hebi	Warring States – Han	An ironworks site at Luloucun in Hebi Municipality 鶴壁市鹿樓村, Henan. Remains of 13 furnace bases were excavated, together with red-baked earth, charcoal, furnace-wall fragments, tuyères, ore, slag, Han tiles and bricks, ceramic moulds, and iron implements and weapons. The furnaces are elliptical and have (outside?) dimensions 2.2–2.4 × 2.4–3 m. Analysis of the slag gave SiO_2 33.40%, CaO 26.75%, TFe 2.25%. Yang Baoshun (1963); Anon. (1978c, p. 5); Wang Wenqiang and Li Jinghua (1991); Wang Wenqiang (1994); Li Jinghua (1997b, pp. 31–7) .	14

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
10	**Henan** Huixian	Warring States	An iron foundry site outside the walls of the ancient city of Gongcheng 共城 in the city of Huixian 輝縣市, Henan. Among the artefacts found were tuyères, fragments of clay models and moulds, and 36 iron artefacts. Li Jinghua (1997b, pp. 37, 42–3); He Huilu and Zhang Youxin (1996); note also Zhang Shiying (1987).	
11	**Henan** Lingbao	Han	A Han ironworks at Hanguguan 函谷關 in Lingbao County 靈寶縣, Henan. Li Jinghua (1994c, p. 161), citing unpublished information from Lingbao Municipal Cultural Relics Office 靈寶市文物保管所 .	15
12	**Henan** Linru	Han	A Han ironworks site near a large Han settlement site at Xiadian in Linru County 臨汝縣夏店 , Henan. A furnace of tamped earth was found, with a diameter of 2 m. Mixed into the tamped earth were a number of Han potsherds. A nearby pit contained over 300 cast-iron mattock-heads. Ni Zili (1960).	13
13	**Henan** Linxian	Han–Yuan	Seven ancient iron mining and smelting sites have been excavated in Lin County 林縣 , Henan, of which only one was in use in the Han, the ironworks site at Zhengyangji 正陽集,where Song remains are also found. In the Han stratum potsherds and slag were found. Li Jinghua (1992a, pp. 48–55).	14
14	**Henan** Luoyang	Late Eastern Zhou	A kiln site inside the walls of the Eastern Zhou capital in Luoyang, Henan. Artefacts found include crucibles, tuyères, and pieces of iron. The date is based on stratigraphic relations and ceramic artefact styles. Ye Wansong and Huang Jibo (1995).	
15	**Henan** Lushan	Han	Two Han ironworks sites were excavated at Wangchenggang in Lushan County 魯山縣望城崗, Henan. One furnace was found: it has an elliptical shaft, with inside diameter 2.2–3.6 m, outside diameter 7.2–8 m. Near the furnace were found slag, furnace fragments, tuyère fragments, mould fragments, and Han potsherds. One mould fragment had the inscription *Yang yi* 陽一 . Zhao Quanjia (1944); Li Jinghua (1992a, pp. 57–8); Liu Haiwang (2001); Liu Haiwang and Zhao Zhiwen (2002).	25
16	**Henan** Mianchi	Han – Six Dynasties	A scrap-heap containing several tonnes of iron artefacts dating from the Han and after was excavated near the Mianchi Railway Station in Mianchi County 澠池縣, Henan. A good deal of slag was found in the vicinity. Presumably there was an ironworks here as early as the Han. Li Jinghua (1976).	15
17	**Henan** Nanyang	Han	A Han ironworks site inside the walls of the site of the ancient city of Wan 宛 at Wafangzhuang, Beiguan, in Nanyang 南陽北關瓦房莊, Henan. Two strata were distinguished, dated Western Han and Eastern Han on the basis of pottery styles and coins. In the Western Han stratum were found the bases of four foundry furnaces with diameters 2.50–4 m, thickness 5 cm. In the Eastern Han stratum were found the bases of five foundry furnaces. These are elliptical, with dimensions ranging from 1.90 × 2.40 to 3.50 × 4.20 m, thickness 0.15–0.40 m.	25

(*Cont.*)

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
			Nothing resembling ore was found anywhere at the site, and this is why the furnaces are taken to be foundry furnaces rather than blast furnaces. Artefacts in the two strata included large accumulations of refractory bricks, foundry slag, and fragments of ceramic blast-pipes and tuyères; fragments of iron artefacts and cast-iron plates measuring 19.6 × 9–10 × 0.3–0.6 cm, apparently raw material for casting; pieces of charcoal; ceramic and cast-iron moulds; and iron castings. There were also moulds dug into the earth (*di mian fan* 地面范) for casting large objects such as cooking pots. Li Jinghua (1965; 1991; 1992b); Anon. (1959a; 1978c); Liu Xin and Li Jinghua (1994); Li Jinghua and Chen Changshan (1995, pp. 7–9); Pei Mingxiang (1960); Li Jinghua and Wei Renhua (2000).	
18	**Henan** Qixian	Han	A Han ironworks site at Fuzhuang 付莊 in Qi County 淇縣, Henan; no details have been published. Li Jinghua (1994c, p. 161).	14
19	**Henan** Queshan	Han?	An ironworks outside the walls of the ancient city-site of Langling 朗陵 in Queshan County 榷山縣, Henan. Charcoal, slag, potsherds, fragments of iron objects, and furnace wall fragments were found here. Presumably the Han date has been determined from the potsherds. Zhong Huabang (1987).	30
20	**Henan** Ruzhou	Han	A Han ironworks at the ancient city-site of Fan in Ruzhou Municipality 汝州市范故城. Li Jinghua (1994c, p. 161), citing unpublished information supplied by Ru'nan Municipal Museum 汝南市博物館.	13
21	**Henan** Tongbai	Warring States? – Han	Two ancient mining sites and one iron-smelting site at Maoji in Tongbai County, Xinyang District 信陽地區桐柏縣毛集, Henan, were excavated. At the sites furnace wall fragments, slag, tuyère fragments, ore, Warring States and Han potsherds, a piece of iron, and an axehead cap were found. The bases of two furnaces were also found. Local people said the upper parts of the furnaces had been destroyed in ploughing in the 1950s, and that numerous iron artefacts had been found in the vicinity over the years. Analyses of three slag samples indicate:	25

SiO_2	CaO	MgO	TFe	FeO	MnO	S	P_2O_5
40.50	16.62	6.01	5.89	5.30	1.64	0.05	0.070
48.40	18.20	4.55	4.24	3.45	0.64	0.05	0.081
44.62	18.09	5.48	5.72	4.80	1.58	0.06	0.060

Wood taken from the axehead cap had a radiocarbon date of 2215±110 b.p. [Dendrochronological calibration gives, at the 'two sigma' 95% confidence level, a date in the range –525 to –15 (Klein et al., 1982).]
Three Han kilns were also excavated at Maoji.
Another Han ironworks site was excavated at Zhangfan 張畈. Fragments of furnace walls, slag, iron implements, and Han potsherds were found here.
Li Jinghua and Yang Zhenwei (1988); Li Jinghua (1992a, pp. 55–7); Li Jinghua and Chen Changshan (1995, pp. 6–7, 9).

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
22	**Henan** Wenxian	Han	The site is outside the wall of the Han prefectural city of Wenxian 溫 at Zhaoxian 招賢 in Wen County 溫, Henan. Surface finds include iron slag, refractory bricks, red-baked earth, and ceramic mould fragments. Local people have in the course of agricultural work dug up the remains of four furnaces. The only feature excavated by archaeologists is one of two large kilns; in it were found about 500 stack-moulds for casting multiple small iron objects including belt-buckles, horse-bits, and axle fittings. Tang Wenxing (1976); Anon. (1978a); Hua Jue Ming (1983a); Hua Jueming (1983b).	14
23	**Henan** Xinzheng	Warring States	An iron foundry site within the outer wall of an ancient city of Zheng 鄭 and Hán 韓 at Cangchengcun in Xinzheng County 新鄭縣倉城村, Henan. The base of a furnace, 1.7 m in diameter, was found here, along with remains of two mould-kilns. Artefacts include ceramic moulds, tuyères, potsherds, tiles, iron implements, and slag. Liu Dongya (1962); Anon. (1980b); Li Jinghua (1997b, p. 43); Li Xiusong and Zhang Xianping (1999, p. 65); Ma Juncai and Cai Quanfu (2000).	
24	**Henan** Xiping and Wugang	Warring States – Han	Eight ancient ironworks sites in the region of the Han prefecture of Xiping 西平, in modern Xiping County 西平縣 and Wugang Industrial Region 舞鋼區, Henan. The region has a very large and easily mined deposit of relatively lean ore, with 25–30 per cent iron. Some 30 ancient mine workings are known. Eight ancient ironworks sites have been investigated here, and others are known or suspected on the basis of place-names or local tradition. There is also a settlement site at Xiegudong 謝古洞, located roughly equidistant from the ironworks sites, which is believed to have been the Warring States city of Po 柏 and the administrative centre of the Han prefecture of Xiping. At the ironworks site at Yangzhuang 楊莊, 38 km SW of modern Xiping, iron slag is distributed over an area of 2500 m N–S × 1500 E–W. Artefacts include slag, fragments of furnace walls, and Warring States potsherds. The nearby Zhaozhuang 趙莊 site has largely been destroyed by the change of course of a river. One furnace, believed to be of Warring States date, is well preserved: its base is rectangular, constructed of tamped earth containing a large amount of charcoal powder. At the Tieluhoucun 鐵爐後村 site, iron slag, fragments of furnace walls, and Warring States – Han potsherds have been found. At the Xugoucun 許溝村 site in Wugang, surface finds include ore, fragments of furnace walls, slag, some fragments of ceramic and stone moulds, and Warring States and Han potsherds. Geologists state that the ore comes from a deposit 5 km to the NW. At the Goutouzhaocun 溝頭趙村 site, 3 pieces of furnace-base bear material were found, the largest weighing 65 kg. At the Zhaizhuangcun 翟莊村 site, surface finds include ore, slag, fragments of furnace walls, and Warring States tile-sherds. Local people have in the past destroyed one ancient smelting furnace and cleared out large quantities of slag. Geologists state that the ore comes from Jianshan 尖山, 3.5 km north of the site.	30

(*Cont.*)

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
			At the Gedangzhaocun 圪壋趙村 site, surface finds include green, brown, grey, and blue glassy slag, furnace wall fragments with brown and black glassy layers, and Warring States tile- and potsherds. The base of one round furnace remains; three others have been destroyed by a river shifting course. Geologists state that some of the ore comes from Jianshan, some from an unknown place. At the Jianshan 尖山 mine site large quantities of ore and waste rock have been found, as well as a piece of iron weighing 5 kg. Surface finds also include potsherds ranging in date from the Warring States to the Song period. Li Jinghua (1990; 1994e; 1997b, pp. 43–5); Huang Keying and Kang Xiaohua (1998).	
25	**Henan** Yiyang	Han	A Han ironworks near the ancient city of Yiyang 宜陽 in Yiyang County 宜陽縣, Henan. Li Jinghua (1994c, p. 161), citing unpublished information received from Luoyang Cultural Relics Team No. 2 洛陽市文物工作第二隊 .	15
26	**Henan** Yuzhou	Han	A Han ironworks at Yingli in Yuzhou, Henan 禹州市營里. Li Jinghua (1994c, p. 161), citing unpublished material held by the Henan Provincial Institute of Cultural Relics.	36
27	**Henan** Zhengzhou	–1st century	Ironworks site outside the walls of the ancient city of Xingyang 滎陽 at Guxingzhen 古滎鎮 in Zhengzhou 鄭州, Henan. Borings indicate that the site measures about 400 m N–S × 300 m E–W. An area of 1700 m^2 was excavated in the NW part. Features excavated include the bases of 2 blast furnaces, large pieces of bear material, ore heaps, slag tips, and 13 kilns. There are also signs of buildings on the site. Artefacts include 318 iron implements, cast-iron moulds, and ceramic moulds. The date is based on ceramic artefact styles as well as a few coins. Anon. (1978b; 1978d); Alley (1966); Cheng Shih-po (1978); Qin Wensheng (1983); Xie Suilian (1986); Lin Yulian and Yu Xiaoxing (1983); Liu Yuncai (1978; 1984; 1992).	13
28	**Henan** Zhenping	Han	A hoard of cast-iron moulds for iron hammer-heads was found near an ancient city site at Anguocheng in Zhenping County, Henan 鎮平縣安國城, and it is reasonable to suppose that there was an ironworks nearby. The date is suggested by inscriptions on the artefacts. Li Jinghua (1982); Li Jinghua and Chen Changshan (1995, pp. 9–10).	25
29	**Jiangsu** Sihong	Han	An ironworks site 7 km N of Fengshanzhen in Sihong County 泗洪縣峰山鎮 , Jiangsu. A section exposed in the excavation of a 400 m drainage ditch shows a stratum about 1.5 m thick with baked earth, iron slag, iron ore, and Han potsherds. Half of an 'iron-smelting furnace' was also found. Yin Huanzhang and Zhao Qingfang (1963, pp. 2, 7).	21

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
30	**Hunan** Sangzhi	Han	Two iron-foundry sites at Zhujiatai in Sangzhi County, Hunan 桑植縣朱家台. In the Han period this area was occupied by the non-Chinese Pu 濮 people. Features include two melting furnaces, one of which may be a crucible furnace rather than a cupola. Artefacts include ceramic and iron moulds, tools used in furnace operation, and 95 cast-iron implements, weapons, and vessels.	
31	**Jiangsu** Xuzhou	Han	The base of a furnace was excavated near Tongshan 峒山 in Liguoyi 利國驛, Xuzhou County 徐州縣, Jiangsu. Near it were found slag, iron ore, iron implements, and Han potsherds. The furnace is of tamped clay and sand, rectangular, with dimensions outside 470 × 380 cm, inside 250 × 140 cm. It rests on a thick tamped-earth base. Its inner walls are partially melted due to exposure to high heat. Analysis of the slag gives: SiO_2 30.47, Al_2O_3 13.24, CaO 6.36, MgO 1.58, FeO 47.98, MnO 0.038, S 0.052. Li Zhongyi (1960).	5
32	**Liaoning** Ningcheng	Han	Li Jinghua (1997a, p. 88) states that a Han kiln for stacked moulds for iron has been excavated in Ningcheng County 寧城縣, Liaoning; no details are available.	38
33	**Nei Mongol** Hohhot	Han	A Han iron-smelting works near an ancient city site at Meidai 美岱, in the suburbs of Hohhot, Inner Mongolia. No details are given. Anon. (1961, p. 7); Zhang Yu (1961, p. 21); He Tangkun et al. (1985, p. 60).	
34	**Shaanxi** Fengxiang	Warring States? – Han	An ironworks site near the village of Nangucheng 南古城 in Fengxiang County 鳳翔縣, Shaanxi. Surface finds include ceramic moulds, copper slag, and iron slag. In a 10 × 2 m test trench, three strata were found: **1**: Modern, 0.3–0.5 m. **2**: Han, 0.5–1 m, yellowish-brown spongy soil mixed with a large amount of ashes, charcoal, and red-baked powdery earth. Finds include whetstones and ceramic moulds. **3**: Warring States, 0.5–1 m, grey-brown hard-packed earth containing some charcoal and red-baked earth. Finds include stone moulds, ceramic moulds, and copper slag. In all, 5 ceramic moulds, 4 stone moulds, and one 'brick' mould (*zhuan fan* 磚范) were found. All are for casting small implements. Zhao Xueqian and Wu Zilin (1962).	39
35	**Shaanxi** Hancheng	Western Han	A Han ironworks site at Zhichuanzhen in Hancheng County 韓城縣芝川鎮 , Shaanxi. The site measures 219 × 194 m. A slag accumulation, of unknown extent, is 1.6–2 m thick. An accumulation of ceramic mould-fragments covers some 100 m^2. Large numbers of Western Han potsherds were also found. Han Zhao et al. (1983).	45
36	**Shaanxi** Xi'an	Western Han	An iron-foundry site within the walls of the Han city-site of Chang'an 長安 in Xi'an, Shaanxi. Features include several mould-kilns, the base of one cupola furnace (round, diameter 0.9 m), and waste-pits containing slag and fragments of moulds and tuyères. The date is based on ceramic roof-tile styles. Li Yufang et al. (1995); Liu Zhendong and Li Yufang (1997); important corrections, Li Jinghua (1997a).	

(*Cont.*)

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
37	**Shandong** Dongping	Han or before	Ironworks site at Linggucheng in Dongping County 東平縣陵故城, Shandong. At the site were found furnaces, baked earth, charcoal, slag, iron implements, iron ore, ironsand, and pieces of cast iron. Yang Huiqing and Shi Bensan (1955); Zheng Tongxiu (1996); Zheng Tongxiu and Yuan Ming (1997).	17
38	**Shandong** Laiwu	–2nd century	Numerous cast-iron moulds for iron implements have been found at Niuquan in Laiwu County 萊蕪縣牛泉公社, Shandong. The date is suggested by the inscriptions on many of these. No other technical details have been published. Zhu Huo and Bi Baoqi (1977); Anon. (1972a, pls. 102–3).	33
39	**Shandong** Linzi	Warring States – Han	Just outside the walls of the ancient city site of Qi 齊 in Linzi 臨淄, Shandong, six iron-smelting sites were excavated. They are dated to the Warring States and Han periods on the basis of stratigraphic relations with the city site. No technical details have been published. Qun Li (1972, pp. 50–1); Huang Hai (1999); Bai Yunxiang (1999, p. 361).	27
40	**Shandong** Qufu	Warring States – Han	Two ironworks sites at the site of the ancient capital of Lu 魯 in Qufu 曲阜, Shandong. The ironworks sites measure 450 × 120 m and 250 × 200 m respectively. Artefacts found include pieces of iron, iron slag (*tie zha* 鐵渣), 'sulphur slag' (?*liu zha* 硫渣), red-baked earth, and charcoal. A very unusual furnace, of unknown function, was also found (Zhang Xuehai et al., 1982, p. 50, fig. 29, pls. 7.1, 7.3). Anon. (1978e); Zhang Xuehai (1982); Tian An (1982); Zhang Xuehai et al. (1982); Buck (1986); Huang Hai (1999).	23
41	**Shandong** Tengxian	Han?	An ironworks site inside the walls of the ancient city of Xue 薛 in Teng County 滕縣, Shandong. Judging from features visible on the surface, the site measures about 300 × 200 m. Surface finds include iron ore, iron slag, moulds, powdered ore, and fragmentary iron artefacts. There are remains of kilns and what may be an iron-smelting furnace. Li Buqing (1960); Ren Shinan and Hu Binghua (1965, pp. 631, 634); Gong Yanxing et al. (1991, p. 454).	
42	**Shandong** Zhangqiu	Han	A Han ironworks site at the site of the Eastern Han city of Pingling 平陵. The total area of the ironworks is about 42,000 m^2. The remains of an 'iron furnace' (blast furnace or cupola furnace?) were found, as well as slag, casting models, casting moulds, and iron artefacts. Some 350 iron artefacts were found, representing about 50 types. Zheng Tongxiu and Yuan Ming (1997); Zheng Tongxiu (1998, p. 66).	
43	**Shanxi** Xiaxian	Middle to late Western Han	A Han ironworks inside the walls of an ancient city-site called Yuwangcheng 禹王城 ('City of King Yu') in Xia County 夏縣, Shanxi. Artefacts found include ceramic moulds, potsherds, roof-tiles, and a single cast-iron implement-cap. The date is deduced from the potsherds.	

Table 2 (*cont.*)

No.	Place	Date	Description	Han Iron Office, item in Table 1
			Tao Zhenggang and Ye Xueming (1962); Zhang Yanhuang and Xu Diankui (1963); Tong Xin (1994); Zhang Tongxin (1994); Li Jinghua (1994c, p. 161), citing unpublished information supplied by Zhang Tongxin 張童心 of the Shanxi Provincial Institute of Archaeology 山西省考古研究所.	12
44	**Xinjiang** Lop	Han	Li Jinghua (1974, p. 65; 1994c, p. 162) cites Huang Wenbi (1962) for the presence of a Han ironworks site at the ancient city-site of Yutian 于闐 in Lefu 樂甫縣 or Lepu County 樂浦縣 (probably Lop [Luopu] County 洛浦縣), Xinjiang. On p. 16 of this article there is a brief and very general mention of iron production, and on p. 19 there is a brief mention of the Yutian site. No details are anywhere given on exactly what the evidence for iron production is.	
45	**Xinjiang** Lop and Kucha	Han	Two Han iron mining and smelting sites were discovered, in Lop County 洛浦縣, and Kucha County 庫車縣, Xinjiang, respectively. At Aqikeshan 阿其克山, 30 km S of Lop, sintered iron, broken tuyères, and stone tools for ore dressing were found. At Aaishan 阿艾山 , 120 km N of Kucha, small crucibles, iron slag, ore, and tuyères were found. A complete tuyère is 26 cm long, with inside diameter 4.5 cm. Shi Shuqing (1960, pp. 27–8).	
46	**Xinjiang** Minfeng	Han	A Han ironworks site was found at the Niya 尼雅 city-site in Minfeng County 民豐縣, Xinjiang. No details have been reported except that iron ore and cast-iron implements were found. Shi Shuqing (1962, pp. 24–5).	

Kong family, ironmasters of Wan, translated above,[118] suggests that in the area of Nanyang, Henan, large-scale iron production was introduced rather late, perhaps in the middle of the –3rd century, so it may be that there are not a great many pre-Han ironworks sites to be discovered in Henan.

There is however a geographical consideration of another kind, one that gives an important clue concerning the administration of the Han monopoly. A curious fact about the Han ironworks sites in Table 2 is that so many are located very close to contemporary city-sites: this is not at all what one would expect on the basis of ordinary principles of economic geography. At the Guxingzhen ironworks site, for example, the wall of the Han city of Xingyang 滎陽 can be clearly seen in the middle distance, a few hundred metres away.[119] The large blast furnaces excavated at Guxingzhen consumed enormous amounts of charcoal, competing with the fuel

[118] Pp. 140–1. Note also the archaeological considerations discussed on pp. 122–4 and the *Xun zi* passage quoted on p. 116.

[119] As I saw for myself while visiting the site in the company of Dr Li Jinghua in 1987.

needs of the population of the city, and surely also created a nuisance with their flames and sparks and the slag which had to be got rid of.[120] We should rather expect such an ironworks to be located out in the mountains, near sources of wood for charcoal and away from population centres – and we are told in the *Yan tie lun* passage translated earlier that the pre-monopoly iron smelters 'assembled in deep mountains and remote marshes'.[121]

This suggests, I think, that the introduction of the state monopoly brought with it a change in the geography of the iron industry. While economic and environmental considerations favoured remote locations for the ironworks, the necessity of bureaucratic control may have dictated locations close to administrative centres. Ironworks sites in such locations are more likely to be discovered and excavated in modern times than those located in 'deep mountains and remote marshes'.

Management

It is likely that the 'Iron Offices', *tie guan* 鐵官, were not mere administrative 'offices', as we usually understand the term *guan*, but large ironworks, including the necessary technical machinery as well as living quarters for hundreds of workers. They may in fact have been industrial villages, the successors of the 'iron plantations' which, I have suggested, may have been common in pre-monopoly times.[122] One example of a *guan* 官 of considerable size is the 'Office for brocades' (*jin guan* 錦官) near Chengdu, which several sources indicate was a walled village.[123]

Texts recently excavated from a tomb in Jiangsu shed further light on the management of the Iron Offices. Texts on 156 wooden and bamboo strips were found in Tomb M6 at Yinwan in Donghai County 東海縣尹灣, Jiangsu, dated ca. –10.[124] Among them are six wooden tablets, measuring 23.5 × 7–9 cm, which are believed to be part of a report to higher authorities on the administration of the Han Commandery of Donghai 東海. One of these (no. 1) is an outline of the general administrative conditions of the commandery. It begins: 'prefectures, estates, and marquisates [*xian, yi, hou guo* 縣邑侯國], 38: prefectures, 18, marquisates, 18, estates, 2. Of these, 24 have fortifications. *Du guan* 都官, 2'.[125] The text goes on to give numbers of districts (*xiang* 鄉), neighbourhoods (*ting* 亭), and other subordinate administrative divisions, with information on population, taxes, administrative staff, and other matters. The total number of administrative staff is 2203.

[120] See pp. 231–7 below.
[121] P. 144.
[122] Pp. 144–6 above.
[123] The sources are quoted in Anon. (1979b, pp. 13–14, 83–5).
[124] The excavation report is Anon. (1997). A major study in English is Loewe (2004, pp. 38–88). Related studies include Ji Dakai and Liu Jingsong (1996); Teng Zhaozong (1996a, pp. 27–9; 1996b); Anon. (1996a); Xie Guihua (1997); Xing Yitian (1997); Liao Boyuan (1997); Giele (1997); Kamiya Masakazu (1997); Gao Min (1997; 1999); Yang Jiping (1998); Gao Heng (1999). From dated texts in the tomb it is clear that the tomb is not earlier than –10, and is unlikely to be much later (Anon., 1997, p. 166).
[125] Anon. (1997, p. 77).

Box 10 *Selected entries from a commandery personnel list excavated from Tomb M6, dated ca. −10, at Yinwan in Donghai County* 東海縣尹灣, *Jiangsu. The text is transcribed by Anon. (1997, pp. 79–84); cf. Teng Zhaozong (1996a, pp. 27–9); Loewe (2004, pp. 80–1).*

[obverse, line 2:]

Governor's staff [*li yuan* 吏員], 27:

1 Governor [*tai shou* 太守], ranking . . .[a]
1 Governor's Aide [*tai shou cheng* 太守丞], ranking 600 *shi* 石;
9 Clerks [*zu shi* 卒史];
5 Subsidiary Clerks [*shu* 屬];
9 Administrative Clerks [*shu zuo* 書佐];
1 Assistant Calculator [*yong suan you* 用筭佑];
1 Subordinate Office Bailiff [*xiao fu se fu* 小府嗇夫];
Total 27.

[line 3:]

Chief Commandant's staff, 12:

1 Chief Commandant [*du wei* 都尉], ranking exactly 2000 *shi*;
1 Chief Commandant's Aide [*du wei cheng* 都尉丞], ranking 600 *shi*;
2 Clerks;
3 Subsidiary Clerks;
4 Administrative Clerks;
1 Assistant Calculator;
Total 12.

. . .

[line 5:]

Xiapi 下邳 [Prefecture], 107 staff:

1 Magistrate [*ling* 令], ranking 1000 *shi*;
1 Aide [*cheng* 丞], ranking 400 *shi*;
2 Commandants [*wei* 尉], ranking 400 *shi*;
2 Office Petty Officials [*guan you zhi* 官有秩];
1 District Petty Official [*xiang you zhi* 鄉有秩];
6 Magistrate's Clerks [*ling shi* 令史];
4 Judiciary Clerks [*yu shi* 獄史];
3 Office Bailiffs [*guan se fu* 官嗇夫];
12 District Bailiffs [*xiang se fu* 鄉嗇夫];
6 Patrol Leaders [*you jiao* 游徼];
1 Supervisor of Sacrifices [*lao jian* 牢監];
4 Clerks of Command [*wei shi* 尉史];
7 Office Assistants [*guan zuo* 官佐];
9 District Assistants [*xiang zuo* 鄉佐];
2 Postal Assistants [*you zuo* 郵佐];
46 Neighbourhood Heads [*ting zhang* 亭長];
Total 107.

. . .

(*Cont.*)

Box 10 *Continued*

[line 8:]

Qu 朐 [Estate], 82 staff:

1 Magistrate, ranking 600 *shi*;
1 Aide, ranking 300 *shi*;
2 Commandants, ranking 300 *shi*;
1 District Petty Official;
3 Magistrate's Clerks;
2 Judiciary Clerks;
4 Office Bailiffs;
6 District Bailiffs;
2 Patrol Leaders;
1 Supervisor of Sacrifices;
2 Clerks of Command;
4 Office Assistants;
6 District Assistants;
47 Neighbourhood Heads;
Total 82.

. . .

[reverse, line 21:]

Yilu 伊廬 Salt Office, 30 staff:

1 Chief [*zhang* 長], ranking 300 *shi*;
1 Aide, ranking 200 *shi*;
1 Magistrate's Clerk;
2 Office Bailiffs;
25 Assistants [*zuo* 佐];
Total 30.

[line 22:]

Beipu 北蒲 Salt Office, 26 staff:

1 Aide, ranking 200 *shi*;
1 Magistrate's Clerk;
2 Office Bailiffs;
22 Assistants;
Total 26.

[line 23:]

Yuzhou 郁州 Salt Office, 26 staff:

1 Aide, ranking 200 shi;
1 Magistrate's Clerk;
1 Office Bailiff;
23 Assistants;
Total 26.

Box 10 *Continued*

[line 24:]

Xiapi Iron Office, 20 staff:

1 Chief, ranking 300 *shi*;
1 Aide, ranking 200 *shi*;
3 Magistrate's Clerks;
5 Office Bailiffs;
9 Assistants;
1 Neighbourhood Head;
Total 20.

[Line 25:]

. . .[b] Iron Office, 5 staff:

1 Aide, ranking 200 *shi*;
1 Magistrate's Clerk;
1 Office Bailiff;
2 Assistants;
Total 5.

[line 26:]

Grand total, 2,202 staff.

[a] Four illegible characters, probably *zhong er qian shi* 中二千石, 'fully 2000 *shi*'. Teng Zhaozong (1996a, p. 27); cf. Bielenstein (1980, pp. 93, 182).
[b] Illegible place-name, possibly *Qu* 朐 (Teng Zhaozong, 1996a, p. 29).

The two *du guan* mentioned here are believed to be one Iron Office and one Salt Office, and the term may be translated 'national offices': administrative instances under central government authority rather than that of the commandery.[126]

Another tablet (no. 2, containing 3560 characters) lists the positions and ranks of administrative staff in each of the prefectures, marquisates, and estates, together with three Salt Offices and two Iron Offices. It gives the total number of staff as 2202 rather than 2203. Several items on the tablet which are relevant to the present discussion are translated in Box 10. Other tablets (nos. 3–4)[127] give names and places of origin of the persons holding these positions.

The Yinwan texts are valuable source material for many aspects of Han history, but we may start by noting one in particular: they indicate a number of scribal errors in the geographical section of the *Han shu*.[128] An example is that several place-names are written in the *Han shu* with incorrect characters, e.g. *Haiqu* 海曲 for *Haixi* 海西 and *Zhuqi* 祝其 for *Kuangqi* 況其.[129]

[126] See Anon. (1996a, p. 70); Xie Guihua (1997, p. 43); Giele (1997, p. 126); Qiu Xigui (1981, p. 231). Teng Zhaozong (1996a, p. 26) transcribes the first character of *du guan* as *jun* 郡, but all others who have studied the texts read it as *du*.
[127] Anon. (1997, pp. 85–94).
[128] These are discussed by Anon. (1996a, pp. 70–1); Gao Min (1997, p. 54). Another apparent scribal error in the *Han shu* is pointed out by He Shuangquan (2000, p. 25).
[129] Anon. (1996a, p. 70).

More seriously, the population figures given in the *Han shu* for the year +2 may be exaggerated. Long ago Wang Mingsheng 王鳴盛 (1722–98) pointed out that in that year Wang Mang already held *de facto* power at court, and was likely to have inflated the population figures to prove his beneficial influence.[130] Nevertheless modern scholars, especially in the West, have generally ignored this caveat and assumed that the *Han shu* figures are quite reliable.[131] For Donghai Commandery in +2 the *Han shu* reports 358,414 households, 1,559,357 persons.[132] The Yinwan text reports, for a time very close to this (shortly after −10), only 266,290 households, 1,397,343 persons.[133] The editors note that this would imply a 10 per cent increase in population in 12 years or less, and do not consider this credible.[134]

Of the three Salt Offices and two Iron Offices listed in the Yinwan text (see Box 10), one of each is administered by a Chief (*zhang* 長) ranking 300 *shi*, assisted by an Aide (*cheng* 丞) ranking 200 *shi*. The others are administered by Aides ranking 200 *shi*. It is likely that the latter offices were subordinate to the former, and that the two *du guan* (noted above) were one Salt Office and one Iron Office, each headed by a Chief.

Of the three locations of Salt Offices, two can be identified today: Yilu and Yuzhou were in Qu Prefecture, which at that time was on the seacoast.[135] The *Han shu* does not list a Salt Office in Donghai Commandery, but it lists two Iron Offices, in Xiapi and Qu Prefectures (see Table 1, item 6).[136] In the Yinwan text, the Iron Office headed by a Chief is in Xiapi; the location of the subordinate Iron Office is unfortunately illegible. Teng Zhaozong, following the *Han shu*, suggests that the illegible place-name is Qu,[137] but other scholars who have studied the text believe it more likely that we have here another error in the *Han shu*. The listing of an 'Iron Office' under Qu Estate, they believe, is an error for 'Salt Office'; the subordinate Iron Office would not have had a separate entry in the *Han shu*, and it could have been anywhere in the commandery.

The Han bureaucracy was a finely crafted system for the administration of a large agricultural population. The Salt and Iron Offices were an anomaly in the system; this fact was hazily known before, but the Yinwan texts make it clear. The industrial offices were placed in the administrative hierarchy at the same level as the prefectures in which they were located (see Box 10). They presumably reported to the commandery administration rather than to the prefecture, and perhaps (if the term *du guan* 都官 has been understood correctly) directly to the capital as well.

[130] *Shi qi shi shang que* 十七史商榷, ch. 15, p. 126; Anon. (1996a, p. 70).
[131] E.g. Bielenstein (1987, pp. 11–14).
[132] *HS*, ch. 28a, p. 1588.
[133] Tablet no. 1, obverse, lines 10–11, transcribed Anon. (1997, p. 77); Teng Zhaozong (1996a, p. 26); cf. Anon. (1996a, p. 70). The text also gives the following additional statistics: male, 706,064 persons, female, 688,132 persons (the sum of these is 1,394,196); 80 years and over, 33,871 persons; 6 years and under, 262,588 persons; 90 years and over, 11,670 persons (reverse, lines 3–5; Anon., 1997, p. 79).
[134] But note Loewe (2004, p. 61).
[135] Teng Zhaozong (1996b, p. 33); Anon. (1996a, p. 70). The location of the seacoast at that time is shown by Tan Qixiang (1982–87, vol. 2, p. 20).
[136] *HS*, ch. 28a, p. 1588.
[137] Teng Zhaozong (1996a, p. 29).

The Salt and Iron Offices were headed by Chiefs (*zhang* 長) of rank 300 *shi* with Aides (*cheng* 丞) of rank 200 *shi*, the same as the smaller prefectures. It is perhaps not an accident, however, that the ranks of the Chief and his Aide were distinctly lower than the ranks of the Prefect and Aide in the prefectures where they were located (see Box 10). We may be sure that the two instances, representing agriculture and industry within a single administrative area, were often at odds, and a built-in bias in favour of agriculture may have been a firm principle.

The Yinwan texts seem also to confirm that the Iron Offices were fairly large population centres. The prefectures were divided into 'neighbourhoods' (*ting* 亭); the text states that there were 688 of these,[138] so that their average population was about 2000 persons. The administration of each prefecture, marquisate, and estate included a number of Neighbourhood Heads (*ting zhang* 亭長), and these numbers add up to precisely 688, so obviously each neighbourhood had a single Head.[139] However the Xiapi Iron Office administration included an additional Neighbourhood Head, seemingly without a neighbourhood to be head of (see Box 10). A great deal is unknown here, but in our ignorance we may speculate as follows. A Neighbourhood Head no doubt dealt with matters of order, corvée, and tax collection in the agricultural population at the lowest level. An Iron Office was not strictly speaking a 'neighbourhood', but it had a sufficiently large population to require a person to perform the same duties, and for convenience he was given the same title. Here again the industrial offices cause anomalies in the pleasingly logical structure of the bureaucracy.

Several sources indicate, as we have seen above,[140] that in the early days of the monopoly the officials in charge of the Iron Offices were wealthy industrialists, who had the necessary technical and commercial expertise. Later the situation may have been different. An Eastern Han tomb inscription tells us of the only Iron Officer whose name we know:[141] Zhao Menglin 趙孟麟, who died in +99, had what seems to have been quite a normal bureaucratic career, starting as a Prefectural Clerk (*shu zuo* 書佐), moving up to Commandery Postmaster (*jun du you* 郡督郵) and Commandant of Qingyi (Prefecture, in Shu Commandery 蜀郡, in modern Sichuan, *Qingyi wei* 青衣尉), before being appointed Chief of the Iron Office of Shu Commandery (*Shu tie guan zhang* 蜀鐵官長).[142] Nothing in the inscription suggests any experience with iron production before he was appointed to this position, and we should probably assume that by this time the technical expertise needed in iron production was provided by persons in positions below the regular civil service.

. . .

[138] Tablet no. 1, obverse, line 3; Teng Zhaozong (1996a, p. 26).

[139] Tablet no. 2, *passim*; Teng Zhaozong (1996a, pp. 27–9); sample entries are translated in Box 10. Xie Guihua (1997, pp. 47–8) gives a useful table of the numbers in this list, unfortunately with several typographical errors. Note in particular that in the column *ting zhang* 亭長 on p. 48 there should be a 1 (instead of a blank) in the third-from-last row and 689 (instead of 589) in the last row.

[140] Pp. 177, 178.

[141] One of the Yinwan administrative texts lists three persons employed in Iron Offices, but this information seems difficult to interpret. Anon. (1997, pp. 93–4).

[142] *Li shi* 隸釋, ch. 4, pp. 2b–3b; cf. Chen Zhi (1980, p. 113).

The Iron Offices seem to have been required to send quite detailed reports to the capital.[143] An example is given by reports on two blast-furnace explosions at Iron Offices. These would normally not have come down to us, but they were useful to Ban Gu when he wrote the 'Treatise on [derangements of] the five elements' (*Wu xing zhi* 五行志) of the *Han shu*:[144]

In the second year of Zhenghe 征和 [–91], in the spring, the Iron Office of Zhuo Commandery[145] 涿郡 [in modern Hebei] was casting iron. When the iron melted, it all flew upward.

. . . [The explosion is interpreted as a portent of the great witchcraft affair of –91.[146] A leading actor in that affair, Liu Quli 劉屈氂, was Grand Administrator (*tai shou* 太守) of Zhuo Commandery at the time of the explosion. In the following month he was appointed Chancellor (*cheng xiang* 丞相); a year later he was publicly executed.]

In the reign of Cheng-di 成帝, in the first month of the second year of Heping 河平 [–27], in the spring, the Iron Office of Pei Commandery[147] 沛郡 [in modern Jiangsu] was casting iron. The iron did not descend; there was a roaring sound, as of thunder, and also a sound like that of drums [*long long ru lei sheng, you ru gu yin* 隆隆如雷聲，又如鼓音]. Thirteen workers fled in alarm. When the sound had ceased, they returned to inspect the site; there were crevices in the earth several *chi* 尺 long, and the furnace had broken up into ten parts. [This case of] molten iron in one furnace scattering like meteors, all flying upward, was the same phenomenon as the events of the second year of Zhenghe.

. . . [The second explosion is interpreted as one of the numerous portents of the rise of the house of Wang and the usurpation of Wang Mang. Shortly afterward, five maternal uncles of the Emperor, surnamed Wang, were enfeoffed as marquises. The connection with Pei Commandery is perhaps that the founder of the Han, Liu Bang 劉邦, was from there.]

When Homer H. Dubs was translating these passages he went for technical help to the mining engineer Thomas T. Read, who had worked in China and written on the history of ferrous metallurgy there. Read pointed out that it is quite clear from the text that the furnace involved is a shaft furnace (a cupola for casting or a blast furnace for smelting), and that the accidents are what American metallurgists called 'furnace breakouts'.[148] At that time this was the only evidence available that shaft furnaces had ever been used in ancient China. In the 19th century John Percy described a great many comparable explosions in English blast furnaces.[149] Someone involved in the reporting of the second event must have been rather familiar

[143] Another sign that such offices sent technical information to the capital is a memorial quoted in *Wei shu* (ch. 110, p. 2865) which gives quantitative information on grades of copper ores in several places, and states that these are where there were Copper Offices 'in former times'. Clearly the memorialist's source was the Han archives, directly or indirectly.

[144] *HS*, ch. 27a, p. 1334, note also ch. 10, p. 309; tr. Dubs (1938–55, vol. 2, p. 385); Needham (1958, p. 8); Liu Yuncai (1978, p. 19); Wang Chunguang (1990). On the *Wu xing zhi* chapters of the *HS* see *SCC*, vol. 2, p. 247; Eberhard (1933).

[145] See Table 1, item 44.

[146] See e.g. Loewe (1974, pp. 37ff); Jongchell (1930, pp. 29ff).

[147] See Table 1, item 26.

[148] Dubs (1938–55, vol. 2, p. 385, fn. 5.9).

[149] Percy (1864, pp. 521–6).

with the operation of a shaft furnace. That 'the iron did not descend' clearly refers to a phenomenon known as 'scaffolding': if the furnace burden adheres to the side of the furnace it can accumulate, forming a 'scaffold' which prevents the charge from descending. When the scaffold suddenly falls, an explosion can occur.

The mention of 'a sound of drums' is peculiar. The text as it stands can hardly mean anything else, but it may be the result of the historian's editing of some statement concerning the bellows which he did not understand: *gu* 鼓, 'drum', often means 'to operate a bellows' in Han texts.[150]

Labour

There is not much direct evidence on the labour force of the Iron Offices, but a good deal of indirect evidence which at least makes possible some educated guesses. Perhaps the first point to be brought out is that an ironworks required a small group of skilled workers and a very large force of unskilled or semiskilled workers. This would seem to be a requirement in any ironworks using a charcoal-fuelled blast furnace producing a few hundred tonnes of iron per year. William Byrd in the 18th century wrote that an iron plantation in Virginia required about 10 skilled workers and 120 slaves.[151] He added, 'the more Virginians among them the better'[152] – blacks born in slavery rather than newly imported from Africa – for the work required more sophisticated communication than most colonial slave labour. In the 17th century Qu Dajun wrote in his *Guang dong xin yu* of the hundreds of workers used in the ironworks of Guangdong.[153] In the –3rd century the Zhuo family had 800 or 1000 slaves, who presumably worked in the family ironworks,[154] and a passage in the *Yan tie lun* speaks of ironmasters 'gathering together a multitude of over a thousand persons'.[155]

Our only view of the skilled workers of the Iron Offices is in the *Han shu* passage on blast-furnace explosions quoted above: the 13 workers mentioned would have included the furnace master as well as workers engaged in more routine but still responsible tasks such as charging and tapping the furnace, plus whatever unskilled workers happened to be nearby.

The unskilled labourers worked in mining or ore gathering, ore dressing, forestry, charcoal production, transportation, and all manner of fetching and carrying at the ironworks. In an ancient Chinese context they would normally have worked the bellows of the blast furnace as well.

150 See for example the gloss by Ru Chun 如淳 in *HS* (ch. 64, p. 2818) and that of Hu Guang in *HHS* (p. 192, fn. 110 above). A possible much older example is the occurrence of the expression *gu zhu* 鼓鑄 in a bronze inscription, though this is controversial (Zhao Chao, 1987, p. 74).
151 P. 145 above.
152 Byrd (1966, p. 348).
153 Box 4, pp. 49–52 above.
154 Pp. 140–1 above.
155 P. 144 above.

Among the changes which occurred with the establishment of the state monopoly was that much of the unskilled work was taken over by convict labourers, as we have seen in the quotation from the *Yan tie lun* in Box 9.[156] The problems of organising and controlling large numbers of forced labourers is probably the reason that the central administration of the monopoly was at some time transferred from the Ministry of Agriculture to a military office, the Chief Commandant of Waters and Parks (*Shui heng du wei* 水衡都尉), which was established in –116 and had a variety of miscellaneous duties concerning technical administration.[157]

Towards the end of the Western Han period the histories note a great increase in the frequency of local revolts,[158] and two of these involved convict labourers at Iron Offices:

[In the 3rd year of Yangshuo 陽朔], in the summer, the 6th month [July/August, –22], 180 convict labourers of the Iron Office of Yingchuan 穎川 [Commandery],[159] Shentu Sheng 申屠聖 and others, killed a Senior Subaltern [*zhang li* 長吏], plundered an arsenal, called themselves Generals, and passed through nine (commanderies).[160] An Aide to the Counsellor-in-Chief [*cheng xiang zhang shi* 丞相長史] and a Palace Aide to the Imperial Counsellor [*yu shi zhong cheng* 御史中丞] were sent to pursue and arrest them, proceeding according to [the law for] levying military supplies. All were punished.[161]

[In the 3rd year of Yongshi 永始], in the 12th month [January/February, –13], 228 convict labourers of the Shanyang 山陽 [Commandery] Iron Office,[162] Su Ling 蘇令 and others, attacked and killed a Senior Subaltern [*zhang li* 長史], plundered an arsenal, called themselves Generals, passed through 19 commanderies and Kingdoms, and killed the Governor [*tai shou* 太守] of Dong Commandery 東郡 and the Defender [*du wei* 都尉] of Ru'nan 汝南 [Commandery]. An Aide to the Counsellor-in-Chief [*cheng xiang zhang shi* 丞相長史] and a Palace Aide to the Imperial Counsellor [*yu shi zhong cheng* 御史中丞] were sent with credentials to superintend and encourage their pursuit and arrest. The Governor of Ru'nan,[163] Yan Xin 嚴訢, arrested and beheaded Su Ling and the others. Yan Xin was promoted to Minister of Agriculture [*da si nong* 大司農] and granted 100 *jin* 斤 of gold.[164]

[156] See also Zhang Zhenglang (1951; 1958). The Han system of punishments by hard labour has been described briefly by Hulsewé (1955, pp. 128–32). A statement by Gong Yu in –44 suggests that conscripted soldiers (*zu* 卒) were also employed in both iron and copper production (*HS*, ch. 72, p. 3075). Perhaps some seasonal work was done by peasants as corvée, for example forestry and charcoal production, but this is less clear.

[157] *SJ*, ch. 30, p. 1436; Watson (1993b, vol. 1, pp. 77–8); *HS*, ch. 24b, p. 1170; ch. 19a, p. 735; Swann (1950, p. 297); Bielenstein (1980, pp. 82–3).

[158] See e.g. Dubs (1938–55, vol. 2, pp. 362–3); Gao Min (1982b).

[159] See Table 1, item 44, which indicates that in +2, in Yingchuan Commandery, there was an Iron Office for Yangcheng Prefecture. The passage quoted here, and the implement inscription *Chuan* 川, indicate that there had earlier been an Iron Office for the commandery. One wonders whether its abolition had anything to do with the revolt of Shentu Sheng.

[160] Commentators believe that 'nine commanderies' represents far too large an area, and that 'nine prefectures' must be meant. See Dubs (1938–55, vol. 2, p. 391, fn. 7.10).

[161] *HS*, ch. 10, p. 314; cf. Dubs (1938–55, vol. 2, p. 391); Ch'ü (1972, p. 143); Wilbur (1943, pp. 224–5).

[162] See Table 1, item 31.

[163] Some scholars transcribe this surname Zhuang (e.g. Twitchett and Loewe, 1986), apparently because it originated as a substitute for the taboo character *zhuang* 莊. Chinese dictionaries give only the pronunciation *yan* for the surname.

[164] *HS*, ch. 10, pp. 323–4; cf. ch. 26, p. 1311; ch. 27a, p. 1341; Dubs (1938–55, vol. 2, pp. 406–7); Ch'ü (1972, p. 143); Wilbur (1943, pp. 224–5).

We may possibly have further glimpses of these workers in some archaeological material. A stele inscription commemorating the building of the Bao–Ye Road 褒斜道 from Shaanxi to Sichuan,[165] erected near Baocheng 褒城 , Shaanxi, includes the following:

In the 6th year of Yongping 永平 [+63], Hanzhong Commandery 漢中郡 received by Imperial command 2690 convict labourers [*tu*

徒] from Guanghan 廣漢 [Commandery], Shu Commandery 蜀郡 , and Ba Commandery 巴郡 to construct the Bao–Ye Road. The labour [*gong* 功]used was more than 766,800 persons [*ren* 人, presumably worker-days].

Chen Zhi suggests that these convict labourers were seconded to the construction project from Iron Offices and other state industrial offices in the commanderies listed.[166]

Other convict labourers who may have worked for an Iron Office are those buried in a graveyard near the site of the Han city of Luoyang.[167] It appears that the graveyard measures about 250 × 200 metres. In excavations of about 2300 square metres of it, 522 graves were found. Figure 92 shows some of the graves under excavation. A single person was buried in each, in a coffin, usually with one or two inscribed bricks like the one shown in Figure 93 placed on top of the coffin, and sometimes with a large number of unrelated inscribed bricks under the coffin, presumably from older graves disturbed in later grave-digging. Some 820 such bricks were found. A typical inscription is:[168]

Xie Lang, from E [Prefecture] in Jiangxia [Commandery], without guarantors, serving a sentence as an unmutilated wall-builder with the Right Division, died on the 1st day of the 7th month of the first year of Yongchu [+107]. His body lies hereunder.
右部無任江夏鄂完城旦謝郎永初元年七月一日物故死在此下

Cheng dan 城旦, here translated 'wall-builder', was the standard term for a convict labourer serving a four-year sentence, and did not necessarily indicate the actual work he was doing.[169] Of the bricks found in this excavation, 229 bear dates, and

[165] See *SCC*, vol. 4, Part 3, pp. 20ff; Chen Mingda (1961); Huang Shengzhang (1963). The inscription is still extant, and was declared a National Treasure in 1961, but the stone itself, as opposed to rubbings from it, appears not to have been studied in the 20th century. A rubbing of the inscription is reproduced by Shimonaka Yasaburō (1930, pp. 36–41). The text is transcribed by Wang Chang (1805, ch. 5, pp. 12b–13a); Guang Chaokui et al. (1832, ch. 8, pp. 1b–2a, repr. pp. 272–3); Chen Mingda (1961, p. 58), following Wang and Guang; Huang Shengzhang (1963).

[166] Chen Zhi (1980, p. 161). There were definitely Iron Offices in Ba and Shu; see Table 1, items 1, 32. Chen Zhi also suggests that dividing the amount of labour by the number of labourers gives 766,800/2690 = 285 days as an approximation of the time needed to build the road; a different interpretation is given by Qu Fei (1963).

[167] The graveyard was discovered in 1907, in the construction of the Long–Hai 隴海 Railway. The inscriptions have been studied by Hamaguchi Shigekuni (1936, pp. 229–33); Zhang Zhenglang (1951; 1958); Hulsewé (1955, p. 132); Wang Zhongshu (1982, pp. 212–13). Duanfang (1909) published 113 of the inscriptions; publications of Luo Zhenyu give full-sized tracings of 31 inscriptions (1915), and transcriptions of 232 inscriptions (1917). Zou An (1976, ch. 4) reproduces full-size rubbings of several inscriptions. New excavations undertaken in 1964 are to be published in a book entitled *Luoyang Dong Han xingtu mu* 洛陽東漢刑徒墓 ; until it is available see Anon. (1972b); Pan Qifeng and Han Kangxin (1988).

[168] Artefact no. T2M13:2, obverse; Anon. (1972b, p. 6 + fig. 5.5). There are numerous uncertainties in the interpretation of the inscriptions, and this translation is highly tentative. See Zhang Zhenglang (1958, pp. 181–4); Chen Zhi (1963, p. 83); Yu Haoliang (1964, p. 158; 1985, pp. 210–11). Note that *wu gu* 物故 means 'to die', and that all commentators take *si* 死 to be a loan for *shi* 尸, 'corpse'.

[169] Hulsewé (1955, pp. 128ff).

Figure 92 Eastern Han period graves of convict labourers near the Han city of Luoyang, under excavation in 1964. Reproduced from Anon. (1972b, pl. 4).

Figure 93 Inscribed brick from the cemetery of convict labourers near the Han city of Luoyang (artefact no. T2M77:1). Reproduced from Anon. (1972b, pl. 5.2).

these range from +103 to +125.[170] There are two clusters of dates: 14 are in a short period in the 5th and 6th months of +107 and another 14 are between the 20th and 29th days of the intercalary month of +119. These would seem to mark major outbreaks of disease, or perhaps industrial accidents of one kind or another.

Study of 390 skeletons indicates that very nearly all of the persons buried were men in the age range 14–44, though there were also three children under 7, seventeen men over 44, and seven women in the age range 14–34.[171] The examination shows that several had been beaten to death, while others had been subjected to severe beatings at some time before death. No wood remains in the graves, but the presence of nails indicates that all were buried in coffins. Very few grave-gifts were found – a few coins, two ceramic vessels, and a silver ring buried with one of the women.[172] Perhaps if wooden artefacts had been preserved we should see more of what these convicts' fellows laid with them in their graves – they came from all over the Empire, and it is unlikely that their families were present.

We cannot be sure what work these labourers did, but within a range of 100 km of the site there were several Han ironworks, including the important Iron Offices of Henan Commandery 河南郡.[173] Perhaps the various tasks of iron production were among their duties.

(iv) Reasons for the Monopoly, Reasons for Opposition

Looking at the reasons for the establishment of the monopolies, and for the opposition to them, some are explicit in the *Yan tie lun* while others, not mentioned there, can be surmised.

State finance

The monopoly was a good source of income for the state. The government side argues this in the context of defence needs:

The Imperial Counsellor: The Xiongnu are rebellious, and will not submit; they have frequently terrorised the borderlands. Opposing them is gruelling for the soldiers of the Central States, but if we do not oppose them their incursions and plundering will never stop. The former Emperor [Wu-di] felt for the protracted troubles of the people of the borderlands, and suffered with those taken captive by those barbarians. For this reason he strengthened the passes, built signal-relay stations, and established garrisons in order to oppose them. [However, for these undertakings] the resources of the border region were inadequate, and therefore

[170] The 232 inscriptions transcribed by Luo Zhenyu (1917) include dates in the range +86 to +106, plus two with the dates +170 and +172.

[171] Pan Qifeng and Han Kangxin (1988, p. 277); translation David Yu (2001). There is much more of interest here on various aspects of the buried persons' health. Note that the excavation report (Anon., 1972b, pp. 3, 9) gives some rather different findings from preliminary bone studies.

[172] Anon. (1972b, p. 4).

[173] See Table 2, items 27, 20, 8, 12; Table 1, item 13.

he instituted the Salt and Iron [Offices], set up the monopoly on fermented liquors, and established Equable Transportation, producing an abundance of goods while stretching resources, in order to subsidise the expenses of the borderlands. [The government's critics] now propose the abolition of these [economic interventions]. Within, this would empty the coffers of the state; without, it would impoverish the defences, leaving the soldiers who guard the passes and defend the walls to starve and freeze on the borders. How are they to be supplied? Abolition would not be advantageous.[174]

On the other hand we have seen that the critic Bu Shi 卜式 saw the monopolies as 'putting the officers of the government in stalls in the market', and this complaint is echoed elsewhere: manufacturing and buying and selling for profit are, in the opinion of the critics, demeaning, not proper activities for the state.

Contraband trade

A fragment of the Han law of contraband is preserved in a commentary by Ying Shao 應劭 in the +2nd century:[175]

The statute of 'Barbarian markets': Neither officers nor common people are permitted to go out through the pass carrying weapons or iron. Even if they have been purchased in the capital, the law is still the same.
律，胡市，吏民不得持兵器及鐵出關·雖於京師市買，其法一也·

There is some slight doubt about the words 'or iron',[176] but the most likely interpretation is that it was illegal to supply iron articles of any description to the Xiongnu and other nomads. It may be that a similar statute is mentioned in a Han text unearthed in Dunhuang.[177] On the other hand, excavations of Xiongnu sites and graves have yielded so many iron artefacts, including weapons with Chinese inscriptions, that many historians believe the law was routinely flouted.[178]

Ying Shao's comment is attached to the story in the *Shi ji* and *Han shu* of what must have been a major scandal in the year −121, when some 500 persons were sentenced to death for selling contraband goods to a group of surrendered Xiongnu.[179] We may suspect that this event was one important factor in the decision only four

[174] *YTL*, ch. 1, Wang Liqi (1958, p. 2; 1992, p. 2); note also chs. 13 and 28, Wang Liqi (1958, pp. 95, 192; 1992, pp. 171, 332). Cf. Baudry-Weulersse et al. (1978, pp. 46, 95, 158); Gale (1967, pp. 3–4).

[175] *HS*, ch. 50, p. 2321 n. 7; note Hulsewé (1955, p. 41). It is not possible to determine whether the last sentence belongs to the text of the law or is a comment by Ying Shao. On the 'Barbarian markets' see e.g. Huang Jinyan (1999).

[176] Ying Shao's comment is quoted by Pei Yin 裴駰 in the +5th century, in his comment on the parallel passage in *Shi ji* (ch. 120, p. 3110 n. 3), with the words *ji tie* 及鐵, 'or iron', omitted.

[177] Yü (1967, p. 129); but cf. Loewe (2002, pp. 127–8). Note also the proposal made during the reign of the Empress Lü 呂后 (−194 to −180) for a prohibition of the export of iron products to the kingdom of Nan Yue 南越 (in modern Guangdong). *SJ*, ch. 113, p. 2969; *HS*, ch. 95, p. 2848; Watson (1993b, vol. 1, p. 208); Twitchett and Loewe (1986, p. 136).

[178] E.g. Yü (1967, p. 130). Reports of iron artefacts from Xiongnu contexts include Yetts (1926, p. 1); Rudenko (1969, pp. 28, 45, 52, 54, 134, 136); Sun Shoudao (1960); Zhao Shengchen (1979, p. 52); Guo Suxin and Tian Guangjin (1980, pp. 5–6); Tian Guangjin (1976, p. 139; 1983, pp. 15–17); Sun Ji (1991, pp. 421–6); Davydova (1996, e.g. pl. 70). Note also the slightly later Xianbei iron artefacts examined by Chen Jianli et al. (2001).

[179] *SJ*, ch. 120, pp. 3109–10; *HS*, ch. 50, pp. 2320–1; tr. Watson (1993b, vol. 2, pp. 312–13). The few available sources on contraband trade in the Han period are discussed by Ying-shih Yü (1967, pp. 117–32).

years later to establish the monopoly, which ought to have made it easier to enforce the law and prevent the Xiongnu from obtaining iron weapons. Curiously, however, no such connection is ever made explicit, either in the *Yan tie lun* or – it would seem – in any other Han source.

Control of the wealthy

We have already seen the argument that the monopoly made it possible to bring under control the rich and powerful ironmasters, who 'gathered a multitude of over a thousand persons' who 'abandoned the graves of their ancestors' and 'assembled in deep mountains and remote marshes'.[180] The government side takes up this argument again in another passage:

The Imperial Counsellor: When an ordinary man has a valuable object, he will put it in a box to keep it safe.[181] How much more carefully should the Ruler then treat the mountains and seas! The places of abundance are always in the midst of deep mountains and extensive marshes, and only a wealthy and powerful person can fully exploit their benefits . . .

Now [the government's critics wish to] release the common people [to seek] power and profit and abolish the salt and iron [offices], thereby enriching the brutal and tyrannical [industrialists]. They [would then] follow their greedy hearts, the many evil-doers would form gangs, and individual households would form factions. The recalcitrant would become increasingly ungovernable, and among the followers of [heterodox] leaders, perverse tendencies would emerge.[182]

Blast-furnace iron production is highly capital-intensive, and wealth is required for its exploitation. Further, a certain charisma and knowledge of men is required to keep order among the hundreds of workers at an ironworks. Organising and leading men was, for the government side, one of the prerogatives of the state. The establishment of Salt and Iron Offices brought these potentially dangerous wealthy leaders under the control of the state while simultaneously giving them a secure place within the Imperial order. The use of convict labour removed the command of large gangs of workers to other administrative instances, and the establishment of ironworks near cities brought the industry from its 'deep mountains and extensive marshes' to become a part of civilised society.

In the quotation above the government side presents this transformation of the rôle of the industrialist as a victory of the state over the forces of disorder, but on its face it would seem in many ways to have been an excellent bargain for the industrialists as well. We have seen that Sima Qian and others felt that the wrong persons were obtaining official positions.[183] The government's critics in the *Yan tie lun*

[180] P. 144 above; note also pp. 190–1.

[181] This statement brings to mind the political parable in *Zhuang zi* (ch. 10, Guo Qingfan, 1961, pp. 342ff; tr. Graham, 1981, pp. 207ff) that the man who locks his valuables in boxes, baskets, and bags simply makes it easier for the robber to make off with them. One must wonder whether Huan Kuan intended the reference.

[182] *YTL*, ch. 5, Wang Liqi (1958, p. 37; 1992, p. 67); note also chs. 4, 41, Wang Liqi (1958, pp. 29, 274; 1992, pp. 56, 462). Cf. Baudry-Weulersse et al. (1978, pp. 71, 65, 207); Gale (1967, pp. 30–1).

[183] P. 175 above.

constantly repeat that official position is for those who have studied the Classics and thereby acquired the proper moral habitus for a servant of the Emperor and administrator of the people.

Product quality

The large-scale ironworks of the monopoly, according to the government's spokesman, provides abundant raw materials and good working conditions, so that all necessary technical processes are carried out properly. This makes for a product of higher quality than is possible in small-scale production units.[184] The claim may very well have a solid basis, for metallographic examination of early cast-iron implements indicates that their production often involved several stages, each of which could be technically complex as well as time-consuming.[185] Several axeheads, for example, were cast, then annealed in an oxidising atmosphere to reduce the carbon content, then cold-hammered, then annealed in a reducing atmosphere to increase the carbon content at the surface.[186] The two annealing processes required at least a day or two each, and maintaining the appropriate temperature and atmosphere required skill on the part of the workers. That things did sometimes go wrong is shown by several new and unused axeheads, apparently discarded, in an ancient iron scrap-heap excavated in Mianchi, Henan.[187] We do not have metallographic examinations of these, but presumably they had failed to pass some quality check after annealing, and were to be recycled.

The government's critics, on the other hand, claim that the monopoly ironworks produce mostly 'large implements', *da qi* 大器, made to meet quotas rather than for practical use. They further claim that the products are inferior in quality and high in price. Bu Shi had said the same as early as −111, using the same expression, *ku e* 苦惡 or *gu e* 鹽惡, 'inferior'. Much later,[188] about +150, Cui Shi 崔寔 made a complaint that seems to show both sides of the issue of quality control in government production:[189]

It is written: 'If a craftsman wishes to do good work, he will surely start by sharpening his tools.'[190] In the past, between the Yongping 永平 and Jianchu 建初 periods [i.e., around +75], the results of going to war had not lasted long, and the Court began to pay attention to military preparations. The materials were plentiful and the men in charge were personally

[184] Box 9 and pp. 187–8 above.
[185] Pp. 159–69 above.
[186] Wagner (1993, pp. 359–60, 481).
[187] Li Jinghua (1976, p. 48). On the Mianchi scrap-heap see Wagner (1993, p. 237, fn. 131); also pp. 250–1 below.
[188] *SJ*, ch. 30, p. 1440; *HS*, ch. 24b, p. 1123; Watson (1993b, vol. 2, p. 81); Swann (1950, p. 311). On the terms *ku e* and *gu e* see Chen Zhi (1979a, p. 282; 1979b, p. 81). It seems quite possible that the *Shi ji*, *Han shu*, and *Yan tie lun* all draw on the same source here, some memorial by Bu Shi.
[189] *Zheng lun* 政論, surviving abridged version in *Qun shu zhi yao*, *SBCK* edn, ch. 45, pp. 7a–9a, *CSJC* edn, p. 785; Yan Kejun (1894, Hou Han sect., ch. 46, pp. 6b–7a); cf. Dien (1982, p. 15). This passage is not in the *Hou Han shu* and *Zi zhi tong jian* versions. In the translation I have followed all of the variant readings in *TPYL*, ch. 356, p. 3a. Note that this passage does not directly concern the Iron Offices, which produced raw materials and implements, but the various instances which produced weapons, for example the *gong guan* 工官, 'Offices of Craftsmen'. On Cui Shi and his works see Kuhn (1914); Herzer (1963); Ebrey (1974, pp. 43–9 *et passim*).
[190] Confucius in *Lun yu*, ch. 15, p. 2517b; cf. Waley (1938, p. 194).

involved; therefore the weapons made by the government agencies [*guan bing* 官兵] were always strong and sharp. To this day the 'Crossbows of Grand Coachmen Xie and Cai' and the 'Longting sword of the ninth year'[191] are famous throughout the Empire.

But not long thereafter the overseers stopped being attentive, and the wrong men have been promoted by Imperial decree. Greedy officers [*li* 吏] fight over the materials, and shifty craftsmen cheat them. Things have gone so far that bows and crossbows are strung with hemp, and lacquer is adulterated with rice gruel. Iron [i.e. steel] is quenched in vinegar,[192] making it brittle and easy to . . . [?][193] The suits of armour are too small and do not fit properly. Knives and spears are dull. Therefore the daring and sturdy warriors of the border population all make their own weapons, and are unwilling to use those provided by the government.

This passage presents a number of technical questions which we must leave unanswered. The point it makes is clear: with good administration the government can produce the best weapons, but poor administration leads to inferior quality.

Two related complaints in the *Yan tie lun* may also be mentioned here. The monopoly ironworks have inappropriately standardised the implements without considering the different needs of peasants in different parts of the Empire.[194] And there is sometimes overproduction, in which case the Iron Offices force the peasants to purchase more than they need.[195]

The question of 'large implements', which according to the critics were produced by the monopoly ironworks for the sole purpose of fulfilling quotas, has inspired some interesting archaeological research, especially by Zhang Chuanxi.[196] It seems that ploughshares found in Han contexts can be classified in three sizes, small, medium, and large.[197] The largest of these (e.g. Figure 94) are by modern standards huge, over 40 cm in breadth and weighing over 20 kg; doubt has therefore been expressed as to whether they were practical implements at all.[198] This question has been convincingly answered in the affirmative in an admirable piece of experimental archaeology organised by Zhang Chuanxi and carried out at the Beijing Institute for Agricultural Mechanisation (Beijing Nongye Jixiehua Xueyuan 北京農業機械化學院). Reproductions of two of the largest Han ploughshares were cast. A master carpenter built two wooden ploughs to fit them, basing his design on Han representations of ploughing (e.g. Figures 95–97). The experiments showed that such a ploughshare produces a useful furrow when drawn by two oxen; both artistic representations and textual sources indicate that this was the usual arrangement in

[191] *Xie Cai Da pu zhi nu ji Long ting jiu nian zhi jian* 謝蔡大僕之弩及龍亭九年之劍. These seem to be abbreviated references to inscriptions on famous weapons; the full inscriptions are likely to have referred to government workshops, e.g. *gong guan* 工官,'Office of Craftsmen'. Longting is near modern Yangcheng 羊城, Shaanxi.

[192] On quench-hardening in various liquids see above, p. 136. Vinegar would probably give as fast a quench as salt water, and the steel would therefore be very hard and brittle. One of the unanswered questions is what advantage this use of vinegar might give to a dishonest craftsman.

[193] At this point the text has *ye* 冶, 'smelt', and the *TPYL* version has *zhi* 治, 'administer'. Neither seems to make sense here.

[194] *YTL*, ch. 5, p. 68; Baudry-Weulersse et al. (1978, p. 73); Gale (1967, p. 33).

[195] Box 9.

[196] Zhang Chuanxi (1985c).

[197] Huang Zhanyue (1981, pp. 39–40).

[198] See Zhang Chuanxi (1985c, p. 77).

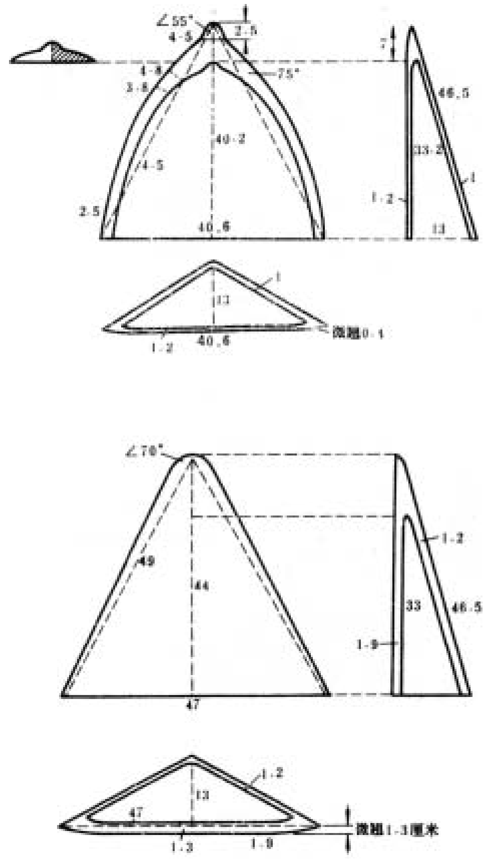


Figure 94 Diagrams of two exceptionally large ploughshares of the Han period, reproduced from Zhang Chuanxi (1985a, p. 253, figs 4–5; cf. 1985c, p. 78, figs. 2–3). The dimensions are given in centimetres. **1**. From a Han tomb at Sandaohao 三道壕 in Liaoyang 遼陽, Liaoning. **2**. From a Han tomb at Changchengcun 長城村 in Teng County 滕縣, Shandong.

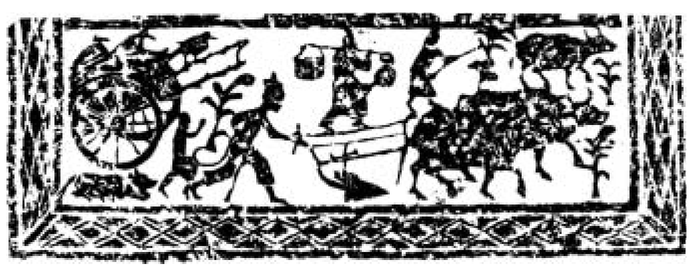


Figure 95 Ploughing scene; detail from a stone relief, probably of the Han period, found at Shuanggou 雙溝 in Suining County 睢寧, Jiangsu. Reproduced from Zhang Daoyi (1985, p. 11, fig. 243). Cf. Figure 97 (no. 4).

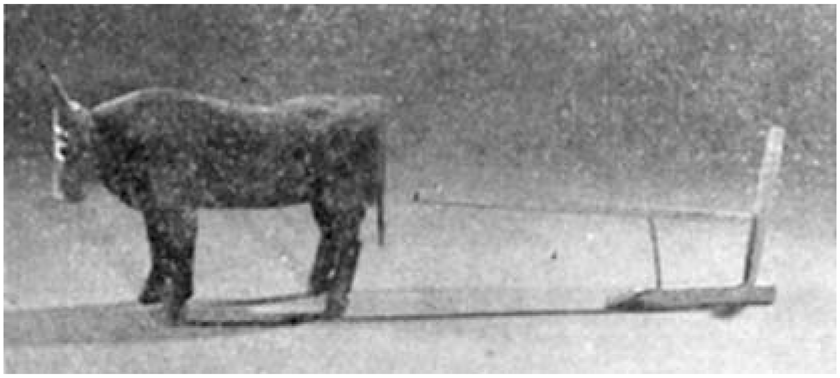


Figure 96 Wooden models of an ox and a plough from Tomb no. 48 at Mojuzi 磨咀子 in Wuwei 武威 County, Gansu, reproduced from Anon. (1972c, p. 22); another photograph of the same artefact is given by Chen Wenhua (1987, p. 109). Cf. Figure 97 (no. 1). The excavators date the tomb to late in the Western Han period. The model is 18 cm long and its ploughshare is 3 cm broad; this suggests that the breadth of the full-sized ploughshare may have been in the range 25–35 cm.

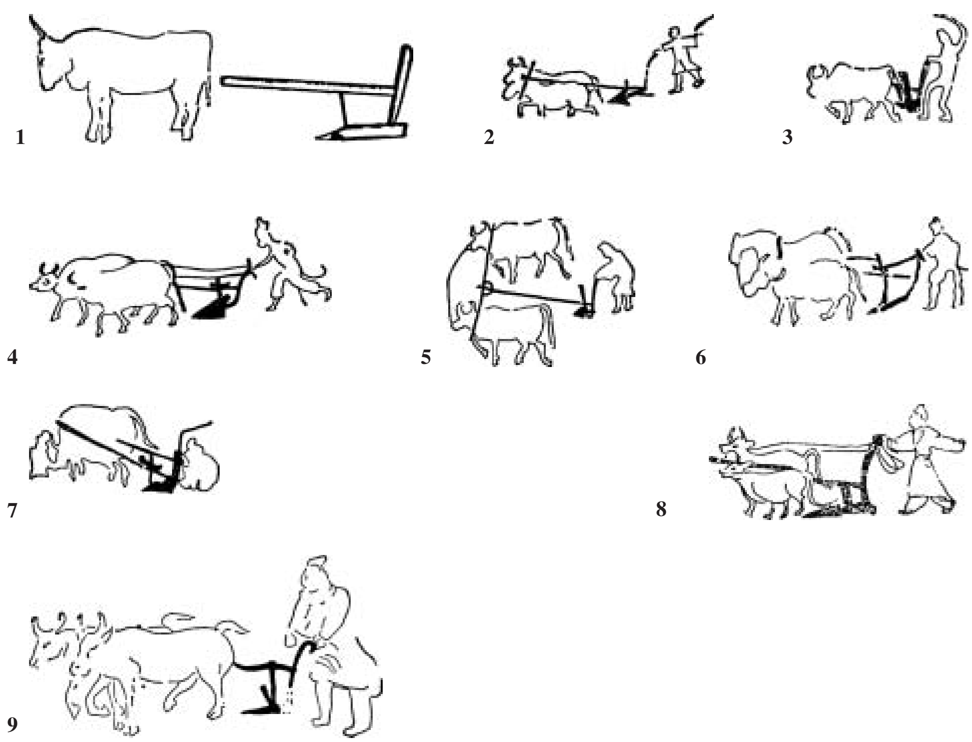


Figure 97 Sketches of ploughing scenes from various Han-period artistic representations, reproduced from You Zhenyao and Zhou Xiaolu (1984, p. 78). **1**. Wooden model, Wuwei, Gansu. Cf. Figure 96. **2**. Painted tomb mural, Pinglu 平陸 County, Shaanxi. **3**. Tomb relief, Suide 綏德 County, Shaanxi. **4**. Tomb relief, Suining County, Jiangsu. Cf. Figure 95. **5**. Tomb relief, Mizhi 米脂 County, Shaanxi. **6**, **7**. Tomb reliefs, Teng County, Shandong. **8**. Painted tomb mural, Jiayuguan 嘉峪關, Wuwei County, Gansu. **9**. Painted tomb mural, Horinger 和林格爾, Inner Mongolia.

Han ploughing. Zhang Chuanxi argues that the three sizes of ploughshare were made for three distinct ploughing situations.

It has become a standard assumption in Han archaeology that the expression *da qi* 大器 in the *Yan tie lun* refers precisely to the largest of these three ploughshare types.[199] This is an attractive idea, though hardly a proven fact. Tentatively accepting the assumption, we can conclude with Zhang Chuanxi that the *da qi* were not devoid of practical use; the critics' claim is rather that, of the three types of ploughshare which the peasants need, the Iron Offices produce only the one type which makes it easiest to fill their quotas. One would like more conclusive evidence, but the conclusion is certainly plausible, for like Cui Shi we all know the problems that can arise when government agencies have inadequate political supervision and are allowed to fill quotas in whatever way is easiest for them.

Environmental issues

Many Chinese thinkers, starting perhaps with Mencius, have emphasised the proper use of natural resources.[200] In the *Yan tie lun* both sides of the debate make very general statements on the subject,[201] but neither points out the environmental damage which is likely to have been caused by blast-furnace ironworks. That such damage by metallurgical industry could be a problem, and that it was noticed by people of the time, is shown by a passage in the *Huai nan zi*. It occurs in a discussion of wasteful consumption:[202]

The source of all disorder is extravagant consumption, and of this there are five sources:

. . . [The first four are Wood, Water, Earth, and Metal; the last is Fire:]

They boil and roast, seasoning [the food] to exhaust the variations of Jing 荊 and Wu 吳. They 'hunt by burning the forest'.[203]

They burn large trees, blowing the bellows through the tuyère, to melt bronze and iron. [The metal] flows and is hardened and hammered,[204] but there never comes a day when they are satisfied.[205] In the mountains there are no tall trees, and in the forests there are no [useful trees:] mulberries or catalpas.

They char wood to make charcoal and burn straw to make ashes. The plants of the wilds are bare, not reaching maturity. Above they obscure the light of heaven [with smoke]; below they exhaust the resources of the Earth.

Such is extravagance with fire.

Of these five [extravagances], any one is sufficient to bring about the loss of the Empire.

199 E.g. Li Jinghua (1976, p. 50); Zhang Chuanxi (1985c, pp. 240–1).

200 *SCC*, vol. 6, part 3, pp. 659ff; note also Wang Zijin (1996); Elvin (2004, pp. 19–39 *et passim*).

201 E.g. *YTL*, ch. 29, 41, Wang Liqi (1958, pp. 209, 274; 1992, pp. 356, 462); Baudry-Weulersse et al. (1978, pp. 180, 207). See also *SCC*, vol. 6, part 3, p. 561.

202 *Huai nan zi*, ch. 8, *SBBY* edn, pp. 8b, 10a; cf. Zhao Zongyi (2003, pp. 382–6); Morgan (1935, pp. 93–6). On this book see *SCC*, vol. 2, p. 36 + index.

203 A common metaphor for considering only short-term interests, corresponding to the modern expression, 'pissing in their boots to keep their feet warm'.

204 ? *Mi liu jian duan* 靡流監鍛.

205 Accepting the variant *ri* 日for *mu* 目; see Yang Shuda (1985a, p. 73).

The monopoly ironworks near cities, competing for fuel with the general population, undoubtedly contributed significantly to local deforestation.[206] This may have been gradual enough that it was not immediately obvious, but the nuisance caused by the blast furnaces[207] was surely well known, and it seems odd that it is not mentioned in the *Yan tie lun*.

The trade cycle

In a more speculative vein, macroeconomic phenomena may also have played a part in the decision to establish the monopolies. A large-scale industry divided into many independent units, operating in free competition with very limited knowledge of current market conditions, will very likely experience the 'boom-and-bust cycle' which is familiar from early capitalist industry. In the demand-led 'boom' period, overinvestment and over-production lead to falling prices and the ruin of over-extended industrialists; a 'bust' period follows, with unemployment, insufficient production, and, in time, rising prices leading to a new boom. Such a cycle would have been a danger to the stability of the Han state, especially if it involved many hundreds of unemployed workers in the mountains who had 'abandoned the graves of their ancestors' and had little choice but to become bandits. There seems to be nothing anywhere in the sources of Han history which can easily be interpreted as a reference to a boom-and-bust cycle, but the historiographic question is how such a cycle would have appeared from the vantage point of the government's ministers. This would depend very much on what sort of information the central government received from its representatives in the provinces, and the question seems impossible to answer. On the other hand we may note that under the state monopoly the same underlying economic causes could have led to chronic over-production, and this is in fact one of the complaints of the government's critics in the *Discourses* (see Box 9).

(v) The Technology of the Iron Offices

In a previous Section we have considered what can be known of the technology of iron production *before* the introduction of the Han state monopoly.[208] The evidence available for that period consists largely of the microstructures of iron artefacts, which show that both foundry and smithy techniques were used. Steel was regularly used in edged weapons and tools, and could be quench-hardened. Tools of cast iron were often annealed to improve their mechanical properties, making them tougher and less likely to break in use. We also have the evidence of excavations of iron-foundry sites of the pre-monopoly period, which have clarified the construction of the furnaces and moulds used in iron casting.

[206] Gong Yu (see p. 186 above) seems to make an explicit connection between the monopoly and deforestation. *HS*, ch. 72, p. 3075; cf. Ni Genjin (1995, p. 179).
[207] Pp. 209–10 above and 231–7 below.
[208] Pp. 128–40, 147–70.

For the period before the state monopoly we have virtually no material to clarify the primary iron-production technology: how iron was produced from ore, how (or whether) cast iron was converted to wrought iron, and how steel was made. There have not been enough proper excavations of iron-smelting sites of the period.

The archaeology of ironworks after the introduction of the monopoly is, on the other hand, very rich, as can be seen in Table 2. I have above attempted to explain this contrast, and concluded that we probably owe our wealth of knowledge of the state ironworks to the administrative needs of Han bureaucrats.[209] The needs of the bureaucracy dictated that the ironworks should be near administrative centres, rather than in mountain forests, a more economically rational location; and the continuity of Chinese economic geography means that sites in such locations are more likely to be discovered and excavated by modern archaeologists.

In the following we shall take a careful detailed look at the primary production technology of the Han state ironworks as it is revealed by several important excavations in Henan. There is some evidence which suggests that it may not have been greatly different in earlier times.[210]

For the structure of iron production in the Han the diagram of Figure 1 will serve.[211] The basic technology of the 20th-century traditional Chinese iron industry seems already to have been in place by the Han. Cast iron was produced in blast furnaces, and this was either cast into useful products in a cupola furnace or converted to wrought iron in a fining hearth. Three well-published major excavations of Han state ironworks sites, all in the province of Henan, give us good information on all three processes. These are:

Tieshenggou, in Gong County (Table 2, item 8)
Guxingzhen, in Zhengzhou Municipality (Table 2, item 27)
Wafangzhuang, in Nanyang Municipality (Table 2, item 17).

Minor excavations in other provinces, listed in Table 2, have often been less professional as well as being poorly published, but they seem to indicate that the technology of the state ironworks did not vary greatly throughout the Han Empire. One thing we should very much like to know is whether this invariance of technology existed before the monopoly was established: no doubt future excavations will answer this question.[212]

209 P. 210.
210 Table 2, item 24.
211 P. 6 above.
212 One indication that there may have been a greater variation in iron-production technology in pre-monopoly times is a very odd furnace excavated at an ironworks site at the ancient capital of Lu in Qufu, Shandong (Table 2, item 40). It is believed to be from the Warring States period, and it resembles nothing known from the Han. It does have some resemblance to a much later type of kiln, excavated in Hong Kong, which I have suggested was used for pelletising ironsand. There is ironsand in Shandong, which German colonial industrialists at one time proposed to smelt, but I know of no evidence that ironsand was ever used by Chinese iron smelters in Shandong. Meacham (1994); Meacham et al. (1994); Wagner (1996); Dahms (1901).

One thing we seem to know for sure, though there is no direct evidence for it, is that the bloomery was used to some extent in early times in China.[213] A peculiar aspect of that fact is that there is no sign of bloomery smelting in the Han or later,[214] so that it appears that the bloomery dropped entirely out of use at some fairly early stage. This is odd, and needs an explanation, for bloomery smelting, though less efficient for the production of wrought iron than the blast furnace plus finery, is a useful small-scale process whose use can be economically rational in many circumstances, and we should not expect that it would immediately disappear after the introduction of the blast furnace. Bloomery smelting supplied local needs in parts of Europe and America well into the 19th century, when most iron was being made in large blast furnaces.[215]

Future archaeology may show that the bloomery was in fact used in China in the Han or even later, but at the moment the most likely explanation for its absence is that the introduction of the state monopoly standardised the technology of iron production throughout China and eliminated the use of the bloomery completely. When the critics of the Han government spoke of household production of iron implements, 'father and son pooling their labour', they may have been referring to bloomery iron smelting.[216]

Blast furnaces

Readers may remember from Section 2 above that a blast furnace is a shaft furnace in which cast iron is produced from ore. Ore, fuel, and a flux (normally limestone) are charged periodically into the top of the shaft, an air blast is blown continuously into tuyères near the bottom, and iron and slag are periodically tapped out at the bottom. Operation continues day and night for periods of days, weeks, or even years. Several different types of blast furnace used in the 19th and 20th centuries were described in Section 2; understanding those will be of help in understanding the Han blast furnaces.

At the Tieshenggou ironworks site the bases of seven round blast furnaces, with inside diameter 1–2 metres, were excavated.[217] Much larger blast furnaces, elliptical in shape, have appeared in excavations elsewhere in Henan: thirteen at the Luloucun site in Hebi County, and two at the Guxingzhen site.[218] In no case has enough of the

[213] Pp. 89–90, above; note also p. 105 above.

[214] Three furnaces at the Tieshenggou site were originally identified as bloomeries (feature nos. 12–14, Anon., 1962, pp. 8–9, 16). A later reinvestigation showed that these were in fact kilns for firing ceramic moulds (Zhao Qingyun et al., 1985, pp. 168–9, table 6, items 1, 2, 3).

[215] E.g. Percy (1864, pp. 278ff); Gordon and Killick (1992; 1993); Rostoker and Bronson (1990, pp. 153ff).

[216] Box 9, pp. 180–2 above. The impression given by that discussion is reminiscent of Percy's description of 18th-century bloomery smelting by families in Dalecarlia in central Sweden. Percy (1864, pp. 320ff, esp. p. 326); cf. Swedenborg (1734, pp. 105–13); tr. Swedenborg (1762, pp. 65–70); Sjögren (1923, pp. 130–9). See Figure 40, p. 91 above.

[217] Table 2, item 8; Zhao Qingyun et al. (1985, p. 160).

[218] Table 2, items 9, 27.

walls of the furnace shaft survived to allow direct reconstruction of the furnace, but at Guxingzhen important material was found which allows an indirect reconstruction.

Furnace no. 2 at Guxingzhen was built on a very thick foundation, apparently made by digging a large hole and filling it with a layer of tamped loess followed by a layer of tamped clay mixed with powdered charcoal and powdered iron ore. The excavation seems not to have reached the bottom of the foundation, but it is at least 2 metres thick. The furnace base, about 50 cm thick, is of tamped earth with a high proportion of fine sand, powdered charcoal, and powdered iron ore. This is not a very strong material, and it was reinforced with a retaining wall of tamped red clay. About 50 cm of the walls of the furnace, of the same material, remain. Around the site were found large quantities of furnace-wall fragments, and study of these shows that different ceramic materials were used at different points.[219] In general, those parts which were exposed to the greatest temperatures were made of materials heavily tempered with powdered charcoal, which is stable at all temperatures so long as it is not exposed to air.[220]

It is apparent that the builders of these furnaces were well aware of the refractory properties of ceramic materials and made great efforts to design furnaces which were both solid and capable of withstanding the high temperatures encountered in iron smelting. However, excellent refractory clays of the type found for example in Shanxi[221] seem not to have been available locally, and the furnaces show signs of extensive heat damage. There are deep cracks in the furnace base, into which the molten iron flowed, and there are other signs of the punishment endured by the furnace.

What makes a reconstruction of the furnaces at Guxingzhen possible is the large piece of sintered iron, estimated to weigh 20 tonnes, shown in Figures 98–99. This is what is known in English as a 'bear' (or 'horse', or 'salamander'). It is iron which has frozen in the furnace because of imperfect operating conditions and cannot be removed until the furnace is dismantled.[222] It was found buried in a pit near the remains of one of the blast furnaces (no. 1), and it appears to fit very well what remains of the base of that furnace. It gives us the shape of the lower part of the furnace, as well as the location of one of the tuyères.

Studies by Liu Yuncai, Li Jinghua, and others have produced a reconstruction of Guxingzhen Blast Furnace no. 1 which I have modified slightly in Figure 100.[223] The steps in this reconstruction will need some explanation.

Bear material always collects at the bottom of a blast furnace as the molten iron gradually burns away the bottom of the furnace hearth, leaving a certain amount of

[219] Details of the materials used are from Lin Yulian and Yu Xiaoxing (1983). These authors refer to an illustration, presumably a diagram of the excavated part of the furnace, which by some mischance was not printed with their article.

[220] The same principle is used in modern crucibles, though powdered graphite is now more often used than charcoal. Searle (1940, pp. 189, 586ff).

[221] P. 43 above.

[222] See e.g. Gale (1971, p. 19).

[223] Anon. (1978c, pp. 8–10); Liu Yuncai (1978, pp. 20–1; 1992); Li Jinghua in Tylecote (1983).

Figure 98 A large blast-furnace 'bear' of sintered iron at the Guxingzhen Han ironworks site museum. Dr Li Jinghua 李京華 points out where the blast-furnace tuyère would have been. In the foreground is his assistant, Huang Keying 黃克映. Photograph by DBW, September 1987.

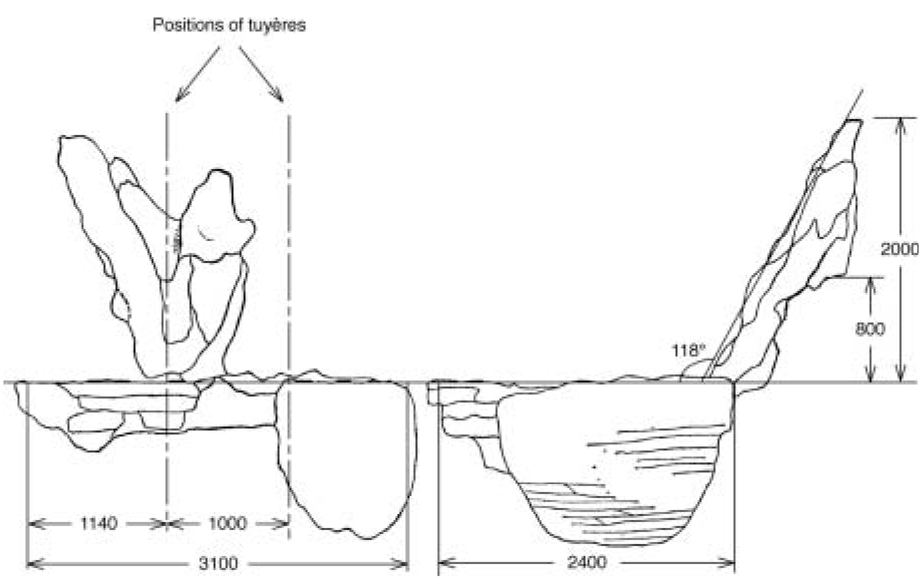


Figure 99 Diagram of the 'bear' shown in Figure 98, reproduced from Anon. (1978c, p. 6, fig. 2).

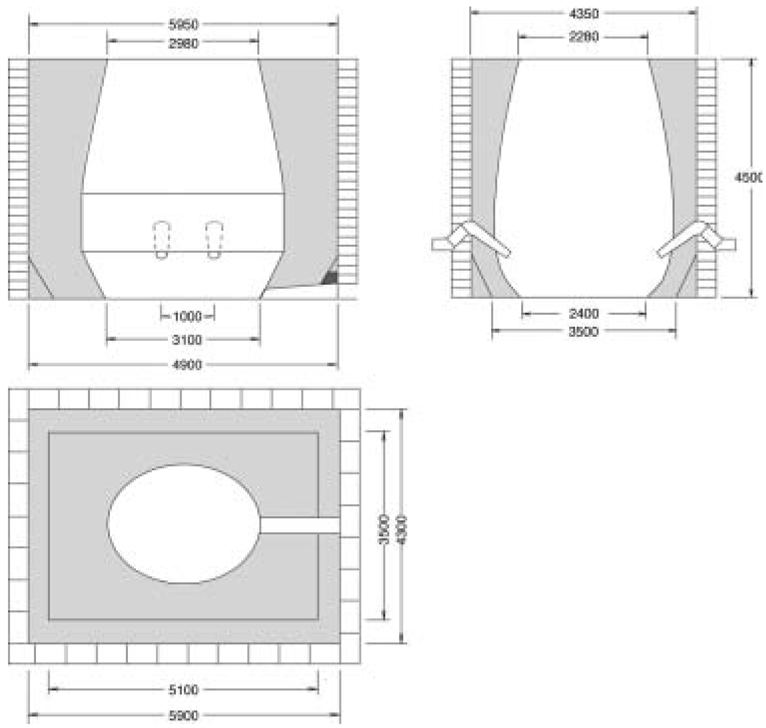


Figure 100 Speculative reconstruction of a blast furnace at the Han ironworks site at Guxingzhen. Originally due to Liu Yuncai, Li Jinghua, and others (Anon., 1978c, p. 8, fig. 3; Liu Yuncai, 1992, pp. 118–19); modified by DBW.

iron below the level of the taphole and therefore inaccessible. The bear we have here, however, has an unusual shape, apparently the result of a failure in furnace operation. It would seem that one of the tuyères was allowed to burn too short, with the effect that the furnace lining just above the tuyère became too hot and burned away. This failure then produced a cold spot below the tuyère where molten iron froze, leading to the formation of the arm extending upward at an angle from the main body of the bear. The great mass of iron at one end of the bear is the result of another failure, in which molten iron burned a large cavity in the hearth bottom. Perhaps the two failures occurred in the same incident.

The remains of Furnace no. 1 and the shape of the bottom of the bear indicate that the shaft of the furnace was elliptical, about 3 × 4 metres, with the hearth somewhat smaller. The elliptical shape made it possible to run a blast furnace with smaller blast pressure; it was used to some extent in the 19th century in the USA and Britain,[224] and clearly it was very useful in the Han, when most blast furnaces were operated by human labour rather than water or steam power.

[224] Percy (1864, pp. 489–91).

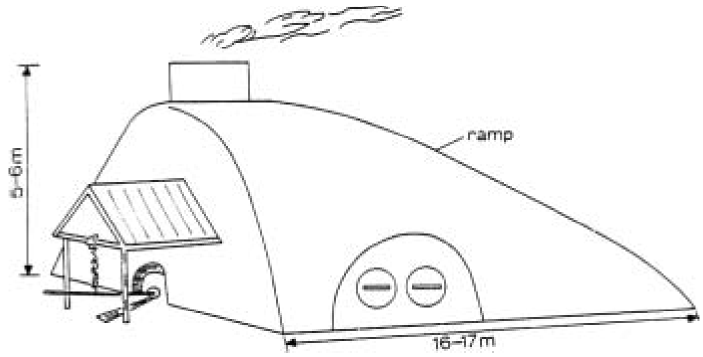


Figure 101 Sketch by Li Jinghua of the operation of a Han blast furnace. Redrawn by R. F. Tylecote (1983).

There appears to have been an outer brick facing, but the excavation report is vague as to the dimensions and properties of the bricks found at the site.[225] There is no firm evidence concerning the original height of the furnace, but estimates based on the height of the tuyères range from 4.5 to 6 m.[226] There is evidence that the furnace was shored up with tamped earth extending quite far (9 m or more) from the walls.[227] Presumably this shoring also acted as a ramp for the charging of the furnace, as shown in the sketch by Li Jinghua reproduced in Figure 101.

Numerous tuyère fragments were found on the site, and study of these indicates that several different shapes of tuyère were used. The ones used in the blast furnace seem likely to have been larger versions of the cupola tuyère shown in Figure 103 (which is from the Wafangzhuang foundry site), with inner diameter 11 cm at the narrow end, 32 cm at the wide end, and perhaps a metre long.[228]

As we shall see presently, the blast could have been powered by human, animal, or water power. At Guxingzhen, however, there is no evidence on the form of the bellows or on how they were powered, and my reconstruction includes no guess on this question.

Examination of raw materials and slag allows some conclusions on the operation of the blast furnace. The charge consisted of ore, charcoal, and limestone, all of which were found in large quantities on the site. The ore is a rich hematite with very low sulphur. Hammers and anvils were used in breaking up the ore into pieces generally ranging in size from 2 to 5 cm, the largest pieces charged being 12 cm across.[229] These were sieved to eliminate smaller pieces, leaving enormous hills of ore-gravel here and at other ironworks sites;[230] this was done because small pieces in the charge

225 Anon. (1978b, p. 29; cf. pp. 28, 37).
226 Anon. (1978c, pp. 5, 8); Liu Yuncai (1992, p. 118).
227 Anon. (1978b, pp. 28–9).
228 Anon. (1978c, p. 6). On tuyères see also Zhou Esheng (1960).
229 Anon. (1978b, p. 30).
230 Anon. (1978b, p. 30; 1978c, p. 10).

would have made the furnace burden less porous, necessitating greater blast pressure. The ore was not calcined (roasted) before being charged into the furnace;[231] this is a surprise, for calcining is a normal part of most smelting processes, ancient or modern. One of the reasons for calcining is to make the ore more porous and friable, but a more friable one would have made the furnace burden *less* porous by breaking up and filling in empty spaces. Another function of calcining is the elimination of sulphur, but this ore is very low in sulphur.

Some estimates of blast-furnace operating parameters can be made by calculating materials balances, if the samples of ore and slag analysed in Table 3 are assumed to be representative. Since the ore contains about 50 per cent iron, and very little iron is found in the slag, about 2 tonnes of ore were needed for each tonne of iron produced. Most of the silica (SiO_2) in the slag comes from the ore, and there is about five times as much silica in the slag as in the ore, so at least 0.4 tonnes of slag were produced; this figure may be rounded up to 'about a half tonne' to allow for silica entering the slag from the limestone, the charcoal, and the furnace walls. The lime (CaO) in the slag comes largely from the ore and the limestone, and since limestone is about 50 per cent lime, a quick calculation indicates that somewhat less than 100 kg of limestone was used per tonne of iron produced.[232] However this calculation is highly sensitive to the lime content of the ore: if the average lime content of the ore was about 2 per cent rather than the 4 per cent of the one sample analysed, the result would be that about twice as much limestone was charged, and if it was over about 6 per cent, no limestone at all was charged.[233]

There appears to be no reliable way to estimate pig-iron production per day or (more relevant) per year. Perhaps we can assume that production per year was of the same order of magnitude as that of 19th- and 20th-century Chinese traditional blast furnaces of the same size, a few hundred tonnes per year. If we were to assume an average annual production of 100 tonnes per Iron Office, then total annual legal

[231] See p. 23 above.

[232] In colonial Virginia, according to William Byrd in 1732, a charcoal blast furnace used 1 tonne of limestone to 10 tonnes of ore (Byrd, 1966, p. 353). This works out to about half of the figure given here.

[233] This problem of the sensitivity of calculations to small errors in the given data plagues Liu Yuncai's attempt (1984) to calculate the operating parameters of the same blast furnaces. He solves a system of seven linear equations in seven unknowns, and gives the result that 1.995 tonnes of ore, 0.13 tonnes of limestone, and 7.850 tonnes of charcoal were needed to produce 1 tonne of iron (and 0.61 tonnes of slag). These results do not actually satisfy the equations which he gives, possibly because of typographical errors, but calculating backward from his solution allows adjustment of the coefficients so that the equations give his results. But the system of equations is so severely sensitive to small errors in the coefficients that the whole calculation is useless. For example he assumes (lacking an actual analysis) that the ash content of the charcoal was 1 per cent, but if this figure were 1.05 per cent, the calculated charcoal consumption would be 59 tonnes (with a *negative* amount of limestone, –0.7 tonnes), while a figure of 0.95 per cent would give a result of only 4 tonnes. Analyses of charcoal given by Percy (1861, pp. 109, 110) give ash contents between 0.61 and 3.06 per cent; using the lower of these in Liu Yuncai's calculation gives a result of 1 tonne of charcoal, while using the larger gives a negative result, –0.2 tonnes. Another example of the hypersensitivity of the equations is that varying the lime content of the limestone between 50 and 52 per cent gives results between 9 and 4 tonnes of charcoal consumed.

In the same calculation Liu Yuncai also attempts to find the amount of iron produced per day, but here, in addition to the same sensitivity problems, there is the fundamental problem that there is no way of estimating with any credibility the amount of air input per hour or the ratio of CO to CO2 content in the furnace top gas.

Table 3 *Analyses of ore, slag, and pig iron from the Guxingzhen ironworks site, from Anon. (1978c, pp. 8, 9, 10). Slightly different values for the same analyses are given by Anon. (1978b, pp. 30, 40) and Liu Yuncai (1984, p. 73), indicating typographical errors somewhere.*

	Fe %	FeO %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	MnO %	C %	Si %	Mn %	P %	S %	notes
ore	48.39	0.29	11	6.9	4.3	0.29	0.22				0.068	0.054	1 sample, Anon. (1978b, p. 30)
slag		2.94	52.20	12.06	24.95	2.64	0.43					0.223	mean of 4 samples
pig iron								4.0	0.21	0.21	0.29	0.091	mean of 3 samples

production in the Han Empire as a whole would have been about 5000 tonnes, or about 0.1 kg per person. Obviously it would not be wise to lend much credence to this figure, but perhaps it gives a feel for the general scale of Han iron production.[234]

Cupola furnaces

It is possible that molten iron was sometimes cast directly into moulds from the blast furnace, as was common in the West until comparatively recent times, but there is no evidence for this, and it seems likely that for most, perhaps all, iron casting the iron was melted in a cupola furnace. As was explained earlier,[235] a cupola furnace is a shaft furnace charged with fuel (coal or charcoal) and iron (pig or scrap) through the top and supplied with a blast blown in at the bottom. The iron melts in contact with the burning fuel and is tapped out at the bottom. A modern cupola functions continuously for a day or two at a time, seldom longer.

Cupola furnaces have been found at numerous Han ironworks sites (see Table 2), including Guxingzhen, Tieshenggou, and Wafangzhuang. Nine were found at Wafangzhuang, and from this material Chinese metallurgists and archaeologists have produced the reconstruction shown in Figure 102.[236] It is built of brick with an inner and outer layer of refractory clay. The height is 3–4 metres, inside diameter about 1.5 m. The base includes a hollow space, 17 cm high, supported by 12–15 cylindrical bricks. The fuel used was charcoal.

The design of the furnace suggests that great attention was paid to the generation of high temperatures at a relatively high fuel efficiency. The hollow base and the thick walls (20–30 cm) provided thermal insulation. It can be seen that air from the bellows passes through a pipe up one side of the furnace, over the top, and down the other side to the tuyère. This arrangement provides for recycling of heat otherwise

[234] Note also Peng Xi (1993).
[235] Pp. 60–4.
[236] Anon. (1978c, pp. 11–13); cf. Li Jinghua (1991, pp. 7–9, 20ff); Li Jinghua and Chen Changshan (1995, pp. 16–21).

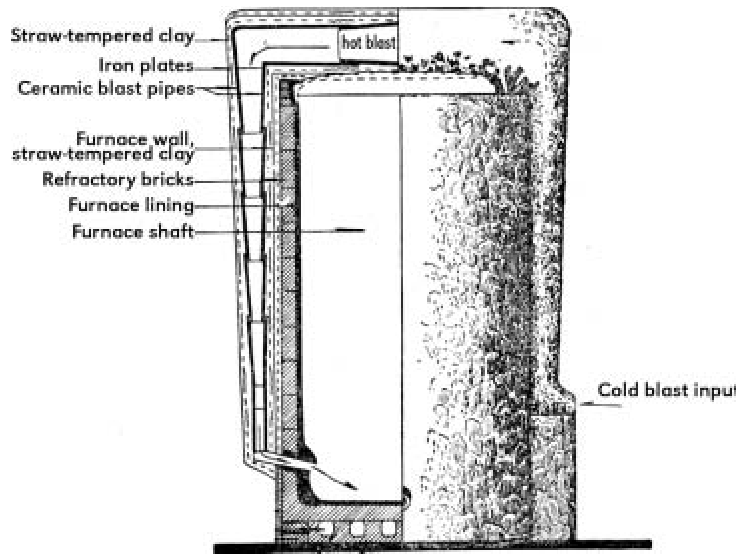


Figure 102 Reconstruction of a Han-period cupola furnace excavated at Wafangzhuang in Nanyang, Henan 南陽瓦房莊. Reproduced and translated from Anon. (1978c, p. 12, fig. 4). Outer diameter at base, 2.3 m, height 3–4 m.

Figure 103 Ceramic tuyère from the Han-period foundry site excavated at Wafangzhuang in Nanyang, Henan, reproduced from Anon. (1978c, pl. 1.1).

lost through the top. There are good reasons for assuming some such arrangement: many of the earthenware pipes found have been subjected to such high heat that their surfaces are partially vitrified, and the directions of glass drips indicate the spatial orientations of the pipes in use.[237]

At the Wafangzhuang site a large number of moulds were found. In the later strata of the site, believed to be Eastern Han, the moulds are of the same types as have already been described for pre-Han times,[238] including ceramic moulds, both single and stacked, and cast-iron moulds. Curiously, in the Western Han strata there were very few ordinary moulds of these kinds, for small objects; but the remains of eight very large moulds were found, apparently for cauldrons with outer diameter 1.2–1.8 metres and wall thickness usually 8 cm.[239] As the excavators suggest, these may have been the *lao* 牢 cauldrons for salt-boiling which were to be supplied by the Iron Offices[240] – though it is worth mentioning that such huge cauldrons are also seen in kitchen scenes on Han tomb reliefs.[241] From the little that is left of these moulds it appears that they were made by the same piece-mould method which had been used since the Shang period and would continue in use into modern times.[242]

The bellows

Nothing remains of the apparatus which produced the powerful air blast required by the blast furnaces and cupola furnaces. Liu Yuncai and others believe that it was a small leather bellows like that shown in Figure 109 below; but that is from the reconstruction of a fining furnace, and there is no reason to assume that the same type of blowing apparatus was used in these enormous blast furnaces. Han carpenters were surely capable of designing and building the large wooden blowers which we know were used in the Yuan (Figure 130);[243] but since there is no evidence I have made no assumptions in the reconstructions above.

Whatever the precise form of the bellows, three ancient texts indicate that it could be powered by human, animal, or water power. The first is the biography of a Han official named Du Shi 杜詩.

[In the year +31] he was appointed Governor [*tai shou* 太守] of Nanyang [Commandery 南陽郡, modern Nanyang, Henan]. His nature was frugal and his government honest and

[237] Several of the publications referred to above in fn. 122 on p. 150 suggest that not much would be gained by this arrangement. Nevertheless very similar arrangements for recycling the heat of top gas have been used in traditional Chinese cupola furnaces in recent times (Li Jinghua, 1991, p. 29, fig. 25.4) and in 19th-century American bloomeries (Gordon and Killick, 1992, p. 145; 1993, p. 250, fig. 1).

[238] Pp. 150–6 above.

[239] Li Jinghua (1991, pp. 9–11).

[240] P. 177 above.

[241] See e.g. An Jinhuai and Wang Yugang (1972, p. 61); Chen Xianshuang (1983, p. 899); Sun Ji (1991, p. 339); *SCC*, vol. 6, part 5, p. 87.

[242] P. 290 below.

[243] P. 324 below.

equitable; he established authority by punishing the violent. He was excellent at planning, and was sparing with the people's corvée labour. He built a water-powered bellows [*shui pai* 水排][244] and cast agricultural implements; this was a relief for the people, as it decreased labour and increased production.[245]

There is more in the biography of Han Ji 韓暨 (before +160 to +238), an official of Cao Cao's 曹操 usurper government towards the end of the Han. Around +210 Cao Cao appointed him Internuncio Supervisor of Smelters (*jian ye ye zhe* 監冶謁者).

In former times the smelters had built horse-powered bellows [*ma pai* 馬排], and whenever ore was processed [i.e. smelted], one hundred horses were used [*mei yi shu shi yong ma bai pi* 每一熟石用馬百匹]. When a man-powered bellows [*ren pai* 人排] was substituted, much labour was expended. Han Ji therefore constructed water-powered bellows [*shui pai* 水排] on major rivers; when the resulting profit was calculated, it was three times what it had been. By the time he had been in office seven years, [the state's] production needs were entirely filled.[246]

State-sponsored water-powered smelting by Cao Cao's Wei dynasty and the following Jin is confirmed by a passage from a travel book[247] quoted in the +5th- or +6th-century *Shui jing zhu*, referring to a place somewhere near Luoyang:

Baichao Rampart 白超壘 . . . lies fifteen *li* 里 from Quemen 缺門. By the side of the rampart was formerly a walled area [*wu* 塢, a weir?]; this is the location of an ancient Smelting Office [*ye guan* 冶官]. In the days of the Wei and Jin the Gu River 穀水 was conducted here for water-powered smelting [*shui ye* 水冶] in order to provide for the needs of the state. The remains are still extant.[248]

Finally, we have a report of difficulties in the +5th century with water-powered smelting (not necessarily of iron) in an otherwise unknown book, *Wu chang ji* 武昌記, 'Description of Wuchang', quoted in the +10th-century *Tai ping yu lan*. Wuchang was a commandery near modern Daye 大冶, Hubei:

Beiji Lake 北濟湖 was originally the dammed pond of the Xinxing Smelter 新興冶. A water-powered smelter [*shui ye* 水冶] was established here at the beginning of the Yuanjia 元嘉 period [+424–53]. A 'water-powered smelter' uses water to work the bellows [*pai* 排].[249] The Director of Smelting [*ye ling* 冶令] Yan Mao 顏茂,[250] because the dam was

244 Most commentators take *pai* 排 to be a phonetic loan for *bai* 韛 or *bei* 橐, either of which means 'a bellows', and I have followed this tradition here (see Lu Bi, 1936, ch. 24, p. 2a). All three characters can be members of an Archaic Chinese family of cognates related to the idea of 'breathing' (Karlgren, 1933, p. 94, items 139–40, 77–82). On the other hand the translation 'reciprocator', proposed by Joseph Needham (*SCC*, vol. 4, part 2, p. 370), keeps the normal meaning of *pai* and would also be suitable here.

245 Translated from the version in the *Hou Han shu* (ch. 31, p. 1094). Its source is undoubtedly the biography in the *Dong guan Han ji*, an extant fragment of which includes the essential sentence on the water-powered bellows (*TPYL*, ch. 260, pp. 3b–4c; cf. Wu Shuping, 1987, p. 568). While the *Dong guan Han ji* was compiled over a long period, this biography is likely to have been in the first version, compiled in +72. For two other early versions of the passage see Zhou Tianyou (1986, pp. 27, 688).

246 *San guo zhi*, ch. 24, p. 677.

247 *Xi zheng ji* 西征記, by Dai Yan 戴延; both book and author are otherwise unknown.

248 *Shui jing zhu*, ch. 16; Wang Guowei (1984, p. 523); Yang Shoujing (1915, ch. 16, pp. 2a–b); accepting Yang Shoujing's emendation of two occurrences of *zhi* 治 to *ye* 冶.

249 See fn. 244 above.

250 Otherwise unknown.

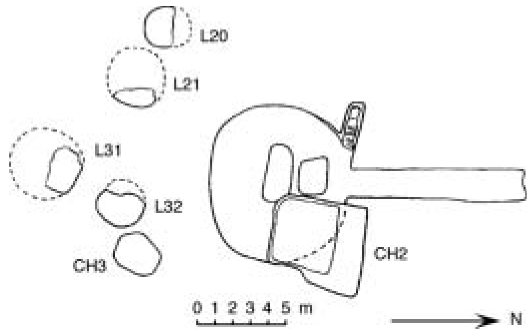


Figure 104 Plan of certain features at the iron-foundry site at Wafangzhuang in Nanyang, Henan (Table 2, item 17), reproduced from Li Jinghua and Chen Changshan (1995, p. 24, fig. 9.1). L20, L21, L31, and L32 are the remains of Western Han cupola furnaces; CH2 and CH3 are water pools. CH2 cuts into the 'ladle-shaped pit' (*shao xing keng* 勺形坑)which is believed to be related to a human- or animal-powered bellows for the furnaces. The diameter of the circular part is 7.8–8.5 m, depth 2.6 m. The channel (for drainage?) leading north from the circular part is 9.4 m long and 1.4–1.6 m wide. The two approximately rectangular pits in the centre of the circular part are 1 m deep. A stairway, 0.5 m wide, leads into the circular pit on the western side.

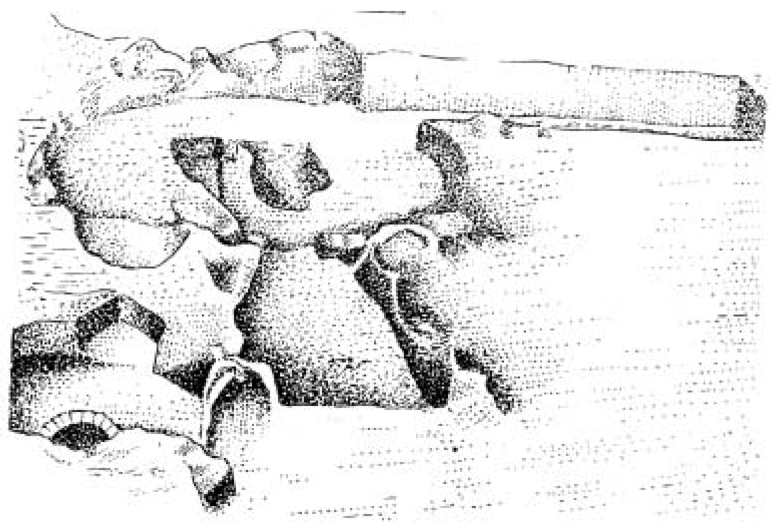


Figure 105 Sketch of the 'ladle-shaped pit' of Figure 104, reproduced from Li Jinghua and Chen Changshan (1995, p. 24, fig. 9.2).

repeatedly wrecked [*po huai* 破壞] and was difficult to repair, abandoned water-powered smelting and went over to using manpower to work the bellows. This was called 'footstep smelting' [*bu ye* 步冶].[251]

The texts quoted here indicate with some certainty that human, animal, and water power were used in iron production in the early +1st century and continued in following centuries. There is not much archaeological material to throw more light on

[251] *TPYL*, ch.833, pp. 3b–4a

this subject, but a Western Han feature at the Wafangzhuang foundry site gives an interesting hint;[252] see Figures 104–105. Near the remains of several cupola furnaces is a circular pit, 2.6 m deep and about 8 m in diameter. A narrow stairway cut into the earth leads down into it. The excavators believe that workers walked around in this pit turning some mechanism which powered the bellows. Two rectangular pits in the floor of the large pit were probably related to some part of the mechanism. I am surprised that the excavators do not suggest that animal power was used here, for later illustrations of human-powered bellows of the Song, Yuan, and Ming periods do not show such large and presumably complex mechanisms.[253] There is no obvious way for an animal to be brought down, but part of the pit was destroyed in the later digging of a pond (feature CH2 in Figure 104), and a ramp could have been located there; or a wooden ramp might have been used.

Whatever the mechanism used here, its purpose was to convert rotary motion to reciprocal motion, and a similar arrangement could have been used for water power. It is fairly easy to imagine a version of the mechanism for a water-powered bellows shown in the *Nong shu* of +1313, with its horizontal wheel, being used here.[254]

When was water power first used in metallurgy in China? The question has already been discussed by Joseph Needham,[255] but a bit more evidence can now be brought to bear. The Kong family of Wan, in modern Nanyang, Henan, 'smelted and cast on a large scale and regulated ponds'; the 'ponds' might have been related to the use of water power.[256] The Nanyang area has shown up again in the present discussion: Du Shi was Governor of Nanyang Commandery, and Han Ji came from Duyang Prefecture 堵陽縣 in Nanyang Commandery.

We should certainly like to have better evidence on this matter, but the slight evidence we do have suggests that the use of water power in metallurgy may have begun in the vicinity of Nanyang as early as the –3rd century.

Fining hearths

In the traditional Chinese iron industry in recent centuries the usual method of converting the high-carbon cast iron from the blast furnace to low-carbon wrought iron was by the *fining* process, which has been described in Section 2 above.[257] In the Iron Offices of the Han, one method definitely used was solid-state decarburisation of cast-iron plates and rods,[258] but fining appears also to have been used. The remains of a number of small hearths, believed to be fining hearths, have been found at several Han ironworks sites, among them the one shown in Figures 106–107.[259]

[252] Li Jinghua (1991, pp. 8, 19); Li Jinghua and Chen Changshan (1995, pp. 14–15, 24); Anon. (1978c, p. 10).
[253] E.g. Figures 130 and 133, pp. 324, 340 below.
[254] *SCC*, vol. 4, part 2, p. 371, figs. 602–3.
[255] *SCC*, vol. 4, part 2, pp. 369ff.
[256] Pp. 140–1, 144 above.
[257] Pp. 16–17, 30–4.
[258] Wagner (1993, pp. 294–5).
[259] Anon. (1978c, pp. 21–3).

Figure 106 Remains of a fining hearth (feature no. *lu*-17) excavated at the Tieshenggou ironworks site, reproduced from Anon. (1962, pl. 6.2). Cf. Figure 107.

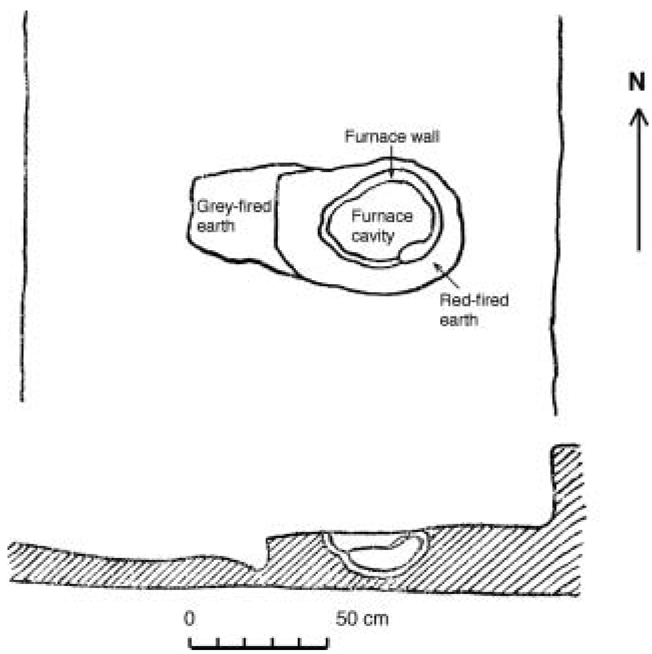


Figure 107 Diagram of the Han-period fining hearth shown in Figure 106, reproduced from Anon. (1962, p. 13, fig. 10).

Figure 108 Detail of a rubbing of an Eastern Han period tomb-relief discovered at Hongdaoyuan 宏道院 in Teng County 滕縣, Shandong. Archives of the Needham Research Institute (obtained for Joseph Needham by Rewi Alley in 1959). This is believed to show a fining hearth of the same sort as those shown in Figures 11 and 12 in Section 2. The full stone from which this is a detail is illustrated in Anon. (1950–51, vol. 1, pl. 73); on its interpretation see Anon. (1959b); Wang Zhenduo (1959); Anon. (1978c, p. 22); Wagner (1985, pp. 76–80). Cf. Figure 109.

Other evidence for the early use of fining is thin, and late, but interesting. Perhaps from the +4th or +5th century is a passage in the Taoist text *Tai ping jing* in which the Celestial Master (*Tian shi* 天師) replies to a disciple on the necessity of preparedness:[260]

Now armies, soldiers, and weapons are inauspicious implements; the *jun zi* 君子 ought in principle not to have them; he denigrates them and hates them. Therefore he should keep them in their sheaths and securely store them away. He must not esteem their possession, nor their use.

But if the weapons have not been prepared, and he only after there is an emergency has the workers break up stone, seek out the iron in it, and fire it to make it liquid; and thereafter has the artisans forge it a myriad times to make a Moye 莫耶 [sword] so that he can fight; can he then be successful in dealing with the emergency?

The last part of this passage gives a capsule outline of the process of making a sword: (1) mining, (2) smelting in a blast furnace, and (3) fining and smithing. The author must have known something of iron production. There is no sign that he knew the distinction between fining and smithing, but since the iron was liquid it must have been fined.

It is possible that we have a picture of iron-fining in the Han period. Figure 108 shows a detail of a tomb-relief unearthed in 1930 at Hongdaoyuan, in Teng County, Shandong.[261] It can be dated by stylistic criteria to the +1st or +2nd century. It seems clear that the relief depicts metallurgical work of some sort. There has been considerable discussion as to precisely what this might be, but the suggestion which seems most credible is that it shows iron fining in a hearth similar to the traditional

[260] *Tai ping jing*, ch. 72; Wang Ming (1960, p. 296).

[261] Anon. (1959b); for the full context of this detail see Anon. (1950–51, vol. 1, p. 73). Note also Wu Wenqi (1991, pp. 36–8).

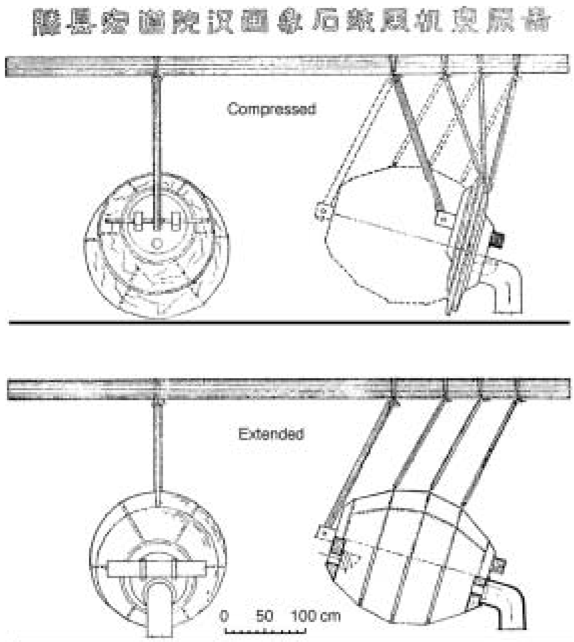


Figure 109 Speculative reconstruction of the bellows shown in the Teng County tomb-relief, Figure 108, reproduced and translated from Wang Zhenduo (1959, p. 43).

Chinese fining hearths of the +20th century.[262] The bellows has been reconstructed as shown in Figure 109. The blast is directed downward, presumably into a cavity dug into the ground. The worker standing on the left works the bellows. The activities of the next two workers, one lying down and one standing, are unclear. The next may be holding a piece of hot iron with tongs on an anvil while several (perhaps four) workers hammer it.

(vi) Concluding Remarks

The state monopoly of the iron industry in Han China was a real monopoly of both production and sale. Both archaeological and written sources make it clear that this was no trivial matter, but one that brought significant advantages to the government and directly affected the daily life of a significant part of the population.

At the other end of the Eurasian continent, by contrast, the idea of a Roman state monopoly of the iron industry would have been absurd. While there did exist large state ironworks run by the Roman army, most iron production occurred in thousands of tiny units scattered in villages throughout the Empire. There would have been no way at all of enforcing a monopoly, and it is also difficult to imagine any advantage the Roman state would have derived from such a monopoly.

[262] Anon. (1978c, p. 22).

The difference lay in the technology of iron production. Bloomery smelting, the only iron-smelting process known in Europe until medieval times, lends itself well to small-scale production. It was used in early China to some (unknown) extent, but by the –3rd century it appears that most iron was being produced in blast furnaces. Bloomery smelting was definitely also used, and it is likely that the small-scale ironworks mentioned in Section 5(ii) above used this technology,[263] but the blast furnace dominated production.

As to the actual fabrication of artefacts from the iron produced in one of these ways, the work of the blacksmith, East or West, is an inherently small-scale operation, while iron casting, used in China very early but not in Europe until medieval times, is most efficient at a somewhat larger scale of production.

Production of iron outside of the state ironworks was forbidden. We may suppose that the prohibition was relatively easy to enforce against the private large-scale blast-furnace works, for in spite of their remote location they produced for large markets and were necessarily highly visible. Furthermore many (perhaps most, or even all) of the private ironmasters were brought into the state bureaucracy as managers of the new ironworks.

Quite another question is whether it was possible to enforce the prohibition against the small-scale bloomery-smelting works, which cannot have had nearly the same visibility. While this seems unlikely on its face, there is one piece of evidence which suggests that the prohibition was in fact effective. As far as we can tell from presently available archaeological material, bloomery technology seems to have disappeared totally in China by the early Han period. This is odd: we should expect that the small-scale bloomery technology would have continued in use virtually indefinitely in numerous parts of the Empire, especially those which were remote and isolated. Future archaeological findings may disprove this view, but if it is true that bloomery technology disappeared in China in the early Han then this is more likely to have been caused by the state prohibition than by straight competition with blast-furnace technology. If the prohibition was effective for a generation or two the technology would have been forgotten. Significantly, when at some later time a new very small-scale iron-production technology was developed in China, it used a small blast furnace rather than anything resembling a bloomery.[264]

A possible factor in the effectiveness of the prohibition is what we might call 'dumping' by the state. If the products of the monopoly ironworks were sold – at least in the early years – at prices distinctly lower than those of the illegal producers, clearly the prohibition would have been easier to enforce. The prices of the monopoly products are likely to have been almost arbitrary, for it would have been difficult

[263] Pp. 180–2, 187–8, above.
[264] Sections 2(i), 2(iv), pp. 16–18, 30–4.

to estimate the true cost of convict and corvée labour, which are likely to have appeared in the accounts as costing nothing.

In Roman Europe, though *iron* production was rarely concentrated, there were other industries whose technology did encourage large-scale production. Rostovtzeff notices a trend in the Imperial period away from 'house-economy' towards large-scale 'capitalist' industry and then back towards a smaller scale of industrial production.[265] This course of development is loosely analogous to that seen in Han China, with the rise of blast-furnace iron production, the establishment of large ironworks under the monopoly, and the later rise of illegal iron production, very likely on a smaller scale than the monopoly ironworks. Any detailed comparison is of course rendered pointless by two important differences in Han China: a technology which provides extremely large economies of scale, and a powerful interventionist government.

Rostovtzeff, writing in the 1920s, discusses several possible explanations for the 'failure' of large-scale industry to develop further in Roman Europe. He concludes that a major factor was a failure of demand. The belief is still widespread today that technological progress will naturally tend towards large-scale production; only when this development does not take place is a historical explanation thought to be necessary. However, many historians and economists now recognise both the complexities of industrial scale and the assumptions hidden in the idea that certain familiar developments constitute necessary 'progress'.[266]

The quotations above[267] from the debate in Han China include arguments which are common today. Small-scale production can have important political, social, and ecological advantages; large-scale production can be technically superior, producing a better product, and can be more efficient in its consumption of scarce resources. In a pre-modern context, however, its overall economic efficiency is limited by the cost of transportation. An explanation appears to be needed for the rise of large-scale production as well as for the later tendency towards a smaller scale.

A factor which tends to be ignored is one particular scarce resource, skilled labour. In the context of rising demand in a large market, localised small-scale production may not be capable of spreading out to all regions of demand because of a scarcity of skilled workers; demand can be satisfied only by concentrated large-scale production, which usually requires fewer skilled workers for a given production rate. This advantage can very well outweigh the disadvantage of higher transportation costs, at least for a time. As more workers learn the necessary skills and establish themselves in the industry, however, local small-scale production may well again become dominant. This argument fails only with the radically lowered transport costs of modern times.

. . .

[265] Rostovtzeff (1957, pp. 349–52).
[266] See e.g. Sabel and Zeitlin (1985; 1997).
[267] Pp. 187–8.

I have already stated my conviction that we must study the historical consequences of particular technologies.[268] In the case considered here, the iron-production technology of Roman Europe encouraged small-scale localised production, and a direct consequence of this was that iron was never politically or financially interesting to the state. In China, one consequence of a technology which gives significant economies of scale was that a powerful state took a direct interest in iron production and thereby further increased its economic and political power.

[268] P. xxix above.

6 THE ARTS OF THE SMITH FROM LATE HAN THROUGH TANG

From the early +2nd century onward the power of the Han central government declined; in time the court was reduced to a ceremonial cipher, while real power devolved to regional warlords and influential local families. In +220 Cao Pi 曹丕, adopted son of the famous Cao Cao 曹操, usurped the throne and dropped the fiction of Han unity.[1] This date is taken by historians as the start of the Period of Disunion, which lasted until the reuniting of China under the Sui and Tang dynasties (+581–618, +618–907).[2]

(i) Iron and the State

On the fate of the Han iron monopoly in the late Han and after, the best guess is that the Iron Offices lost their importance while iron production more and more was taken over by the large, almost self-sufficient, 'manors' which developed and grew with decline of the central government's ability to keep the local peace. Though our sources, both textual and archaeological, are inadequate, this seems to be the hypothesis that best fits the generally accepted picture of the period's social and economic history.[3] The 'proto-industrialists' of the pre-monopoly period[4] do not reappear in the sources, and we should probably suppose that iron production now generally took place in smaller ironworks which supplied local needs; a memorial of +515 states that there are iron foundries everywhere.[5] The decline of long-distance trade in the period made investment in production for large markets less attractive.

The production of weapons seems to have taken place in small-scale military ironworks. The 'agricultural garrisons' (*tun tian* 屯田) established by Cao Cao and his successors had their own production of implements and weapons.[6] Other armies too had their own ironworks: an interesting example is seen in the sources on an Eastern Jin campaign which reconquered the region south of the Yellow River in +319. Zu Ti[7] 祖逖 crossed the Yangzi with a hundred men, camped at Huaiyin 淮陰, 'built a smelter and cast weapons' (*qi ye zhu bing qi* 起冶鑄兵器), trained his soldiers, and 'did not advance until he had recruited over 2000 men'.[8]

1 See e.g. de Crespigny (1967); Goodman (1998).
2 The most readable account of the history of the Period of Disunion is still that of Eberhard (1977, pp. 109–68). Bielenstein (1996–97) gives a very detailed and schematic account of the political history of south China in this period.
3 On the manorial economy of this period see e.g. *SCC*, vol. 6, part 2, pp. 593–7; Ebrey (1974); Herzer (1963); Sun and De Francis (1956, pp. 137–41, 142–56).
4 Pp. 140–1 above.
5 *Wei shu*, ch. 110, p. 2857.
6 *Wei lüe* 魏略, quoted in *San guo zhi*, ch. 11, pp. 347–8.
7 +266–321, an ancestor of the mathematicians Zu Chongzhi and Zu Geng 祖暅. See *SCC*, vol. 3, e.g. pp. 35–6, 101–2.
8 *Jin shu*, ch. 62, p. 1695 (cf. n. 15, p. 1702); *Jian kang shi lu*, ch. 5, Zhang Chenshi (1986, p. 132).

One military ironworks of the period was in Mianchi 澠池 (modern Mianchi County, Henan). There had been an Iron Office here under the Han state monopoly.[9] The place was just inside the southern border of the state of Later Zhao 後趙 (which occupied a large part of north China, +319–351),[10] was the scene of much fighting, and was heavily garrisoned.[11] A decree of about +341 by the Later Zhao ruler Shi Hu 石虎 tells us a little about the ironworks:

> Earlier, because the Fengguo 豐國 and Mianchi smelters [*ye* 冶] were newly established, convict labourers were transferred there to man them. This was necessary in order to deal with a crisis. But those in charge have continued [to use convict labour] as a fixed rule, and this has caused great resentment. From now on, whenever convicts are used as labourers, this is to be reported [to the central government]; they are not in general to be employed.[12]

The date of the establishment of the two state ironworks is unknown, but we may perhaps assume that it was shortly after the establishment of the dynasty in +319.

Fengguo cannot be securely identified,[13] but there is no doubt that Mianchi was in the modern county of the same name. Here a remarkable ancient scrap-iron collection was excavated in 1974: it contained 4195 iron artefacts and fragments, weighing a total of 3.5 tonnes. The excavators believe that when the land of a former ironworks was cleared at some time, perhaps in the +5th century, these iron artefacts were collected and buried simply to get rid of them. The circumstances of the burial happened to be favourable for the preservation of the artefacts, and they provide a marvellous body of material for the study of many aspects of ancient iron production.[14]

The artefacts were scrap, originally collected for remelting, and came from different times and places. Many have inscriptions giving place-names along the middle reaches of the Yellow River, where the artefacts presumably were produced. Some of the inscriptions name Iron Offices under the Han state monopoly,[15] while others name offices which seem to have been military:

jun 軍, 'army'
zuo 左, *you* 右, 'left', 'right'
jun zuo 軍左, *jun you* 軍右, 'army left', 'army right'
ye zuo 冶左, *ye you* 冶右, 'smelter left', 'smelter right'.

[9] See Section 5 above, Table 1, item 15.
[10] On the history of Later Zhao see e.g. Rogers (1968, pp. 22–7).
[11] See e.g. *Jin shu*, chs. 61, 103, 104, 105, pp. 1663, 2686, 2698, 2712, 2755.
[12] *Jin shu*, ch. 106, p. 2770. This was the last of a number of measures relaxing the laws in response to a severe drought. The historian reports that the rains came on the very day the decree was issued.
[13] Perhaps it was at the place where a prefecture of the same name was established by the Southern Qi dynasty (+479–502), somewhere in modern Jiangsu Province and probably not far from the famous Liguo Industrial Prefecture 利國監 of the Song period (Section 7 below, pp. 300–1). 'Fengguo' and 'Liguo' both mean 'enriching the state'. See *Nan Qi shu*, ch. 14, p. 257.
[14] Li Jinghua (1976). Artefacts from the Mianchi scrap-heap have been discussed above, pp. 162, 224.
[15] See Section 5 above, especially pp. 190–200.

Inscriptions on numerous artefacts name Mianchi, and several point directly to a military ironworks here, probably the one established by Later Zhao:

Mianchi jun zuo 澠池軍左, 'Mianchi army left'
Mianchi jun you 澠池軍右, 'Mianchi army right'
Mian zuo 澠左, *Mian you* 澠右, 'Mian[-chi] left', 'Mian[-chi] right'.

There are some indications of non-military state involvement in the iron industry in the Period of Disunion, but it seems impossible to determine what this involvement may have amounted to.[16] The likeliest guess is that state bureaux and officers were concerned with collecting taxes and keeping order in iron-production centres rather than with the technical details of iron production.

There was one proposal for direct involvement of the civil government in iron production, towards the end of the Northern Wei period (perhaps about +500).[17] This was by Cui Ting 崔挺, Regional Inspector (*ci shi* 刺史) of Guāngzhou 光州, at the tip of the Shandong peninsula. In the Han period there had been an Iron Office in Guāngzhou, and later, in the Song period, this would become a major iron-producing region.[18] But at this time very little iron was being produced here, and the region imported most of its iron from elsewhere. Cui Ting memorialised that it would be advantageous to both the state and the populace to reinstate the Iron Office here (or perhaps to reinstate the whole Han monopoly system throughout the land), but what happened to this proposal is not known.

A *salt* monopoly was established by the Tang in the mid-8th century, and the office set up to administer it, called the Commission for Salt and Iron (*yan tie shi* 鹽鐵使), gradually developed into a kind of Ministry of Finance, with a broad range of responsibilities concerned with monopolies and taxation.[19] The name of this commission was a reference to the Han precedent rather than a description of its duties; it seems never to have been involved in iron production.[20] The consensus of Tang historians seems to be that 'there was never any question of a monopoly tax on iron production'.[21] A few laconic sources indicate, however, that this is not the whole story. A report of +811 gave the receipts from sale of salt *and iron* as 6,859,200 strings of cash.[22] Around the same time, and perhaps based on the same source, is a note that there were Copper Offices and Iron Offices[23] in three circuits (*dao* 道) and twelve

[16] *Jin shu* (ch. 15, p. 458) mentions two Iron Offices in E Prefecture 鄂縣 (near modern Daye 大冶, Hubei, famous for its copper and iron mines). *Song shu* (ch. 39, p. 1232, 1230) mentions Jin administration of iron production briefly and states the titles of some officers concerned with iron production under the Liu-Song Dynasty. Note also *Nan Qi shu*, ch. 16, p. 318, ch. 30, p. 557; *Chen shu*, ch. 6, p. 115; *Nan shi*, ch. 30, p. 305, ch. 80, p. 1996.

[17] *Wei shu*, ch. 57, p. 1265; also *Bei shi*, ch. 32, p. 1171.

[18] See Section 5 above, Table 1, item 7 (pp. 193–7) and Section 7 below, Table 4, items 32–5 (pp. 295–8).

[19] Twitchett (1970, pp. 49–65, 200–1).

[20] Note for example that, when the Tang Emperor Wu-zong 武宗 in +845 ordered the destruction of Buddhist statues, the *bronze* statues were recast by the Salt and Iron Officers, but the *iron* statues were recast by local authorities.

[21] Twitchett (1970, p. 51).

[22] *Jiu Tang shu*, ch. 15, p. 442.

[23] *Tong tie guan* 銅鐵官, conceivably 'Offices for Copper and Iron'.

prefectures (*zhou* 州), collecting an annual 'smelting tax' (*ye fu* 冶賦) amounting to millions.[24] No Chinese government was likely to ignore the iron industry as a source of necessary materials, tax income, and administrative problems, but here, as so often happens, we are at the mercy of our sources and have no way of determining exactly what arrangements were made.

(ii) Wider Knowledge of Siderurgical Techniques

Economic and social conditions in the troubled centuries from the late Han period seem thus to have led to a spread of iron production to a larger number of iron-works, operating on a smaller scale and producing for smaller local markets.

A part of this change was the spread of the skills of iron making, including specifically those of the blacksmith.[25] The sources for the period show for the first time that some knowledge of the techniques of iron making had spread from the artisans to the general literate population. We have already seen a religious text, *Tai ping jing* 太平經, use the smelting, fining, and forging of iron as a metaphor.[26] In the +1st century, Wang Chong 王充 used the work of a smith as a metaphor for the forming of a person's character – nurture, not nature.[27] He was also familiar with iron *casting*, and in his discussion of the physics of thunder and lightning gave a vivid description of casting in moulds and of the accident that will occur if water is poured into the melting furnace.[28] In the mathematical text *Xia hou Yang suan jing* 夏侯陽算經 (perhaps +5th century, perhaps +8th) several problems concern losses in iron fining and steelmaking.[29] The Tang poet Li Bai 李白 saw in +754 what seems to be a blast furnace in Qiupu District 秋浦縣 (modern Guichi County 貴池縣, Anhui):

> Furnace flames light up heaven and earth,
> Red stars mingle with purple smoke.
> A worker's red face brightens in the moonlit night,
> His song moves the cold river.[30]

24 *Xin Tang shu*, ch. 179, p. 5318.

25 Cf. p. 247 above.

26 P. 244 above.

27 *Lun heng* 論衡, ch. 2, part 8, *SBCK* edn, p. 15a; Anon. (1979c, p. 111); tr. Forke (1907–11, vol. 1, p. 377). On Wang Chong see *SCC*, vol. 2, e.g. pp. 368ff.

28 *Lun heng* 論衡, ch. 6, part 23, *SBCK* edn, p. 23a; Anon. (1979c, p. 397); tr. Forke (1907–11, vol. 1, p. 294).

29 *Xia hou Yang suan jing*, Qian Baocong (1963, pp. 586–7). Cf. *SCC*, vol. 3, p. 34. The problems concern the conversion of given amounts of cast iron (*sheng tie* 生鐵) to 'yellow iron' (*huang tie* 黃鐵) and of 'yellow iron' to steel (*gang tie* 鋼鐵). 'Yellow iron' is something of a mystery, but here it seems likely to mean 'wrought iron'.

30 *Qiu pu ge shi qi shou* 秋浦歌十七首, no. 14, *Li Tai bai quan ji*, ch. 8, p. 423; cf. Ōno Jitsunosuke (1980, p. 680); Guo Moruo (1971, pp. 189–90). Some commentators suggest that the poem describes an alchemical furnace, but the Qing commentator Wang Qi 王琦 argues that the furnace is for smelting metals on an industrial scale.

The alchemist and polymath Tao Hongjing 陶弘景 (+456–536) also reveals a knowledge of iron and steel making in one of his books of materia medica, probably *Ben cao jing ji zhu* 本草經集注 (+492), known today only from quotations in later works:[31]

Tie luo 鐵落 [usually glossed as 'hammer scale'] is an iron paste [*jiang* 漿] which has been coloured black.

Sheng tie 生鐵 [cast iron] [is iron which] has not been transformed into wrought iron [*shi bu bei rou* 是不被鍒]. [It is used in making] such things as wine-warmers [*cheng* 鎗] and cooking pots.

Gang tie 罡鐵 [steel, 鋼鐵] is cast and wrought [iron], refined together [*za lian sheng lian* 雜練生鍊], to make knives and *fu* 鉘 [sickles?].[32]

Tie jing 鐵精 [essence of iron] (is the purest part of iron).[33] It comes from the smithy forge; the best is dust-like, purplish in colour, and light in weight. [In addition to its medical use] it is also used in polishing bronze vessels.[34]

Later, in +659, a comment by Su Jing 蘇敬 on this passage once again clearly suggests direct observation of a smith:

Tie 鐵 [iron], referred to alone [without a qualifying adjective], refers to *lian tie* 鍊鐵 [wrought iron].

Tie luo is the scale [*pi jia* 皮甲] which falls [*luo*] when the smith heats iron until it is red and makes a crackling sound [*fei* 沸], then hammers it on the anvil . . . When Tao [Hongjing] says it can be dyed black, and that this is an iron paste, he is mistaken.

The disagreement on terminology between these authors need not detain us here; what is important is that both texts suggest direct observation of a smith at work. They had seen the smith hammering the red-hot iron and heard the sound of the iron oxide layer scaling off. This 'hammer scale' does indeed have a purplish-grey colour and a low density. That Tao Hongjing considered it to be the 'essence' of iron is an interesting speculation which deserves more attention than I can give it here.

Tradition has it that the poet and philosopher Xi Kang 嵇康 (+223–262) was also familiar with the arts of the smith. His biography tells us that he was 'fond of forging

[31] On Tao Hongjing and this book see *SCC*, vol. 6, part 1, pp. 243–8; Franciscus Verellen in Nienhauser (1986–98, vol. 2, pp. 154–8); Strickmann (1977). The passage comes to us in a number of versions, the earliest of which is an unattributed quotation in a Tang work, *Xin xiu ben cao* (ch. 4, p. 122, 1985 edn, p. 27). A Yuan work, *Chong xiu Zheng he jing shi zheng lei bei yong ben cao* (ch. 4, p. 114), includes virtually the same passage and attributes it to Tao Hongjing. A Ming work, Li Shizhen's famous *Ben cao gang mu* (ch. 8, pp. 490, 486, 491) also quotes the passage. I have used the Tang version here, following some but not all of Shang Zhijun's (1981) emendations based on the Yuan edition.

[32] This *fu* is an extremely rare character whose meaning is uncertain. The *Chong xiu . . . ben cao* version replaces it with *lian* 鐮, 'sickle'.

[33] The four characters *tie zhi jing hua* 鐵之精華 are in the *Ben cao gang mu* version only (ch. 8, p. 491) and are therefore suspect.

[34] From these details it is clear that Tao Hongjing takes *tie jing* to mean hammer scale. This was used as an abrasive in the West as well.

[iron]', and worked in his garden under a willow tree.[35] Unfortunately, in his few surviving poetic and philosophical works he seems not to have referred to the siderurgical processes and transformations which he would have observed at the forge.

A story which has come down to us in many versions has Xi Kang working at his forge when the powerful minister Zhong Hui 鍾會 (+225–263) visited him. Xi Kang continued working, 'sitting with his legs apart', and this arrogant disregard for rank led in time to his execution.[36] We need not worry about whether the story is true or false, but it can make us wonder whether Chinese smiths in the +3rd century sat (or squatted) while working, as smiths in some parts of the world do today.

A number of works of this period concern swords. Some of these may be classified as folklore collections, some as manuals for connoisseurs, and while few appear to be technically informed they do manifest a general interest in the crafts of the smith. Perhaps the earliest texts which touch on the mythology of swords and swordsmiths are two collections of legends of the semi-barbarian states in southeast China, *Wu Yue chun qiu* 吳越春秋 and *Yue jue shu* 越絕書, both of the Eastern Han period.[37] These books are the *locus classicus* for the legends of the great swordsmiths Ganjiang 干將 and Ouye 歐冶.

A short text on bamboo concerning the evaluation of swords, probably from the +1st century, was discovered at Juyan 居延 in northeast China in 1974.[38] It is not easy to read, but it appears to tell how to recognise a good sharp sword from its outer appearance alone. The writer uses technical terms which suggest that he knew a good deal about swordsmithing, but this knowledge does not come to expression in the text.

Tao Hongjing wrote a text, now lost, which judging from a surviving quotation had the same purpose.[39] He also wrote a 'Record of swords ancient and modern' (*Gu jin dao jian lu* 古今刀劍錄), which describes a large number of swords and transcribes their inscriptions. Swords seem in fact to have been a special interest of

[35] *Jin shu*, ch. 49, p. 1369. Different traditions point to two different locations for Xi Kang's forge, near modern Zhengzhou or Luoyang, Henan (*Yuan he jun xian tu zhi*, ch. 16, He Cijun, 1983, p. 446; *Xiang Xiu bie zhuan* 向秀別傳, quoted in *TPYL*, ch. 409, p. 3b). See Van Gulik (1969, p. 28); Holzman (1957, p. 39, n. 1); Balazs (1964, pp. 239–42). Rolf Stein (1941, pp. 443–4) thinks it unlikely that Xi Kang actually worked at the forge; the *duan* 鍛 of the sources refers, according to him, to procedures of inner alchemy, 'forging' an immortal embryo (or 'enchymoma') inside the body (see *SCC*, vol. 5, part 5, esp. pp. 288ff). However, I am not aware of any Taoist text which refers to the creation of the enchymoma as 'forging' (*duan* 鍛、煅).

[36] *Shi shuo xin yu*, ch. 24, *SBCK* edn, ch. *xia zhi shang* 下之上, p. 49b, 1985 edn, p. 188; *Wen shi zhuan* 文士傳, quoted *ibid.; Wei shi chun qiu* 魏氏春秋, quoted both *ibid.* and in *San guo zhi*, ch. 21, commentary, p. 606. Tr. Mather (1976, p. 393); Van Gulik (1969, p. 30); Holzman (1957, p. 39); Henricks (1983).

The expression used, *ji ju* 箕踞, 'sitting in the form of a winnowing basket' (see e.g. *SCC*, vol. 6, part 2, pp. 368–9, figs. 184–5), goes back to *Zhuang zi*, and was common in the context of insulting behaviour (Morohashi, 1955–60, items 26143.8, 9).

[37] *Wu Yue chun qiu*, ch. 4, pp. 3a–5a; tr. Eichhorn (1969, pp. 31–3); Lanciotti (1955, pp. 107–8); *Yue jue shu*, ch. 11; Yue Zumo (1985, pp. 79–81); Schüssler (1966, pp. 97–106). I have discussed these in detail (Wagner, 1993, pp. 107–15), where I suggest that the legends of swordsmiths in these two books are adaptations of very early legends about the casting of *bronze* swords.

[38] Anon. (1983b); Ma Mingda (1983); Zhong Shaoyi (1994); Chen Li (2002).

[39] An untitled text quoted in *TPYL*, ch. 665, pp. 4b–7a.

many Taoist alchemists. A curious text in the Taoist canon, *Shang qing she xiang jian jian tu* 上清含象劍鑑圖, probably from the Tang period, describes and illustrates a number of swords.[40] The Song encyclopaedia *Tai ping yu lan*, in its section on Taoism, has a chapter devoted to swords with quotations from numerous texts of the Tang and before.[41]

A study of all this material on swords and swordsmithing would probably lead to some insights into the smithy techniques of the time, but the difficulties in such a study will be very great. Consider for example two lines from a poem by Zhang Xie 張協 in the Western Jin period.[42] The poet is describing the making of a sword by Ouye:

Nai lian nai shuo,
wan pi qian guan

乃鍊乃鑠　萬辟千灌

There are four technical terms here, and the lines might be translated,

Then he refined and then he melted,
A myriad pilings and a thousand irrigations.

From a technical point of view it is difficult to make sense of this, and since the poet just before it has Ouye casting an alloy of copper, tin, and iron to make a superior sword, it is obvious that he is not trying to make technical sense. But the passage does in fact have some value, for it shows that the term *guan* 灌, here translated 'irrigation', used in relation to steelmaking, was current at this time; otherwise it is known only from the Song and Ming periods.[43]

(iii) Co-fusion Steelmaking

As has already been mentioned in Section 2(vi) above,[44] the 'wrought iron' produced by Chinese fining processes was really *mild steel*, with carbon content in the range 0.1–0.3 per cent. This was an excellent material for many purposes, but edged weapons and tools required *tool steel*, with a higher carbon content, typically in the range 0.5–1.0 per cent. In this book I follow traditional English terminology and call this latter product simply *steel*. Steel was until the 19th century a speciality product produced on a small scale by skilled craftsmen.[45]

The methods used for making steel can be broadly classified as (1) adding a controlled amount of carbon to wrought iron; (2) removing a controlled amount of carbon from cast iron; or (3) mixing cast and wrought iron to obtain a product with the desired carbon content.

[40] *Zheng tong Dao zang*, vol. 196, text no. 431; Schipper (1975, p. 9*); Chen Guofu (1983, p. 220).
[41] *TPYL*, ch. 665. There is also a good deal on swords and swordsmithing in three chapters in the section on weapons, chs. 344–6.
[42] *Qi ming* 七命, *WX*, p. 1605; *Jin shu*, ch. 55, p. 1522; cf. von Zach (1958, p. 634).
[43] See below, p. 321, fn. 153.
[44] Pp. 65–6.
[45] See e.g. Barraclough (1984, pp. 11–12 *et passim*).

It is this third category of methods which Joseph Needham called 'co-fusion', a term which has attained general acceptance.[46] The apparently simple idea of mixing irons of different carbon contents to obtain an intermediate carbon content brings with it a variety of technical complications, for which steelmakers have used different approaches.

The earliest description of a co-fusion steelmaking process occurs in the biography of Qiwu Huaiwen 綦母懷文, who was active in the +6th century:[47]

Qiwu Huaiwen, whose place of origin is unknown, used Taoist techniques in the service of Shenwu-di 神武帝 [Gao Huan 高歡, +496–547, father of the first Emperor of Northern Qi 北齊].

Huaiwen made sabres [*dao* 刀] of 'overnight iron' [*su tie* 宿鐵]. His method was to anneal [*shao* 燒] powdered cast iron [*sheng tie jing* 生鐵精] with layers of soft [iron] blanks [*ding* 鋌, presumably thin plates]. After several days the result is steel [*gang* 剛=鋼]. Soft iron was used for the spine of the sabre. He washed[48] it in the urine of the Five Sacrificial Animals and quench-hardened it in the fat of the Five Sacrificial Animals.[49] [Such a sabre] could penetrate thirty armour lamellae [*zha* 扎].

The 'overnight soft blanks' [*su rou ting* 宿柔鋌] cast today [in the Sui period?] by the metallurgists of Xiangguo 襄國 represent a vestige of [Qiwu Huaiwen's] technique. The sabres which they make are still extremely sharp, but they cannot penetrate thirty lamellae.

As usual we should like to know more about the background of this source, but, again as usual, no more information seems to be obtainable. Perhaps the best guess would be that the original source for the description came from Xiangguo, a place near modern Handan, Hebei. The name was used for a district (*xian* 縣) and a commandery (*jun* 郡) at some times in the Sui period and before, but not later.[50] This was a major iron-producing region in both the Tang and the Song,[51] and it is where Shen Gua observed a different steelmaking technique, to be discussed in Section 7 below,[52] in +1075. Shen Gua's account starts with a description of the making of what he calls 'false steel', which is obviously a co-fusion process similar to Qiwu Huaiwen's:[53]

What the general run of blacksmiths call 'steel' [*gang tie* 鋼鐵] [is made as follows]. Take wrought iron [*rou tie* 柔 [=鍒] 鐵], bend and coil it, and insert cast iron into the interstices. Seal with clay, 'refine' [*lian* 煉] it, and hammer to cause [the soft iron and the cast iron] to interpenetrate. [The product] is called 'combination steel' or 'irrigated steel'.[54]

Shen Gua uses the word *lian* 煉、鍊, which seems to have both a general meaning, 'to purify', and a large number of very specific technical meanings in particular contexts.

46 Needham (1958, pp. 26–31).
47 There are three versions of the text: (1) *Bei Qi shu*, ch. 49, pp. 679–80; (2) *Bei shi*, ch. 89, p. 2940; (3) *TPYL*, ch. 345, pp. 6b–7a. Of these the *Bei shi* version seems to be best, and is followed here. Cf. Yang Kuan (1956, p. 73); Yoshida (1966; 1972, pp. 356–7).
48 *Yu* 浴, possibly a term for a hard quench, as opposed to the soft quench in animal fat.
49 The Five Sacrificial Animals (*wu sheng* 五牲) are usually identified as ox, sheep, pig, dog, and chicken.
50 *Sui shu*, ch. 30, pp. 854, 855; Aoyama Sadao (1933, p. 282).
51 Yang Yuan (1982, pp. 15, 72, 119); Table 4, rows 19–22 (p. 296 below).
52 P. 321.
53 *Meng xi bi tan*, ch. 3, Hu Daojing (1962, no. 56, p. 135).
54 *Tuan gang* 團鋼, *guan gang* 灌鋼; cf. Sun and Sun (1966, p. 250); Needham (1958, pp. 30, 33). Another possible interpretation for *tuan gang* would be 'lump steel'; note pp. 270, 321, 324, 341–2, 346 below.

It therefore corresponds very well to the equally vague and irritating English word 'refine', and this is the standard translation for it. In this case *lian* corresponds to *shao* 燒 in the earlier text. The basic meaning of *shao* is 'to roast', and here it clearly means 'to anneal', i.e. to subject a metal object to a high heat for an extended period.

Each of these texts describes a process in which wrought iron and cast iron are heated together. In the first the process takes several days, while the second gives no information on the time required. What happens in these processes depends on whether the annealing temperature is above or below the eutectic temperature of the iron, about 1147°C.[55]

Lower-temperature co-fusion

Below the eutectic temperature of the iron, the process is rather like the familiar cementation process with cast iron as the carbon donor: the basic reactions are $C + CO_2 \rightarrow 2CO$ at the surface of the cast iron and $2CO \rightarrow C + CO_2$ at the surface of the wrought iron.[56] Solid-state diffusion in both materials carries carbon from the interior of the cast iron and to the interior of the wrought iron. Since this is a diffusion-limited process, the time required is determined by the thickness of the cast and wrought iron and by the temperature. Qiwu Huaiwen's process is said to require an anneal of several days, and we can therefore assume that it used a fairly low temperature.

A possible reconstruction of Qiwu Huaiwen's method was the subject of experiments in 1955 on the initiative of Joseph Needham.[57] Strips of wrought iron, 1 mm thick, were piled up and wired together with varying amounts of crushed white cast iron between layers. This faggot was heated in a non-oxidising atmosphere to a temperature between 950° and 1000°C, then immediately withdrawn from the furnace and hand-forged, welding it into a single bar. At the original welded surfaces in this bar were highly carburised zones as well as some unchanged white cast iron. A homogenising anneal of 8 hours at 900°C resulted in a uniform carbon content of 0.8 per cent throughout the bar.[58]

This proposal fits reasonably well with the little we know of Qiwu Huaiwen's method, though the original description includes no mention of forging the faggot into a

[55] The eutectic temperature of iron with no alloying elements other than carbon is 1147°C. Alloying elements such as silicon and sulphur lowers the eutectic temperature slightly.

[56] See pp. 66–9 above. In this case 'co-fusion' is strictly speaking a misnomer, since nothing actually becomes liquid, but in popular usage the English word 'fuse' has a broad semantic range, and we can think of it as meaning, 'to unite by heating together'.

[57] The experiments were carried out by Mr P. Whitaker of Stewarts and Lloyds, Ltd, Corby. His original report is in the archives of the Needham Research Institute, and will in the near future be made available on the Institute's web-site. It has been summarised briefly by Needham (1958, pp. 30–1) and in more detail by Whitaker and Williams (1969, pp. 41–5). Later K. C. Barraclough (1984, p. 33) examined the samples produced by Mr Whitaker and confirmed his results.

[58] Note a related process reported by al-Bīrūnī in the +10th or +11th century: he was told that, in Sind, a smith had been seen sprinkling powdered cast iron on a steel sword while forging it. The passage is translated by al-Hassan and Hill in Bosworth et al. (1960–2002, p. 973) and by Allan (1979, p. 79). Some scholars reject the idea that cast iron was the material used here (e.g. Rāġib, 1997, p. 37), but this would seem to be an excellent method of producing steel.

bar at the beginning of the anneal. The forging undoubtedly speeds up the process considerably, but is unlikely to be a strict necessity. Another aspect is that the wrought-iron strips were very thin in these experiments; an ancient smith would certainly have been capable of producing wrought-iron strips which were only 1 mm thick, but this would have been time-consuming, and would have involved the loss of a considerable amount of iron through oxidation. The 'wrought-iron blanks' of the description would no doubt have been thicker, perhaps 2–3 mm, necessitating a longer annealing time.

Higher-temperature co-fusion

If the temperature is above the eutectic the wrought iron is annealed in a bath of liquid cast iron. We shall see in Section 8(ii) below that Song Yingxing in the 17th century describes a higher-temperature co-fusion technique.[59] See the iron–carbon equilibrium diagram, Figure 110. Two processes occur, the balance between them depending on the exact temperature and carbon content. If for example the temperature is 1250°C and the carbon content of the cast iron is 4.0 per cent, wrought iron (0.1–0.3 per cent carbon) will be dissolved until the bath is diluted to a carbon content of about 3.5 per cent. After this, carbon diffuses into the wrought iron; still at 1250°C, an equilibrium is quickly reached in which the carbon content at the surface of the solid iron is about 1.5 per cent and the carbon content of the liquid iron is about 3.5 per cent.[60] As carbon diffuses into the interior of the solid iron, using up the carbon in the liquid iron, more solid iron (with 1.5 per cent carbon) precipitates from the bath until no liquid is left. A few minutes at this temperature would result in an inhomogeneous lump of steel with carbon content varying between about 0 and 1.5 per cent. Perhaps an hour at this same temperature (the time would depend on many unknown parameters), or many hours at a lower temperature, would homogenise the lump: if the original charge had been 20 per cent cast iron and 80 per cent wrought iron, the result would be a steel with 0.8 per cent carbon, excellent for many purposes.

It is not impossible that Qiwu Huaiwen used a higher-temperature co-fusion process like the one I have described here, though a lower-temperature process seems more likely in his case.

What Shen Gua describes, in the second quotation above, might well have been a higher-temperature co-fusion process, and the *intended* result might in fact have been a non-homogeneous steel which could be used in making pattern-welded swords. The 'bending and coiling' of the wrought iron seems otherwise superfluous. Elsewhere Shen Gua refers to steel swords with the sort of pattern that might result:[61]

[59] P. 346.

[60] In the iron–carbon equilibrium diagram (Figure 110), the maximum carbon content of solid iron (austenite) in the relevant temperature range is given by the line JE; the minimum carbon content of liquid iron is given by the line BC. Rehder (1989, p. 34), in an otherwise useful article, overlooks these facts and is therefore mystified by his experimental results.

[61] *Meng xi bi tan*, ch. 19, Hu Daojing (1962, no. 325). The sword names are found in *Wu Yue chun qiu* 吳越春秋 and *Yue jue shu* 越絕書 (Wagner, 1993, pp. 111–15). Most of the names seem to be transcriptions of non-Chinese words, but Shen Gua is not the only writer to treat them as having meaning in Chinese.

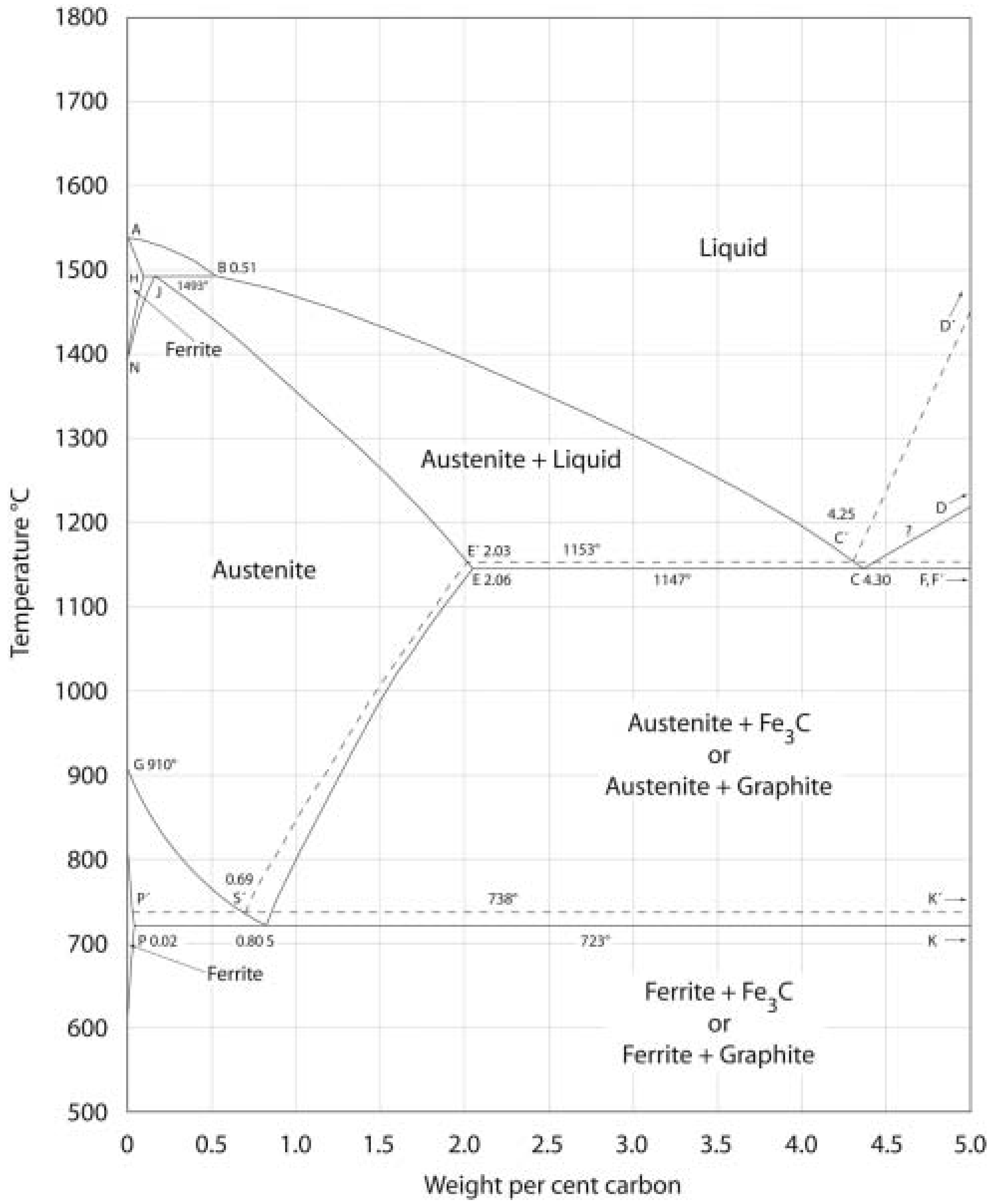


Figure 110 Iron–carbon equilibrium diagram. After Hansen (1958, p. 354).

Among the names of ancient swords . . . Yuchang 魚腸 [‘Fish Gut’] was what today is called a *pan gang* 蟠鋼 [‘coiled steel’] or *song wen* 松文 [‘fir patterned’] sword. If one takes fish, bakes them, and strips off the ribs to reveal the guts, they have a distinct resemblance to the pattern on a modern *pan gang* sword.

The possibilities of ‘pattern-welding’ steel and soft iron to make intricate patterns have been exploited by swordsmiths in Europe and Japan as well as in

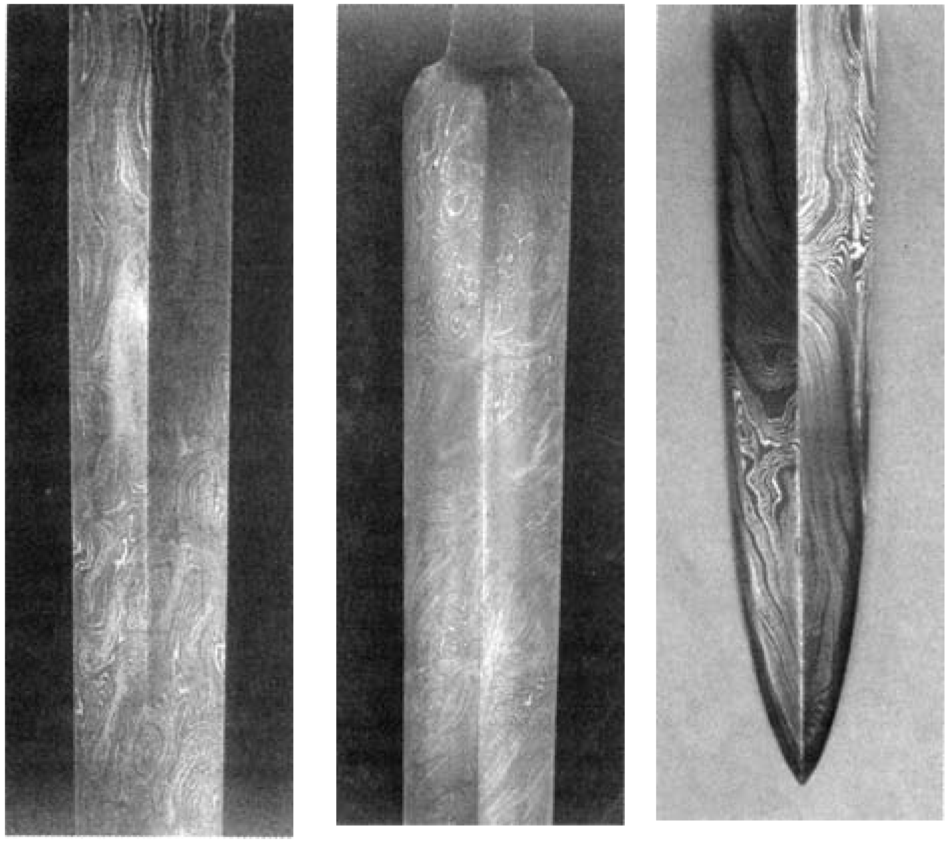


Figure 111 Photographs of three patterned-steel swords in private Chinese collections. They are difficult to date, but are believed to be from the Yuan period. Reproduced from He Tangkun (2001, p. 70, figs. 1–3).

China.[62] The pattern is made by variations in carbon and phosphorus content, which become visible when the sword is polished and etched. He Tangkun has examined several patterned-steel swords in private Chinese collections, and gives the three photographs shown in Figure 111.[63]

What sort of furnaces were used in these processes, and how was the metal held together while it was heated? Were crucibles used? We have seen from the experiments by P. Whitaker reported above that a lower-temperature co-fusion process can be carried out without a crucible or other container for the material.[64] In those experiments a modern electric furnace was used, but the same conditions – a temperature

[62] One good discussion is C. S. Smith (1988, pp. 1–66); see also Needham (1958, pp. 44–5).
[63] He Tangkun (2001). Wayman and Michaelson (2006) describe the microstructure of another Chinese pattern-welded sword, dated 13th–15th century, in the collection of the British Museum.
[64] Pp. 257–8 above.

in the range 950–1000°C in a non-oxidising atmosphere – is regularly attained and held for long periods in a charcoal-fuelled smithy hearth. A furnace specifically designed for heating crucibles, such as the Persian furnace described in Box 11 below,[65] would be easier to control and much more fuel- and labour-efficient, but would not, strictly speaking, be necessary.

In Shen Gua's description of a higher-temperature co-fusion technique he states that the mixture of cast and wrought iron is sealed with clay. Perhaps he meant that the material is placed in a crucible whose mouth is then sealed. On the other hand an equally plausible interpretation is that the material is plastered all over with wet clay to hold it together and protect it from the furnace atmosphere while it is heated to the necessary high temperature. When the co-fusion is complete and hammering begins, the hard-fired clay breaks up and the steel remains. The heating can easily be done in a smithy hearth.[66]

Some Han steelmaking crucibles

Crucibles which could have been used for co-fusion steelmaking have been found at a few Han ironworks sites.[67] The only early Chinese crucibles which have been properly studied, however, are eleven which were found in a grave at Jili 吉利 in Luoyang, Henan.[68] The grave is believed to be from the Eastern Han period, but the dating is very difficult, and it could well be a few centuries earlier or later.[69]

The eleven crucibles from Luoyang are made of clay tempered with a large amount of powdered coal or charcoal (14 per cent by weight).[70] They are cylindrical, with round bottoms, diameter 14–15 cm, height 35–6 cm, wall thickness 2 cm. Both inside and outside surfaces are vitrified from exposure to high temperatures.

[65] P. 266.

[66] Temperatures over 1200°C are regularly used by smiths in forge-welding. In fact it appears that temperatures high enough to melt wrought iron, over 1550°C, in a non-oxidising atmosphere, were regularly used by Norwegian smiths in the 18th century. This is clear from a report by Ole Evenstad (1790, pp. 437–41), together with experiments undertaken by Robert Thomsen (1975, pp. 31–3) to confirm the report; see Wagner (1990). It is probably important that the fuel here is charcoal and that the hearth is designed for charcoal, with the tuyère at the side rather than the bottom (Light, 1987); it seems unlikely that such temperatures could be maintained in a non-oxidising atmosphere with mineral coal or coke as the fuel.

[67] He Tangkun (1985, pp. 59–60) notes crucibles found at three Han ironworks sites: Qinghezhen in Beijing, Hohhot in Inner Mongolia, and Kucha in Xinjiang; see Table 2 in Section 5 above, items 1, 33, and 45. In addition Pei Mingxiang (1960, pp. 59, 60, fig. 3; cf. Lu Da, 1966, p. 1, pl. 3.9) describes three 'crucibles' found at Wafangzhuang in Nanyang, Henan (Table 2, item 17), but these are not mentioned in the final excavation report on this site (Li Jinghua and Chen Changshan, 1995). They are unlikely to have been used as crucibles, for they appear to have been subjected to higher temperatures on the inner than on the outer surface; perhaps they are the remains of furnace linings.

[68] Ye Wansong et al. (1982); He Tangkun et al. (1985).

[69] The only artefacts found in the grave are the eleven crucibles and five coins. The coins are similar to coins from a famous tomb in Mancheng, Hebei, dated –113, and therefore the excavators date the grave to the Western Han period (Ye Wansong et al., 1982; Anon., 1980c, pp. 208–12). On the other hand, thermoluminescence dating of the crucibles gives a date of 1832 ± 147 BP, and He Tangkun et al. (1985, p. 59) are inclined to date the grave to the Eastern Han.

[70] On the use of carbon in refractories see p. 232 above.

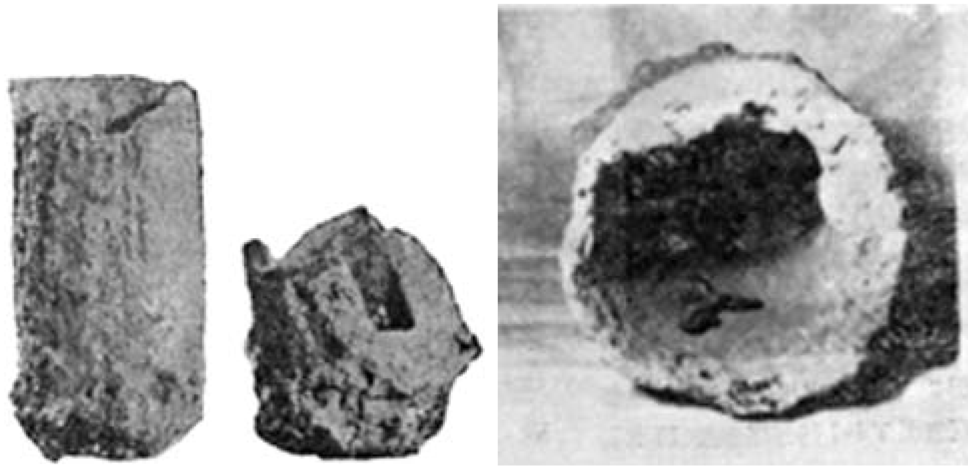


Figure 112 Crucibles from a Han grave excavated at Jili 吉利 in Luoyang, Henan. Reproduced from Ye Wansong et al. (1982, p. 23, fig. 2) and He Tangkun et al. (1985, p. 59, fig. 1). In the rightmost crucible can be seen a piece of steel adhering to the inside wall: it is 15 cm long and 0.4 cm thick.

It is not in general possible to estimate the temperature that a refractory material has actually been exposed to, but laboratory tests show that the crucibles would have been usable at temperatures as high as 1580–1610°C, high enough for any steelmaking process. Carbonaceous material adhering to the outside surfaces has been identified by geologists as mineral coal:[71] this is the most definite evidence presently available of the use of coal in metallurgy in the Han period.[72]

A piece of steel adhering to the inside of one of the crucibles (Figure 112) has been studied by He Tangkun and his associates.[73] Both form and microstructure indicate that the object has been molten, and the investigators also state that it is obvious from the object's appearance that before solidification it had flowed towards the mouth of the crucible; that is, it solidified while the contents of the crucible were being poured or dumped out.

Wet chemical analysis shows a carbon content of 1.21 per cent. Other element percentages were determined by scanning electron microscope (energy spectrum):

Fe %	P %	S %	Si %	Al %	[total %]
98.637	0.277	0.584	0.117	0.383	[99.998]

[71] Ye Wansong et al. (1982, p. 39).
[72] Cf. *SCC*, vol. 5, part 13, p. 194, and p. 311 below.
[73] He Tangkun et al. (1985).

The high sulphur content is strange: if steel produced in the crucible had this much sulphur throughout, it would have been so hot-short (brittle at high temperatures) as to be almost unusable.

The first of many questions raised by this find of crucibles is *why* they should have been placed in a grave at all. Perhaps, as the excavators suggest, the person buried was a steelmaker, and the crucibles symbolise his mastery of the craft. On the other hand it is not impossible that he had nothing to do with metallurgy, but his family could not afford any other ceramic objects for his grave. In any case the place where the crucibles were used would have been nearby.

Removed as they are from their use-context the crucibles are difficult to interpret. He Tangkun et al. argue that they were used for direct production of steel from ore by a version of the crucible smelting technique known in later times.[74] It seems that the crucibles were heated with mineral coal. If this was also used as the reducing agent inside the crucibles, as in the early modern process, then the high sulphur content of the product would be explained. What would not be explained is what this extremely hot-short steel could have been used for.

Further possibilities become apparent if we drop the assumption that the material left behind in the crucible is directly representative of the product which was made in it. In particular, it is quite possible that the piece of steel left in the crucible was the incidental result of partial decarburisation of a liquid iron with a much higher carbon content. If molten cast iron were poured out of the crucible, the tail end of the pour could lose enough carbon to solidify, adhere to the side of the crucible, and lose more carbon while cooling slowly from a temperature over 1150°C.

It is thus possible that these crucibles were used in higher-temperature co-fusion steelmaking. With the same hypothetical parameters as were used in the explanation above,[75] we can suppose that a mixture of wrought iron (zero carbon) and cast iron (4 per cent carbon) was heated to 1250°C. A few minutes after the cast iron had melted, the contents of the crucible were dumped out. In this particular case the full process of carburisation and precipitation, described above, had not run to completion, and some liquid iron (about 3.5 per cent carbon) also poured out. Some of this remained behind, adhering to the crucible. Emptying the crucible before the liquid iron was exhausted could even have been intentional, since whatever sulphur was in the original cast iron would to some extent concentrate in the liquid phase and be discarded.

It is not necessary to accept this suggestion. The important point about the Luoyang crucibles is not whether they were actually used in this way, but rather the fact that crucibles were available in Han China which would have been suitable for use in higher-temperature co-fusion steelmaking.

74 On crucible smelting see pp. 38–44 above.
75 P. 258.

Crucible steel?

In the modern archaeometallurgical literature the term *crucible steel* normally refers specifically to steel produced at temperatures high enough to melt it.[76] Of course a crucible is necessary when liquid steel is produced, but it is also quite useful at lower temperatures as well, so this terminology can cause considerable confusion. It will be avoided here.

The Chinese written sources give no reason to suppose that the temperatures used in steelmaking were high enough to melt the steel produced (perhaps 1400°C or higher). If the steel had been produced in liquid form, the long anneal of Qiwu Huaiwen's method would have been unnecessary, as would the 'bending and coiling' of the wrought iron noted by Shen Gua. On the other hand the Han crucibles described above could easily have been used at such high temperatures, and perhaps liquid steel was also produced in ancient China.

Other times and places

The co-fusion of cast and wrought iron is of course a Chinese innovation – it was practised in China long before cast iron was known anywhere else. In later times various co-fusion techniques were used widely in Central Asia and to some extent in India, Africa, and Europe. The medieval polymath al-Bīrūnī (+973–1048)[77] described a co-fusion method practised at Herat in Afghanistan,[78] and al-Tarsusi (d. +1348) appears to describe something similar in Egypt.[79] One variant of the Indian *wootz* steelmaking process, used in Hyderabad, was in fact a co-fusion process.[80] Biringuccio (d. ca. 1539) in his *Pirotechnia* described a steelmaking process with some resemblance to co-fusion (essentially a fining process in which wrought iron is added to the liquid iron as it is being fined).[81] This process seems to have been in use in Italy at least a century after Biringuccio.[82] In North Cameroon in the 20th century Mafa ironmasters heated bits of cast and wrought iron, both produced in a bloomery, in an open crucible to effect both decarburisation and co-fusion.[83]

Archaeology in the new states of Central Asia has revealed the remains of steel-making centres which appear to have used co-fusion techniques. At the site of an important ancient city in the Merv oasis, in the southeast corner of Turkmenistan,

[76] Barraclough (1984, vol. 2); Rehren (2003, pp. 210–11); Craddock (2003).

[77] It is odd that several recent archaeometallurgical writers mistakenly place al-Bīrūnī in the 12th century. There is no doubt that his dates are 973–1048; see e.g. *The encyclopaedia of Islam* (Anon., 1960ff, vol. 1, pp. 1236–8).

[78] Allan (1979, p. 71–5); Craddock (1998, p. 50); Lang et al. (1998, p. 13); al-Hassan and Hill (1986, p. 253); al-Hassan (1978, pp. 40–1); Rāġib (1997, p. 40); Bronson (1986, p. 44); Allan and Gilmour (2000, p. 75).

[79] Cahen (1948, pp. 127–9); Craddock (1998, p. 50); Lang et al. (1998, p. 13); al-Hassan and Hill (1986, p. 253); al-Hassan (1978, pp. 40–1); Rāġib (1997, p. 40); Allan (1979, pp. 71–4, 75); Bronson (1986, pp. 44, 73–4).

[80] Voysey (1832); Bronson (1986, pp. 43–5).

[81] Smith and Gnudi (1943, pp. 67–70); Percy (1864, pp. 807–9). A similar text, presumably copied from Biringuccio, appears in Agricola's *De re metallica* of 1556 (Hoover and Hoover, 1912, pp. 423–6).

[82] Martin Lister (1693, pp. 867–8) quotes the 17th-century Jesuit Athanasius Kircher on a steelmaking process much like this one which was used on the island of 'Ilva', i.e. Elba. See also Percy (1864, p. 809).

[83] David et al. (1989, p. 199).

one of the features excavated in a major cooperative project between British and Turkmen archaeologists was a steelmaking workshop dated to the +9th–10th century.[84] Four furnaces and a scatter of crucible fragments were found. The crucibles seem all to have been of one type, reconstructed as having diameter about 8 cm and height about 20 cm. Laboratory tests indicate that the ceramic fabric could withstand temperatures as high as 1550°C. Metallic prills in the slag adhering to the crucible fragments were generally either steel, with about 0.8 per cent carbon, or cast iron (carbon content not stated). Three of the furnaces appear to have been used to heat the charged crucibles. The excavators conclude that a co-fusion process was used here. They suggest that the temperature used was at least 1250°C, but do not take a stand on whether the temperature was high enough to melt the steel produced.

Further east from Merv along the Silk Road is a region praised for its iron and steel production by Greek, Islamic, and Chinese writers. The Sogdian state of Ustrūshana, a mountainous region east of Samarkand, and the Ferghana basin have been the focus of renewed archaeological attention in recent years, and a great deal of material related to the medieval iron and steel industry has been uncovered here.[85] Most relevant to our present concern is a workshop excavated at a city-site of the +9th–13th centuries in Ferghana, at Eski Achsy, Uzbekistan. Here a large number of crucible fragments were found; the original crucible form appears to have been rather like the Merv crucibles, but higher: 7–8 cm in diameter, height 32–40 cm.[86] The excavators consider that the process used here was direct production of steel from ore, just as He Tangkun argues for the Luoyang crucibles. It is quite possible, however, that they were (also) used in co-fusion steel production as suggested by the Merv excavators.

From the early 19th century we have the excellent description of a co-fusion steelmaking process which is translated in Box 11. It was published in French by a certain Captain Massalski in a Russian mining journal in 1841, and is clearly based on both direct observation and interviews with craftsmen. He describes steelmaking in 'Persia', and it is not altogether clear what a Russian of that time would have included in this term: perhaps even the region of modern Afghanistan, Turkmenistan, Tadjikistan, and Uzbekistan.[87] It seems at least possible that Massalski had seen the techniques he describes in much the same general area as the archaeological remains described above, rather than further west in modern Iran.

[84] Feuerbach et al. (1997; 1998); (Feuerbach and Griffiths, 2003); Herrmann and Kurbansakhatov (1994, esp. pp. 70–1; 1995, esp. pp. 42–5); Herrmann et al. (1993; 1996, esp. pp. 15–17 and pl. 3; 1997, esp. pp. 10–13); 1998; 1999, esp. p. 13; 2000). On the history of Merv archaeology see Bader et al. (1994).

[85] Papachristou and Swertschkow (1993); Bosworth (1960–2002); Anon. (1973–82).

[86] Papachristou and Swertschkow (1993, pp. 126–9); Rehren and Papakhristu (2000); Rehren and Papachristou (2003).

[87] Allan and Gilmour (2000, pp. 68, 75) suggest that Massalski observed steelmaking either in northern Iran or in Bukhara (in modern Uzbekistan).

Box 11 *The preparation of Damascus steel in Persia in the early 19th century. Translated from Massalski (1841, pp. 297–9); cf. Allan and Gilmour (2000, pp. 535–9). The illustration referred to is reproduced here as Figure 113.*

The metals used in the preparation of Damascus steel are wrought iron, cast iron, and a small amount of silver. The former should be previously worked scrap (nails, plates, etc.), but free of rust. For the cast iron one of the best grades of white cast iron should be chosen. The silver should be extremely pure. The usual proportion is one part cast iron to three parts wrought iron by weight.

The wrought iron and cast iron are broken up into small pieces, mixed as thoroughly as possible, and charged into refractory crucibles (no. 3 in the illustration) whose height, upper diameter, and lower diameter are in the ratio 5 : 4 : 3. The size of the crucibles depends on the amount of steel to be prepared. In Persia the quantity [per crucible] is usually between $\frac{1}{5}$ and 1 *bacheman*. (One *bacheman* is equivalent to . . . 2.46 kg.) The charged mixture occupies one-third of the capacity of the crucible.e

The fusion furnace (nos. 4 and 5 in the illustration) is composed of a cubical brick chamber (ABCD) with flat bottom. At each corner is an opening (C) for the nozzles of the bellows. An opening is left in one wall of the box to allow the charging of additional coal[a] if necessary during the operation. A false floor (*mn*) in the chamber has round holes with diameter equal to the diameter of the crucibles at $\frac{2}{3}$ of their height . . . Usually this floor is placed at $\frac{3}{4}$ of the height of the chamber (ABCD). The holes (*o*) are arranged in such a way that the crucibles are . . . 0.051 m apart. Around each of these holes are placed four small holes (*q*) through which the flames pass and envelop the crucibles on all sides. The furnace is closed with a cover of iron or brick, plastered with clay, which is manoeuvred with the help of a simple lever. Several holes in the cover allow the passage of air out of the furnace.

The furnace is initially loaded with sufficient coal to reach the bottoms of the crucibles. These are lodged in the holes (*o*) in the floor (*mn*), positioned as nearly horizontal as possible. The space between the floor (*mn*) and the furnace cover is completely filled with coal, and the cover is carefully sealed with potter's clay. The fuel is ignited at the four corners (C), and the operation of the bellows begins. When the metal begins to melt, which occurs after 5 to 6 hours, a bubbling sound is heard which increases as the metal melts and stops when fusion is complete. As soon as the bubbling sound has stopped, the furnace cover is lifted. The crucibles are cleared of the coal which covers them and into each is introduced . . . 13–17 g of silver in small pieces. The contents are stirred briskly with a metal rod, the crucibles are again covered with coal, the furnace cover is replaced, all of the furnace openings are closed with clay, and the furnace is allowed to cool for about three days.

When the furnace has cooled completely, the crucibles are removed and the buttons [of steel] are collected. The buttons are cleaned, and any silver which may adhere to their surface is removed. In this state these are what is referred to as *Damascus steel.* All that remains is to test them . . . [A detailed description of the testing process follows.]

[a] The fuel used in this process is referred to simply as 'coal' (*charbon*). This is surely charcoal, as the journal in which the description appears refers consistently to mineral coal as *houille*.

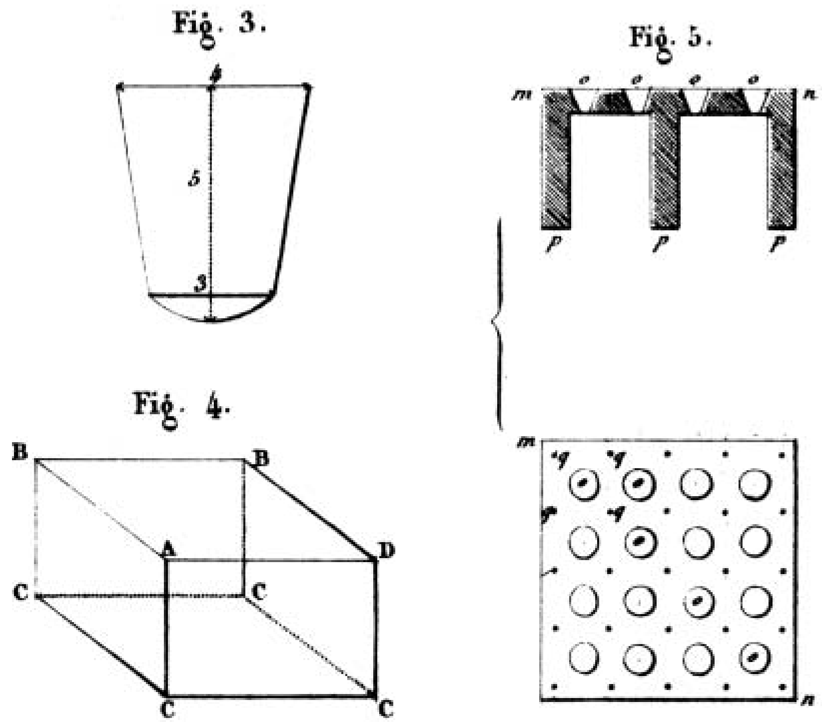


Figure 113 Illustration accompanying Massalski's description of the preparation of watered steel in Persia. Reproduced from Massalski (1841, pl. 5).

This is definitely a process in which the melting temperature of the steel product is reached: the contents of the crucible are stirred with a rod, and the product is a 'button' (*culot*) of steel from each crucible. It takes quite a long time, 5–6 hours, to reach the temperature at which the cast iron melts, but then things happen quickly. The wrought iron and cast iron fuse as the temperature continues to rise, and the resulting steel melts. The very long cooling time, three days, results in a microstructure with fine cementite globules at grain boundaries which is necessary for the production of some of the types of pattern found on Damascus swords.[88]

The addition of silver to the crucible charge is curious. It is unlikely to have improved the quality of the steel;[89] if it had any function at all, this was perhaps in quality control. Silver does not alloy with iron, and in Massalski's description of the technique the silver is found adhering to the steel button. Its physical appearance would no doubt have told an experienced craftsman a good deal about the course of temperatures through which the button had passed.

[88] See e.g. C. S. Smith (1988, pp. 14–24); Piaskowski (1978; 2001); Verhoeven (1987); Craddock (1998, p. 13).
[89] See e.g. Percy (1864, pp. 175–7).

(iv) What was *Bin* Iron – Persian Steel, Indian Steel, Watered Steel?

Among the exports of Western nations to China listed in sources of the +6th and +7th centuries is a product called '*bin* iron 鑌鐵'.[90] The identifiable items in these lists are virtually all luxury raw materials rather than finished products, and clearly *bin* iron must be some highly esteemed type of iron or steel. It comes from two places, Bosi 波斯, i.e. Persia, and Cao 漕, which is identified as Jaguda, the modern province of Ghaznī in central Afghanistan.[91] *Bin* is undoubtedly a transcription of some non-Chinese word, but scholars have considered this word unidentifiable. Berthold Laufer, in his learned *Sino-Iranica* of 1919, notes ironically that 'even the Pan-Turks have not discovered it in Turkish'.[92] I was therefore surprised, upon consulting experts, to find that there are two quite plausible candidates, one in Sanskrit and one in Persian. These will be discussed further below.

Reports of the origins of distant imports are always subject to some suspicion, for they often give the nationality of middlemen rather than the actual producers. Arabic and Persian sources from the +5th century onward indicate that India and Sri Lanka produced fine steel,[93] and it is quite possible that the *bin* iron of the earliest Chinese sources was not produced in Persia and Jaguda, but carried to China from southern Asia by merchants of these places. On the other hand we have just seen that high-carbon steel was being produced in the eastern Iranian regions from about the +10th century at the latest, and continued into modern times.[94] The Chinese reports may therefore support the rather skimpy evidence available for steel production here in earlier, pre-Islamic times.[95]

[90] *Wei shu*, ch. 102, p. 2270; *Zhou shu*, ch. 50, p. 920; *Bei shi*, ch. 97, pp. 3222, 3239; *Sui shu*, ch. 83, p. 1857 (twice). There seems to be a general scholarly consensus that the *Zhou shu* account, completed in +635 but based on earlier sources, comes closest to being a primary source. The *Wei shu* was completed in +554, but there is good evidence that the relevant parts of this book were at some time lost and were later restored from the corresponding parts of one or more of the other dynastic histories. Miller (1959, pp. 47–51); Ware (1932, esp. p. 45); Maenchen-Helfen (1945, pp. 225–31); Pulleyblank (1952, pp. 320–2, fn.; 1960).

[91] Feng Chengjun and Lu Junling (1980, p. 37). They note that the *Bei shi* and *Sui shu* accounts incorrectly identify Cao with the state of Jibin 罽賓 of the Han and Wei periods, which is generally identified as Kashmir (Pelliot, 1959–73, p. 242; but note that Chavannes (1903, p. 52, fn. 1) identifies it as the province of Kāpisā in Afghanistan). It is not impossible that this place-name is the source of the term '*bin* iron', but there seem to be no early Chinese sources which connect Kashmir with the production of any ferrous materials. The *Han shu* (ch. 96A, p. 3885), in its description of Jibin, states specifically that it produces gold, silver, copper, and tin, and makes implements of these, but it does not mention any other metal (note also Eberhard, 1941, pp. 226–7, 237). Laufer (1919, p. 515; note also p. 379, fn. 6) notes that the *Tai ping huan yu ji* (ch. 182, p. 15a) (completed +981) mentions *bin* iron from Kashmir, but this mention is in fact in a direct quotation from the *Sui shu* account of Cao.

[92] Laufer (1919, pp. 515–16). He does suggest some possible connections: 'Iranian **spaina*, Pamir languages *spin*, Afghan *ōspinā* or *ōspana*, Ossetic *äfsän*'. Cf. Pelliot in Bagchi (1929–37, vol. 1, pp. 49, 280–1); Pelliot (1959–73, pp. 41–2).

[93] Bronson (1986, pp. 19–21); Juleff (1990; 1998); Allan and Gilmour (2000, pp. 47–50, 113–22); Rehren and Papachristou (2003). Hanneder (2005) reviews the textual and archaeological evidence on ancient Indian iron and steel.

[94] Pp. 264–7 above.

[95] Allan and Gilmour (2000, pp. 46–7).

A very curious fact is that, after these reports of the early +7th century, *bin* iron virtually disappears from the Chinese sources for several centuries. The dynastic histories of the Tang and Five Dynasties periods include accounts of Persia and other Western nations, and sometimes list their exports, but never mention any ferrous products.[96]

From about the beginning of the +10th century to at least the 17th there are numerous mentions of *bin* iron in Chinese texts, written with either of the characters 鑌 or 賓. Some sources include it in lists of the products of places to the west of China.[97] There is also a report from the 12th century that *bin* iron was produced within the Chinese Empire, in Yunnei Prefecture 雲內州, near modern Hohhot, Inner Mongolia.[98]

In 1259 an embassy was sent by the Yuan to Hülegü, the Mongol conqueror of Iraq and Persia. An account of that mission by Liu Yu 劉郁 notes that the land of Yindu 印毒, i.e. India,[99] produces *bin* iron.[100] Since the mission never came near India, this information no doubt came from merchants encountered along the way. It would seem to be the only real evidence we have that India produced *bin* iron.

Perhaps from the early +10th century is a quotation by Li Shizhen 李時珍 in the 17th century from a now-lost book entitled *Xuan yuan shu Bao zang lun* 軒轅述寶藏論 (The Yellow Emperor's discourse on the hidden treasures [of the earth]).[101] After some remarks about the places where iron is produced in China, Li Shizhen writes:

> *Bin* iron, which is produced by the Western Barbarians [Xi Fan 西番], is especially fine. The *Bao zang lun* states: 'There are five kinds of iron . . . [The first two come from Hubei and Jiangxi.] *Bin* iron is produced in Persia [Bosi 波斯]; it is so hard and sharp that it can cut gold and jade . . . [The last two kinds come from Shanxi and the Southwest.]

There are many more mentions of *bin* iron in contexts which indicate that it was a steel considered to be of extremely high quality.[102] An example is the story of a colourful incident of +895 in which a general declaims that if rebels arise they will have to nick (*chi* 齒) his sword of *bin* iron – apparently something very difficult to do.[103]

[96] *Jiu Tang shu*, ch. 198, esp. pp. 5297, 5305, 5312; *Xin Tang shu*, ch. 221A–B, esp. pp. 6219, 6224, 6230, 6236, 6241, 6244, 6248, 6249, 6255, 6256, 6258; *Jiu Wu dai shi*, chs. 137–8, esp. pp. 1841, 1842, 1843; *Xin Wu dai shi*, chs. 72–4, esp. pp. 907, 911, 915, 916, 917, 919, 921, 922. Note also Eberhard (1941).

[97] E.g. *SS*, ch. 490, pp. 14111, 14115, 14119; *Ming shi*, ch. 332, p. 8620.

[98] *Jin shi*, ch. 24, p. 569.

[99] In this context *Yindu* presumably transcribes the Persian *Hindūstān*, which corresponds roughly to modern India (Yule and Burnell, 1903, p. 416); but note Bretschneider (1937, vol. 1, p. 155). A more common, but equivalent, Chinese transcription is *Yindu* 印度 (Feng Chengjun and Lu Junling, 1980, pp. 35).

[100] *Xi shi ji*, p. 11b; tr. Bretschneider (1937, vol. 1, p. 146).

[101] *Ben cao gang mu*, ch. 8, pp. 48, 609. The full title of the book quoted is given in ch. 1, p. 25; perhaps it was a Taoist complement to the Buddhist *Bao zang lun*, attributed to Sengzhao 僧肇 in the +4th or +5th century. The date of the book is given as the +10th century by Laufer (1919, p. 515), and by Needham (1980a, p. 538) specifically as +918, but neither gives the reasoning behind his proposed date.

[102] E.g. *Jin shi*, ch. 2, p. 26; ch. 43, p. 985; ch. 87, pp. 1933, 1936; *Jin shui qiao Chen Lin bao zhuang he za ju*, p. 1; *Yuan shi*, ch. 9, p. 192; ch. 78, p. 1952; ch. 120, p. 2956; ch. 203, p. 4546; *Ming shi*, ch. 247, p. 6396; ch. 332, p. 8598; *Qing shi gao*, ch. 244, p. 9612.

[103] *Xin Wu dai shi*, ch. 63, p. 786. The story seems not to be known from other histories, and it cannot be assumed to come from a source as early as +895. The *Xin Wu dai shi* was completed in +1072.

An 'Office for *bin* iron' (*Bin tie ju* 鑌鐵局), established by the Yuan dynasty in +1275, administered 'the artisans in steel and iron' (*lou tie gong* 鏤鐵工).[104] Nothing more appears to be known about this office, but its name probably reflects the idea that *bin* iron was an especially excellent steel, signalling that the office is concerned with an elite among the smiths.

In the +6th century *bin* iron appears to have been a type of fine steel, imported as a raw material rather than in finished products. One possible identification of the original word behind *bin* is Sanskrit *píṇḍa*, which some Sanskrit lexica define as 'steel', though this meaning is not attested in texts.[105] The usual, well-attested, meaning is 'a lump' (usually of food), and this recalls the fact that several Chinese terms for varieties of steel include characters that mean 'lump'.[106] *Bin tie*, which I have been translating as '*bin* iron', could easily be a transcription of *píṇḍa*, with the Chinese character for the second syllable chosen not only for its sound, but also because it means 'iron'.[107] This would also explain the odd fact that an especially admired type of *steel* was called *iron*.

There is also a chance that *bin tie* transcribes a Persian or Arabic word meaning 'Indian steel'. Marco Polo in the 13th century states that *ondanique* (*andaine*, *andanicum*), apparently a type of steel, is produced in the Kingdom of Kerman (the province of Kerman in modern Iran). Henry Yule, in a long footnote, identifies this as Persian *hundwáníy*, 'Indian steel', which shows up in Arabic sources as e.g. *hindia*, *hint*, or *al-hint*.[108] Both *bin tie* and *píṇḍa*, could be transcriptions, in one of the region's languages, of a form like *hindia*. Or *hindia* could be a transcription of *píṇḍa*.

'Lump steel' or 'Indian steel' might have been what today is generally called *wootz*, which was produced by cementation of wrought iron in small crucibles at very high temperatures.[109] Or it might have been produced directly from ore in specialised furnaces like those recently excavated by Gillian Juleff in Sri Lanka.[110]

. . .

[104] *Yuan shi*, ch. 85, p. 2145; note also p. 2146.

[105] Monier-Williams (1899, p. 625). I am grateful to Kenneth Zysk, Stefan Baums, and Srinivasan Kalyanaraman for advice on this matter.

[106] Pp. 256 above and 321, 324, 341–2, 346 below.

[107] The pronunciation of *bin tie* 鑌鐵 at this time would have been something like *pi̯ĕn t'iet* or *pjin tʰɛt* (resp. *GSR* 389a, 1256b; Pulleyblank, 1991, pp. 38, 308). A Sanskrit–Chinese dictionary of the +8th century, *Fan yu za ming* (Bagchi, 1929–37, vol. 1, p. 49), gives for *bin tie* the Sanskrit equivalent *piṇa* in the Sanskrit script known as *siddham*. Pelliot (in Bagchi, 1929, pp. 280–1; Pelliot, 1959–73, vol. 1, pp. 41–2) notes that this word is not otherwise known in Sanskrit or Prakrit, so that we cannot determine whether it transcribes *bin tie*, or *bin tie* transcribes it, or both transcribe a word in some other language. The dictionary gives the pronunciation of the Sanskrit as 比拏 (*pji: ńa* or *pji' nraɨ*; *GSR* 566g, 94b; Pulleyblank, 1991, pp. 33, 221). If my suggestion that *bin tie* transcribes *piṇḍa* or *hindia* is correct, we should expect a *t* or *d* somewhere after the *n* in *piṇa*. It is therefore interesting (though perplexing) that the Japanese edition of 1732 gives the Japanese pronunciation *hida* rather than the expected *hina* for 比拏.

[108] Yule (1903, pp. 92–6).

[109] See e.g. Bronson (1986).

[110] Juleff (1998).

It is natural to suppose that the disappearance of *bin* iron from the Chinese sources in the +7th century is related to the Islamic conquest of Persia. Its reappearance in the +10th century would seem to reflect the rise of Arabic trade with China by land and sea. However we should also remember that it is precisely from this time that we have the first firm evidence of steel production in the eastern Iranian region. Steel was produced at Merv by co-fusion, which is a Chinese technique, but other techniques may also have been used in the region.

From the +10th century onward *bin* iron is well known in China, but now the term seems to mean no more than 'especially fine imported steel' (and it is not always imported), with no specific technical or geographic implication.

Of all the sources on *bin* iron from all the centuries there seems to be only one which gives any specific information about this type of steel. Cao Zhao's *Ge gu yao lun* 格古要論 ('The essential criteria of antiquities', a handbook for connoisseurs published in 1368) has:[111]

Bin iron: It is produced by the Western Barbarians. Some [types] have a spiral self-patterning, while others have a sesame-seed or snowflake patterning. When a knife or sword is wiped clean and treated with 'gold thread' alum,[112] [the pattern] appears. Its value is greater than silver.

An ancient saying holds that 'knowing the strength of iron is like knowing gold' [i.e., the ability to judge the properties of steel is as valuable as the ability to assay the purity of gold]. Forgeries have a black patterning. One should examine [a steel object] very carefully.

There are three rules for knives. The first is that in the blade there should be perfect control of fire, metal, and water [i.e., the blade should be correctly quench-hardened and tempered].[113] The second is that the haft should be of *xichi* wood from the Western Barbarians,[114] and the third is that the sheath should be of Tatar birchbark.

I once had a pair of scissors of *bin* iron, of exquisite workmanship. It had a raised gilt pattern on the inside, and on the outside a silver-inlaid inscription in Islamic characters.

The first paragraph may well be the earliest extant description in any language of the famous 'watered steel' blades of Persia (sometimes called 'Damascus' or 'damascened' steel).[115] The pattern was produced by etching the finished blade to reveal the microstructure of pearlite and finely divided spherulitic cementite characteristic of *wootz* and other crucible steels which are allowed to cool very

[111] *Ge gu yao lun*, ch. 2, p. 36b; cf. David (1971, p. 137, 152); Needham (1980a, p. 538). The expanded version by Wang Zuo, *Xin zeng Ge gu yao lun*, ch. 6, pp. 14b–15a, has essentially the same text, with a few variants, none significant.

[112] *Jin si fan* 金絲礬, unidentifiable. The medieval European book of recipes *Mappae Clavicula* (late +8th to early +9th century) also mentions the use of alum for etching iron. Smith and Hawthorne (1974, p. 49).

[113] See pp. 136–7 above. Here I follow David (1971, p. 137, fn. 3) in taking *da* 大, 'great', as a scribal error for *huo* 火, 'fire', in the phrase, *da jin shui zong guan* 大金水總管.

[114] *Xichi mu* 鸂鶒木 (the second character has several variants) is a finely patterned wood native to Guangdong and Hainan, used for furniture (Mao Xingjie, 1991). Presumably Cao Zhao refers here to some similar wood imported from the Western Regions. A sword with blade of *bin* iron and haft of *xichi* wood plays a part in a Yuan-period drama, *Jin shui qiao Chen Lin Bao zhuang he za ju* 金水橋陳琳抱粧盒雜據 (e.g. p. 1).

[115] Compare the photographs of Persian watered steel blades given by Allan and Gilmour (2000, pp. 201–5, figs. 27b, 28, 29b).

slowly from the liquid state.[116] I know of no explanation for the 'black patterning' of 'forgeries'.

The scissors of the last paragraph are directly comparable with the exquisite Persian scissors of the 18th and 19th centuries in the Tavoli Collection, described and illustrated by Allan and Gilmour.[117] But Cao Zhao's scissors are unlikely to have been of watered steel, for as far as is known this patterning technique was used only for swords and knives.

(v) 'Hundredfold Refined Steel'

A traditional Chinese saying is *bai lian cheng gang* 百煉成鋼, which may be rendered, 'it takes a hundred refinings to turn iron into steel'; it is in the school of hard knocks that a boy becomes a man.[118] In earlier times this 'hundredfold refining' is found in poetry in references to steel of very high quality. The poet Liu Kun 劉琨 (+271–318), for example, lamenting the fall of the Western Jin Dynasty in +316, wrote,[119]

> Unexpectedly, steel of a hundred refinings
> Softened and could be wound round a finger.
>
> 何意百鍊剛 化為繞指柔

The poets who use this word *lian* (written with any of several characters: 湅、漱、煉、鍊、練) provide no clue as to what it might mean as a technical term, and it is usually translated with such vague words as 'refine' or 'temper'.[120] If we had only the literary references to judge by, it would not seem necessary to take this idea of 'a hundred refinings' seriously as a technical term. It becomes very interesting, however, when we see the artefacts in Figures 114, 115, and 116. These are three scribe's-knives, a ring-pommelled sabre, and a sword, with inlaid inscriptions which give dates in the +1st and +2nd centuries (+104, +112, and +77) and indicate that they are 'thirtyfold refined' or 'fiftyfold refined' using this same word *lian*. A sword unearthed in Nara Prefecture, Japan, has an inscription indicating that it was made by 'hundredfold refining' in China in the Zhongping 中平 period, +184–189.[121]

[116] This is as far as I dare to go in discussing watered steel; it is a subject of great complexity and some controversy. See e.g. C. S. Smith (1988, pp. 14–24); Verhoeven (1987); Piaskowski (1978; 2001); Allan (1979, pp. 76–82); Allan and Gilmour (2000, pp. 76–9, 201–7).

Note that 'watering' is quite distinct from 'pattern-welding', in which etching brings out a different kind of pattern, formed by forge-welding irons of different compositions. On this see p. 324 below.

[117] Allan and Gilmour (2000, pp. 351–6).

[118] Note for example the novel with this title by Ai Wu (1958), translated as *Steeled and tempered*, Ai Wu (1961). It gives a vivid impression of life among Chinese industrial workers in the Great Leap Forward period.

[119] *Chong zeng Lu Chen* 重贈盧諶, *WX*, ch. 25, p. 1176; *Jin shu*, ch. 62, p. 1686; von Zach (1958, p. 417). He Tangkun (1985) gives many more examples.

[120] See p. 322.

[121] Umehara Sueji (1962); cf. Han Rubin and Ke Jun (1984, p. 316); He Tangkun (1985, p. 123). The inscription is transcribed by Umehara Sueji as: 中平口年・五月丙午・造作支刀・百練清剛・上應星宿・下辟不祥・ 'Sword made on a *bingwu* day of the fifth month of the . . . [year] of Zhongping [+184–189]. The steel was purified by hundredfold refining . . .' The tomb in which the sword was found is described briefly in English by Okauchi Mitsuzane (1986, p. 142).

Figure 114 Sketches of three scribe's-knives with gold-inlaid inscriptions (Luo Zhenyu, 1931, ch. 15, pp. 11a–12a). Dimensions not given; probably about 20 cm long. Each of the inscriptions is partially illegible. Luo Zhenyu reconstructs the first by reference to the others as follows:

永元十六年廣漢郡工官卅練書刀工口造護工卒史成長荆守承熹主

'Sixteenth year of Yongyuan [+104], Guanghan Commandery Office of Artisans. Thirtyfold refined scribe's-knife, made by the artisan . . . [name illegible] under the direction of Cheng, clerk commissioner over artisans; Jing, office chief; and Xi, assistant administrator.'

(For the administrative titles in this inscription see Yu Weichao and Li Jiahao, 1975, pp. 346–7; Song Zhimin, 1979, p. 460; Chen Zhi, 1979a, p. 144; note also Chen Zhi, 1980, p. 136; Li Guangjun, 1987, pp. 35–6; Bielenstein, 1980, pp. 95, 99).

Several other relevant artefacts are known from Japan. The inscription on a very strange 'hundredfold refined seven-branched sword' dates it to +369 using a Chinese reign-name, and it was presumably made in China (or perhaps Korea). It seems from the inscription to have been a gift from a king of Paekche in Korea to a king of Japan.[122] Found in two large tumuli of the Kofun period are the 'eightyfold refined' Eta-Funayama 江田 船山 sword, dated +5th century, and the 'hundredfold refined' Sakitama-Inariyama 埼玉稲荷山 sword, dated +471 or possibly +531.[123] The latter two swords were made by Japanese rather than Chinese smiths, and all three are much later than the swords and knives mentioned above, which are dated

[122] Anon. (1968a, p. 130, pl. 6); Sasaki Minoru (1982, p. 179). The *Nihongi* 日本紀 (Chronicles of Japan, compiled +720) mentions a gift from the king of Paekche of a 'seven-branched sword', using the same characters, *shichishi-tō* 七支刀), seen in the inscription (Aston, 1896, vol. 1, p. 251). According to the uncorrected chronology of the *Nihongi* this event took place in +252, but it is now known that the section in question is chronologically displaced by exactly two 60-year cycles; this gives +372 as the date of the gift, three years after the date inscribed on the artefact.

[123] Anazawa Wakou and Manome Jun'ichi (1986); note also Murata and Sasaki (1984); Anon. (1985f).

Figure 115 Thirtyfold refined ring-pommelled sabre from Cangshan 蒼山, Shandong (reproduced from Chen Zijing and Liu Xinjian, 1974, pl. 5.1–3). Length 111.5 cm, breadth 3 cm, thickness 1 cm. **1**. Full view. **2**. Inscription. **3**. Magnified inscription:

永初六年五月丙午造卅湅大刀吉羊宜子孫

'Thirtyfold refined large knife [i.e. sabre] made on a *bingwu* day in the fifth month of the sixth year of Yongchu [16 June, +112]. Auspicious, suitable for sons and grandsons.'

(The last three characters of the inscription are hidden by corrosion products, and were revealed by X-ray examination; see Li Zhong, 1975, p. 14; Han Rubin and Ke Jun, 1984, p. 317.)

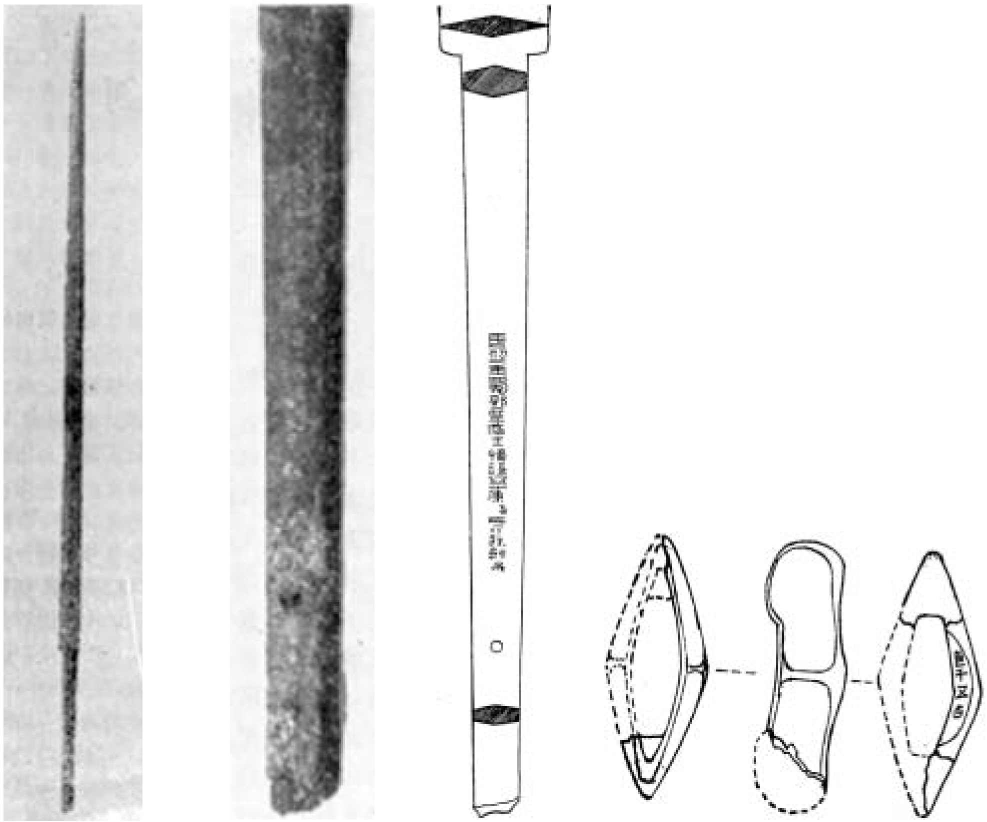
between +77 and +189. Therefore it is probably best to leave them out of account in the present discussion.[124]

Metallographic work by Han Rubin and Ke Jun[125] has yielded a suggestion as to what this *lian* might mean. They examined samples cut from two artefacts, the 'thirtyfold refined' sabre and 'fiftyfold refined' sword of Figures 115 and 116.[126]

124 Sun Ji (1990, pp. 75–7).

125 Han Rubin and Ke Jun (1984); cf. Li Zhong (1975, pp. 13–16).

126 It is necessary to warn the reader against three very misleading English abstracts of this work: Rostoker et al. (1985, p. 100); Ke Jun (1986, pp. A49–A51); and Han Rubin et al. (1986, pp. 15–16). The last is especially unfortunate: my guess is that an editor 'improved' the English of Dr Han's original manuscript, producing for example the statement that the sword of Figure 116 is composed of 'about 40 alternate layers of medium carbon and low carbon steel, each about 1.5 mm thick'. Thus the sword is 6 cm thick! This may be compared with the correct translation in Wagner (1993, pp. 469–70).



1 **2** **3** **4**

Figure 116 Fiftyfold refined sword from Pankuang in Tongshan County, Jiangsu 銅山潘壙 (Wang Kai, 1979, p. 52; note also Li Guohua, 1988). Total length 109 cm; blade length 88.5 cm, breadth 1.1–3.1 cm, spine thickness 0.3–0.8 cm; haft length 20.5 cm, breadth 1.2–1.7 cm, thickness 0.6–0.9 cm. **1**. Sword. **2–3**. Haft, showing the inscription:

建初二年蜀郡西工官王愔造五十湅□□□孫劍□,

'Sword . . . fiftyfold refined, made in the second year of Jianchu [+77] by Wang Yin of the Western Office of Works of Shu Commandery . . . grandsons.'

4. Bronze guard, showing the inscription: 直千五百 , 'Valued at fifteen hundred.'

The two artefacts show a definite layering in their microstructures, with about 30 and about 60 layers respectively through the thickness. In the sabre of Figure 115 the structure is virtually uniform, and the layering can be detected only through patterns in the distribution of slag inclusions.

The cross-section of the sword is composed of three regions: a central region, about 2 mm thick, and two side regions, each about 1.5 mm thick. The side regions are composed of layers of lower- and higher-carbon steel, and appear to be mirror images of each other, while the central region is uniformly about 0.7–0.8 per cent carbon.

The sword could have been made as follows. A core, destined to become the cutting edge, was made of 0.7–0.8 per cent carbon steel. An outer wrapper was made by laminating two steels with different carbon contents. The wrapper was folded over the core and forge-welded. The sword was then fashioned by further heating and hammering of this laminate. Curiously, the edge of the finished sword was not finally quench-hardened.

Both the core and the wrapper were made by repeated folding and forge-welding to give the observed layered structure. Han Rubin and Ke Jun suggest that it was this folding and welding that was called 'refining', *lian*, and that the number prefixed to this word indicates the resulting number of layers. The 'thirtyfold refined' sword (Figure 115) is composed of about 30 layers and the 'fiftyfold refined' sword (Figure 116) about 60. In each of these cases the number of layers is difficult to count, but the inscription need not in any case be taken as giving an exact figure. In the case of the 'fiftyfold refined' sword we may imagine the following sequence. (1) A bar of steel is folded, welded, and hammered out four times, giving the core with 16 layers. (2) Bars of higher- and lower-carbon steel are welded together and hammered out. (3) The resulting bar is folded, welded, and hammered out three times, giving the wrapper with 16 layers. (4) The wrapper is folded over the core and welded, giving a bar with $3 \times 16 = 48$ layers. (5) The sword is made by hammering out this bar.

The authors are at pains to make clear that this interpretation of the numbers of 'refinings' is a hypothesis which will require much more work to confirm or refute. But it is certainly attractive. The inscriptions and the texts suggest that the given number is a count of something concrete, and that this number directly reflects the amount of work done on the iron as well as its resulting quality.

In 19th-century England this process of folding and reworking was known as 'piling', and such grades as 'best', 'best best', 'treble best', etc. reflected, among other factors, the number of times the iron was piled.[127] This is an essential treatment for any iron which contains slag inclusions. Each piling breaks up, elongates, and redistributes the slag inclusions in the iron and thereby improves its strength and ductility. Smiths have always known this, but it became the object of intense study in the 19th century, when the use of wrought iron for such products as rifle barrels, bridges, and ship hulls made increased demands on the strength and ductility of the iron; and also made failures both more catastrophic and more visible. Thomas Turner quoted figures to show that each piling up to about six continues to improve the tensile strength of the iron, but that only the first three give a sufficient improvement to be worth the added expense.[128] Unfortunately it is likely that most of the tests on which Turner based this conclusion suffered from poor experimental design and/or a lack of understanding of the distinction between strength and ductility.[129] The first modern studies of the influence of slag-inclusion form on the

[127] Gale (1979, p. 45–51); Percy (1864, pp. 720–1); Hall (1928, p. 41); but note the sceptical remarks of Thomas Turner (1895, pp. 328–9) on these terms; also Belford (2004).
[128] Scoffern et al. (1857, p. 318); Turner (1895, p. 328).
[129] See Gordon (1988, esp. pp. 110–18, 131–4).

mechanical properties of historical wrought iron are those of Robert B. Gordon.[130] Comparison of the slag-inclusion morphology of the two swords studied by Han Rubin and Ke Jun with the micrographs in Gordon's article indicates that they have an excellent structure which could only have been achieved by repeated folding and reworking.[131]

Further confirmation of this interpretation of *lian* was later provided by Sun Ji.[132] He pointed out a very unusual character, *lian* 湅, obviously related to the *lian* we are discussing here, which seems to occur only once in all of China's literature, in the Han dictionary *Shuo wen jie zi* (+100). Here the character is defined with the words *pi lian tie yeh* 辟湅鐵也. It seems that this definition can be translated, 'to pile up and "refine" iron', for the character *pi* 辟 is found in connection with the making of swords in several poetic texts of the Six Dynasties period, and the Tang commentator Li Shan 李善 (ca. +630–689) explains it as meaning, 'to pile up' (*pi wei die zhi* 辟謂疊之).[133]

130 Gordon (1988).

131 A different interpretation of the term *lian* is given by Rostoker et al. (1985), based on the microstructure of a sword in the Field Museum in Chicago. It is very similar to the sabre shown in Figure 115, and is 100 cm long. All that is known of its provenance is that it was acquired by Berthold Laufer in Henan in 1923. 'Style, dimensions, microstructure and hardness all suggest that the Field Museum's sword would have been given a quality designation of the form ". . . refined". That it lacks an appropriate gold foil label may well be because the label fell off when corrosion of the sword blade's metal penetrated deeply beneath it' (Rostoker et al., 1985, p. 103). In style and dimensions the Field Museum sabre is only one of hundreds of similar sabres from the Han and after (Wagner, 1993, pp. 191–9; Trousdale, 1975). Arguing as here on the basis of microstructure prejudges the issue, which is what '. . . refined' actually means; but furthermore the authors themselves show that in several respects the microstructure of the sabre is different from those of the two artefacts discussed above, which are known by their inscriptions to have been classified as '*n*-fold refined'. The speculation concerning a 'gold foil label' is mysterious; to my knowledge nothing which could reasonably be denoted by this term is known in Chinese archaeology from any period. See also Wagner (1993, pp. 287–8).

132 Sun Ji (1990).

133 Zhang Xie 張協, *Qi ming* 七命, in *WX*, p. 1605. See p. 255 above.

7 TECHNICAL EVOLUTION AND ECONOMIC REVOLUTION IN THE SONG PERIOD

From the late Tang through the Song was a time of fundamental changes in social, political, and economic life in China. As one scholar has put it, the period from +750 to +1000

> marks a watershed in the history of political institutions, in economic organization and in the basic structure of Chinese society. One of the most striking features of this great social transformation is the enormous expansion of trade, and accompanying this the growing complexity of commercial organization, and the emergence of an identifiable urban class with its own sub-culture. These changes were accompanied by an almost equally radical change in official policy towards commercial activity and the merchant community, and a fundamental re-alignment of government financial policy, which mark off the ninth century as the end of an era in economic theory and practice.[1]

The iron industry played a rôle in these changes which we shall investigate here. At the same time progress in siderurgical technology was made on a number of fronts, for example in the use of mineral fuel, in the use of water power, and in methods of steelmaking. Thinkers such as our old friend Shen Gua and others continued to speculate on the complex phenomena of ferrous metallurgy.[2] If much of this development was a continuation of that of earlier times, it was nevertheless in the Song that many earlier beginnings came to fruition.

Studies of the great changes that took place from Tang to Song were first pursued at the beginning of the 20th century by Japanese scholars, especially Naitō Torajirō 內藤虎次郎 and Miyazaki Ichisada.[3] Miyazaki saw the Tang–Song transition as an 'Oriental Renaissance',[4] pointing out parallels between the rise of Neo-Confucianism and the revival of Greek learning, and between the polymaths Shen Gua and Leonardo da Vinci. The newly widespread use of important inventions – printing, the compass, gunpowder – began in the respective Renaissances, East and West.

Naitō was the first to place the beginning of the 'modern' period in China in the Song. As Miyakawa Hisayuki writes, 'Those who doubt the reality of Chinese modernity should try to observe Yuan China through the eyes of Marco Polo and Ming China through the eyes of Matteo Ricci.'[5] *Modernity* is of course a modern term, and tends to be defined idiosyncratically, each writer putting into it those aspects of the modern world which seem important and positive to him or her.[6] I shall avoid using the word here, but emphasise that in fundamental ways China in

[1] Twitchett (1968, p. 63).
[2] See e.g. *SCC*, vol. 2, pp. 266–8; p. 256 above, and 320–4 below.
[3] Miyakawa (1955); Liu and Golas (1969).
[4] Miyazaki Ichisada (1940–41); Miyakawa (1955, pp. 545ff).
[5] On these two travellers see e.g. *SCC*, vol. 1, pp. 141, 148–9.
[6] Cf. Zurndorfer (1997a; 1997b).

+1000 had much more in common with the China of 1900 than it had with the China of +750.

Later work has given less attention to these cross-cultural comparisons and more to the delineation and explanation of the specific social and political changes which occurred in China. Recent Western studies of the Song have embraced the new historiographic direction suggested by the Japanese pioneers, while Chinese historians have tended to be less enthusiastic, preferring to stay with the traditional periodisation by dynasties or to adopt the much broader periodisation proposed by Marx and Engels, in which the Song lies in the middle of the Feudal stage of Chinese history.

The widespread use of printing, and the parallel spread of literacy, in the Song had – of course – profound effects at every level, but a particular effect to be noted is that our historical sources from this period on are incomparably richer than for earlier periods. This makes it possible to look much more closely at the changes taking place. Much of the best Western research on the Song in recent years has looked at individual regions of China, investigating the ways in which the overall changes in Chinese society manifested themselves at the local level.[7]

A 1982 paper by Robert M. Hartwell is a *tour de force* relating the historical trends at the level of the Empire to trends in a sample of fifty localities. His conclusions are worth quoting here:

> During the period between 750 and 1550, there were major changes in the relative positions of the macro-regions of China owing to [1] catastrophes . . . [2] political decisions . . . [3] the improvement of transport and communication facilities . . . and [4] the introduction of novel techniques in agriculture . . . The shift in the comparative advantages of the regions and their combined growth in population and wealth not only brought about changes in the intraregional development process, but also had an aggregate impact on empire-wide political and social structures. The expansion of the densely populated areas of the empire created administrative difficulties leading to a localization of central authority . . . at the same time that the process of bureaucratization of the central government was brought to a halt, if not reversed. These transformations in the economic and political landscape also resulted in the demise of a semi-hereditary professional bureaucratic elite . . . and its replacement during the Sung by a multitude of local elite gentry families.[8]

Years before this, Hartwell, in a Ph.D. dissertation and three articles, had done the first important work on the Song iron industry in the framework of economic history.[9] That work fits into his later work, demonstrating that there was a great growth in iron production in north China in the +11th century, that this was a geographically limited development, and that the industry later declined. These main results of Hartwell's study of the iron industry appear to be solid, but he made other claims which are under dispute. He attempted to calculate precisely the annual production of the Northern Song iron industry, and concluded that in the late +11th century this was 125,000 English tons, i.e. about 115,000 metric tonnes or

[7] Sichuan has been one of the favourite regions for study, for example by Smith (1991).
[8] Hartwell (1982, pp. 425–6); note also Cheng Minsheng (2004).
[9] Hartwell (1962; 1963; 1966; 1967a).

1.2 kg per capita.[10] I have in a separate publication considered the sources and assumptions on which this calculation is based. My conclusion is that the result may perhaps be of the right general order of magnitude, but is expressed in much too precise a form, and not convincingly argued.[11] More problematic is his statement that per capita production never again in Chinese history reached this level; the sources on which the statement is based do not appear to be reliable enough to sustain such a far-reaching conclusion. His work also contains important misunderstandings of technical aspects of iron production; it may be that recognition of these is the reason that he never published his 1963 dissertation.

Hartwell also made a contribution of another kind to the study of the Song iron industry. In the research for his dissertation he performed the heroic task of going through most of the major sources for Song history, page by page, seeking out references to iron and steel. We therefore have in that dissertation a massive collection of references to sources relevant to all aspects of the present study.[12] These, together with a few more sources noted by other scholars or by myself, form the basis of much of what follows.

In approaching this period it is important to keep constantly in mind that it is a time of 'China among equals'.[13] The Song state was never militarily strong, and found it necessary to treat with its neighbours on a basis of equality. These neighbours, in the north the Liao 遼 and later the Jin 金, in the northwest the Xi Xia 西夏, and in the south the Nan Zhao 南詔, were ruled by non-Chinese elites, but their populations were largely Chinese, and the historian must include them in any study of the Chinese world of the time. We shall see in the following that these not-quite-Chinese neighbours provide some useful contrasts to complement a history which of necessity must concentrate on the Song, the Chinese state in which the most important developments (for China and for ferrous metallurgy) occurred.

(i) The Uses of Iron

We may start by looking at some of the ways in which iron was used in this period. More details on these applications will be found in other volumes of *Science and Civilisation in China*; for example agricultural implements are discussed in Section 41d.[14]

Artefacts from some Yuan ships

An interesting sample of iron artefacts of daily use has been provided by the excavation of six 14th-century shipwrecks in Ci County 磁縣, Hebei, in 1976.[15] The

[10] Hartwell (1967a, pp. 104–5, long footnote; 1963, p. 35).
[11] Wagner (2001c).
[12] Note also Hartwell's *Guide to sources of Chinese economic history, A.D. 618–1368* (1964), which includes a different range of sources and a wider range of subjects.
[13] To borrow the title of Rossabi (1983), an excellent introduction to this aspect of Song history.
[14] *SCC*, vol. 6, part 2, pp. 130–378.
[15] Excavation report, Zhu Jinsheng (1978); metallographic examination Anon. (1978g).

ships were excavated in the former bed of the Zhang River 漳河, whose course today is a few kilometres away. Inscriptions on the ships and on some artefacts indicate that they were official grain transport ships which were wrecked in one incident, presumably a storm, not long after 1352.

Thirty-nine iron artefacts from the ships are sketched in Figure 117. What strikes the eye immediately is the sheer variety of objects made of iron. The ship was built using iron spikes and nails (e.g. Figure 117, no. 15),[16] it was provided with a variety of hooks and rings and oarlocks (not illustrated) of iron (nos. 14, 24, 25), a punt-pole was tipped with iron (no. 28), and such fittings as a door handle, a door latch, a lamp holder, and a lamp were likewise of iron (nos. 22, 36, 19, 34). Cooking was apparently done on board, and we find an iron stove grate, cooking pot, and kitchen knives (nos. 5, 4, 6, 11). For fishing, two net-weights were found, one of iron (no. 1) and one of bronze. Perhaps the fork-head (no. 30) was also used in fishing.

Iron artefacts related to the ships' official function include a steelyard weight (no. 2), several padlocks and keys (nos. 12, 16, 20), and a single weapon, a sabre (no. 10).

Quite a few carpenter's tools were found, including an ink-box (used for laying down straight lines with an inked string), a glue-pot, an axehead, a chisel, and a drill (nos. 13, 7, 3, 26, 37). Agricultural implements include a mattock-head, a scythe-blade, a sickle-head, a spade-head, and a hoe-head (not illustrated) (nos. 8, 17, 23, 29).

Some agricultural implements

An article by Su Tianjun brings together a large number of iron agricultural implements (as well as some other implement types) of the Liao and Jin periods discovered in the Beijing area.[17] Two of his illustrations are reproduced here in Figures 118 and 119. Besides implements which are well understood there are some which are very curious, for example what appears to be a very long scythe-blade with two chain-links at one end (Figure 118, no. 6 and Figure 119, no. 9). As Su Tianjun notes, the most likely explanation is that it was attached by the chain-links to a long handle and somehow used for the same purposes as a scythe.

We see a few more implements in Figure 120, a mural from a Xi Xia cave temple in Gansu.

A blacksmith's story

A story written by Fan Jun 范浚 in +1127, just after the Jin conquest of north China, tells of a blacksmith whose rise from rags to riches illustrated how times had changed. When Fan Jun first meets him the blacksmith and his family live in a

[16] But as the excavators point out, iron cramps, *guaju* 挂鋦, were not used in the building of these ships, though these were commonly used at least two centuries earlier and are still used in wooden ship-building today. See also Xu Yingfan (1985); Li Zebin (1992, p. 58 + fig. 4, nos. 10, 11, 15, 18).

[17] Su Tianjun (1963).

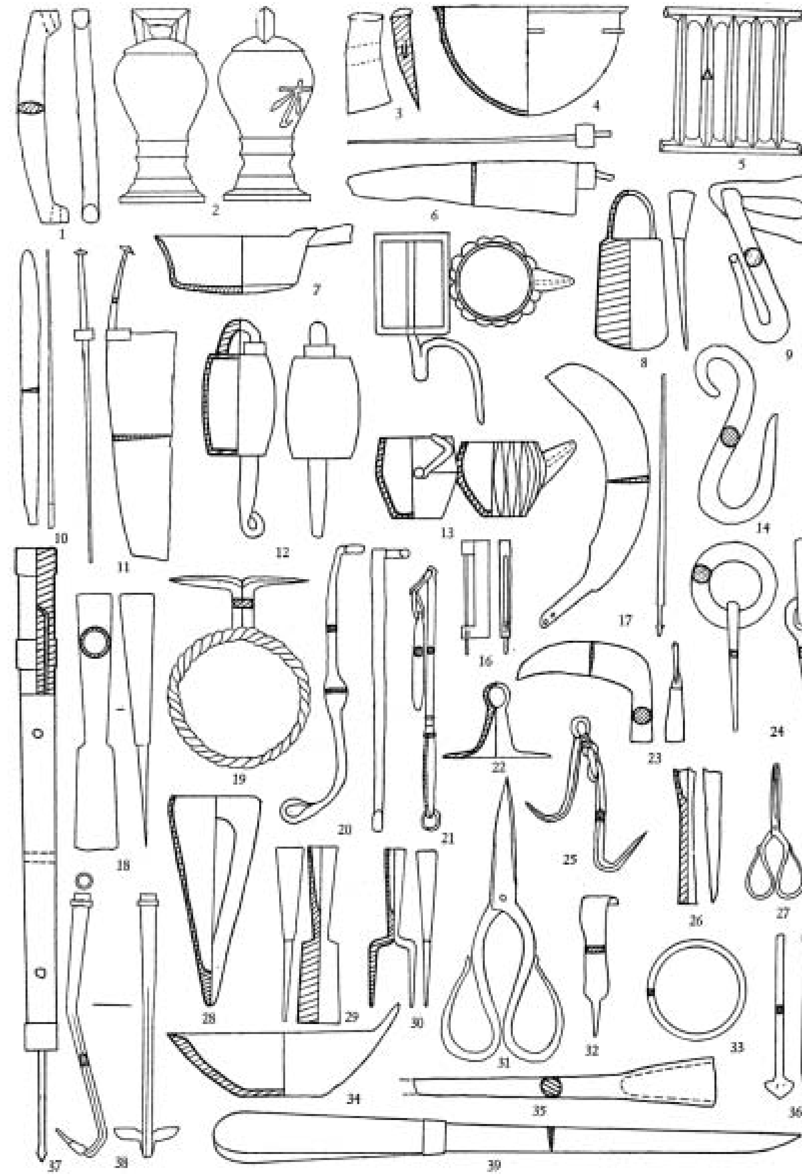


Figure 117 Sketches of iron artefacts from six 14th-century shipwrecks excavated at Nankaihecun in Ci County, Hebei 磁縣南開河村 , reproduced from Zhu Jinsheng (1978, p. 394, fig. 10). **1**. Net-weight (artefact no. 4:15). **2**. Steelyard weight (3:3), weight 700 g (height approx. 11 cm). **3**. Axehead (2:53), length 14 cm, edge 6.5 cm. **4**. Pot (2:55). **5**. Stove grating (2:28). 16 × 16 cm. **6**. Kitchen knife (4:20). Length approx. 37 cm. **7**. Glue-pot (*biao guo* 鰾鍋, 1:62). Length 22 cm, height 7.8 cm. **8**. Mattock-head (4:16), edge 10 cm. **9**. Oarlock (*lu bei* 櫓杯, 2:21). **10**. Sabre (*jian* 劍, 2:29). **11**. Knife (2:52), length 44 cm. **12**. Padlock (1:98), length 12 cm. **13**. Carpenter's ink-box (*mo dou* 墨斗, 1:97). 11.2 × 4.6 cm. **14**. Hook (3:10). **15**. Spike (*chang ding* 長釘, 3:11). **16**. Padlock (2:41), length 12 cm. **17**. Scythe-blade (*shan dao* 芟刀, 5:1), length 37 cm, edge 23 cm. **18**. Spade-head (4:9), length 35 cm, edge

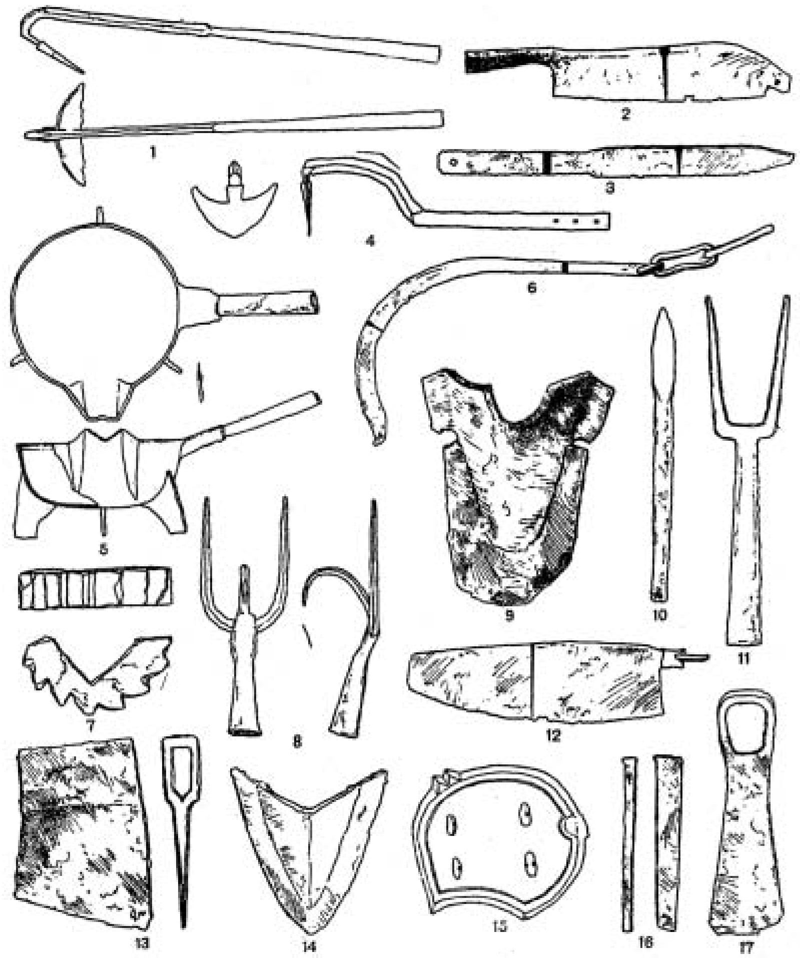


Figure 118 Sketches of iron implements from a hoard of 64 iron artefacts discovered at Jiaozhuangcun 焦莊村 in Fangshan County 房山縣, Beijing, reproduced from Su Tianjun (1963, p. 142, fig. 4). **1**. Hoe, length approx. 65 cm. **2**. Fodder chopper (*zha dao* 鍘刀), length approx. 68 cm. **3**. Long-handled knife, length 45 cm. **4**. Weeding hoe (*yun chu* 耘鋤), length of iron shaft 84.5 cm. **5**. Dipper (*liushao* 流勺), diameter 21 cm. **6**. Articulated scythe-blade, total length 53 cm (cf. Figure 119, no. 9). **7**. Fragment of toothed wheel, largest dimension 6.5 cm. **8**. Fork-head, length approx. 25 cm. **9**. Ploughshare, length 24 cm. **10**. 'Spearhead' (*mao tou* 矛頭), length 31 cm. **11**. Fork-head, length 36.5 cm. **12**. Kitchen knife, length 37 cm. **13**. Axehead, length of edge 7 cm. **14**. Ploughshare, 'length' approx. 14 cm. **15**. Mouldboard, breadth 32 cm. **16**. 'Wedge' (*xie* 楔), length 23 cm. **17**. Pickaxe-head, length 25 cm.

Figure 117 *contd.* 6 cm. **19**. Lamp fixture (*dengzhan jia* 燈盞架, 2:43), height 13 cm. **20**. Key (1:122). **21**. Unidentified (1:372). **22**. Door-handle (*menpu* 門鋪 , 2:56). **23**. Sickle-head (4:21), length 19 cm, edge 16 cm. **24**. Ring (4:19). **25**. Coupling hooks (*guagou* 挂鉤 , 1:101). **26**. Chisel (1:102), length 7.6 cm, breadth of edge 1.1 cm. **27**. Scissors (3:9), length 19 cm. **28**. Punt-pole point (*gao jian* 篙尖 , 3:13), length 11.6 cm. **29**. Spade-head (2:37), length 24.5 cm, edge 6 cm. **30**. Fork-head (2:23), length 22 cm. **31**. Scissors (3:5), length 15.8 cm. **32**. Silver-inlaid object (4:3). **33**. Hoop (*qi gu* 器箍, 2:70). **34**. Lamp (*dengzhan* 燈盞, 2:31), diameter 12.4 cm. **35**. Nail-holder (*song ding qi* 送釘器, 4:23), length 16.6 cm. **36**. Door latch (*shuan* 閂). **37**. Wood-drill (3:7), length 68 cm. **38**. Hoe-head (4:5), length 74 cm, edge 19 cm. **39**. Scraper (3:8), length 32.6 cm, edge 19.8 cm.

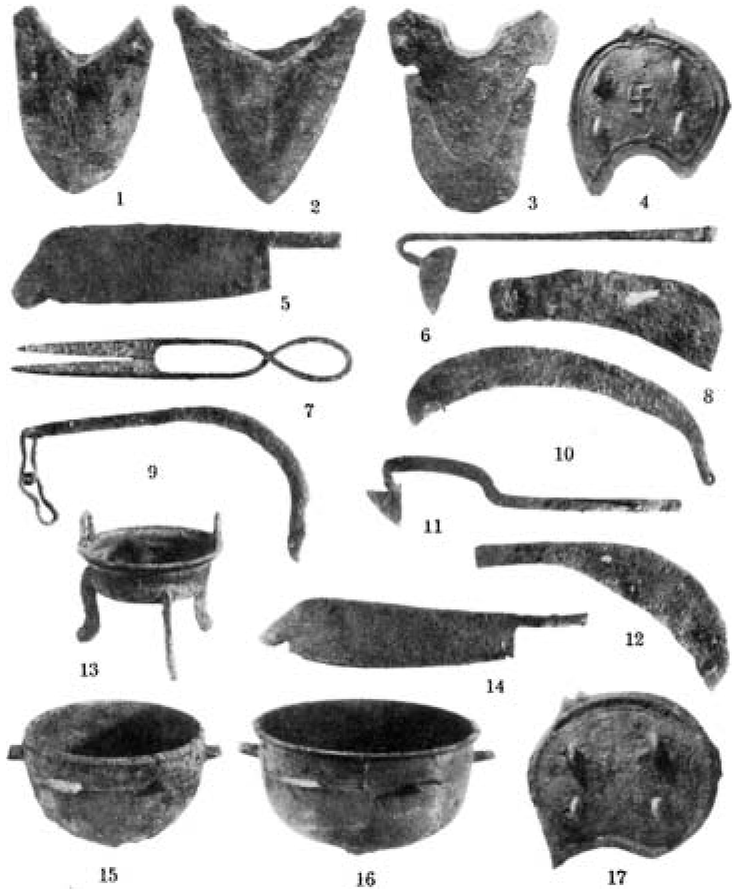


Figure 119 Photographs of iron artefacts from several sites of the Liao and Jin periods in the vicinity of Beijing, reproduced from Su Tianjun (1963, p. 4). **1**. Ploughshare, length approx. 28 cm. **2**. Ploughshare, length approx. 14 cm (cf. Figure 118, no. 14). **3**. Ploughshare, length 24 cm (cf. Figure 118, no. 9). **4**. Mouldboard, breadth 35.5 cm. **5**. Fodder chopper (*zha dao* 鍘刀), length 80 cm. **6**. Hoe, length approx. 65 cm (cf. Figure 118, no. 1). **7**. Shears, length 50 cm. **8**. Sickle-blade, dimensions not given. **9**. Articulated scythe-blade, total length 53 cm (cf. Figure 118, no. 6). **10**. Sickle-blade, dimensions not given. **11**. Weeding hoe (*yun chu* 耘鋤), length of iron shaft 65.1 cm. **12**. Sickle-blade, dimensions not given. **13**. Three-legged pot, diameter 20.5 cm. **14**. Fodder chopper (*zha dao* 鍘刀). **15**. Six-handled pot (*liu pan fu* 六鋬釜), one of three with diameters 33.5, 38, and 41.5 cm. **16**. Six-handled pot (*liu pan fu* 六鋬釜), diameter 33.5 cm. **17**. Mouldboard, breadth 32 cm (cf. Figure 118, no. 15). **Provenances**: Nos. 1, 4, 11: Liao–Jin period habitation site at Dagucun 大固村 in Shunyi County 順義縣, Beijing. No. 16: One of four artefacts unearthed together at Dongmenwai 東門外 in Tong County 通縣, Beijing. Nos. 5, 7, 13, 15: Shangzhuangcun 上莊村 in Huairou County 懷柔縣 , Beijing. Nos. 2, 3, 6, 8, 9, 10, 12, 14, 17: from a hoard of 64 iron artefacts discovered at Jiaozhuangcun 焦莊村 in Fangshan County 房山縣, Beijing.

hovel, they eat coarse vegetables and greens, and the children are dispirited and hungry. Five years later he returns and finds the blacksmith living in a splendid mansion with vermilion doors.

I asked him how it had come about that he had become so wealthy, and he said:

'I am one of the fortunate; perhaps I might tell you about it. When I was poor, and unable to support myself, I depended on charcoal and iron for a livelihood, and for many years there was no trouble. I forged [*duan ye* 鍛冶] nothing but agricultural implements. Then came a

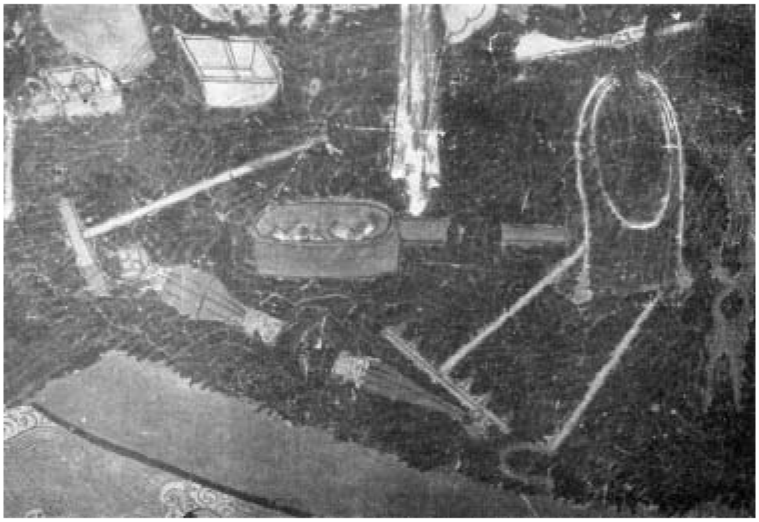


Figure 120 Implements. Detail from a mural in a cave-temple at Yulin 榆林 in Anxi 安西, Gansu (Wang Jingru, 1980, pl. 6.2; note also Shi Jinbo et al., 1988, p. 291, pl. 36). Dated to the period of Xi Xia domination in the area, +1038 to 1227.

series of calamitous years. The peasants, not being able to pay the interest on their loans, abandoned their fields and left to take up branch [non-agricultural] occupations. Cultivators became daily fewer. I made ploughshares, large hoes, weeding hoes, and hoes [*li, yao, bo, chu* 犁、銚、鎛、鋤], but though I expended a whole day's labour on a single implement, I might not sell it for a month and fifteen days; thus it was that I was so poor when I saw you last.

'But then there was military activity under Heaven, and [men with] dagger-axes and halberds filled the roads. Men wished to carry keen-edged [weapons], and families wished to store up sharp-pointed [weapons]. Those who wished to protect themselves with knives, swords, crossbow-bolts, and arrowheads [*dao, jian, zu, di* 刀、劍、鏃、鏑] daily filled my courtyard.

'Day and night I "served the furnace and hammer" without rest. Within a half year I had this house, and after a year I had a great abundance of the means of life. Today I wear both fur and silk; I live comfortably, fill my belly, and have no more anxieties – such is my good fortune.'

After hearing his story I left and said, ill at ease, 'Alas! The smith's good fortune is the misfortune of the common people!'[18]

For our purposes the most important detail of this story is that a writer in the +12th century assumed that agricultural implements were made by a smith. In earlier times, certainly in the Han and before, virtually all agricultural implements were of *cast* iron. Many iron implements known archaeologically from the Song period are cast, but by far the greater part are wrought (see e.g. Figure 117). An exception is ploughshares. Even in relatively modern times the preferred material for these has often been white cast iron, because of its abrasion-resistance.[19] There were however

[18] *Xiang xi ji*, *SKQS* edn, ch. 5, pp. 7b–9a. The version in *Jin hua cong shu* (ch. 5, pp. 6b–7a) has a number of variants which seem clearly to be typographical errors. Cf. the translation of Hartwell (1963, pp. 134–5).

[19] Massari (1938, pp. 217, 233).

cases in which wrought iron was preferred for its toughness: the following is from the Yuan agricultural writer Wang Zhen, in a discussion of land clearance in different kinds of soil.[20]

On wet hills and in areas which have been uncultivated for some time, so that there are many roots and trees [*ke mu* 科木], it is necessary to use a mattock to dig them out. If there remain incompletely cleared roots (these are commonly called 'roots with buried heads'), it is necessary to have wrought iron forged into a ploughshare-point [*chan jian* 鑱尖] (which is fitted onto a discarded cast-iron ploughshare). When this strikes the roots at a right angle it will not break or hinder the work.

Iron coins

The use of cast-iron coins had been known since the Han period, and would continue sporadically until the 19th century (see Plate XXVIII), but the Five Dynasties and the Song were the only periods in which it had much real significance.

The earliest iron coins known from written sources are the 'Iron Office coins' (*tie guan qian* 鐵官錢) issued by the warlord Gongsun Shu 公孫述, who in +24 declared himself King of Shu 蜀 (Sichuan) and in the following year Emperor.[21] Earlier than these, however, are iron coins found in Western Han graves excavated in Shaanxi and Hunan; they have also been found from the Wang Mang period and from the Eastern Han.[22]

Several more attempts to circulate iron coins were made in south China through the centuries: in the kingdoms of Shu 蜀 and Wu 吳 of the Three Kingdoms period, again in +523 (the Liang dynasty), and to a much greater extent in the Five Dynasties period, when both iron and lead were used for coinage in various places throughout the south.[23]

Iron coins have always been considered inferior to copper-alloy coins, and we have here another of those applications in which iron replaces other materials, not because it is superior, but because it is cheaper. The use of iron coins is no doubt a reflection of the increasing commercialisation of the economy in this time. The Song greatly increased production of copper for coins, using both technical and organisational improvements, but copper production was never able to keep up with increasing demand for coins. Iron coins were one substitute, paper money another. Much later the increased use of silver, and later still the Qing colonisation of Yunnan with its rich endowment of copper, tin, and zinc, would provide a

[20] *Wang Zhen Nong shu*, 1777 edn, ch. 2, p. 2a; 1783 edn, ch. 2, p. 2a; 1956 edn, p. 11; cf. *SCC*, vol. 6, part 2, p. 97, where the passage is translated differently. Matter in parentheses translates text in smaller characters. Original text, from the 1777 edition, with variants from the 1783 edition in brackets: 沾 [沿] 山或老荒地內, 科 [樹] 木多者, 必須用钁斸 [劚] 去· 餘有不盡根 [耕] 科, 俗謂之埋頭根也 當使熱 [熟] 鐵鍛 [煅] 成鑱尖, 套於退舊生鐵鑱上 縱遇根株, 不至擘缺, 妨誤工力.

[21] *HHS*, ch. 13, p. 537; Bielenstein (1959, pp. 181ff). The people did not accept the new currency, and it became part of a popular call to restore the Han.

[22] Pei Wenzhong (1959, pp. 222, 226); Gao Zhixi (1963); Hu Cheng (1987); Zhou Weirong (1999b, p. 22). Frick (1998, p. 152) describes one iron coin and one of lead from the Wang Mang period, but suggests that these are *Totengeld*, made for placing in graves rather than actual use.

[23] *Liang shu*, ch. 3, p. 67; *Chen shu*, ch. 19, p. 253; *Nan shi*, chs. 7, 25, pp. 203, 678; *Sui shu*, ch. 24, pp. 689–90; L. S. Yang (1952, p. 27); Qiu Licheng and Li Yifeng (1985).

conservative solution to the problem, allowing a step back from experiments with currency whose monetary value was entirely independent of its intrinsic value.

Various attempts were made in the early Song to bring the economy back to a copper standard, but iron coins continued to be used.[24] It was in Sichuan that their use lasted longest, down to the end of the Southern Song, possibly for another reason as well: it provided a buffer zone to prevent the export of copper coins out of the Empire.[25]

The iron coins generally had the same size and shape as the copper-alloy coins of the time, though in Sichuan some large iron coins, weighing 15 g each, were also cast.[26] The iron coins tended to have a low value per weight; Hartwell calculates that the price of a pound of salt was a pound and a half of iron coins.[27] The inconvenience of this currency in large-scale commerce led to the establishment of proto-banks called *gui fang* 櫃房, 'deposit houses', which kept iron coins on deposit and issued receipts called *jiao zi* 交子, 'exchange medium', which were the ancestors of all paper money; the story has already been told by Tsien Tsuen-hsuin.[28]

Another response to the increased demand for coinage in the Song period was an attempt in about +1035 to adulterate copper coins with iron. A very interesting passage tells the story, and also gives some useful technical details on the subject of coin-casting. The central person is a man named Xu Shen 許申.

In the casting of copper coins, 88 *liang* 兩 [3.3 kg] of alloy [*ji* 劑] are used to produce 1000 coins, weighing 80 *liang* [a loss in casting of 9 per cent]. Dividing the alloy in 10 parts, the copper occupies 6 parts and lead and tin occupy [a total of] 3 parts, each with a small remainder. In the casting of large iron coins, 240 *liang* [9 kg] of iron are used to produce 1000 coins weighing 190 *liang* [a loss in casting of 21 per cent].[29] These are the approximate figures. When Xu Shen was in the State Finance Commission [*san si* 三司] he proposed to 'transform' iron with a 'drug' and alloy copper with it [*yi yao hua tie, yu tong za zhu* 以藥化鐵，與銅雜鑄]. The weight [of alloy] was to follow the rule for copper coins, but with copper

[24] On the monetary history of iron coinage in the Song period see especially Liao Bao-seng (1939–41, 1940, pp. 229–50); Hartwell (1967b); L. S. Yang (1952, pp. 27–9); Eichhorn (1955, pp. 203–5); Peng Xinwei (1994, pp. 332–45); Hino Kaisaburō (1935); Nakajima Satoshi (1936); Chen Guangsheng (1990); Qiu Sida (1983; 1988); Zhu Huo (1990); Hu Fangping (1994); Li Qinglan (1990); Zhang Junxian (1996); Dai Zhiqiang (2000); Miake Shungen (2004, pp. 61–2). Of scores of reports published since the 1980s on particular finds of iron coins, some interesting examples are Zhang Shufan (1988); Yan Jingping (1988); Cheng Xiaozhong (1991); Zhang Fengzhi (2002); Wang Shiguo (2003). Published chemical analyses and metallographic examinations of iron coins include Wayman and Wang (2003); Yan Jingping (1988); Wang Lijun et al. (1999); Zhou Weirong and Li Yanxiang (2000).

[25] A Qing numismatist, Liu Yanting 劉燕庭, is said to have counted 391 distinct types of Song-period iron coin found in Sichuan. Qiu Sida (1983, p. 21).

[26] Hartwell (1967b, p. 287). Possibly relevant here is a huge iron coin of the Northern Song period found in Yu County 禹縣, Henan, which is 15.3 cm in diameter, 0.8 cm thick, and weighs 733 g (Jiao Zhizhong and Hou Zhiyuan, 1980).

[27] Hartwell (1967b, p. 288). Another example is given in *Song shi* (ch. 180, p. 4378): in +991, in Sichuan, a roll of silk gauze (*luo* 羅, a light and airy stuff which would have weighed a few hundred grams) cost 20,000 iron coins. Chen Guangsheng (1990, p. 29) calculates that these would have weighed about 65 kg.

[28] *SCC*, vol. 5, part 1, pp. 96ff.

[29] These losses seem rather high, and we may ask whether the figures take into account the recycling of sprue. Iron coins would probably require a larger casting head to obtain a clean casting than copper coins, making for a larger apparent loss.

occupying 3 parts and iron occupying 6 parts, each with a small remainder, and 1000 coins would still be obtained. This would reduce expenditure and increase profit.

[This proposal] was submitted through the Eunuch Office Manager Yan Wenying 閻文應. The Court accepted it, and Xu Shen was commanded to use his method to cast [coins] in the capital region. However, in general when casting coins, when lead and tin are added, the liquid [metal] flows quickly and [the casting] is easy to complete. When [copper] is alloyed with iron, the flow is impeded, and in many cases [the casting] is not finished [*bu jiu* 不就], causing difficulties for the founders.[30] Originally [Xu] Shen was ordered to cast 10,000 strings [of 1000 coins], but after a month he had produced only 10,000 coins.[31]

I doubt that there is any technical information available on this alloy of iron with about 33 per cent copper (and a few per cent carbon, since cast rather than wrought iron would have been used), but it is certainly plausible that it would be difficult to cast. A certain amount (2–3 per cent) of sulphur in the alloy would have helped,[32] and perhaps 'transforming' the iron with a 'drug' was a way of forming a sulphide of iron, the reagent being either sulphur or one of its compounds.

It is more difficult to imagine what advantages coins of this alloy would have had over ordinary cast-iron coins. Their mechanical properties are unlikely to have been good. Perhaps they had a colour nearer to that of copper, though this seems doubtful. Historically, coins of an alloy of iron and copper with the opposite proportions have been more common: copper with 20–40 per cent iron plus some sulphur.[33] These probably look more like copper, and may have better casting properties, than Xu Shen's alloy. Considering that the text refers consistently to adding iron to copper rather than the reverse, we may well wonder whether the author of the passage above has got the proportions the wrong way round.[34]

A few iron coins of the Song period have a very high tin content, between about 0.3 and 3 per cent.[35] This is surprising, for tin in these or even much smaller amounts makes iron or steel very brittle.[36] In fact the tin was intentionally added, precisely in order to make the iron brittle. According to Ma Duanlin's *Wen xian tong kao*,

[30] The metal does not fill out the details of the mould, resulting in a poor casting.

[31] *XZZTJCB*, ch. 116, pp. 2718–19. Cf. *SS*, chs. 180, 299, pp. 4380, 9928; *Wei tai pu wen ji*, ch. 10, p. 12a; Nakajima Satoshi (1940, p. 422, n. 10). Note also *SCC*, vol. 5, part 13, p. 376, fn. 35.

[32] This seems to be the implication of statements by Gregg and Daniloff (1934, p. 86).

[33] E.g. Sutherland (1955): 'silver' coins, Britain, Late Iron Age, with 55–73% Cu, 7–29% Fe. Hegde (1975): copper coins, India, +7th century, with 21.76–23.21% Fe. Craddock and Meeks (1987): copper bars (*ramo secco*), Italy, –6th to –3rd century, with up to 31.3% Fe. No Chinese examples of *coins* of such alloys are known, but note an ancient ingot (Wagner, 1993, pp. 129–30) and a large Tang statue in the Victoria and Albert Museum, London (Larson, 1988, pp. 121–3). It is interesting that as late as 1906 an attempt was made in Britain to market a copper–iron alloy under the trade name *cuferal* (*Daily Express*, London, 4 January 1906, quoted by Harvie, 1986, p. 11).

[34] In this connection we may also note two curious passages in a +12th-century geographical compendium which appear to state that blacksmiths in Rongzhou 融州 and Wuzhou 梧州 (both in modern Guangxi) make swords and other fine products of an alloy of iron and copper. *Ling wai dai da*, ch. 6, pp. 6a, 7b; cf. Netolitzky (1977, pp. 101, 103); Yoshida Mitsukuni (1972, pp. 360–1).

[35] Zhou Weirong and Li Yanxiang (2000).

[36] Kumar et al. (1996).

The 'tin-alloyed coins' [*jia xi qian* 夾錫錢] originated in the 2nd year [of the Chongning 崇寧 period, +1103], when Hong Zhongfu 洪中孚 reported: 'the "Two Barbarian Enemies" [*er lu* 二虜, the Liao and the Xi Xia] are using iron from Chinese coins to make weapons. If it is alloyed with lead and tin it will be brittle and unusable. I request permission to cast "tin alloyed" [coins], with three to have the value of ten iron coins.' His proposal was approved.[37]

If, as this text suggests, lead was added with the tin, it would probably not have come through the foundry furnace, but ended up in the slag, for molten lead and iron are almost totally immiscible.[38]

A number of metallurgists and historians have been misled by a passage in the *Song shi* to the conclusion that the 'tin-alloyed coins' contained 29 per cent lead and 14 per cent tin, but Zhou Weirong has shown very convincingly, by comparison with parallel passages in other texts, that the author of the *Song shi* passage was confused between two types of coin, one iron, one bronze.[39] Such an alloy, if it could be cast at all, would no doubt have been very brittle, but it would have been an expensive way to foil the coin-smugglers.

Iron monuments

The Tang Emperor Wu-zong 武宗, in the great persecution of Buddhism of +841–845, ordered that all Buddhist statues of iron should be melted down for agricultural implements.[40] In +972 an edict of Tai-zu 太祖, the first Emperor of the Song, forbade the casting of such 'useless things' as iron Buddhas and other human figures.[41] Obviously the casting of iron statues was, at least from the Tang, a common practice, and the number of Song monumental iron castings still extant today indicates that it continued in spite of prohibition.

Monumental iron castings such as statues, bells, and pagodas weighing many tonnes have been produced in China at least since the Tang period. One example is an iron Buddha, 1.8 m high, unearthed in Xi'an, Shaanxi.[42] The magnificent 'iron men' and 'iron oxen' cast in +724 as anchors for the floating bridge over the Yellow River at Pujin 蒲津, in modern Yongji 永濟 County, Shanxi, have long been known from written accounts, and were excavated in the 1980s (see Plate XXXII).[43] Some other early iron statues are known in Korea, for example a seated Vairocana

[37] *WXTK*, ch. 9, p. 96.

[38] Yan Jingping (1988, p. 47) reports semiquantitative analyses of 15 Northern Song iron coins from a hoard found in Baoji, Shaanxi, of which one, from the Chongning period, has 'a few per cent' lead. A surprise is that five of the coins were found to contain large amounts of calcium; this cries out for further investigation.

[39] *SS*, ch. 180, p. 4392. Hua Jueming and Zhao Kuanghua (1986); Zhao Kuanghua et al. (1986); Ye Shichang (1996); Dai Zhiqiang and Zhou Weirong (1998); Zhou Weirong (1999a); Liu Shunqiang (2001).

[40] *Jiu Tang shu*, ch. 18a, p. 605.

[41] *XZZTJCB*, ch. 13, p. 278; Hartwell (1962, p. 156).

[42] Li Gong (2003).

[43] *SCC*, vol. 4, part 1, pp. 40–1; part 3, pp. 160–1; Paludan (1994); Wagner (2000, pp. 199–200); excavation report Fan Wanglin and Li Maolin (1991).

Buddha, 2.51 m high, dated +858, at the Porim-sa 寶林寺 Temple in Chŏllanamdo 全羅南道.[44]

A good example of the art of monumental iron casting in the Song is given by the famous four iron warriors of the Zhongyue Temple 中嶽廟, shown here in Plates XXIX–XXXI. They were cast in +1064. The rectilinear network of 'flash' (impressions of mould-seams) which can be seen in Plate XXX makes it clear that these pieces were cast by the traditional 'piece-mould' method.[45] First an exact full-scale model was made of the intended casting. This was of clay, suitably reinforced with wooden or metal supports. When the model was dry it was plastered to a considerable thickness with moist clay; when this clay had dried to a leather-hard consistency it was cut into blocks which were carefully removed, retaining the impression of the model. These separate blocks were dried and perhaps fired for greater durability. In order to form the mould-core the model was then carefully scraped down, removing a thickness of clay corresponding to the intended thickness of the casting. The previously formed blocks were reassembled around this core to form the 'cope' (the outer mould). This was reinforced with a wooden framework and buttressed with earth. One or more casting inlets were made, and the molten metal was poured into the mould thus formed.

Castings made by this method show obvious seams at the joins between the individual blocks of the outer mould. In bronze castings these were usually removed by filing and polishing, but in iron castings this was usually not practicable, for the iron used was 'white cast iron', harder than any steel and almost any grindstone.[46] We must wonder whether this did not detract from their aesthetic qualities. Osvald Sirén takes note of an iron Arhat in a German collection, dated 1499, with 'traces of paper and paint',[47] and it is easy to imagine that some of the statues discussed here were originally covered with some kind of papier mâché or gesso to hide the flash-lines.[48] The Korean Vairocana Buddha cast in +858, mentioned above, is described as having 'paint and clay embellishments', and though these appear to be modern they may well be faithful restorations of earlier embellishments.[49] In photographs some flash-lines are visible on this statue, but they are presumably less obvious than they would be without the clay covering.

An interesting aspect of the piece-mould method can be seen in the 'Iron Rhinoceros' near Kaifeng, dated +1446, shown in Plates XXXIII–XXXIV.[50] Clearly it too

[44] Best (1990, pp. 14–15).

[45] Curiously, there are still some art historians who cling to the absurd idea that flash-lines like these indicate that the statues were cast in many separate pieces and somehow assembled afterward. See e.g. Shi Yan (1988, pp. 19, 35); Best (1990, p. 16). On the piece-mould method see e.g. Fairbank (1962); Karlbeck (1935).

[46] Pp. 161–3 above; also Wagner (1993, pp. 345–7).

[47] Sirén (1927, p. 14).

[48] At the Kaifeng Museum (Kaifeng Bowuguan 開封博物館) in 1987 Mr Li Kexiu 李克修 kindly showed me in a storehouse several iron Arhats (*luohan* 羅漢) which may have been treated in this way, but our only light was a flashlight and I was unable to inspect them properly.

[49] Best (1990, p. 15).

[50] Wang Xinmin (1982, pp. 61–3).

was cast by the piece-mould method. Plate XXXIV shows what at first appears to be a later repair; close inspection shows, however, that the metal is continuous through it. What we see here are traces of a repair to the *mould* rather than to the casting. It would seem that while the cope was being built up around the core some accident occurred which resulted in the break clearly outlined here. At this point the model had already been destroyed to make the core, and it was not possible to start again. Therefore the broken piece was replaced in position as well as it could be; the three excrescences are traces of some arrangement used to hold it in place.

The Lion of Cangzhou

Plates XXXV–XXXVIII show what is often said to be the largest iron casting on record in the world, the famous Cangzhou Lion in the city of Cangzhou 滄州, Hebei, cast in +953. It is 5.4 m high, 5.3 m long, and 3 m broad; its weight is estimated at 50 tons. Art historians believe that the lion was originally inside a Buddhist temple, now long gone, and that a bronze statue of the bodhisattva Mañjuśrī rode in the lotus flower on the lion's back. The bodhisattva was at some time removed for the value of its bronze; this could have happened as early as the reign of Shi-zong 世宗 (r.+954–958), Emperor of the minor dynasty of Later Zhou 後周, in his campaign against Buddhism.

By 1603 the tail was missing. The lion toppled over in a storm in 1803, with the result that the snout and belly were damaged. In 1886 the Department Magistrate Gong Yu 宮昱 sent masons to prop it up with bricks and stones.[51] When the American mining engineer Thomas T. Read saw it in 1910 the casting was broken into four parts: the body, the lotus seat, the head, and the lower jaw, which lay on the ground.[52] The lower jaw has not been seen since. In 1984 the lion was professionally restored and placed on a reinforced-concrete pedestal 2 m high.

The chemical analysis and metallographic examination of a sample from the lion were reported by Read, and a team of Chinese archaeologists and metallurgists has published a more thorough study of the way in which the lion was cast.[53]

The rectangular grid of casting seams on the surface of the lion indicates that it was cast by the piece-mould method. When the cope was built up, numerous round-headed wrought-iron spikes were driven into the sides of the core to establish the correct spacing. On the lion's back, cast-iron blocks (called 'chaplets' by foundrymen) were used for the same purpose. When the iron was poured into the mould the spikes and chaplets were incorporated into the casting; their traces can be found by close examination of the outer and inner surfaces.

[51] On the history of the casting see *Wan li Cang zhou zhi* (ch. 1, pp. 9b–10a, 12b; ch. 8, pp. 12a, 19a–b, 21b, 22b, 43a–45a); Zhang Ping and Xu Guoyuan (1933, frontispiece, ch. 13, pp. 1b–2a; text appendix ch. 1, pp. 26b–27a; ch. 2, pp. 1a–2a, 17a); Luo Zhewen (1963); Wang Minzhi (1985).

[52] Read (1936; 1937).

[53] Pinel et al. (1938); Wu Kunyi et al. (1984).

Examination also shows that a reinforcing framework of wrought iron was cast into the neck and back of the lion (see Plate XXXVII), presumably because cast iron alone would not have been strong enough to carry the 5 ton lotus and the bronze bodhisattva.

Horizontal lines of what foundrymen call 'cold shuts' are found at regular intervals from about middle height upward. A cold shut is a fault in a casting caused by premature cooling in the mould before the mould is filled. Study of these indicates that the lion was cast in several stages. First the outer mould was built up to about half of the total height and iron was cast into this (Plate XXXIX). Hereafter the building of the rest of the mould and the casting into it proceeded upward in alternating stages. Cold shuts severely weaken a casting. The founders were aware of this problem, and dealt with it by inserting pieces of wrought iron into the solidifying iron surface, after each partial pour, to act as pegs holding the separately cast levels of the casting together. The operation was not entirely successful, and some of the pegs were displaced by the hot running metal from their intended positions. Some have since fallen out of the casting, leaving characteristic cavities or even holes behind.

Cast-iron artillery

The Chinese artisans' experience with statues and other monumental iron castings was a useful background when, towards the end of the Yuan, a demand developed for iron guns.[54] Bronze was a better metal for the purpose, for when a bronze gun fails it does so in a less disastrous way than one of cast iron; but economic necessity seems to have led to the use of cast iron, and this use led to new and interesting techniques to ameliorate the mechanical properties of iron guns.

In Europe the earliest iron artillery was of *wrought* iron,[55] and the need for a less laborious technique is, in the opinion of many historians, what led to the development of iron casting here. The great advantage of bronze or wrought iron over early cast iron for artillery lay in what happened when a gun failed: a bronze or wrought-iron gun merely split, but a cast-iron gun shattered and threw fragments in all directions, most often killing the crew as well as any nearby spectators.[56]

[54] The history of artillery in China has been covered in *SCC*, vol. 5, part 7. From Table 1 in that volume (pp. 290–2), which lists the earliest dated examples of bronze and iron guns, it seems that the earliest extant Chinese iron gun is one dated '*c.* +1338' in the Rotunda Museum in Woolwich, near London (note also Blackmore, 1995, pp. 40–2, fig. 6). The only other pre-Ming iron guns in the table are the famous 'Cannons of Zhou' (*Zhou pao* 周炮) discovered in Nantong, Jiangsu, in the 19th century and said to have been cast for Zhang Shicheng 張士誠, founder of the short-lived Da Zhou 大周 dynasty, in 1356 and 1357 (see also Wu Yuming, 1987). However, it now appears that these are actually from another minor Zhou dynasty, that of Wu Sangui 吳三桂 (1612–78), and should be dated 1680 and 1681. Ma Feibai (1955) argued this point in the exhaustive manner for which he was justly famous; see also Liu Xu (1989, pp. 41–6); Wang Zhaochun (1991, pp. 58–61). The source for the date of the Woolwich piece is not clear, and may perhaps turn out to be mistaken. Nevertheless numerous iron guns are known from the first years of the Ming, and it seems quite plausible that their invention was in the Yuan.

[55] See e.g. Ritter (1938).

[56] Rostoker (1986).

Plate XL shows an early Qing-period cast-iron gun, and it is clear from the lines of casting flash that it was made using the piece-mould method. On the other hand the gun shown in Plate XLI, cast in 1841, does not have these lines, and probably was made using a different moulding technique, perhaps that shown in the drawings and paintings of Plates XLII–XLV. The cope seems to have been made without a model. At first glance it looks as if the core is of wood. This is hardly possible considering the high temperature of the molten iron; however there seems to be an answer to this problem.

There have as yet been no modern metallurgical examinations of Chinese iron guns, but Plate XLVI gives sketches (made by a surgeon in English service in the Sino-British 'Arrow War' of 1856) of two which were damaged in such a way that something of their internal structure was revealed. In each case a barrel of wrought iron provides strength and toughness while the iron cast around it provides weight and additional strength. Combining wrought iron and cast iron in this way provided an economical gun which nevertheless would not fail in a disastrous way.

It seems likely, then, that the wooden shaft inserted into the mould in Plates XLII–XLV is not a casting core, but is being used to hold a wrought-iron barrel (which is not visible) in position while iron is cast around it. The tilt of the mould was necessary to prevent damage to its bottom by the molten iron falling a distance of 2 or 3 m; at some point in the pouring process it would have been raised to an upright position. The use of an open mould like this, with no 'casting head', would almost surely result in blowholes at the upper end of the casting. Such blowholes can be seen in the 19th-century gun of Plate XLI. Such a 'rotten casting' (to use a technical term of ironfounders) would have been unacceptable in a normal cast-iron gun, but if the gun had a wrought-iron barrel (I found it impossible to determine this by inspection alone), this would explain how it could have been an acceptable weapon. With a wrought-iron barrel encased in the cast iron, the cast iron would not be required to provide much strength at the muzzle end of the gun.[57]

Another composite gun, dated 1643, is shown in Plates XLVII–XLVIII. It has an iron barrel (wrought or cast?), around which bronze has been cast. There are two more Chinese bronze–iron guns in the Rotunda Museum, Woolwich, which Brian Gilmour is presently investigating. Bronze–iron guns have also been used in India, as early as the 17th century.[58]

Still another interesting use of a composite of materials is a small gun in the Tower of London, which was captured by English forces in the Opium Wars.[59] It has an iron barrel wrapped about with layers of silk cloth; I do not know whether

[57] A rather different casting technique was used at a gun foundry near Xiamen in about 1841. J. F. Davis (1852, vol. 2, pp. 79–80) visited the ruins of the foundry in connection with the First Opium War: 'The fragments of clay moulds, the remains of the fused metal, and a number of the half-finished pieces were still on the ground . . . Being cast muzzle-downwards, the more drossy portion of the metal had collected in the breech, which was honey-combed.'

[58] See Balasubramaniam (2005).

[59] Anon. (1988a, p. 100); Blackmore (1995, p. 41); Wagner (2000, pp. 214, 217–19).

the barrel is cast or wrought. Silk is about as strong as wrought iron, but much lighter and also much more elastic, and no doubt this made an excellent portable weapon.

(ii) The Ironworks

On the ironworks themselves we have written sources of two kinds. A number of memorials to the central government concern iron production in particular places, often giving useful information on social and economic aspects of iron production, and we shall look closely at several immediately below.

A second class of source consists of those which give broad statistical overviews of the mining and smelting industry, including the iron industry, at particular times. Robert Hartwell has studied them closely, and concludes that they have their information from official surveys carried out in the years +997, 1021, 1049–53, 1064–67, 1074, and 1078.[60] Another seems to have been carried out at some time in the +12th century.[61] These sources give the locations of industrial prefectures (*jian* 監), mining and smelting works (*chang* 場), and smelting tax offices (*ye wu* 冶務); and two, those for +1064–67 and 1078, give some quantitative data.

We therefore have some excellent material for a study of the Chinese iron industry in the latter half of the +11th century. The data on iron delivered to the government in various places is shown here in Table 4: these are the 'Total mountain-and-marsh receipts' (*fan shan ze zhi ru* 凡山澤之入) of iron in 14 circuits for +1064–67, the 'original quota' (*yuan e* 元額) of iron in 28 prefectures, and the 'receipts' (*shou* 收) of iron in the same prefectures in +1078. The geographical distribution of this last statistic is shown in the map of Figure 121: prefectures listed for 1078 are indicated by filled circles, and rings around these are proportional in area to the 'receipts' of 1078.

How can we use these data? It has sometimes been believed that they give total iron production,[62] so that China produced about 3300 tonnes of iron in the year +1078, or about 35 gram per capita. But this is clearly erroneous, for government receipts were only a part of total production. Some authors appear to assume that the government received a 20 per cent tax in kind, so that the figure of 3300 tonnes should be multiplied by five,[63] but there appears to be no evidence for a definite in-kind tax percentage which was enforced throughout the Empire. Robert Hartwell

[60] Hartwell (1963, p. 178, n. 6). The sources for the respective years are: **+997** and **+1021**: *WXTK*, ch. 18, p. 179b, lines 7–14; *XZZTJCB*, ch. 97, p. 2259. **+1049–53** (the Huangyou 皇祐 period): *WXTK*, ch. 18, p. 179c, lines 9–13; *SS*, ch. 185, p. 4525, lines 1–3; **+1064–67** (the Zhiping 治平 period): *WXTK*, ch. 18, p. 179c, lines 14, 18; *SS*, ch. 185, p. 4525, lines 4ff; *SHY:SH*, ch. 33, p. 27b (1957 edn p. 5387); *Yu hai*, ch. 180, p. 34a. **+1078**: *SHY:SH*, ch. 33, pp. 1a–6a, 7a–18b (1957 edn pp. 5375–6, 5380–1); *WXTK*, ch. 18, p. 180a, lines 14–19; *SS*, ch. 185, p. 4526, lines 1–4.

[61] *SHY:SH*, ch. 33, pp. 20b–23a (1957 edn pp. 5384–5).

[62] E.g. Collins (1922, p. 17); Tegengren (1923–24, p. 313).

[63] Hua Shan (1982, p. 114). The anonymous authors of a history of Chinese metallurgy state that production at Liguo Industrial Prefecture 利國監 was 1,540,000 *jin* 斤 per year, which is exactly five times the figure given for this place in the *Song hui yao* (see Table 4, item 38). But they do not otherwise mention or discuss the *Song hui yao* figures. Anon. (1978h, p. 139).

Table 4 *Statistics given in* Song hui yao ji gao *concerning iron mines and smelters in the Song period.*

A1: *Iron quota for +1078, believed to be the average of returns in 1075, 1076 and 1077.*
A2: *Actual returns in 1078.*
B: *'Total Mountain-and-marsh receipts'* (fan shan ze zhi ru 凡山澤之入) *related to iron. Hartwell (1963, pp. 178–9 fn. 6) argues that these figures give total receipts of this tax in the three years 1064–67, but everywhere else in his book takes them to be total receipts in the single year 1067.*

The units of weight used are jin 斤, liang 兩, *and* qian 錢. *10* qian = *1* liang, *16* liang = *1* jin, *1* jin ≈ *0.6 kg.*

				A. Iron quota, +1078 *SHY:SH* 33.12b–14a					B. Mountain-and-marsh receipts: Iron, *SHY:SH* 33: 27b	
	Circuit	Approximate location of circuit	Place in circuit	Page and line no.	Notes	**A1** Quota	**A2** Returns	[Total of A2 for circuit]	Page and line no.	*jin* 斤
1	Chengdu fu lu 成都府路	W Sichuan						—	27b.11	76,611
2			Yazhou 雅州	13b.6	名山縣蒸礦爐三所熙寧六年置	—	—			
3	Fujian lu 福建路	Fujian						32,652	27b.10	69,224
4			Jianzhou 建州	13b.9		500	3400			
5			Nanjianzhou 南劍州	13b.10		15,179	13,350			
6			Quanzhou 泉州	14a.1	永春縣倚洋場舊置熙寧七年罷	—	—			
7			Shaowu jun 邵武軍	14a.2	光澤縣新安場熙寧二年置又邵武縣萬德場	6902	6902			
8			Tingzhou 汀州	13b.11	□熟務一本作銅務	9000	9000			
9	Guangnan Dong lu 廣南東路	Guangdong						52,831	27b.11	31,344

(cont.)

Table 4 (*cont.*)

	Circuit	Approximate location of circuit	Place in circuit	A. Iron quota, +1078 *SHY:SH* 33.12b–14a: Page and line no.	Notes	A1 Quota	A2 Returns	[Total of A2 for circuit]	B. Mountain-and-marsh receipts: Iron, *SHY:SH* 33: 27b: Page and line no.	*jin* 斤
10			Duanzhou 端州	14a.1		1404	1410[a]			
11			Guangzhou 廣州	14a.3	清遠縣定理場熙寧三年置	—	—			
12			Huizhou 惠州	14a.4		6128	6128			
13			Huizhou Boluo xian 惠州博羅縣							
14			Nan'enzhou 南恩州	14a.7	陽春縣覽往場	—	—			
15			Shaozhou 韶州	14a.4		1500	1800			
16			Yingzhou 英州	14a.6		43,493	43,493			
17	Guangnan Xi lu 廣南西路	Guangxi + Hainan						860		
18			Rongzhou 融州	14a.8	古帶坑場	500	860			
19	Hebei Xi lu 河北西路	SW Hebei						4,144,202	27b.8	1,067,232
20			Cizhou 磁州	13a.1	武安縣固鎮冶務	1,814,261	1,971,001			
21			Xiangzhou 相州	12b.11	沙河縣一冶務元額闕	—	—			
22			Xingzhou 邢州	13a.3	棋村冶	1,716,413	2,173,201			
23	Hedong lu 河東路	S Shanxi						258,384	27b.8	64,786
24			Jinzhou 晉州	13a.9		569,776	30,098			
25			Weisheng jun 威勝軍	13a.11		158,506	228,286			
26	Jiangnan Dong lu 江南東路	SE Anhui + NE Jiangxi						3133	27b.9	21,769

Table 4 (*cont.*)

	Circuit	Approximate location of circuit	Place in circuit	A. Iron quota, +1078 *SHY:SH* 33.12b–14a Page and line no.	Notes	**A1** Quota	**A2** Returns	[Total of A2 for circuit]	B. Mountain-and-marsh receipts: Iron, *SHY:SH* 33: 27b Page and line no.	*jin* 斤
27			Xinzhou 信州	13b.1		3133	3133			
28	Jiangnan Xi lu 江南西路	Jiangxi						100,808	27b.9	1,741,809
29			Qianzhou 虔州	13b.1	元額闕	—	—			
30			Xingguo jun 興國軍	13b.3	大冶縣磁湖冶務熙寧四年進□納入官七年罷	88,888	59,215			
31			Yuanzhou 袁州	13b.2		41,593	41,593			
32	Jingdong Dong lu 京東東路	E Shandong						8065	27b.6	472,999
33			Dengzhou 登州	12b.6		2655	3775			
34			Laizhou 萊州	12b.7	萊陽縣冶課生鐵	4800	4290			
35			Yanzhou 兗州	12b.9		396,000	242,000			
36	Jingdong Xi lu 京東西路	W Shandong						308,000	27b.6	197,400
37			Xuzhou 徐州							
38			Xuzhou Liguo jian 徐州利國監	12b.8		300,000	308,000			
39	Jinghu Nan lu 荊湖南路	S Hunan						504	27b.10	312,724
40			Daozhou 道州	13b.5	江華縣鎮頭坑	504	504			
41	Jingxi Nan lu 京西南路	N Hubei + S Shaanxi						84,410		—

(cont.)

Table 4 (*cont.*)

	Circuit	Approximate location of circuit	Place in circuit	A. Iron quota, +1078 *SHY:SH* 33.12b–14a: Page and line no.	Notes	**A1** Quota	**A2** Returns	[Total of A2 for circuit]	B. Mountain-and-marsh receipts: Iron, *SHY:SH* 33: 27b: Page and line no.	*jin* 斤
42			Dengzhou 鄧州	12b.10	長安坑粟平冶	69,360	84,410			
43	Lizhou lu 利州路	NE Sichuan						—	27b.12	203,965
44			Xingzhou 興州	13b.9	鐵炭場	—	—			
45	Qinfeng lu 秦鳳路	E Gansu						85,068	27b.7	137,557
46			Fengxiang fu 鳳翔府	13a.7		40,560	48,248			
47			Fengzhou 鳳州	13a.8	梁泉縣冶	36,820	36,820			
48	Yongxing jun lu 永興軍路	S Shaanxi						168,850	27b.6	1,256,663
49			Guozhou 虢州	13a.5	清水貓猴冶上□槽冶	139,050	155,850			
50			Shanzhou 陝州	13a.6		13,000	13,000			
51	Zizhou lu 梓州路	C Sichuan						7549	27b.12	5771
52			Rongzhou 榮州	13b.7		300	295			
53			Zizhou 梓州	13b.6	通泉縣三冶東關縣一冶	—	—			
54			Zizhou 資州	13b.8		6706	7254			
55	Sum according to source			14a.9	鐵坑冶[租]額總計元豐元年收總計 . . .	5,482,770	5,501,097		27b.5	5,659,646
56	Actual sum					5,489,835	5,500,526			5,659,854
57	Equivalent in tonnes					3293	3300			3396

[a] Typo: 元年收一千收一千四百一十斤

Figure 121 Map showing locations of prefectures mentioned in Table 4. Modern province names and boundaries are also shown. Prefectures listed for +1078 are indicated by filled circles, and rings around these are proportional in area to the 'receipts' of 1078. Receipts from prefectures without rings were too small to be shown in this way.

also attempted to use the data to calculate total production, but his work too appears to be flawed.[64] It is not likely that a rigorous calculation of annual total production will ever be possible, but his result, 115,000 tonnes, or 1.2 kg per capita, appears to be reasonable as a *guess*.

. . .

Perhaps more interesting than these quantitative data are some sources which give narrow glimpses of the actual production of iron in particular places in the +11th century.

Liguo Industrial Prefecture

Parts of the Empire in which industrial production was important required a different sort of administration from agricultural regions, and offices called *jian* 監, usually translated 'industrial prefecture', were often established in these places.

It happens that the poet Su Shi 蘇軾 (better known as Su Dongpo 蘇東坡) was for a time Governor of Xuzhou 徐州, where Liguo 利國 Industrial Prefecture was located. In a memorial written in +1078, on the administrative problems of the place, he includes an interesting description of the iron industry there:[65]

> After being transferred to the governorship of Xuzhou I have inspected the topography of [the region's] mountains and rivers, investigated what is esteemed by its customs, and studied it in written records. After all this I have realised that Xuzhou is a strategic point between North and South, on which the security of the [two] circuits East of the Capital[66] depends.
>
> . . . [The region is protected on three sides by rugged mountains. Four historical examples show the strategic importance of the prefecture, especially its administrative seat, the walled city of Pengcheng 彭城.]
>
> About 70 *li* 里 [50 km] northeast of the prefectural city is Liguo Industrial Prefecture. From ancient times it has been the gathering place of Iron Offices [*tie guan* 鐵官][67] and merchants, and its people are prosperous. There are 36 smelters, each run by a wealthy and influential family with great myriads of cash in its coffers. They are a constant target for bandits, but the military guard is weak, and it is child's play [to rob them].
>
> I have pondered this far into the night, filled with anxiety. I have had more than ten of the most powerful bandits put to death, [but still,] when they enter the market in broad daylight, the guards abandon their posts and run away.
>
> This region produces fine iron, and the people are all excellent smiths. If some of the smelting households' money is distributed to call up [the local] hoodlums, then a mob could quickly be gathered, and weapons for several thousand men could be supplied in no time.
>
> If [such a mob] were to follow the river and come south, it would arrive [in Pengcheng] in a matter of hours, and Xuzhou would be defenceless. Should the misfortune arise that

[64] See p. 280 above.

[65] *Xu zhou shang Huang di shu* 徐州上皇帝書 (Letter to the Emperor from Xuzhou), *Jing jin Dong po wen ji shi lüe*, 1957, pp. 571–80; cf. *Su Dong po ji*, ch. 14, pp. 61–8; abridged version, ch. 13, pp. 50–8; Kong Fanli (1986, pp. 758–63).

[66] Jingdong Xilu 京東西路 and Jingdong Donglu 京東東路, roughly corresponding to modern Shandong.

[67] There was an Iron Office here in the Han period; see Table 1, no. 5, in Section 5 above, pp. 193–7.

the bandits had exceptional ability . . . and they fulfilled their ambition by taking Xuzhou, then the fate of the region East of the Capital would be in doubt.

Recently the Fiscal Commission of Hebei[68] proposed that iron from Liguo Industrial Prefecture should not be permitted to enter Hebei, and the Court approved . . . The Empire is one family, and the two smelting [regions] of the northeast both benefit the State; is it not narrow to take from the one to give to the other?

Since the time that iron stopped going north the smelting households have been in danger of bankruptcy, and many have come to me to complain. I propose therefore to call on the smelting households to be the defence of Liguo Industrial Prefecture.

There are 36 smelters, and each has several hundred persons who gather ore and chop [wood for] charcoal. They are for the most part poverty-stricken runaways, strong and fierce. I propose to require the smelting households to select and appoint ten men of ability and discipline from each smelter and register their names with the officials. These will be trained in the use of knives and spears. Each month the two offices[69] will assemble them at the administrative headquarters of Liguo Industrial Prefecture for inspection and drill. They will be excused from corvée duty, but any offences will be treated under the law pertaining to 'malfeasance in official service'.

The smelting households have long been threatened by bandits. The people all know this, and they will be delighted to have each smelter send ten men for self-defence. If the officials also remove the recent prohibition, and again allow the iron to go north, then the smelting households will be satisfied and obedient. Treacherous elements will be terrified and will not dare to make plots.

With 36 ironworks, each with several hundred workers, this was indeed a major iron-producing region. Their unskilled workers are 'poverty-stricken runaways, strong and fierce', a description which must remind us of Sang Hongyang's description of early Han ironworkers, 'common bandits' who 'abandoned the graves of their ancestors'.[70] Hired industrial labourers still had no well-defined status in Chinese society. We may suspect that the necessary skilled workers and administrators came from the ironmaster's family, or in some other way enjoyed a more certain social status than the unskilled labourers.

Wealthy ironmasters in Dengzhou

At the tip of the Shandong peninsula was another major iron-producing region, comprising the two prefectures of Dengzhou 登州 and Laizhou 萊州. The great statesman Bao Zheng 包拯 (+999–1062, later made famous by the 'Judge Bao' detective stories)[71] investigated conditions in Dengzhou in about +1046 and submitted a memorial which tells us something of the economics of iron production here:[72]

[68] The two circuits Hebei Xilu 河北西路 and Hebei Donglu 河北東路, comprising the southern part of modern Hebei province, and located between the Liao empire to the north and the two circuits 'East of the Capital' (fn. 66 above) to the south.

[69] *Liang ya* 兩衙, the administrative offices of Xuzhou and Liguo?

[70] P. 144 above.

[71] Franke (1976, vol. 2, pp. 823–32); Schmoller (1982).

[72] *Xiao su Bao gong zou yi*, ch. 7, *CSJC* edn p. 94, pp. 22b–23b. Cf. Hartwell (1963, p. 157).

Request for the removal from the register of the names of certain iron-producing households in Dengzhou. Your servant begs to observe that he has previously set forth the condition of eighteen iron-smelting households in Dengzhou, including the Jiang 姜 and Lu 魯 families. I have stated that they are poor families without the means to smelt iron. Year after year they sell agricultural products and, 'sitting on an empty nest', purchase iron which they pay in to the government. I requested that, in accordance with the regulations, their names be removed from the register [of iron-producing households] . . . I have twice made submissions on this subject, but have not yet received instructions.

My investigations show that in former times, in those areas which produced the most iron products, of the households which originally requested permission to smelt, many have used up their family fortunes, and have no iron to work with; but the officials will not accept that they are poor. Unassisted they have delivered their quotas of iron, and in so doing they have dissipated their assets. [The obligation] continues with their children and grandchildren, who cannot avoid it. This is very often the situation.

Though the potential profit is great, the rich fear future calamity, and are unwilling to establish [iron smelters]. For this reason the production of iron daily decreases, and for a long time there has been no entrepreneurial activity. I request that they [the rich] be required to be smelting households. But those who are truly bankrupt, and do not have the means to engage in industry, should be thoroughly investigated by an Imperial Commissioner; if no fraudulent practice is found, [the situation] should immediately be reported to the Tax Transport Bureau [of the circuit].

The prefectures and districts should as before be ordered to continually and in many ways encourage all manner of persons to establish ironworks, and not be permitted to delay or hinder them.

If this advice is followed, the [iron-smelting] households will be happy in their work and the supply of iron will increase. For the bringing of plenty to the people and enriching the state there is nothing better than this.

Implicit in this text is the assumption that iron production requires a large capital investment. It can be a means to great wealth, but can also lead to ruin. For unspecified reasons many of the wealthy families engaged in iron production have become bankrupt and therefore cannot produce iron. They are nevertheless required to continue delivering an assessed quota to the government, and they can do this only by buying iron on the open market.

This story should remind us that officials appointed to local posts were in a sense negotiators between the broad lines of Imperial policy and the endless variety of local conditions throughout the Empire. Our major sources see the administration from the viewpoint of the capital, and in collections of memorials like Bao Zheng's we see one side of the ongoing negotiations between central and local interests. We do not see the other side, but we may imagine him simultaneously using whatever persuasive and coercive means were available to bring the local families to fulfil the requirements of the central government.

How common was the situation which Bao Zheng describes? If it was at all common then the statistics given in Table 4 for deliveries of iron to the government have a very uncertain relation to actual production. It is interesting to note that there are numerous passages in Song sources concerning the closing of ironworks.[73] It is likely that each actual decision to reduce or eliminate a quota for deliveries of iron was preceded, as in this case, by years of investigation and negotiation, during which time quotas were met by open-market purchases.

Corvée iron production in Hancheng

Among Bao Zheng's collected memorials, printed directly following the one quoted above, is another which likewise concerns a lack of correspondence between name and reality in iron production. It concerns the district of Hancheng 韓城 in the prefecture of Tongzhou 同州, on the Yellow River on the extreme eastern side of the modern province of Shaanxi. The following translation is cryptic in parts because the writer assumes knowledge of an administrative system which is not understood today:[74]

Request for the discontinuation of the system of iron-smelting households in Hancheng District in Tongzhou Prefecture. Your servant has recently heard that the iron-smelting offices of Hancheng District in Tongzhou Prefecture consistently report on 700 households, among which 200 are well endowed with raw materials. [Among the 700] are always seen the household of the village head [*li zheng* 里正] and all the powerful [households]. These are smelting households in name only; for the past 50 years they have only nominally performed the various corvée duties at the prefecture and district level.

Among the smelting households, those of the first rank deliver each year to the smelting offices, counting all the various imposts together, no more than three strings of cash. Other than this they have no expenses.

Furthermore the iron goods received by the government amount to only 100,000 *jin* 斤 [about 60 tonnes], while its outlay for charcoal[75] and the wages of craftsmen amounts to more than 300 strings. Supervision of the corvée requires one government employee.

My investigations have also shown that the households of this district all consider service with the smelting tax offices to be the most onerous corvée; when the corvée is frequent they await orders and do not volunteer.

If the above-mentioned quantity of iron were spread out according to rank among the households of the entire district, so that all were required to supply iron to the government, then the annual [requirement per household] would be only between 10 and 20–30 *jin*. Further, in this place iron is sold at a price of 24–25 cash per *jin*. Each household, in supplying iron to the government, would expend annually between 300 and 500 cash.

Although the government has long forbidden [private] smelting [*peng lian* 烹煉], there are many in the population who sell [iron] privately. If the common people were permitted to smelt freely, then the price of iron would certainly fall.

[73] E.g. *XZZTJCB*, ch. 64, p. 1424, item 2; ch. 67, p. 1511, item 12; *SHY:SH*, ch. 33, pp. 3b–4a; *WXTK*, ch. 18, p. 179c, lines 7–9.

[74] *Xiao su Bao gong zou yi*, ch. 7, *CSJC* edn p. 94, pp. 23b–24b.

[75] On the ambiguous term *tan* 炭 see Hartwell (1963, pp. 89–90, fn. 2). It is possible, but not likely, that it refers here to mineral coal rather than charcoal.

We may perhaps surmise from this that the 200 true iron-smelting households in Hancheng operated on a kind of 'putting-out' system: the government provided charcoal and the services of skilled 'craftsmen', while the designated households provided semi-skilled and unskilled labour, delivering a set quota of iron to the government. The iron-smelting households found this work onerous, and presumably produced no more than their quota. Private smelting was illegal, but privately smelted iron was available on the market – was this produced illegally in Hancheng, or imported legally from other districts?

The situation is confused by the fact that for wealthy families there were advantages to being registered as iron-smelting households. They seem to have been excused from most other obligations, and thus some 500 families could avoid taxes and corvée duties, fulfilling their quotas by buying iron on the market.

The industrial structure described here is very different from that in Xuzhou or Dengzhou seen further above.[76] In those prefectures the ironmasters were wealthy industrialists, supplying their own capital and expertise and employing hundreds of workers. Here in Hancheng production seems to have been tightly supervised by the government, which supplied both capital and expertise.

If 60 tonnes per year was the quota to be delivered by 700 households, production per household was very small compared with other regions.[77] It seems very likely that we are dealing here with a low-capital labour-intensive iron-production technology. While the ironmasters of Xuzhou and Dengzhou presumably operated large blast furnaces like those of 19th-century Sichuan, iron may have been produced in Hancheng in small blast furnaces like those of Dabieshan.[78] The crucible process of Shanxi is another possibility here, but I have suggested above that this may have been a later innovation.[79]

Bao Zheng's plea for a change in the iron-production quota system in Hancheng was in time accepted, and in +1055 an order was sent to the Fiscal Commissioner of Shaanxi circuit that iron smelters here be allowed to 'purchase for transfer' (*cheng mai* 承買).[80]

In +1083 the Fiscal Commission of Shaanxi Circuit reported that in Hancheng district, 'the veins [*miao mai* 苗脈] of iron ore in the mountains are deep and thick; a mint [*qian jian* 錢監] can be established there'.[81] It also proposed that several existing mints further to the west, in modern Gansu, be closed. These measures were presumably part of a general tightening of security against the Xi Xia threat, moving iron production away from the border region.

76 Pp. 300–1, 301–3.
77 This would still to some extent be the case if 60 tonnes was 10 per cent of the production of 200 households, as Hartwell (1963, p. 183 fn. 4) seems to assume.
78 On these processes see respectively pp. 22, 30, and 8–16 above.
79 Pp. 38–44.
80 *XZZTJCB*, ch. 181, p. 4382.
81 *XZZTJCB*, ch. 338, p. 8137. Hartwell (1963, p. 183, fn. 4) appears to have misread this passage.

The report of +1083 mentions only potential production in Hancheng, and gives no information on actual current production.[82] Probably production here was quite low until this move brought renewed development, with a new injection of both capital and technological expertise, and perhaps a new technology as well. It made a great difference to iron production in Hancheng, as the report of an official investigation three decades later indicates.

In +1112 Jiang Yi 蔣彝 (1074–1122) was vested with special powers and sent to reorganise the mining industry of Shaanxi Circuit 陝西路.[83] His report of 1114 appears to indicate that two 'mining and smelting works' (undoubtedly ironworks) in Hancheng have annual quotas of 600,000 *jin*, or about 360 tonnes, each.[84] Thus these two works between them delivered a quota which was twelve times the earlier quota for the entire district. They were now having difficulty delivering their quotas, but an underlying assumption in the report is that the quotas had earlier been realistic. No doubt the two works had been established, and their quotas set, as a result of the proposal of 1083.

(iii) The Technology of Iron and Steel Production

Blast furnaces

Ironworks sites of the Song–Yuan period have been reported in seven Chinese provinces.[85] Of these a few are reported in sufficient detail to give us some idea of how blast furnaces in this period were built, and how they differed from what is known from periods before and after.

A very large blast furnace, 6 metres tall, from the Song period is still standing today near Handan, Hebei. The photograph in Figure 122 was published, with a

[82] It is difficult to find modern studies of mineral resources in Hancheng, but Nyström (1912, e.g. pp. 35–6, 61–2) reports important deposits of both coal and iron immediately across the Yellow River in Shanxi.

[83] See his epitaph-biography in *Bei shan xiao ji*, ch. 30 (pp. 7b–11a), p. 8b.

[84] Quotations from the report are found in several Song texts. The *Song hui yao ji gao* quotes it as stating that the ironworks have annual quotas of 6 million *jin*; this is not credible, for it suggests that each of the two had a quota greater than the *total* of all ironworks quotas in Song China only 36 years before, in +1078 (Table 4, row 55). Hartwell (1963, p. 183, fn. 4) silently corrects 6 million (*liu bai wan* 六百萬) to 600,000 (*liu shi wan* 六十萬), and this seems to be the best *guess* we can make as to the original figure.

The *Song hui yao ji gao* is notorious for the number of banal copying errors it contains (see e.g. Chen Gaohua and Chen Zhichao et al., 1983, pp. 246–7). A good example is seen in overlapping quotations of another part of Jiang Yi's memorial: in one a number is given as 700, in the other as 800, and other obvious copying errors are apparent as well.

SHY:ZG, ch. 43, p. 135a; *SHY:SH*, ch. 34, p. 16a; *SHY:XF*, ch. 4, p. 35a (1957 edn pp. 3341, 5396, 6639). See also *SS*, ch. 185, p. 4528; *WXTK*, ch. 18, p. 180b. Hartwell has a somewhat different interpretation from the one given here.

[85] Yang Kuan (1982, pp. 166–71) gives a general survey. **Anhui:** Hu Yueqian (1959); **Jiangxi:** Li Xiaoping (1995); Peng Zhensheng and Li Xiaoping (1992); Deng Daolian (1991); Wan Shaomao (1994); **Fujian:** Chen Zhongguang (1959); **Heilongjiang:** Wang Yongxiang (1965); **Henan:** Anon. (1978h, pp. 148–50); Li Jinghua (1992a); Wu Kunyi and Yu Xiaoxing (1984); **Hebei:** Ren Zhiyuan (1957); Tang Yunming (1959); Wang Zhaosheng (1994); **Guangdong:** Liu Yuncai (1978, p. 22) (but note important correction, Yang Kuan, 1982, preface, p. 9).

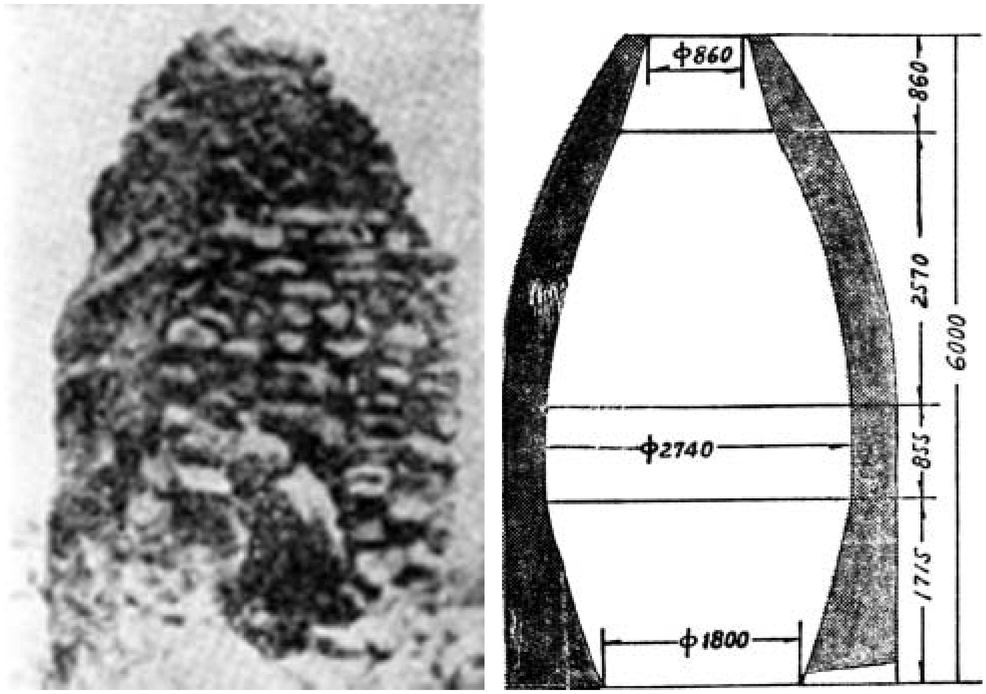


Figure 122 Song-period blast furnace, still standing at Kuangshancun 礦山村 near Handan, Hebei. *Left:* Photograph, originally in *Guangming ribao*, 13 December 1959, here reproduced from Liu Yuncai (1978, p. 23, fig. 8). *Right:* Liu Yuncai's reconstruction of the furnace (*ibid.*).

short description, in a newspaper in 1959,[86] and has often been reproduced.[87] In the Song this was Cizhou 磁州, a major iron-producing prefecture; it can be seen in Table 4 (item 20) and the map of Figure 121 that in +1078 Cizhou and the adjacent prefecture Xingzhou 邢州 between them supplied more than 75 per cent of all quota deliveries of iron to the state.

I have heard that a major investigation of this furnace has recently been completed. Until a report is published we have very little to go on, but it seems to be rather like some of the traditional furnaces, known from the 19th and 20th centuries, which have been described in Section 2 above. Perhaps we see in Figure 122 the internal stone shaft of a furnace like that shown in Figures 123–125, without its wooden frame and tamped-earth fill. Nearby, in Anyang 安陽 and Lin 林 Counties, Henan, several other large blast furnaces have been investigated, but the results have not yet been published in detail.[88]

. . .

[86] Chen Yingqi 陳應祺 in *Guangming ribao* 光明日報, 13 December 1959. This was in a period of paper shortage in China, in which the export of newspapers was stopped, and I have not been able to find a copy in any European library.

[87] E.g. Liu Yuncai (1978, p. 23, fig. 8); Wagner (1985, p. 47, fig. 24). Two similar Song-period blast furnaces, in Henan and Hebei, are described and illustrated by Han Rubin (2002a, pp. 29, 39, figs. 20–21).

[88] Anon. (1978h, pp. 148–9); Li Jinghua (1992a, pp. 47, 48).

Figure 123 'An ancient charcoal blast furnace in the interior of China', reproduced from Gottwald (1938, p. 109, fig. 1). Probably 19th or 20th century, and probably in Hunan.

Figure 124 Blast furnaces in western Hunan, 1958, photographed by Rewi Alley (1961b, no. 10). Cf. Figure 125.

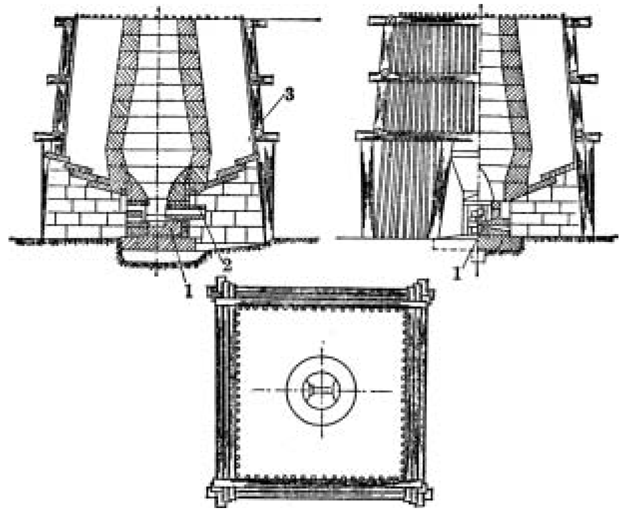


Figure 125 Diagram of a blast furnace in Sichuan, ca. 1958, reproduced from Yang Kuan (1982, p. 185, fig. 47). Cf. Figure 124.

Song–Yuan remains of a curious type of blast furnace, built directly into a hill to obviate the need for a strong outer construction, have been reported in Henan, Jiangxi, and Heilongjiang.[89] The only ones which so far have been described in adequate detail are some +12th-century sites in Acheng County 阿城縣, Heilongjiang. Though virtually nothing is known about the place from written sources, this was clearly a major iron-production region of the Jin 金 (or Jürched) state. A survey found a very large mine site, remains of housing estimated to be adequate for 1000 workers, and more than 50 iron-smelting sites spread out up to about 10 km from the mine. As the authors of the report suggest, the ironworks were no doubt spread so far from the mine in order to make more efficient use of forest resources for fuel.

Figures 126–128 show three blast furnaces found at one of the sites. This type seems to be best suited to the loess regions, with their cloven topography. At a level place above a sheer cliff a few metres high a shaft was dug, 2–3 m in depth. From the side of the cliff a horizontal tunnel was dug to the shaft and reinforced with granite slabs. The whole was lined with smaller stones, mortared with clay, then plastered with a refractory clay. A second tunnel was often dug under the bottom, probably to allow heat to escape and to alleviate cracking of the furnace bottom. In furnace operation the high heat has baked the surrounding untouched loess soil to a hard red layer up to half a metre thick.[90]

[89] Li Jinghua (1992a, pp. 47, 51, 54); Peng Zhensheng and Li Xiaoping (1992); Li Xiaoping (1995); Wang Yongxiang (1965). A similar construction was used in 19th-century Burma for a type of iron-smelting furnace (possibly a blast furnace, more likely a bloomery). See Bronson and Charoenwongsa (1986, pp. 7–8); Suchitta (1983, pp. 43–6).

[90] Wang Yongxiang (1965, pp. 125, 127–9).

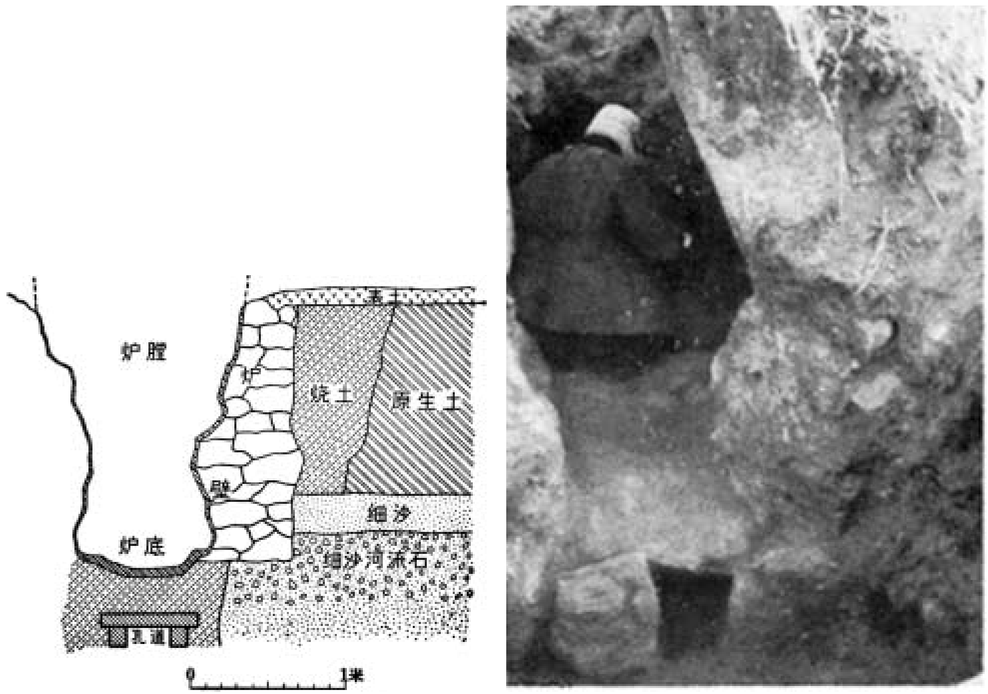


Figure 126 Photograph and diagram of blast furnace no. 2 at Dongchuan 東川 in Acheng 阿城 County, Heilongjiang, reproduced from Wang Yongxiang (1965, p. 127, fig. 5, pl. 7.4). The scale shows 1 m.

Figure 127 Photograph of blast furnaces no. 5 (left) and 4 (right) at Dongchuan in Acheng County, Heilongjiang, reproduced from Wang Yongxiang (1965, pl. 7.1). See also Figure 128.

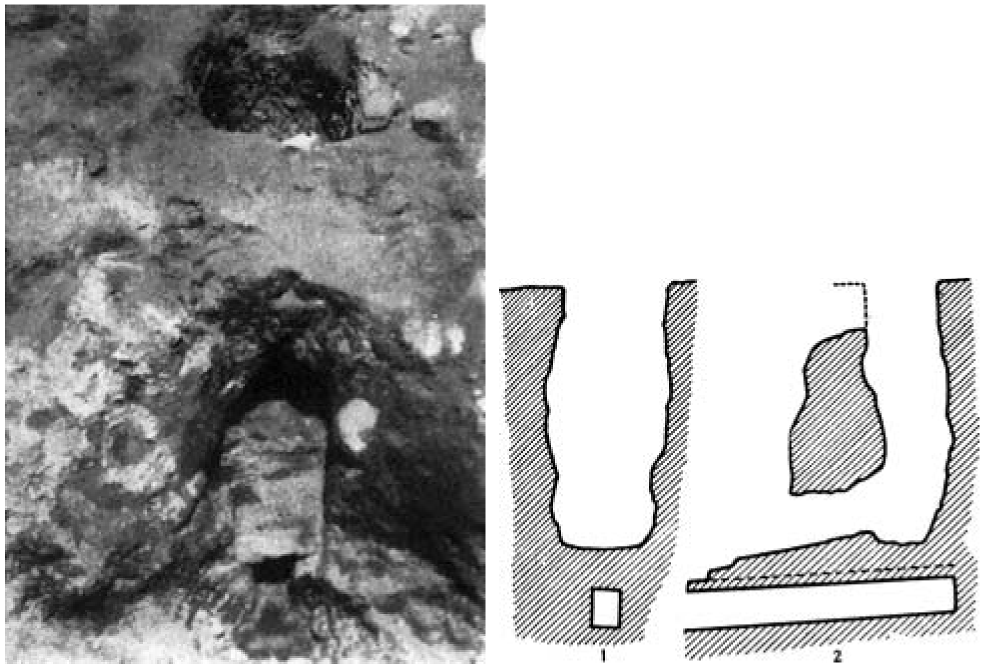


Figure 128 Photograph and diagram of blast furnace no. 5 at Dongchuan in Acheng County, Heilongjiang, reproduced from Wang Yongxiang (1965, p. 128, fig. 6, pl. 3). See also Figure 127.

Presumably the shaft was completed with a stone wall at the point where the tunnel reached it, with holes provided for the blast and for tapping slag and molten iron. This wall, the weakest part of the furnace and subjected to the highest temperatures, would have been replaced often, while the rest needed only to be relined occasionally with a new layer of refractory clay.

In the Heilongjiang furnaces the height is always about 2–3 m, with a rectangular shaft having dimensions ranging from 50 to 80 cm. These are very small, and perhaps had the same operating characteristics as the later 'dwarf' furnaces, such as those of Dabieshan, discussed in Section 2(i) above.[91] They would be best suited to small-scale production in isolated regions, and it is a surprise to see them in use in a large-scale iron-production region like that in Heilongjiang; perhaps future research into the channels by which technology was transferred between the Song and the Jin will produce an explanation.[92]

At an ironworks site near Anyang, Henan, believed to have been in operation from the Song through the Ming period, three much larger blast furnaces of the same type have been excavated. These are 2.4–4 m in diameter, and the incomplete

[91] Pp. 8–16.

[92] Note incidentally the many small military ironworks in Liaodong in the Ming period, pp. 328–9 below, and also Luan Fan (2003) on iron in Jilin in the Ming period.

remaining height of each is about 4 m.[93] We must hope that more will be published on these in the near future.

This type of blast furnace appears to be mentioned, very briefly, in the famous +17th-century technical compendium *Tian gong kai wu* 天工開物. This is the suggestion of Li Xiaoping.[94] The sentence in question can be translated,

The [iron-smelting] furnace is often made in a pit at the side of a mountain; or else it is encompassed using a framework of heavy timbers.
其爐多傍山穴為之, 或用巨木匡圍.[95]

Some published translations ignore the mention of a pit (*xue* 穴) here.[96] Li Chiao-ping translates instead, 'It is generally located near the mine, and sometimes made with a frame of heavy timbers.'[97] This is a possible translation, and takes the 'pit' into account, but in the light of the archaeological material Li Xiaoping's interpretation fits better into the context. The whole passage will be discussed in greater detail in Section 8(ii) below.[98]

The use of mineral fuel in iron smelting

The Northern Song period saw a crisis in the supply of wood for fuel, and the first widespread use of mineral coal, both in domestic heating and in industry, including the iron industry.[99]

There are some signs to indicate that coal may have been used in iron smelting as early as the +4th century, when the Buddhist traveller Daoan 道安 reported:

At a mountain 200 *li* 里 north of Quci 屈茨 [modern Kucha (Kuche 庫車), Xinjiang][100] there is at night a blazing light, in the daytime only smoke. People take the stone coal [*shi tan* 石炭] of the mountain to smelt the iron of the mountain, reliably filling the needs of the Thirty-Six States [i.e. the Western Region].[101]

But this is the only mention before the Song, when we suddenly have many references. Both the fuel crisis and the new use of coal in iron smelting are clear in a famous poem, 'Stone coal', by Su Shi 蘇軾:[102]

[93] Anon. (1978h, pp. 148–9); Li Jinghua (1992a, pp. 47, 48).
[94] Li Xiaoping (1995, p. 110).
[95] *TGKW*, ch. 14, Zhong Guangyan (1978, p. 363).
[96] Sun and Sun (1966, p. 248); Yabuuchi Kiyoshi (1969b, p. 270). Zhong Guangyan (1978, p. 366) does translate *xue* (as *shan dong* 山洞, 'mountain cave'), but does not attempt to explain it.
[97] Li Chiao-ping et al. (1980, p. 351).
[98] Pp. 339–46.
[99] See *SCC*, vol. 5, part 13, pp. 195–6; note also vol. 6, part 3, pp. 654ff; Xu Huimin (1987).
[100] Feng Chengjun and Lu Junling (1980, p. 55).
[101] *Shui jing zhu*, ch. 2, Wang Guowei (1984, p. 40), quoting *Shi shi Xi yu ji* 釋氏西域記. On this lost book see e.g. Cen Zhongmian (1966, p. 213). Note the detailed discussion of the passage by Read (1940, pp. 123–5). On Daoan see Link (1958).
[102] *Ji zhu fen lei Dong po xian sheng shi*, ch. 25, pp. 5a–b; Sivin (1973). Cf. *Yi jue liao za ji*, ch. 1, pp. 11b–12a.

Earlier there was no stone-coal in the city of Pengcheng. It was only in the twelfth month of the first year of Yuanfeng [January +1079] that someone was sent to investigate in the southwest of the prefecture [Xuzhou]. North of Baituzhen they smelt iron and make extraordinary weapons ‘to pierce rhinoceros hide’.

[*The city*:]
Didn’t you see her,
Last winter, when travellers were stopped by the rain and snow,
And city-dwellers’ bones were torn by the wind?
With a half-bundle of wet firewood, ‘bearing her bedding at dawn’.[103]
At twilight [again] she knocked on the gate, but no one wanted her trade.

[*The coal mine*:]
Who would have thought that in those mountains lay a hidden treasure,
In a mass, like black jade, ten thousand cartloads of coal.
Flowing grace and favour, unknown to all.

[*The blast furnace*:]
The stinking blast – *zhen-zhen* – disperses;
Once a beginning is made, [production] is vast without limit.
Ten thousand men exert themselves, a thousand supervise.
Pitching ore into the roiling liquid makes it even brighter,
Flowing molten jade and gold show its vigorous potency.

[*The prefecture*:]
In the Southern Mountains, chestnut forests can now breathe easy;
In the Northern Mountains, no need to hammer the hard ore.
They will cast you a sword of a hundred refinings,
To chop a great whale of a bandit to mincemeat.

彭城舊無石炭, 元豐元年十二月, 始遣人訪獲於州之西南, 白土鎮之北, 冶鐵作兵, 犀利勝常云.

君不見前年雨雪行人斷, 城中居民風裂骭, 濕薪半束抱衾裯, 日暮敲門無處換.
豈料山中有遺寶, 磊落如瑿萬車炭. 流膏迸液無人知, 陣陣腥風自吹散.
根苗一發浩無際, 萬人鼓舞千人看. 投泥潑水愈光明, 爍玉流金見精悍.
南山栗林漸可息, 北山頑礦何勞鍛. 為君鑄作百煉刀, 要斬長鯨為萬段.

There is other text-based evidence as well,[104] but this poem inspires confidence that the author had actually seen a blast furnace fuelled with coal or coke, heard the *zhen-zhen* of the bellows, smelled the sulphurous smoke, and seen the glowing molten metal being tapped.[105] There is also evidence from chemical analyses of artefacts:

[103] The woman is selling her body to obtain firewood. The phrase *bao qin chou* 抱衾裯 comes from *Xiao xing* 小星, ‘Little stars’, Ode no. 21 of the *Book of odes*. Two concubines, ‘carrying in their arms their coverlets and chemises’, stand in the early dawn, watch the stars disappear, and compare their lot to that of their lord’s principal wife. See Karlgren (1950b, pp. 12–13; 1942–46, p. 104). In the next line *qiao men* 敲門, ‘knocking on the gate’, can also mean ‘dowry’.

[104] See e.g. Hartwell (1963, pp. 61–72; 1967a, pp. 118ff); Wang Ling (1982); Hua Jueming (1989); Xu Huimin (1987).

[105] It is perhaps possible that he had merely heard a vivid description, but in any case the blast furnace is instantly recognisable.

high sulphur levels, which strongly suggest the use of coal in smelting, are found in numerous iron artefacts of the Song period.[106]

More definite evidence is provided by the radiocarbon dates of the carbon in three cast-iron artefacts of the Song and Yuan periods.[107] These give dates of 11,540, 12,400, and 13,840 years b.p. respectively. Clearly these much-too-early dates indicate that a part of the fuel used in the production of the artefacts was mineral coal (with effectively infinite age). Qiu Shihua and Cai Lianzhen calculate that the blast furnace in which the iron was produced was charged with a mixture of three-tenths charcoal and seven-tenths coal.[108] This is possible but, as Paul Craddock and others point out, a more likely explanation is that the artefacts were cast of a mixture of charcoal- and coal-smelted iron.[109]

The question to be asked now is what problems were involved in the change from charcoal to coal, and how these problems were solved. There is no straightforward way of answering this question, for we do not have, for any period, the sort of technical evidence – written or archaeological – which is needed. But we shall see that in any case the problems were not all purely technical.

One way of using coal in iron smelting is the crucible smelting process, described in Section 2(iii) above.[110] However, at present there is no reliable textual evidence of the use of this process as early as the Song, and no material evidence at all.[111]

On the other hand, since there is no doubt that coal or coke was used in blast furnaces, we can learn something by looking briefly at the transition from charcoal- to coke-fuelled blast-furnace operation in Britain and America from the 17th to the 19th century.[112]

Digression: the early use of mineral fuel in English iron smelting

The first economically successful use of coal in iron smelting in the West was by Abraham Darby at Coalbrookdale, in Shropshire. Here, at the Ironbridge Gorge

[106] Anon. (1978h, p. 152); Hua Jueming (1989); Wayman and Wang (2003). Craddock et al. (2003, pp. 39, 45) suggest that an unprovenanced 'plaque' in the British Museum, dated +718, with 1.98 per cent silicon and very low sulphur, is evidence of the use of fossil fuel in iron smelting, but this artefact seems likely to be a late fake. Among well-provenanced pre-modern Chinese iron artefacts of any period, I know of none with silicon content over 1 per cent, and most are much lower. Note also Wayman et al. (2004, pp. 12, 14, 20).

[107] Qiu Shihua and Cai Lianzhen (1986); note also Igaki (1994); Saito (1994).

[108] Qiu Shihua and Cai Lianzhen (1986, p. 362).

[109] Craddock et al. (2002, pp. 726–7; note also 2005).

[110] Pp. 38–44.

[111] A number of writers have assumed that crucible smelting was the earliest iron-smelting process used in China, but the evidence is now all against this view. Needham (1958, p. 14); Wertime (1961, p. 48); Hartwell (1963, pp. 71–2; 1967a, p. 119).

[112] On the history of the use of coal in iron smelting in the West see especially Mushet (1840, pp. 34–45, 399–428); Smiles (1863, pp. 43–59, 77–98); Lones (1898, pp. 4–8, 16–17); Ashton (1925); Birch (1967, pp. 22–33); Chaloner (1950); Chevalier (1949); Clark (1993); Cox (1990); Dobson (1982); Flinn (1962); Gericke (1999); Gille (1946); Harris (1988, pp. 30–7; 1998, pp. 238–61); Hyde (1977, pp. 23–9); Ince (1991); King (1996; 2002a; 2002b; 2005, pp. 24–6); Morton and Wanklyn (1967); Mott (1936; 1959a; 1959b); Percy (1864, pp. 879–89); Pfannenschmidt (1977, pp. 128–31); Raistrick (1989); Rehder (1987; 1998); Riden (1992; 1994); Treadwell (1974); Trinder (1988); Wertime (1961, pp. 228–9).

Industrial Museum (a marvellous open-air museum covering many acres), visitors can see the remains of Darby's blast furnace, with a sign informing them that *on this spot*, in 1709, the Industrial Revolution began.

Before Darby a number of other entrepreneurs had attempted to use coal or coke in iron smelting. One simple method which may have been used very early on was to mix small amounts of coal or coke in the charcoal charged into the blast furnace.[113]

The first person to claim success in smelting iron with coal alone as the fuel was Dud Dudley (1599–1684), in his *Metallum Martis* of 1665.[114] The consensus of metallurgical historians today appears to be that he did succeed in producing iron with coal; but he was certainly not an economic success, presumably because his iron was of inferior or unreliable quality.[115]

Another early pioneer was Prince Rupert (Rupprecht von der Pfalz, 1619–82), a cousin of Charles I and a member of the Royal Society.[116] His experiments with the use of coal in iron smelting were reported by Erik Odhelius (1661–1704), one of Sweden's most important metallurgists, who visited England in 1686 and 1691–92.[117] His manuscript report on the European metals industries has never been published, but brief notes from his description of Rupert's experiments have been given in Emanuel Swedenborg's *De ferro* of 1734[118] and in the report of a Swedish Royal Commission in 1744. The latter reads:

> More than 50 years ago, in the blast furnaces of Sussex, Prince Robbert attempted to smelt iron ore with stone coal, but he was unsuccessful, for the furnace became fouled with tar, and the iron was so brittle from sulphur that it was necessary to give up. Later, at the Coalebrooksdal [*sic*] works, the art of blast furnace operation with stone coal as if it were charcoal has been fully accomplished. However, there have still been problems: [1] that the stone coal does not draw [i.e. smelt] as much as half the ore that charcoal does,[119] or rather, the proportion of the iron which it steals through its large sulphur content; and [2] that the iron which remains cannot be used in the forge, except in a small quantity together with good iron, if it is to be useful. On the other hand it is said to lend itself fairly well to all kinds of foundrywork.

[113] Birch (1967, p, 26) notes an agreement of 1728 among Yorkshire ironmasters which explicitly takes such a practice into account. He sees this only as providing for 'a possibility for the future', but the wording of the agreement makes it seem more like a well-known existing practice.

[114] Dudley (1665).

[115] For the recent more positive view of Dud Dudley see especially Simons (1956); Morton (1966); Morton and Wanklyn (1967). Negative evaluations are given e.g. by Mott (1936; 1957); Ashton (1925); Gille (1946, p. 101); Gale (1979, pp. 16–18).

[116] Patrick Morrah's biography of Prince Rupert has a chapter on his scientific and technical accomplishments (1976, pp. 387–99), with numerous references to archival sources, but he does not mention the iron-smelting experiments. Other biographies, including that in the *Dictionary of national biography* (*DNB*, vol. 17, pp. 405–17), barely mention the technical side of his career. It is interesting to note that, in the English Civil War, Dud Dudley held a commission in the regiment of Rupert's brother, Prince Maurice. *DNB*, vol. 6, p. 100; Morton and Wanklyn (1967, p. 62).

[117] See, in English, Birch (1955, p. 24); Heckscher (1954, p. 87); in Swedish, Hofberg (1906, vol. 2, p. 228); Heckscher (1935–49, vol. 1, part 2, pp. 496, xxviii); Rydberg (1951, pp. 142–3). Note that Odhelius' visits to England took place after Rupert's death in 1682, so his report cannot be from direct observation.

[118] Swedenborg (1734, §12, p. 158; 1762, pp. 96–7); Sjögren (1923, §12, pp. 190–3).

[119] See fn. 129 on p. 316.

Time will tell whether this art can be brought to a higher level. The Commission believes, however, that it is not really possible, because of the great enmity between iron and sulphur which cannot be removed against their nature.[120]

It is curious that Rupert's experiments should have been conducted in Sussex, where charcoal was plentiful and coal not readily available;[121] but here (in the forested region known as the Weald) was in the 17th century where most of England's blast furnaces were located.[122] Presumably the choice of venue was determined by the presence of a cooperative ironmaster.

Prince Rupert's trouble with tar fouling the blast furnace suggests that he used raw bituminous coal rather than coke, and the same may have been the case in Dud Dudley's experiments.[123] Use of raw coal can also lead to serious problems of 'scaffolding', in which parts of the furnace burden adhere to the furnace wall and build up, then suddenly fall, sometimes with disastrous results.[124]

Bituminous coal (to make a long story very short) is a polymer of very large and complex hydrocarbons, typically about 75 per cent carbon.[125] The 'coking' of bituminous coal is (like the charring of charcoal) a process of destructive distillation (pyrolysis) which can provide useful organic distillates (coal tar) as well as the coke, which is typically over 90 per cent carbon. Traditionally coke was made by a process very like the charring of charcoal, and both processes were seen as 'the burning away of impurities'. In the respective modern processes the distillation uses a less expensive and more manageable heat source than the coal or wood being distilled.

Coke is preferred to bituminous coal in both domestic and industrial applications because it 'burns clean': the combustion products do not smell of sulphur, and do not contain heavy hydrocarbons which muck up furnaces and flues and pollute the air.

Anthracite, or 'smokeless coal', is a kind of coal in which the geological processes which turn vegetable matter into coal have proceeded much farther, so that it contains over 90 per cent carbon and not more than a per cent or two of hydrogen. It cannot be coked, and for most purposes does not need to be. Because of its very low reactivity it is very difficult to use in a blast furnace.[126]

Coke was used in England in a variety of applications – including copper and lead smelting – from the early 17th century, and it appears to be certain that Abraham Darby used coke rather than coal in his blast furnace.[127] Coke is less reactive

[120] The Commission's complete report on the European iron industry is published in Anon. (1916/18); the passage translated here is on p. 135.

[121] Hodgkinson (1994).

[122] Riden (1994, p. 16).

[123] Morton (1966); Morton and Wanklyn (1967).

[124] Recall the blast-furnace explosions of –91 and –27 (presumably in charcoal-fuelled blast furnaces) reported in the *Han shu*, pp. 216–7 above.

[125] This introduction to the chemistry of coal is based especially on Grayson (1985, pp. 285–9); Mott (1936); Percy (1861, pp. 78–107, 144ff); Pitt and Millward (1979); Rehder (1987); Rosenqvist (1974, pp. 223–7); Rostoker and Bronson (1990, pp. 66–9).

[126] Firmstone (1874); Yates (1974).

[127] Mott (1959a); Rehder (1987; 1998).

than charcoal, and therefore requires a higher temperature in the blast furnace.[128] This in turn means greater fuel consumption and a larger volume of blast. The coke-fuelled furnace burden is less permeable, so that a greater blast *pressure* is also required.[129] The greater fuel consumption shows up clearly in Darby's account books, and the need for greater blast volume and pressure can be seen in the considerable efforts made at Coalbrookdale to increase the available water power.

The remark about foundrywork in the Swedish report points up the most important reason for Abraham Darby's success: he was an honest Quaker, and a better businessman than Dud Dudley and the others. He did not make extravagant claims for his iron, but used it in the humble applications for which it was suited. His pig iron undoubtedly contained too much sulphur to be an appropriate raw material in wrought-iron production, but it is likely to have been an excellent iron for making castings. The higher temperature in the blast furnace led to a higher silicon content in the iron, so that it became possible to make thin products of grey cast iron. And it happens that the local ore contains a good deal of manganese, which combines with sulphur and renders it harmless in cast iron. Darby's ironworks became famous for the production of large thin-walled iron pots; they were superior to thicker pots, and were much more economical because they used less, and cheaper, iron.

The 'red shortness' (brittleness at high temperatures) caused by sulphur in wrought iron and steel would be helped by alloying with manganese, but the fining process removes whatever manganese might be present in the original pig iron. Therefore the production of wrought iron required pig iron with low sulphur. The solution to the problem – more limestone in the blast-furnace charge – was and is simple enough in principle, but took some time to discover and longer to exploit. As has been noted in Box 1 in Section 2 above,[130] limestone ($CaCO_3$) has two functions in a modern blast furnace: as a flux, adjusting the melting point of the slag down to a practicable temperature, and as a desulphuriser, removing sulphur to the slag through the reaction $S + CaO + C = CaS + CO$. The quantity of limestone used in early blast furnaces was normally too small to have much effect on sulphur, but that was unimportant in charcoal-fuelled blast furnaces. At some time it was discovered that more limestone could help with the sulphur problem in coke-fuelled blast furnaces, but the amounts required raised the melting point of the slag considerably. The essential problem in removing sulphur from pig iron was thus the attainment of still higher temperatures in the blast furnace. The use of coke had already raised the temperature of the furnace, but not yet enough. Abraham Darby's pig iron was not used as raw material for wrought-iron production until after the installation of a

[128] Note in the diagram of a blast furnace, Figure 10 in Section 2 above (p. 14), the 'zone of relatively constant temperature'. The equilibrium temperature for the reactions which proceed in this zone is directly dependent on the reactivity of the fuel. In modern blast-furnace practice high temperatures are desirable, and efforts are made to control the reactivity of the fuel.

[129] Rehder (1987) gives a lucid discussion of these points, in part based on records of 19th-century blast-furnace operations which often shifted back and forth among different fuel types as prices changed. Here the fuel and air requirements using coke were each almost twice the requirenent when charcoal was used.

[130] Pp. 14–15.

Newcomen steam engine to increase the water power for the blast furnace, making much higher temperatures possible.[131]

Mineral fuel in Song–Yuan iron smelting

What does this digression into 18th-century Shropshire tell us of the technical possibilities available to Song blast-furnace operators?

One possibility they had was certainly to mix some coal or coke into the charcoal charged into the blast furnace. This would have meant a saving of charcoal, some reduction of overall fuel reactivity leading to some increase in operating temperature, and a modest increase in the silicon and sulphur contents of the pig iron produced. The radiocarbon evidence mentioned above may point in this direction.

A 19th-century blast furnace in southern Hunan (just south of Leiyang 耒陽) which seems to have been fuelled with raw bituminous coal is described by von Richthofen.[132] It was 6 m high, with a sandstone shaft, wooden outer frame, and stamped earth in between.[133] The bellows was driven by three men. His description of the physical appearance of the fracture of the pig iron suggests that it was probably fairly high in sulphur; nevertheless it was fined to wrought iron, which was sold.

This example shows that a blast furnace of the kind known from the Song period could be operated with bituminous coal as the fuel, though we do not know how the technical problems, noted above, were solved. The mention in Su Shi's poem of the 'stinking blast' (*xing feng* 腥風)[134] suggests the smell of hydrogen sulphide, an indication perhaps that coal rather than coke was used in this blast furnace – though we should not base too much reasoning on a single line in a poem.

Rostoker and Bronson, discussing the same question, point to some other traditional Chinese blast furnaces which were wide-mouthed and shallow. In such furnaces, they suggest, the problems of aggregation and scaffolding would have been much less severe than in the more usual type of blast furnace. They refer specifically to the illustration of a 17th-century blast furnace given by Song Yingxing in his *Tian gong kai wu*, reproduced as Figure 133 in Section 8 below.[135] He does not tell us what fuel was used here, but it is interesting that Song Yingxing never mentions coke, and may not have known of it. On the other hand, a very similar early 20th-century blast furnace in central China, shown here in Figure 129, was fuelled with coke,[136] and many other traditional blast furnaces of somewhat similar shape were fuelled with charcoal.

[131] Rehder (1987, pp. 42–3).
[132] von Richthofen (1877–1912, vol. 3, pp. 455–6); cf. Tegengren (1923–24, p. 338). On the district, but not the ironworks, see also von Richthofen (1872, pp. 5–7; 1907, pp. 375ff); Dickson (1864, pp. 168–9).
[133] Some similar blast furnaces are shown in Figures 124–125, pp. 307, 308 above.
[134] P. 312 above.
[135] P. 340.
[136] Lux (1912).

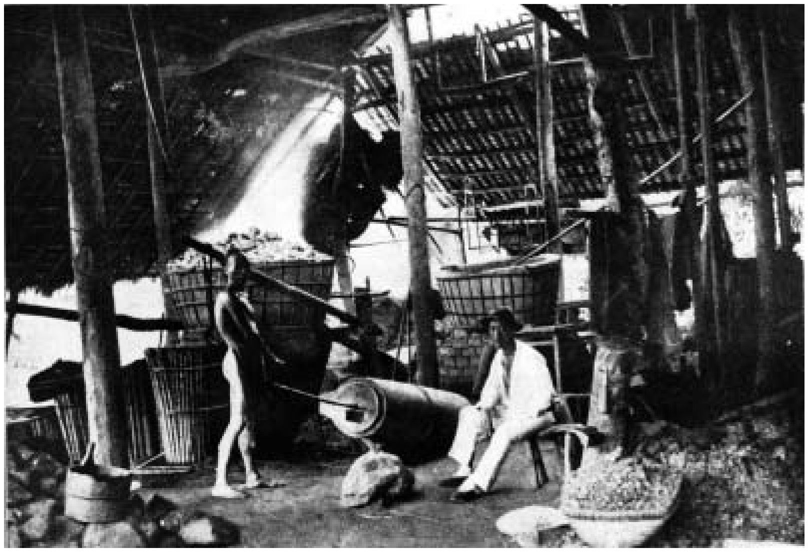


Figure 129 An ironworks in central China (either Jiangxi or Hunan), photographed ca. 1910. Reproduced from Lux (1912, p. 1407, fig. 5).

The use of coke for various other purposes was known from early times in China. The earliest reference to it is from the early +4th century,[137] and Hartwell points to two clear references to its use in the Song specifically in iron smelting.[138] Coke was also the fuel used in a number of traditional Chinese blast furnaces in the 19th and 20th centuries,[139] and it seems likely that this was the commonest fuel for those Song blast furnaces which did not use charcoal.[140]

The Song–Yuan blast furnaces which we know of were shaft furnaces, sometimes with an unusual construction but with a familiar internal form,[141] and the lessons learnt in our discussion of English coke-fuelled blast furnaces should hold for these. The transition from charcoal to coal or coke would have required higher temperatures and therefore a larger fuel consumption and greater blast volume and pressure. Those furnaces which were constructed by digging into the ground would have had much better thermal insulation than the free-standing furnaces with

[137] Letter from Chen Yun 陳雲 to his brother, *TPYL*, ch. 605, p. 5a, translated by Peter Golas in *SCC*, vol. 5, part 13, pp. 193–4; see also Read (1940, pp. 125–6).

[138] *XZZTJCB*, ch. 164, p. 3955; *Ou yang Xiu quan ji*, ch. 118, p. 1819; Hartwell (1963, pp. 69–70; 1966, pp. 55–7). Another clear reference is *Yi jue liao za ji*, ch. 1, pp. 11b–12a.

[139] See e.g. Tegengren (1923–24, pp. 316, 317, 339, 354).

[140] It has sometimes been suggested that the coking process may have been forgotten after the Song, perhaps because Song Yingxing does not mention it (Elvin, 1975, p. 91); but various entirely traditional methods were in use in the early 20th century, and there is no reason to suppose that the process was forgotten and reinvented. Lux (1912); Woo (1906).

[141] Box 1, Figure 10, p. 14 above.

which we are more familiar, and this may have reduced the blast requirement to some extent.

The pig iron produced probably contained a high level of sulphur, unless the effectiveness of limestone as a desulphuriser was understood and applied. But this would have necessitated even higher temperatures, and an even more powerful blast. With human-powered bellows, or with the light undershot water-wheels which seem to have been the rule in pre-modern China,[142] it seems doubtful that the necessary temperatures for desulphurisation were reached. It is important to keep in mind that I am only guessing here: the question cannot be answered with any confidence until slag analyses become available from relevant blast-furnace sites.

Sulphur levels even as low as 0.1 per cent make wrought iron or steel almost unusable. Therefore, if effective desulphurisation was not practised in coal- or coke-fuelled blast furnaces, their product was probably not used as the raw material for making wrought-iron, but was used in foundrywork.

In an iron foundry the higher silicon content which we should expect in pig iron from a coal- or coke-fuelled blast furnace would normally be an advantage, reducing bubbles in the casting and making a grey-cast structure more likely. The higher sulphur content would not necessarily be a disadvantage. If there is approximately twice as much manganese as sulphur in the iron, the two combine to form harmless microscopic inclusions of manganese sulphide (MnS).[143] Even without manganese, the only important effect of sulphur in cast iron is to encourage a white-cast structure, which is very hard and brittle. In many applications, however, white cast iron is fully acceptable or even superior to grey-cast; see the discussion in Section 4(v) above.[144]

We do not know whether the Song iron smelters ever used wide-mouthed shallow blast furnaces like the one illustrated in *Tian gong kai wu*, or the one in Figure 129, and in any case we know nothing about the technical characteristics of such furnaces. They are so different from modern blast furnaces that we cannot assume that any of our modern knowledge of blast-furnace operation holds, regarding temperatures, blast requirements, or even the silicon and sulphur contents of the pig iron produced. In this situation of double ignorance there is nothing to do but to leave the whole question of this type of furnace on one side and hope for future enlightenment.

A charcoal iron industry does not inevitably cause deforestation. This depends very much on the long-term strategies of the ironmasters, and the extent to which they can defend their forest resources from other users of fuel; there are numerous examples in Chinese history of successful forest conservancy over generations.[145] The

[142] E.g. Zhang Baichun (1994).
[143] See e.g. Angus (1976, p. 20).
[144] Pp. 161–3.
[145] *SCC*, vol. 6, part 3, pp. 607ff *et passim*; note also Wagner (1985, pp. 33–7).

problem in all charcoal iron production is that, even with the best possible forest management, there is a definite upper limit on sustainable iron production per unit area of forest land. To produce more, it was necessary either to start up elsewhere or to find an alternative fuel. Both seem to have occurred in response to increasing demand in the Song: iron production increased in the heavily forested south, and coal came into use in the north. The details of these developments are not clear from available sources, but in broad outline this seems to be what occurred.

If it is true, as I have suggested above, that pig iron from coal- or coke-fuelled blast furnaces was not suitable for conversion to wrought iron, then the new fuel could not replace charcoal, but could serve as a supplement in the production of cast-iron products to fill a growing demand. I have earlier noted that a shift is visible in the Song away from the use of cast-iron implements in favour of the use of wrought iron;[146] but in a time of population growth and expanding and intensifying agriculture, there surely remained a considerable market for cheaper cast-iron implements. Demand must have been growing for numerous other cast-iron products as well, for example pots of all sizes, from ordinary cooking pots to enormous salt-boiling cauldrons. Iron coins, too, were made of high-sulphur cast iron.[147] I have been focusing here on the +11th century; a century later the precipitation method of copper production demanded large quantities of cheap iron, and could no doubt have been supplied by coal- or coke-fuelled blast furnaces.[148]

Pig iron from the blast furnace was either used in iron casting or converted to wrought iron by fining or puddling.[149] We do not know much directly about either of these processes as they were practised in the Song–Yuan period, but sources from earlier and later periods[150] do not show much difference in the methods used, and we may presume that the Song–Yuan methods were of the same general sort as those.

Shen Gua on steel and steelmaking

Some steelmaking methods of earlier periods have been discussed in Section 6(iii–iv).[151] For steel and steelmaking in the +11th century we have some very interesting descriptions by the polymath Shen Gua 沈括 (+1031–95) in his *Meng xi bi tan* 夢溪筆談 (Jottings from Dream Brook). The following 'jotting' is one of a number in his book which concern distinguishing the false from the true in different contexts. It describes two different steelmaking methods; though he describes one as 'true' and the other as 'false', both seem from a modern point of view to be quite correct:[152]

146 P. 285 above.
147 Analyses of 37 Song iron coins reported by Wayman and Wang (2003) show sulphur contents ranging from 'undetected' (below about 0.1) to 2.05 per cent. On the iron coinage of the Song period see pp. 286–9 above.
148 *SCC*, vol. 5, part 13, pp. 370–86.
149 On these processes see pp. 16–18, 30–4.
150 Pp. 16–18, 30–4, 242–5 above.
151 Pp. 255–67, 272–7.
152 *Meng xi bi tan*, ch. 3, Hu Daojing (1962, no. 56, p. 135).

What the general run of blacksmiths call 'steel' [*gang tie* 鋼鐵] [is made as follows]. Take wrought iron [*rou tie* 柔 [= 鍒] 鐵], bend and coil it, and insert cast iron into the interstices. Seal with clay, 'refine' [*lian* 煉] it, and hammer to cause [the soft iron and the cast iron] to interpenetrate. [The product] is called *tuan gang* 團鋼 or *guan gang* 灌鋼 ['combination steel' or 'irrigated steel'].[153]

But this is nothing but false steel. It temporarily borrows the cast iron to provide hardness, but in two or three 'refinings' [*lian* 煉] the cast iron becomes 'cooked' [*shu* 熟 , i.e. it becomes wrought iron, *shu tie* 熟鐵], and [the steel] is again soft iron. But if no one considers it false, this is only because they have never known true steel.

On an inspection tour I went to a smithy in Cizhou 磁州 [near modern Handan 邯鄲, Hebei],[154] and there I knew true steel for the first time. The presence of steel in iron is like that of gluten in flour. When 'soft' flour [*rou mian* 柔麵] is thoroughly washed, the gluten appears. 'Refining' steel is similar. One merely takes excellent iron [*jing tie* 精鐵][155] and hammers it for a hundred or more heats [*huo* 火]. After each hammering it is weighed; with each hammering it becomes lighter. When the point is reached at which repeated hammering does not cause the weight to decrease, it is pure steel. This may be 'refined' a hundred times with no loss.

This [true steel] is the essence of iron [*tie zhi jing chun* 鐵之精淳]. Its colour is pure and bright, and when polished it is dark blue–black, unlike ordinary iron.

There are also [irons] which, 'refined' to completion, contain no steel at all. These are always associated with the products of [particular] regions.[156]

The first process described here is a 'co-fusion' process, already discussed in Section 6 above.[157] It would make excellent steel, and it is difficult to understand Shen Gua's belief that this was 'false steel'. When he says that it will lose its hardness if it is 'refined' several times, this may go back to a misunderstanding of a direct observation. If an inexperienced smith requires too many reheatings and hammerings to shape what he is making, some of the carbon will be burned out of the steel, so that it does indeed revert to being wrought iron. But it is unlikely that this was more true of one kind of steel than another.

The method described by Shen Gua for making 'true steel' seems to be to heat the wrought iron repeatedly in the smithy hearth, using a high temperature and a great deal of charcoal so as to provide an atmosphere rich in carbon monoxide. This is a cementation process.[158] The iron takes up some carbon on its surface, and hammering distributes this carbon more uniformly through the piece. A process something like this was used in 18th-century Norway and Sweden.[159]

153 Cf. Sun and Sun (1966, p. 250); Needham (1958, pp. 30, 33). Another possible interpretation for *tuan gang* would be 'lump steel'. See pp. 256, 270, 324, 341–2, 346.

154 The inspection tour was in +1075 (Hu Daojing, 1962, p. 135).

155 A different interpretation of *jing tie* is given by Duan Yibing (1993).

156 *Jie xi di zhi suo chan* 皆繫地之所產. I suspect that *xi* may be a scribal error for some other character, so that the sentence might mean, 'These are always the product of regions which are X [*xi*].'

157 Pp. 255–67.

158 See pp. 66–9 above.

159 The Norwegian and Swedish sources are translated and discussed in Wagner (1990). Rehder (1989) gives what he believes is a proof that carburisation of iron in an open hearth is impossible, but he is clearly mistaken.

The most important reason for the iron losing weight in the process is that it contains a significant quantity of non-metallic inclusions (slag) which are removed by hammering. It is also possible that some of the iron may be burned away, though great efforts would be made to avoid this as it would remove the carburised outer layer.

When Shen Gua says that some irons cannot be made into steel in this way, and that this has to do with their place of origin, he is probably correct. If the iron has a significant phosphorus content it does not take up much carbon in a cementation process like this one. This seems to have been the most important reason why Swedish iron was used in 19th-century British steelmaking: it had much less phosphorus than most British iron.

Here and elsewhere (see below) Shen Gua associates steel with a dark or black colour. This is not a natural colour for steel, which when polished has a mirror-like appearance, but there are Chinese references as far back as the +3rd century to 'dark armour' (*xuan kai* 玄鎧, *xuan jia* 玄甲) and other indications that the best ferrous material was expected to be black.[160] It seems likely that a blue or black surface colour was commonly produced on iron and steel by some chemical process similar to 'gun-blueing'.

We can imagine the problems a pre-modern natural philosopher would have had in understanding how steel could be made by either of two such different processes. The first looks like a matter of combining something extremely hard (white cast iron) with something soft (wrought iron) to obtain something with an intermediate hardness ('false steel'). The second would have looked very like a process of purification, and the idea that the iron takes up from the fire something which makes it hard would have seemed very strange. Hence Shen Gua's conclusion that true steel is a component of wrought iron like the gluten in flour.

Gluten shows up again in another note, on the hardening of wrought-iron or steel armour plate by cold work:[161]

The Qiang 羌 people of Qingtang 青堂 [near modern Xining 西寧, Qinghai] are skilled at forging armour. The colour of the iron is blue-black, so clear and bright that it can mirror a hair. They use musk-deer leather for the thongs to string it together – it is soft, thin, and tough.

In Zhenrong Military Prefecture 鎮戎軍[162] there is a suit of iron armour which is carefully preserved and handed down as an heirloom. When Han Wei-gong[163] 韓魏公 was serving as Military Commissioner[164] of Jingyuan 涇源 he took it out and tested it. At a distance of fifty paces he shot it with a strong crossbow and was unable to penetrate it. One arrow

[160] Dien (1982, e.g. pp. 15, 16).

[161] *Meng xi bi tan*, ch. 19, Hu Daojing (1962, no. 333).

[162] Modern Guyuan 固原, Ningxia, about 300 km east of Qingtang.

[163] Han Qi 韓琦 (+1008–75), a great statesman who served as Prime Minister under three Emperors. Shen Gua refers to him several times: see Hu Daojing (1962, nos. 271, 508, 570).

[164] *Shuai* 帥, a common unofficial term for *jing lüe an fu shi* 經略安府使. Jingyuan was probably in the general vicinity of modern Jingyuan County, Ningxia; but the usual reference works do not mention a place named Jingyuan in the Song period.

did penetrate an armour scale: this one hit a drill-hole, and was pared down by the drill-hole, all of the iron curling back. Such was its hardness.

The method of forging the armour is as follows. At the start it is very thick. They do not use fire, but cold-hammer until the thickness is reduced by two thirds; it is then complete. At the end they leave unhammered some remaining gluten, indistinct and like warts. They wish to demonstrate the thickness before hammering, just as the dredgers of rivers leave behind 'sea cucumbers' [*tu sun* 土筍].[165]

Today there are people who falsely raise faint warts on the backs of armour scales. Even if warts are made, if the original [material] is not fine steel [*jing gang* 精鋼], or if [the armour] is made by hot-forging, then they have no function, but are merely an external ornament.

Cold-forging is a quite good method of hardening any metal. It was used extensively in the ancient West for bronze, but very rarely before modern times for iron. In China, by a curious contrast, it was rarely used for bronze but often for iron.[166]

Cold work with a reduction of 67 per cent, as described here, might approximately double the strength of the steel.[167] The 'warts' may represent spots of higher-carbon steel in the original material, for pre-modern steel is virtually always inhomogeneous. If the object is subsequently heated above the recrystallisation temperature of iron, about 450°C, the hardness obtained by cold work is lost.

Finally, we see a bit more of +11th-century steel in another piece by Shen Gua, this time in a philological note on some ancient names of swords:[168]

Among the names of ancient swords are Zhanlu 沈盧 and Yuchang 魚腸. The character 沈 is pronounced *zhan* 湛;[169] [the name *Zhanlu*] refers to its clear – *zhan zhan ran* 湛湛然 – black colour. [*Lu* means 'black'.]

The ancients used *ji* 劑 steel [see below] to make the edge and wrought iron to make the haft [*jing* 莖] and 'trunk' [*gan* 榦, i.e. the spine]. Otherwise they would often snap. In swords made of steel the edge is often damaged, and this is the origin of the name Juque 巨闕 ['Great Notch']. Thus one cannot use *ji* steel by itself.

Yuchang 魚腸 ['Fish Gut'] was what today is called a *pan gang* 蟠鋼 ['coiled steel'] or *song wen* 松文 ['fir patterned'] sword. If one takes a fish, bakes it, and strips off the ribs to reveal the guts, it has a distinct resemblance to the pattern on a modern *pan gang* sword.

The word *ji* 劑 has several potentially relevant meanings. In medicine it commonly means a 'concoction' of medicinal ingredients, and an extension of this meaning is 'alloy'.[170] On the other hand, in cooking it means a lump of dough taken from a

[165] Presumably underwater sand- or mud-banks resembling the large worms called in English 'sea-cucumbers' or 'bêches-de-mer', in Chinese *tu sun*, lit. 'earthen bamboo-shoots'.

[166] See e.g. Wagner (1993, pp. 280–1); for example, I saw two smiths hardening a hoe-head by cold work in Kaifeng in 1987.

[167] Offer Andersen (1984, p. 265).

[168] *Meng xi bi tan*, ch. 19, Hu Daojing (1962, no. 325). The three sword names mentioned are found in the Eastern Han books *Wu Yue chun qiu* 吳越春秋 and *Yue jue shu* 越絕書 (see e.g. Wagner, 1993, pp. 111–15). Most of the names seem to be transcriptions of non-Chinese words, but Shen Gua is not the only writer to treat them as having meaning in Chinese.

[169] Some editions treat the three characters 沈音湛 as a comment and print them in a smaller size than the main text.

[170] See e.g. p. 287 above.

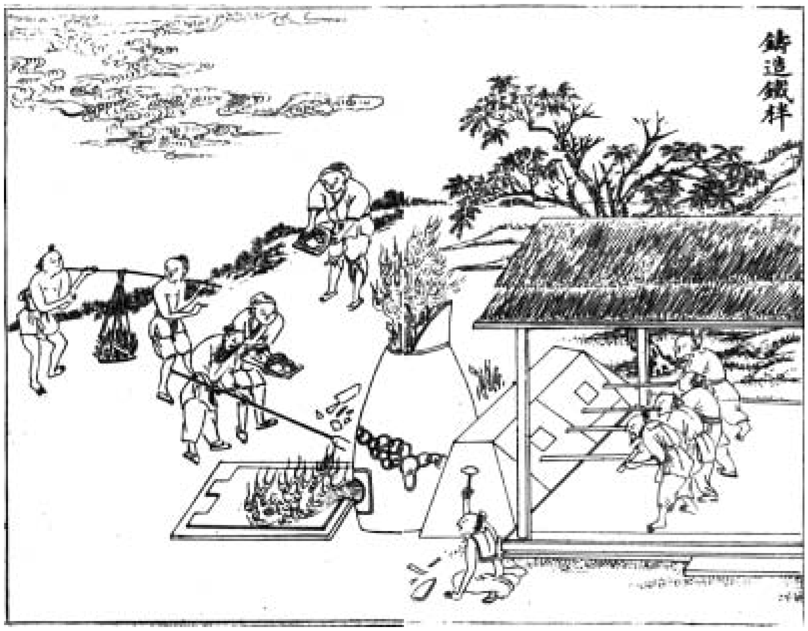


Figure 130 Operation of a Yuan-period cupola furnace, casting large cauldrons for salt-boiling. Orig. *Ao bo tu* (+1334); reproduced here from the 18th-century *SKQS* edn., ch. 2, pp. 31b–32a. Cf. Needham (1958, pp. 15–16, 25, pl. 15, fig. 25); Yoshida Tora (1983, p. 39; 1993, pp. 234–5). The version reproduced by Needham is a 20th-century copy by Luo Zhenyu (1914–17).

larger mass, for example in the making of dumplings. Thus *ji* steel could mean 'combination steel' or 'lump steel', the same two possibilities that I have suggested above for *tuan* 團 steel.[171]

A pattern on a steel sword can be made by variations in carbon and phosphorus content, which become visible when the sword is polished and then etched with acid. The mention of 'fish-gut' patterning has already been discussed in Section 6 above.[172]

A Yuan-period cupola furnace

On the melting and casting of iron in the Song and Yuan we seem to have only one source, a description of the casting of salt-boiling pans at Huating 華亭, near modern Shanghai, by Chen Chun 陳椿 in the period +1333–35. His book, *Ao bo tu* 熬波圖, has been studied and translated by Yoshida Tora and Hans Ulrich Vogel.[173]

A late version of Chen Chun's illustration of the melting furnace is shown here in

[171] Pp. 256, 270, 321, 341–2, 346.
[172] Pp. 258–60.
[173] Yoshida (1993).

Figure 130. It is a cupola furnace with the blast provided by two man-powered single-action box-bellows. Chen Chun states that the furnace was built of 'pitcher sand, white earth, charcoal powder, and wheat ears mixed with clay'.[174] It is charged with equal parts by weight of old iron pots and charcoal. The mould for a large salt-boiling pan, or for a part of a very large pan, is seen dug into the earth in front of the furnace: when the clay seal of the tapping hole is broken out, the molten iron flows through a channel into the mould.

[174] *Bing sha, bai shan, tan xie, xiao mai sui he ni* 瓶沙白炭屑小麥穗和泥. I follow the translation of Yoshida (1993, p. 141).

8 ECONOMIC EXPANSION IN THE MING PERIOD

After the 'commercial revolution' of the early Song and a period of economic stagnation in the Southern Song and Yuan periods, the Ming was a period of economic expansion. Trade, both inter-regional and international, developed greatly in the course of this period.

A consequence of the expansion of trade was that iron production became concentrated in certain regions: certainly Guangdong, perhaps also Shanxi and Hunan. At the same time iron production died out in regions like the Yangzi Delta and large parts of the north, whose comparative advantage lay in other economic activities.[1]

One example of the expansion of trade can be seen in the history of the state ironworks at Zunhua, to be studied in detail further below. At the beginning of the dynasty, good low-sulphur wrought iron for weaponry was produced only in the south, but transportation and trade were not sufficiently developed to provide a sure supply in Beijing. The Zunhua ironworks was established around +1438 to provide the necessary iron using southern technology. For almost 150 years Zunhua produced iron, at great financial expense and great cost to the forest resources of the region, but by 1581 commerce had developed to such an extent that good wrought iron from the south could be reliably obtained for one-quarter of the cost of producing it using convict, conscript, and corvée labour in Zunhua. Continued operation had by this time become absurd, and the Zunhua ironworks was closed.

The southern iron I have mentioned came, in the early Ming, from Jiangnan 江南 (the Yangzi Delta). This was a major iron-producing region in the Yuan and early Ming,[2] but in the course of the Ming its place was taken by a region further south, centred on the mountains of western Guangdong. The large-scale iron industry of Guangdong in the late Ming has already been described in some detail in Section 2 above.[3] This industry had had some importance in the Song and Yuan periods,[4] but seems to have expanded greatly in the Ming; a development which undoubtedly owed much to the expansion of trade. In the late Ming and early Qing, when we are able to see this industry clearly in the sources for the first time, it was supplying high-quality iron and iron products to all of coastal China and Southeast Asia.

Any discussion of iron technology in the Ming period must take as its basic sources three excellent technical descriptions, the best we have for any period of pre-modern China. These are Fu Jun's 傅浚 description of the technology used at Zunhua,

[1] Cf. pp. 279 above and 330 below.
[2] Pp. 329–30 below.
[3] Pp. 47–59.
[4] Table 4, items 9–16; Schurmann (1967, pp. 161–2).

Qu Dajun's 屈大均 description of that of Guangdong, translated and discussed in Section 2(iv) above,[5] and finally the description of iron-production technology in Song Yingxing's 宋應星 famous technological compendium *Tian gong kai wu* 天工開物. This Section will first consider Fun Jun's text in its full historical context, then give a detailed study of Song Yingxing's section on iron-production technologies.

(i) The State Ironworks in Zunhua, Hebei, 1403–1581

It has often been remarked that bureaucracy favours the historian, for it produces great quantities of paper which later become historical sources. The Ming state ironworks in Zunhua 遵化, Hebei, provides a good example: its administration, especially the management of a large force of corvée, conscript, and convict labour, gave the officials of the Ministry of Works (*Gong bu* 工部) enough trouble that a good deal of written communication was required, and some of this has survived to tell us about both the technology and the organisation of the works.

We have in particular a description of the blast furnaces in which the iron was smelted and some quantitative information about inputs of ore, fuel, and labour and outputs of cast iron, wrought iron, and steel. Several authors have studied the details of the administration of the Zunhua works, especially the organisation of the labour force.[6] Here I shall concentrate on the more technical aspects of its operation, but also attempt to place it in its historical context.

Background

Zunhua District (modern Zunhua County, Hebei) lies about 150 km east of Beijing, very close to the Ming Great Wall, and was thus a militarily important peripheral region. Numerous garrisons were stationed here and in neighbouring districts, and these provided a significant part of the labour used by the ironworks.

There was some iron production near here as early as the Warring States period,[7] and possibly in the Tang.[8] Hebei was a very important iron-producing region in the Song[9] and the Yuan.[10]

In the early years of the Ming, state involvement in the iron industry was a contentious issue.[11] Starting in +1364, before the final consolidation of Ming power, state ironworks were established piecemeal in various places throughout the Empire; in 1374 there were thirteen (none anywhere near Zunhua). In 1382 the Emperor ordered an official flogged because he proposed the establishment of

[5] Pp. 48–53.
[6] See e.g. Sakuma Shigeo (1972); Eberstein (1974, pp. 33–7); and several other studies which they cite.
[7] See p. 87 above.
[8] *Da Ming yi tong zhi*, ch. 1, p. 8a; Eberstein (1974, p. 33).
[9] Table 4, items 19–22, pp. 295–8 above.
[10] This is stated in a memorial by Wang Yun 王惲 in the 1260s. See *Qiu jian xian sheng da quan wen ji*, ch. 90, pp. 19a–b; cf. *Chun ming meng yu lu*, ch. 46, p. 68b; Eberstein (1974, p. 33).
[11] The following is largely based on Eberstein (1974, pp. 23–32).

one more, and in 1385 all the state ironworks were closed, 'because they weary the people'.[12]

In the following years many of these state ironworks were reopened, but then in 1395 all were again closed. The order was repeated in 1397, presumably because it had not been obeyed; in 1398 it was ordered that the state ironworks should be opened again for one year, then closed.

The political background of all this opening and closing of state ironworks is not easy to see in the sources, but presumably the fundamental factor was conflict between local and national interests.[13] The central government needed a dependable production of iron to supply the armies with weapons, but the ironworks demanded corvée labour to an extent which conflicted with the interests of the local gentry. No doubt there were also many places where the state ironworks competed directly with local ironmasters.

Zunhua

After 1398 the only major ironworks established and administered by the central government was the one in Zunhua. The reason for the special status of Zunhua seems to have been a need for high-quality wrought iron and steel, smelted and fined with charcoal, conveniently near the capital. We have seen in Section 7(iii) above[14] that by the Song period population growth in north China had led to increased pressure on the land, increased demand for iron, and forest destruction, so that it was necessary to substitute mineral coal for charcoal in iron production. (In the south, charcoal iron production continued.) Iron produced using mineral fuel would have had a high sulphur content: this does not matter much in foundry-work, and there is indeed some evidence that in the Ming, in north China, agricultural implements were generally cast rather than wrought.[15] But fining this iron to produce wrought iron would have resulted in an inferior, 'red-short', product.

Peripheral regions like Zunhua were undoubtedly the last places in north China where significant forests remained and charcoal iron could be produced economically. Further north, in the province of Liaodong, 25 small ironworks were established in the Ming garrisons in 1411.[16] Half of the 120 soldiers assigned to the ironworks 'fined iron' (*chao tie* 炒鐵) while the other half engaged in agriculture to support them. Presumably the soldiers also produced the cast iron to be fined, using small blast furnaces, but it was fining that would have required the most labour. The annual production quotas of the individual ironworks varied from 4 to

[12] *MSL*, Tai-zu 太祖, ch. 176, p. 5b; Li Guoxiang and Yang Chang (1993, p. 120).

[13] We seem to have no sources on this issue with respect to iron production, but one source notes a proposal to start *lead* mining in Zunhua which came to nothing because of opposition by the local gentry (*shi shen* 士紳). *Chun ming meng yu lu*, ch. 46, p. 70b.

[14] P. 311ff.

[15] E.g. *Chun ming meng yu lu*, ch. 46, p. 66b.

[16] *MSL*, Tai-zong 太宗, ch. 115, p. 5a; Li Guoxiang and Yang Chang (1993, p. 121); *Huang Ming shi fa lu*, ch. 61, pp. 8a–16a; Eberstein (1974, p. 38).

19 tonnes, with an average of 10 tonnes. The total of about 250 tonnes per year appears to have been the production of 1500 soldiers (half of a total of 120 × 25); the labour required was thus about 6 man-years per tonne.[17] In the Dabieshan region, production of wrought iron from ironsand and charcoal by traditional methods required only 2–4 man-months per tonne: more labour-efficient by a factor of more than *twenty*.[18]

In Zunhua and neighbouring districts a number of garrisons were established in the early Ming.[19] That these garrisons, like those in Liaodong, engaged in wrought-iron production is made clear by a memorial of 1403 which mentions convict labourers 'fining iron' in Zunhua.[20] This production seems to have become more important as time went on, and in 1426 a major decision was made:[21]

> [An official memorialised:] For the production of weapons there is a shortage of wrought iron, and we request permission to purchase it at various places in the Jiangnan 江南 region. However, because of the distance involved, we are afraid that it will not be delivered on time, and we propose to send people to the ironworks at Zunhua to fetch 20,000 *jin* 斤 [12 tonnes] to meet immediate needs.
>
> The Emperor replied: If iron is available in Zunhua, why purchase it in Jiangnan? Iron is heavy and clumsy, and transporting it would be a burden to the people . . . It will be sufficient to obtain it in Zunhua.

As we shall see directly below, this was the beginning of a process which resulted in the creation of an entirely new organisation for the production of iron for the state, including a large walled ironworks in the mountains in the southeast corner of Zunhua District.

The mention of Jiangnan (the Yangzi Delta: southern Jiangsu, southern Anhui, and Zhejiang) as a source of iron is a surprise, for this region is usually said to be very poor in iron, importing most of its iron from Fujian and other more southerly provinces.[22] However, other sources indicate that this was one of the major Chinese iron-production regions in the Yuan period, and that it had some importance in the Ming as well.[23] According to a Ming gazetteer, the industry died out here because it

[17] The figure of 120 soldiers, of whom half engaged in agriculture, is given in the *Ming shi lu* (cited above). Unfortunately it is not made explicit whether this was the total number or the number at each of the 25 ironworks. If 120 is in fact the total number, then the labour used would be only 3 man-months per tonne, fitting nicely with the Dabieshan figure; but the higher figure is supported by the later production figures for the state ironworks at Zunhua (pp. 334–7 below).

[18] Pp. 13, 17 above; also Wagner (1985, p. 2). And an engineer, reviewing Wagner (1985) in *Neue Zürcher Zeitung*, called the Dabieshan productivity *ein Elend*, miserable, compared with modern methods. Voiret (1986).

[19] *Da Ming yi tong zhi*, ch. 1, pp. 19a–b.

[20] *MSL*, Tai-zong 太宗, ch. 20a, p. 4b; cf. Eberstein (1974, pp. 33, 55 n. 37).

[21] *MSL*, Xuan-zong 宣宗, ch. 14, p. 5a; Li Guoxiang and Yang Chang (1995, p. 790). An abridged quotation of this memorial in Fu Weilin's unofficial history, *Ming shu* (ch. 82, pp. 1669–70) omits the word *shu* 熟, 'wrought', so that the memorial appears to concern iron in general rather than specifically *wrought* iron (see also *Chun ming meng yu lu*, ch. 46, p. 70b). This confused Eberstein (1974, p. 35), who was unaware of the version in *Ming shi lu*. The event is also briefly noted in *Guo que*, ch. 19, p. 1285.

[22] Li Bozhong (1987; 2000, pp. 299ff). Eberstein (1974, p. 35) interprets the term broadly, as the entire region south of the Yangzi, but in fact 'Jiangnan' was a well-defined toponym with the more limited meaning given here.

[23] *SCC*, vol. 5, part 13, pp. 157–8; *Yuan shi*, ch. 94, p. 2384; Schurmann (1967, pp. 161–2); Eberstein (1974, pp. 26, 42–3).

became unprofitable; clearly, commercial development in Jiangnan moved the region's comparative advantage into other activities.[24]

Zhejiang in the 19th and 20th centuries had a traditional small-scale iron industry based on charcoal and ironsand, and this technology could well go back to the early Ming or before.[25] At Zunhua, as we shall see, the same fuel and ore were used. We are accustomed to thinking of iron from Guangdong as being the best in China, but it may very well be that there were advantages – real or imagined – in the use of ironsand iron, produced in small furnaces, for weapons production.[26] It is quite possible that the garrison ironworks established in the border regions near Beijing, including Zunhua, used technology imported from Jiangnan.[27]

Establishment

Three months later a military commander in Jizhou 薊州 Subprefecture (which included Zunhua) noted a 'recent' order to reopen the ironworks at Zunhua and resume iron fining, 'using military and corvée labour as before', and reported that the order was giving difficulties.[28] The 'thousand' soldiers from four nearby garrisons who had worked at the ironworks had long since been sent home, and the 'thousand' peasants from six districts in Yongping Prefecture 永平府 (east of Zunhua) had been assigned other corvée duties. Further, this was a busy agricultural season, and the peasants should not be disturbed in their work at this time. He therefore requested permission to use soldiers from a long list of military units, some quite far away, and only after the harvest was completed go back to the system of using peasants and soldiers from border districts. This is our only information about the earlier arrangements at Zunhua: if we trust the 'thousands' of soldiers and corvée labourers to indicate the order of magnitude of the labour force, it was already a major industrial complex in its earlier period of operation.[29]

Labour problems continued, and in 1432 a military officer at Zunhua reported that the available workers were not familiar with fining; he was given permission to bring in metallurgical experts (*an lian zhi ren* 諳煉之人) from elsewhere.[30] In 1435 the newly enthroned Emperor Ying-zong 英宗 ordered the Zunhua ironworks closed, but the next year it was reopened.[31] Another source has this reopening in 1438;[32] probably a major reorganisation and relocation occurred in this three-year period,

[24] *Jia jing Hui zhou fu zhi*, ch. 7, p. 14b.

[25] See *SCC*, vol. 5, part 13, p. 164; also von Richthofen (1872, pp. 47, 52); Hommel (1937, p. 28); Yang Dajin (1938, vol. 2, pp. 313–15); Wagner (1985, pp. 28–9).

[26] For example, ironsand iron usually has a significant titanium content, and this can be an advantage in steel.

[27] Perhaps it is significant that one of the later directors of the ironworks, Fu Jun, came from Fujian, another place where this technology was used. See p. 332 below.

[28] *MSL*, Xuan-zong 宣宗, ch. 17, pp. 4a–b; Li Guoxiang and Yang Chang (1993, p. 122; 1995, p. 790).

[29] On the complex corvée arrangements in this region in the Ming, see Gao Shouxian (2003).

[30] *MSL*, Xuan-zong 宣宗, ch. 95, p. 10b; Li Guoxiang and Yang Chang (1995, p. 791).

[31] *MSL*, Ying-zong 英宗, ch. 24, p. 9b; Li Guoxiang and Yang Chang (1995, p. 791).

[32] *Da Ming hui dian*, ch. 194, pp. 17a, 19a.

and from this time the ironworks operated continuously for almost 150 years. In 1507 a long memorial concerned with various administrative reforms at the Zunhua ironworks, by an otherwise unknown official, Han Dazhang 韓大章, included a good deal of archival information on the works as it had operated in 1438. Its early history, and its ecological consequences, are summarised as follows:[33]

Investigation indicates that the Zunhua ironworks was established at Shapogu 砂坡谷 in the Yongle 永樂 period [1403–24]. It was later moved to Songzhagu 松柵谷, and in the Zhengtong 正統 period [1436–49] it was moved to its present location at Baiyezhuang 白冶庄 ['White Smelter Village'].[34] At that time the forests were flourishing, and it was not difficult to supply firewood and charcoal. Now, over a hundred years after its establishment, the trees have all been felled and the prices of wood and charcoal are high. If nothing is done to restrict [forest use], within ten years the price will have risen by several-fold.

(Later, in the Qing period, forestry was forbidden in this region because of the proximity of the Imperial tombs, and in 1917 the forests were thriving; but by 1928 deforestation was again a problem here.[35])

One aspect of the reorganisation of 1438 seems to have been the building of a wall around the new works at Baiyezhuang. The early sources do not mention this wall, but the site is today the village of Tiechang 鐵廠 ('Ironworks'), which according to a modern local gazetteer has a stone wall 10 m high, 5 m thick, and 2000 m in circumference.[36] It can be seen in Figure 131, a satellite photograph taken in 1967. This massively walled village deep in the mountains is an extreme oddity, and it had military significance long after the ironworks was closed. It was a factor in 1638 in the Qing conquest of the region, and in 1938 and 1942 in the Japanese invasion.[37]

Still another aspect was a reduction of the labour force by half, to 683 corvée labourers and 465 soldiers.[38] These were in addition to convict labourers and skilled craftsmen. There is more information about these labourers, their organisation, their tasks, and their productivity, but before dealing with this material we must look at their technology.

[33] Han Dazhang in *HMJS*, *bu yi* 補遺, ch. 2, pp. 7a–b; variant text, *Chun ming meng yu lu*, ch. 46, pp. 67a–b; *Tian fu guang ji*, ch. 21, pp. 287–8. All that is known of Han Dazhang is that he received his *jinshi* degree in 1493 (Zhu Baojiong and Xie Peilin, 1980, pp. 1497, 2485).

[34] Shapogu and Songzhagu are places in the north of Zunhua District, at or near mountain passes.

One reason for the two relocations of the ironworks, as well as the building of its wall after the second relocation, may have been their proximity to the border and vulnerability to attack by Mongol raiders.

The two names are also found in the sources with *yu* 峪 for *gu* 谷, *sha* 沙 for *sha* 砂, and peng 棚 for zha 柵. *Da Ming yi tong zhi*, ch. 1, pp. 16a, 23a; *Da Qing yi tong zhi*, ch. 46, pp. 1a, 1b, 1b–2a; *Ming hui yao,* ch. 194, p. 984. Baiyezhuang is presumably named for the nearby mountain Baiyeshan 白冶山, where a legendary smith, 'Master Baiye', produced swords. *Da Qing yi tong zhi*, ch. 45, p. 4b.

[35] Anon. (1928, pp. 36–7).

[36] Anon. (1990c, pp. 61, 561). Some sort of reconstruction or repair of the wall may have occurred in the Hongzhi 弘治 period (1488–1505). Zhang Gang (2000, p. 70, fn. 5) notes briefly a stone inscription of this date entitled *Chong jian tie ye chang cheng bei ji* 重建鐵冶廠城碑記 (Stele to commemorate the reconstruction of the ironworks wall).

[37] *Ming shi*, ch. 273, p. 7006; Anon. (1990c, p. 61).

[38] *MSL*, Ying-zong 英宗, ch. 46, p. 4b; Li Guoxiang and Yang Chang (1995, p. 792); Han Dazhang in *HMJS*, *bu yi* 補遺, ch. 2, pp. 1a–2b; *Da Ming hui dian*, ch. 194, pp. 19b–20a.

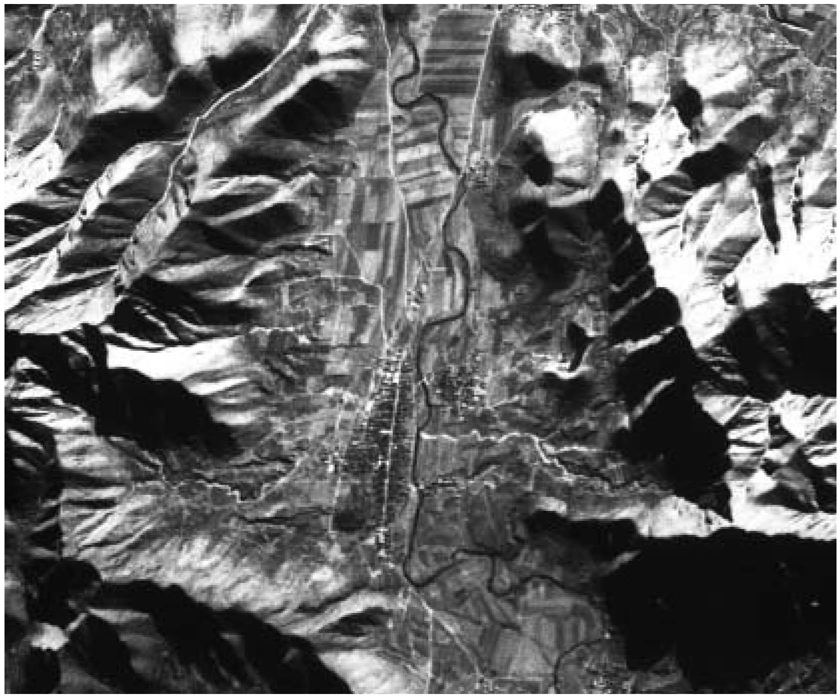


Figure 131 Satellite photograph of the village of Tiechang 鐵遵 in Zunhua County 遵化縣, Hebei, 20 December 1967. South is upward. United States Geological Survey, Global Land Information System, CORONA photograph DS1102-2167DF004. On the CORONA photographs see e.g. Philip et al. (2002) and the web-site http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB13/index.html.

Fu Jun's Description of Technology at Zunhua

Iron production at Zunhua was described in some technical detail in a book by one of its directors. Fu Jun 傅浚 was a native of Nan'an 南安 in Fujian. He received his *jin shi* 進士 degree in 1499, and in 1513 was placed in charge of the Zunhua ironworks. While in office he wrote a book entitled *Tie ye zhi* 鐵冶志, 'Treatise on the ironworks', seemingly a kind of local gazetteer.[39] The book is no longer extant, but it is described briefly in the *Si ku* bibliography of 1798, among books which were considered politically acceptable but not important enough to be included in the *Si ku quan shu*:[40]

[39] The little we know of Fu Jun comes from the following sources: *Si ku quan shu zong mu ti yao*, ch. 17, p. 1759 (only source for the date 1513); *Nan an xian zhi*, ch. 14, pp. 1b–2a, 3b–4b (1973 repr. pp. 754–5, 760–2) (brief biographies of Fu Jun, his father, and his son); *Ben chao fen sheng ren wu kao*, ch. 30, pp. 13a–b (1971 repr. pp. 6431–2); Zhu Baojiong and Xie Peilin (1980, pp. 738, 2488).

[40] *Si ku quan shu zong mu ti yao*, ch. 17, p. 1759. On the *Si ku quan shu* and the literary inquisition which accompanied its compilation see e.g. Hummel (1944, pp. 120–2); Hung (1939); Goodrich (1966).

Tie ye zhi, in two *juan*, by Fu Jun in the Ming period . . . It includes 23 topics, from 'Forestry' [*shan chang* 山場] to 'Miscellaneous tasks' [*za zhi* 雜職], and begins with two illustrations, showing the administrative offices and the ironworks. It records the yearly input and output quantities in great detail, but is useless for evidential research [*kao zheng* 考證].[41]

It seems that we have quotations from Fu Jun's lost book in two books of the 17th century, by Zhu Guozhen 朱國禎 in 1622 and by Sun Chengze between 1654 and 1675.[42] Both describe the blast furnaces at the Zunhua ironworks in the same words, and it appears to be certain that this description was originally in *Tie ye zhi*.[43]

The Zunhua iron furnace has a depth of 1 *zhang* 丈, 2 *chi* 尺 [3.7 m]; a breadth of 2 *chi*, 5 *cun* 寸 [78 cm] in front and 1 *chi*, 7 *cun* [84 cm] in back; to the left and right 1 *chi*, 6 *cun* [50 cm]. In front there is a clearing of several *zhang* [a *zhang* is 3.1 m], the place for tapping the iron.

It is built entirely of stone. The door [forearch] is of *jian qian* 簡千 stone.[44] Oxhead stone [*niu tou shi* 牛頭石] forms the inside [*xin* 心].[45]

Black sand is the basis [*ben* 本] [the ore] and 'stones' [*shi zi* 石子] are an auxiliary [*zuo* 佐] [the flux]. Hour by hour they move downward [*xuan xia* 旋下]. A charcoal fire is used, and two bellows are installed to fan it. Iron can be obtained [i.e. tapped] four times in one day.

The stones are a marvel. They are produced [quarried?] at Shuimenkou 水門口.[46] Their colour is between red and white, rather like that of a peach-blossom. The largest are like a *hu* 斛 [grain measure, about 50 litres], the smallest like a fist. They are pounded and broken and thrown into the fire; then they transform and become liquid. If the 'stone centre' [*shi xin* 石心, apparently the furnace burden] becomes dry, and the sand [ore] cannot descend, it is remedied with this [the flux]. Then the sand begins to melt and turn to iron.

If not,[47] then the centre [*xin* 心, lit., 'heart'] is ill and does not melt [*xiao* 銷, can also mean 'disperse']. It is like a man whose heart is fiery [*xin huo da sheng* 心火大盛]. He takes a prescription [*liang ji* 良劑] to remedy it, his spleen and stomach are harmonised, and food and drink advance [are digested]. Such are the wonders of the Transformations [*zao hua* 造化, i.e. the workings of Nature].[48]

. . .

The 'refining' [*lian* 煉] of pig iron [*shengtie* 生鐵] is completed in three double-hours [*shi* 時].[49] Wrought iron [*shu tie* 熟鐵] is produced from pig iron by five or six 'refinings', and steel [*gang tie* 鋼鐵] is produced from wrought iron by nine 'refinings'.

The furnace begins feebly and then flourishes; after flourishing it declines. At the most it reaches 90 days, and then it is ruined.

[41] The editors go on to cite a single point on which the book can be used in evidential research, correcting an entry in the *Ming shi* 明史 concerning the organisation of the Ministry of Works (*hu bu* 戶部), which had administrative responsibility for the ironworks.

[42] *Yong chuang xiao pin*, ch. 4, pp. 94–5; *Chun ming meng yu lu*, ch. 46, pp. 68a–69a; *Tian fu guang ji*, ch. 21, p. 261.

[43] Liu Yuncai (1978, p. 25).

[44] The version in *Chun ming meng yu lu* has *jian gan* 簡干.

[45] I have been unable to identify the two types of stone.

[46] A place about 15–20 km southwest of the Zunhua district seat, probably at or near the modern village of Shimen 石門. *Da Qing yi tong zhi*, ch. 45, pp. 4b, 7a, 7b, 8a, ch. 46, p. 1b; Anon. (1990c, fold-out map).

[47] This paragraph is not in *Chun ming meng yu lu*.

[48] A reference to *Zhuang zi* (ch. 3a, Guo Qingfan, 1961, p. 262; tr. Graham, 1981, pp. 88–9), in which Heaven and Earth are compared to a furnace, and their Fashioner and Transformer (*zao hua*) to a great smelting master. Cf. *SCC*, vol. 2, p. 564, fn. e.

[49] This fits with the earlier statement that iron is tapped from the blast furnace four times per day.

This furnace is 3.7 m high, with an elliptical shaft only about 50 × 80 cm in section, and is thus extremely narrow in relation to its height. It is quite different from other traditional Chinese blast furnaces used for smelting ironsand.[50] That ironsand was the ore seems certain from the description, and this is confirmed by incidental mentions in Han Dazhang's memorial[51] and by Song Yingxing's mention of ironsand production at Zunhua in *Tian gong kai wu*.[52]

Fu Jun, or whoever wrote the description, was greatly impressed by the action of the 'stones' as a flux in the blast furnace. Ironsand is normally produced by sluicing river sand, as described in Section 2(i) above.[53] The product of the sluicing is an ore with 75–95 per cent iron oxides, the rest being largely quartz. A flux is not absolutely necessary in the smelting of such a rich ore,[54] but it can greatly improve efficiency. Yang Kuan identifies the 'stones' as fluorspar (CaF_2, also called fluorite), which is commonly used in modern steelmaking.[55] It has a low melting point, 1386°C, and can depress the melting point of a silicate slag below 1200°C.[56] This identification is certainly possible from the description, but needs confirmation from slag analyses.

Archaeology seems to be at odds with Fu Jun's description of the furnace. In 1991 the remains of eighteen blast furnaces were investigated at a site east of the village of Tiechang. The only publication of the investigation is a very short journalistic article, which states that the furnaces are built into hillsides (like those discussed in Section 7(iii) above),[57] and are 1–2 m high.[58] But Fu Jun states that the furnace is built entirely of stone, so these seem to be of quite a different type.[59]

Operating parameters

We have some input and output figures in two sources, the 'Collected statutes of the Ming dynasty' of 1587 and the memorial of 1507 by Han Dazhang, already mentioned.[60] Both are primarily concerned with administrative matters, and give a circumstantial (and highly confusing) account of changes through the long period in which the works functioned. However, both give concrete figures for the year 1438; these differ enough to indicate that they are independent sources, but are enough

50 See e.g. pp. 8–16 above and Wagner (1984; 1985).
51 *HMJS*, *bu yi* 補遺, ch. 2, e.g. pp. 2b, 3b, 4b (1964 repr., vol. 30, pp. 756, 758, 760).
52 Translated below, Box 12, pp. 341–2. Liu Yuncai (1978, p. 24–5) has a different interpretation.
53 P. 331; Figure 134 (p. 344 below); *SCC*, vol. 5, part 13, pp. 164–5, 246–55.
54 Box 1, pp. 14–15 above.
55 Yang Kuan (1960, p. 109); also Liu Yuncai (1978, p. 25).
56 Rosenqvist (1974, p. 333).
57 Pp. 308–11.
58 Chang Lijun (1991). The journalistic author seems to be entirely unaware that iron production in Zunhua had a unique history.
59 On the other hand, if Fu Jun's furnace was dug into the hillside, this would explain why he refers to its 'depth' rather than its height.
60 P. 331 above. *Da Ming hui dian*, ch. 194, pp. 18b–22a; Han Dazhang in *HMJS*, *bu yi* 補遺, ch. 2, pp. 1a–9b.

alike to be mutually confirming. The 'Collected statutes' give the following data for 1438:

Specialist artisans in Zunhua
  Charcoal production, 70 households
    producing 143,070 *jin* 斤 (86 tonnes)
  Ironsand production, 63 households
    producing 447.3 *shi* 石 (= hectolitres)
  Iron production, 60 households
Labourers from nearby places
  Corvée, 683 persons, working 6 months per year
  Conscripts, 462 persons, working 6 months per year
Craftsmen from more distant places, on rotating duty, 6 months every 4 years, 630 persons
Convict labourers, number not given, who fined iron.

Han Dazhang indicates that the labourers, working presumably under the supervision of the specialist households, performed such tasks as cutting wood, digging ironsand, working the furnace bellows, transporting materials, transporting iron to the capital, and maintaining buildings and walls. Some of the soldiers also did guard duty. He gives a good deal of information on the rations of grain and cloth which the state supplied to the specialist households, the labourers, and the convicts respectively.[61]

Annual deliveries of iron to the state from Zunhua varied in the 15th century between 300,000 and 400,000 *jin* 斤, i.e. 180–240 tonnes.[62] Using the labour figures above and making some casual assumptions about their interpretation suggests that labour expenditure may have been 4–5 man-years per tonne, i.e. of the same order of magnitude as the Liaodong military production noted earlier, perhaps slightly better.[63]

(Here it is necessary to note that the production figures for charcoal and ironsand in 1438 are not sufficient for the production of 180–240 tonnes of iron. Production of 180 tonnes of iron would require at least 500 tonnes of charcoal and 750 hectolitres of ironsand.[64] Probably the figures for 1438 are atypical, for the new ironworks' first year of production; but another possibility is that they represent only part of the charcoal and ironsand inputs. Perhaps the production of the labourers was registered separately from that of the specialist households.)

[61] *HMJS*, *bu yi* 補遺, ch. 2, pp. 1a–9b. He also gives some information on production of ironsand and charcoal per labourer which unfortunately is very difficult to interpret.

[62] Eberstein (1974, pp. 33–4).

[63] Pp. 328–9.

[64] The best fuel efficiency recorded for charcoal iron smelting (in Sweden in the early 20th century) is about $\frac{3}{4}$ tonne charcoal per tonne pig iron (see e.g. Tegengren, 1923–24, vol. 2, p. 334, fn.); in Dabieshan the corresponding figure was about 3 tonnes per tonne pig iron (Wagner, 1985, p. 33), and this is a much more realistic estimate for the Zunhua ironworks. Sluiced ironsand contains 50–60 per cent iron by weight, and one hectolitre would weigh at most 400 kg (the specific gravity of magnetite is 5.2).

Production increased for a time after this, and the labour force was reduced. Eberstein has collected, from a variety of sources, figures for delivery of iron products to the capital from Zunhua.[65] These, converted from *jin* 斤 to tonnes, are:

15th century	180–240	t
from 1483	180	t
1507	348	t cast iron, wrought iron, and steel
from 1509	292	t cast iron
	125	t wrought iron
	37	t steel
	454	t
from 1529	152	t cast iron
	125	t wrought iron
		steel production discontinued
	277	t
1581	125	t wrought iron

And *deliveries* of iron are not the whole story, for there was a considerable overproduction, and in 1507 the Zunhua ironworks had a stockpile of no less than 2100 tonnes.[66]

Meanwhile the input of labour was falling. The labour force in 1438, discussed above, had just been halved. In 1504 the corvée and conscript labour quotas were further reduced by 60 per cent.[67] Detailed calculation of labour productivity is even more risky here than for the earlier case, but in 1509 a tonne of iron cost perhaps somewhere around 2 man-years per tonne. The improvement from 4–5 man-years is no doubt largely attributable to 'learning by doing', that old stand-by explanation of economists, along with the organisational improvements with which our sources are primarily concerned. But it would seem that technical improvements were also taking place at this time.

That there may also have been technical advances is suggested by a passage in the 'Collected statutes of the Ming dynasty' of 1587. Perhaps this too is quoted from Fu Jun's *Tie ye zhi*.[68] The passage occurs in a chronological survey of the history of the Zunhua ironworks:[69]

[65] Eberstein (1974, pp. 33–4).

[66] 1400 t cast iron, 450 t wrought iron, 136 t steel, and 127 t of a type of iron called *song tie* 鬆鐵, apparently an intermediate product, perhaps to be translated 'spongy iron'. Han Dazhang in *HMJS*, *bu yi* 補遺, ch. 2, p. 6b; Eberstein (1974, p. 34). Note the typographical error, *tong tie* 銅鐵 for *gang tie* 鋼鐵, in Han Dazhang's text.

[67] Han Dazhang in *HMJS*, *bu yi* 補遺, ch. 2, pp. 1b, 3a, 3b.

[68] See pp. 332–4 above. But this assumption would imply that Fu Jun wrote *Tie ye zhi* after 1529, sixteen years after his first appointment at Zunhua.

[69] *Da Ming hui dian*, ch. 194, pp. 21a–b.

In the 4th year of Zhengde 正德 [1509], ten *da jian* furnaces 大鑑爐 were in operation, producing 486,000 *jin* 斤 [292 tonnes] of cast iron. Twenty *bai zuo* furnaces 白作爐 produced 208,000 *jin* [125 t] of wrought iron and 12,000 *jin* [7.2 t] of steel. [In all 424 t of ferrous products.]

In the 6th year [1511] there were five *da jian* furnaces and eight *bai zuo* furnaces in operation, producing cast iron, wrought iron, and steel as before.

From the 8th year of Jiajing 嘉靖 [1529], each year three *da jian* furnaces produced 188,800 *jin* [113 t] of cast-iron plates and 64,000 *jin* [38 t] of 'broken iron' [*sui tie* 碎鐵, granulated cast iron?]. In *bai zuo* furnaces were produced 208,000 *jin* [168 t] of wrought iron in bundles [*shu gua tie* 熟掛鐵], which was delivered to the capital. Steel [production] was discontinued. One bundle of wrought iron is four 'pieces' [*kuai* 塊], weighing 20 *jin* [12 kg], for a total of 10,400 bundles.

The context makes it clear that a *da jian* furnace is a blast furnace, producing cast iron, and a *bai zuo* furnace is some sort of finery in which both wrought iron and steel are produced from cast iron. Neither term makes obvious technical sense in itself, and neither seems to be found elsewhere.[70]

The passage indicates that some major technical improvements took place around this time, leading to greatly increased output per furnace.[71] This would have saved labour in the construction and operation of the furnaces, and quite possibly have saved fuel as well. There seems to be no way of knowing whether technical improvements were made at the same time in charcoal and ironsand production.

Closure

Regardless of whatever productivity improvements were attained, iron from Zunhua remained very costly, as a memorial of 1581 reveals:[72]

The Zunhua ironworks delivers an annual quota of 208,000 *jin* 斤 of [wrought] iron [125 t]. The [market] price of this is not more than 2700 taels of silver, but the expenditures involved in providing for officials, officers, soldiers, and corvée labourers is over 10,000 taels. We recommend that the works be closed and replaced by a tax in silver, with which iron can be bought for use.

The indication of 10,000 taels as the annual cost of production at Zunhua is likely to be no more than a rough estimate, for it is unlikely that accounts were kept in such a way that this information was easily extracted. The market price of 2700 taels for 125 tonnes of wrought iron, on the other hand, was undoubtedly the result of an investigation. It amounts to somewhat less than a gram of silver for a kilogram of wrought iron.[73]

70 One possibility is that a *da jian* furnace was a furnace shaped like a large *jian*-bowl, i.e. one that resembled those shown in Figures 129 and 133, pp. 318, 340 above. But these do not fit Fu Jun's description, written after 1513, so this hypothesis is unlikely to be correct.

71 Eberstein (1974, p. 55, n. 42) has a different interpretation.

72 *MSL*, Shen-zong 神宗, ch. 110, p. 3a; Li Guoxiang and Yang Chang (1993, p. 134); Eberstein (1974, p. 37).

73 For what the comparison may be worth, this is about half the silver price of wrought iron in Britain at this time. My thanks to Peter King and and Peter Claughton for this information (personal communications, 2003).

The proposal to close the works was approved, and after this we hear no more about iron production in Zunhua until 1623, when the now-failing Ming dynasty attempted to reopen it, seemingly without great success.[74]

Recapitulation

Let us now attempt a connected history of the Zunhua ironworks, drawing on the evidence presented above and filling in the gaps in our knowledge with reasonably well-informed speculation.

In the early decades of the Ming dynasty, political controversy over state-run ironworks was finally settled with a firm decision to leave iron production in private hands. The single exception at Zunhua was a response to a technical need: weapons for the armies required high-quality wrought iron, smelted and fined using charcoal as the fuel. It is likely that most iron production in north China now used mineral fuel, and the iron produced was best suited to foundry rather than smithy work. Buying charcoal iron on the open market meant importing it from the south, and the undeveloped market economy of the time meant that the government itself had to arrange transport to the capital. In 1426 the Emperor declared that this would be 'a burden to the people', i.e. politically dangerous, and therefore arrangements were made for state production of high-quality charcoal iron nearer the capital. Presumably it was known that this iron would be more costly than iron from the south, but the use of corvée labourers for transport would take them far outside their home districts, and this had been known to be dangerous ever since the fall of Qin, sixteen centuries earlier.

There had earlier been military iron production in the region, but we know very little about this. Apparently iron was produced and delivered to the capital by small works spread out in the garrisons of Zunhua and neighbouring districts. The garrison works in Zunhua seems to have been closed at some time after 1403 and reopened in 1426; various administrative problems led in time to a complete reorganisation and the establishment in 1435–38 of a single large works in a walled compound at the village today named Ironworks, Tiechang 鐵廠.

Several sources make it clear that at this new large-scale works, ironsand was the ore and charcoal was the fuel. On the blast furnaces used for smelting, the evidence allows more than one interpretation, but the most likely is that a major change in design was made around +1509. The type described in Section 7(iii) above,[75] dug into a hillside, was used widely in China from the Song through the Ming; in the 12th century as far north as Heilongjiang. The archaeological evidence suggests that the same type was used at Zunhua. The furnace described by Fu Jun, sometime after 1513, is very different, however, so it is likely that he describes the *da jian* furnace, a new type introduced around 1509. The efficiency of these furnaces

[74] Eberstein (1974, p. 37).
[75] Pp. 308–11.

improved with experience: roughly the same quota was produced by ten furnaces in 1509, five in 1511, and three in 1529. On the technology used for fining cast iron to wrought iron we seem, unfortunately, to have no direct evidence at all.

In spite of efficiency improvements, wrought iron produced at Zunhua remained much more costly than what could be purchased on the market. This had probably been known from the outset: the disadvantage of importing it from the south was political rather than economic. But in the course of the dynasty the economy stabilised and long-distance trade became more developed. In the late 16th century it is likely that merchants were bringing high-quality wrought iron from Jiangnan and Guangdong to the capital region and selling it at prices that made the enterprise at Zunhua absurd. When this was finally realised, the works were closed and the Imperial arsenals began obtaining their raw materials by purchase on the open market.

The troubles at the end of the Ming disrupted trade with the south and led to the brief attempt to reopen production at Zunhua in 1623. From the beginning of the Qing onward there appears to be no evidence at all for iron production anywhere near Beijing;[76] no doubt trade was by this time so well developed that iron from better-favoured regions was in sure supply and cheaper than what could be produced locally.

(ii) Iron and Steel Production Technology in Song Yingxing's *Tian Gong Kai Wu*

We cannot leave the Ming period without considering what that marvellous technical compendium, *Tian gong kai wu* 天工開物, by Song Yingxing 宋應星 in 1637, has to say about the production of iron.

The relevant section is translated in Box 12, and the accompanying illustrations are reproduced in Figures 132–133. Perhaps the most striking aspect, here and throughout the *Tian gong kai wu*, is the sheer pleasure that Song Yingxing evidently takes in writing clear descriptive prose, and a large part of his purpose with this book was surely to entertain readers whose interest was not practical but that of a dilettante. While technology appears to be his primary concern, he also makes excursions into natural philosophy, economics, and geography.

Song Yingxing seems not to know of iron *mining*, and he states that iron ore is found only near the earth's surface. This tells us something about his sources. Apparently he knew only of scattered small-scale ironworks whose production was small enough that surface ore was sufficient for their needs, and not of large-scale ironworks such as those of western Guangdong, which did often mine their ore.[77]

[76] See e.g. Anon. (1983a, pp. 493–522).
[77] Box 4, pp. 49–52 above.

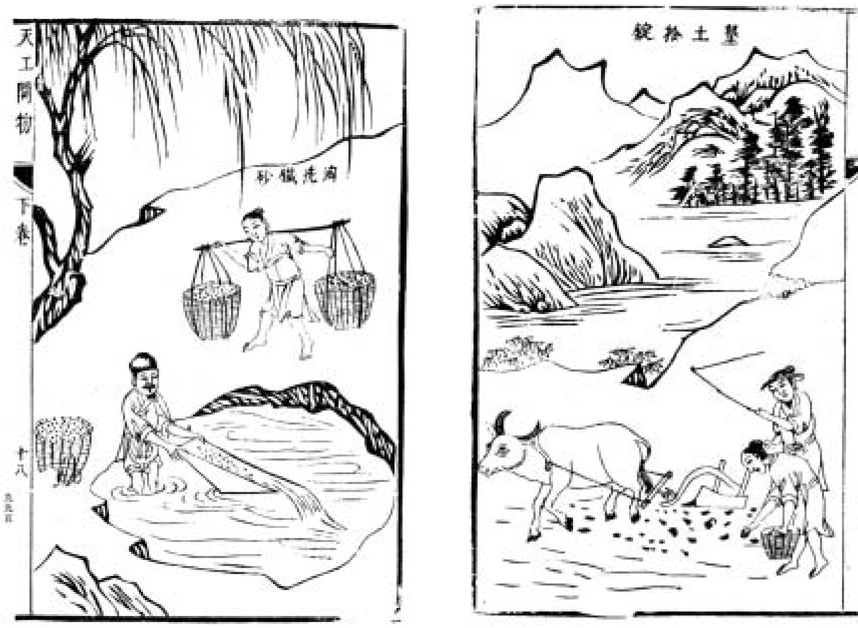


Figure 132 'Washing sand iron' (left) and 'Gathering lump ore by ploughing' (right). Illustrations in *Tian gong kai wu,* ch. *xia* 下, pp. 17b–18a.

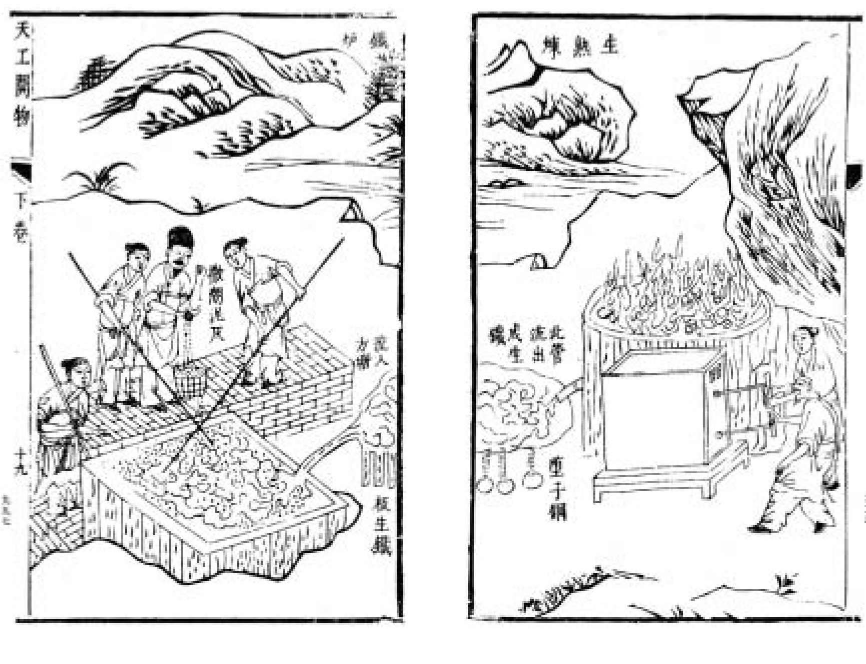


Figure 133 'Furnaces for refining cast and wrought iron'. Illustrations in *Tian gong kai wu,* ch. *xia* 下, pp. 18b–19a.

Box 12 *Song Yingxing on iron and steel production. Translated from* Tian gong kai wu 天工開物 *, 1637 edn, ch. 3, pp. 15b–17a; cf. Zhong Guangyan (1978, pp. 361–7); Pan Jixing (1989, pp. 366–71); Yabuuchi (1969b, pp. 269–72); Sun and Sun (1966, pp. 248–51); Li Chiao-ping (1980, pp. 350–3).*

Iron: Ironworks are found everywhere. The substance [*zhi* 質, i.e. ore] of iron is base: it 'floats' [*fu* 浮] at the surface of the earth and does not 'grow' in deep caverns. It grows profusely on low sunny hillsides,[a] but does not grow in high mountain ranges. The ores include several types of 'lump iron' [*tu ding* 土錠] and fine sand [*sui sha* 碎砂].

Lump iron consists of black pieces which float to the surface. In form these resemble steelyard weights. From a distance they strongly resemble iron. Rubbed with the fingers,[b] they crumble to dirt. If an ironworks is established to 'refine' [*jian lian* 煎煉, i.e. smelt] [this type of ore], the floating [pieces] can be gathered [at the surface]. It is also possible after a rain to turn the earth with an ox-drawn plough and gather [the pieces] which lie a few *cun* 寸 [inches] below the surface. After ploughing the pieces grow day by day, and they can be used continuously without ever being exhausted.

Places where lump iron is found in abundance are Gansu in the northwest and Quanzhou in the southeast, while sand iron is abundant in Pingyang 平陽, Shanxi, and Zunhua 遵化, in Yanjing 燕京 [the capital region].

Sand iron is exposed when the surface earth is cleared away.[c] They take it and wash it, charge it into the furnace, and refine it. After melting it is exactly the same as 'lump iron'.

There are two kinds of iron, **cast** and **wrought** [*sheng* 生, *shu* 熟, lit., 'raw' and 'cooked']. That which comes from the furnace and has not been fined [*chao* 炒, lit., 'stir-fried'] is cast iron. When this has been fined it is wrought iron. When cast iron and wrought iron are 'refined' [*lian* 煉] together [the product is] **steel** [*gang* 鋼].

The iron furnace [the blast furnace] is constructed using salt. This is mixed with earth [clay] and used in mortaring the furnace. Most [furnaces] are made in a pit at the side of a hill, but some are enclosed by a framework of heavy timbers. Moulding the salt–clay mixture requires a month's labour, and great care is required, for if there is any crack in the salt–clay [plaster], all the work is wasted.

To produce one 'furnace' of iron requires more than 2000 *jin* 斤 [1200 kg] of 'earth' [*tu* 土, i.e. ore]. [For the fuel] some use hardwood, others mineral coal, and others charcoal. Each [ironworks], north or south, does what is most convenient in its circumstances. The windbox [*feng xiang* 風箱] requires four or six persons to operate it.

After the 'earth' has been transformed to iron it flows out through a hole in the waist of the furnace. At first this is sealed with clay. Each day at six double-hours [i.e. at noon] they [break this seal and] let out the iron for one double-hour.

If they are producing **cast iron** to be used in foundrywork, [the molten iron] flows into moulds for bars and round pieces for use.

If they are producing **wrought iron** then, when the cast iron flows out, it is led into a rectangular pool [*tang* 塘] which is constructed a few *chi* 尺 [feet] away and a few *cun* 寸 [inches] lower, up against a short wall.

When the iron flows into the pool, several persons holding willow poles stand in a row on the wall. Earlier they have taken *wu chao ni* 污潮泥 [some sort of earth, see pp. 345–6] and dried and sifted it in a fine sieve so it is like flour. One of the men quickly spreads [*sa yan* 灑撒] this while the others quickly stir with the willow poles and it is immediately fined into wrought iron.

(*Contd.*)

Box 12 *Continued*

After fining, when the iron has cooled slightly, some [ironworks] simply chop the iron in the hearth into square pieces; others lift [these] out [while still hot] and hammer them into round bars before marketing [the iron]. Some ironworks, such as those in Liuyang 瀏陽,[d] do not know how to produce these.

The method of 'refining' **steel** [*gang tie* 鋼鐵]: Wrought iron is beaten into thin strips as broad as a finger and about 1½ *cun* 寸 [5 cm] long. The wrought iron strips are tightly tied together in a bundle, and cast iron is placed on this.[e] (In Guangnan 廣南 [south China] there is [a type of cast iron] called 'lump raw steel' [*duo zi sheng gang* 墮子生鋼] which is especially suitable.) The top [of the bundle] is covered with old straw sandals (plastered with clay so that they do not quickly decompose), and the bottom is plastered with clay. [This package] is lowered into a fiery furnace, and the strength of the fire is blown with the bellows. After a certain interval the raw steel first melts and then soaks into the wrought iron, and the two natures [*qing* 情, of the cast and wrought iron] commingle. It is then removed and hammered. It must be 'refined' many times over; once is not enough.

This [steel] is popularly called *tuan gang* 團鋼, but it is more correct to call it *guan gang* 灌鋼.[f]

It is said that among the knives and swords of the Wo barbarians 倭夷 [the Japanese] there are some which are 'purified by a hundred refinings',[g] and which, when placed in the sunlight under the eaves, fill the hall with light. They do not use [the method of] mixing and 'refining' cast and wrought iron. This is also called steel, but it is an inferior product.

It is also said that some barbarians quench-harden knives and swords with *di sou* 地溲 ['urine of the earth']. (*Di sou* is a kind of petroleum which is not produced in China.)

Steel can cut jade, but I have never seen this.

Hard spots in steel which cannot be forged are called *tie he* 鐵核 ['iron kernels']. If painted with fragrant oil [probably sesame oil] they disperse.

If iron is produced on the *yin* 陰 side [the north side, of a mountain], then lodestone is produced on the *yang* 陽 [south] side. But there are several places where this is not so.[h]

[a] Assuming *gang bu* 岡埠 = *gang fu* 岡阜. I follow Peter Golas (*SCC*, vol. 5, part 13, p. 166), as well as most other commentators, in taking *ping yang* 平陽 to be a descriptive term rather than a place-name, even though the prefecture of Pingyang, Shanxi, is mentioned further on in the text.

[b] Taking *ran* 橪 to be a variant of *nian* 撚. Another possibility, with the same meaning, is *nian* 捻, suggested by Zhong Guangyan (1978).

[c] Rich ironsand lodes would often be found buried under a thin layer of earth because of the way rivers shift their course.

[d] Modern Liuyang, Hunan, just east of Changsha.

[e] Assuming, with all commentators, that *tu* 土 is a scribal error for *shang* 上.

[f] On these terms and others for steel see pp. 256, 270, 321, 324, 346.

[g] On 'hundredfold refined steel' see pp. 272–7 above.

[h] On early beliefs concerning this sort of association between minerals see *SCC*, vol. 5, part 13, pp. 30, 217–19.

The text states that iron ore 'grows' in certain places, and of course it was a general assumption in pre-modern China that useful minerals grow in the earth.[78] It is interesting, however (or perhaps merely curious), that the two types of iron ore

[78] *SCC*, vol. 3, pp. 636–41; vol. 5, part 13, pp. 29–32.

which Song Yingxing describes actually can be said to grow, at a rate which is observable over a few generations. 'Lump iron' appears to be *bog iron*, a type of rock with high iron content which precipitates from bog waters under certain specific pedological conditions.

'Sand iron' is *ironsand* (or *black sand*), grains of magnetite (Fe_3O_4) found in small quantities in sand in rivers that flow out of granite mountains. The greater part of the sand is of course grains of quartz (SiO_2). Magnetite is heavier than quartz, so it can become concentrated at certain places in rivers. This is, generally speaking, where the current suddenly slows, for example where a river widens or at the outside of a turn in the river. This naturally concentrated ironsand can contain up to about 7 per cent magnetite. 'Washing' the ironsand can improve this to as much as 95 per cent.

Figure 134, a photograph taken in Henan around 1917, shows how the washing of ironsand was traditionally done.[79] A sluice was built, in this case 1.6 m long and with side-boards 10 cm high. River sand was shovelled onto the sluice and running water was led over it while workers stirred it with forks. If this was done skilfully, most of the quartz sand was carried away by the water and most of the magnetite remained behind.

Song Yingxing's description of 'sand iron' is correct as far as it goes, but his illustration (reproduced here in Figure 132, left) shows *panning* in still water where we should expect to see *sluicing* in running water. It is clear that the illustrator had seen what he depicts, for the implement in the illustration is an accurate depiction of the *bo ji* 簸箕 traditionally used in concentrating minerals from sand. Peter Golas photographed one in use in Guangxi in 1994.[80] But it is doubtful that this method would have been used in washing ironsand.

Panning is an appropriate method for extracting rare or valuable minerals from sand, but ironsand is plentiful in mountainous regions. Extracting magnetite from sand by this labour-intensive method would have meant that very little magnetite was lost; but overall, considering labour input per quantity of magnetite delivered to the blast furnace, panning would have been far less efficient than sluicing. Therefore it seems likely that Song Yingxing, or his illustrator, had seen the concentrating of gold or some other valuable mineral and believed, incorrectly, that the same method was used in concentrating ironsand.

In describing the construction of the blast furnace, Song Yingxing stresses the use of *salt* as a component of the refractory material. I do not know of any technical reason for adding salt to clay – does it improve refractory or plastic properties? One possibility (rather speculative, but consistent with the text) is that coarse grains of salt constituted a very large proportion of the refractory material, and the loam or clay served only to bind the salt grains together. The salt grains would then have had the same function as graphite or charcoal in other refractory materials, keeping their shape at very high temperatures.[81]

79 For details see Wagner (1985, pp. 8–9, 12–13, 28–32).
80 *SCC*, vol. 5, part 13, p. 244, fig. 31.
81 See p. 232 above.

Figure 134 Ironsand sluicing at Lijiazhai 李家寨 in Xinyang 信陽 , Henan, photographed by E. T. Nyström about 1917 (reproduced from Tegengren, 1923–24, vol. 1, pl. 16).

The text describes two ways in which the blast furnace can be constructed: in a pit at the side of a hill, like some blast furnaces known from Song–Yuan archaeology, or in a wooden framework, as was common in the traditional iron industry of recent centuries. Both have been discussed in Section 7(iii) above.[82] So Song Yingxing's description of the two types of blast furnace is accurate. His illustration, the right side of Figure 133, shows however a completely different type of furnace. It is very shallow and open, and it is not dug into a hill, nor does it have a wooden framework. This type of blast furnace is also well known from recent centuries; an example is shown in Figure 129 in Section 7 above.[83] Thus it seems that Song Yingxing in this case used a different source for his illustration than he used for his text.

The process by which cast iron, with typically 3–4 per cent carbon, is decarburised to produce wrought iron is generally called *chao* 炒 in Chinese. As has already been discussed in Section 2(i) above, this word means literally 'stir-frying', and the usual English translation is 'fining' (sometimes 'puddling').[84] Song Yingxing uses the same word, but describes a process which is quite different from any of the fining processes we know of, ancient or modern, in China or elsewhere.

Molten iron tapped from the blast furnace is allowed to flow into an open hearth; a substance called *wu chao ni* is spread on it; and several workers stir it with willow poles. The description and the illustration (the left side of Figure 133) are so precise

[82] Pp. 305–11.
[83] P. 318.
[84] Pp. 16–18, 30–4 above.

that there is no real doubt that Song Yingxing, or the author of his source, had seen something very like this process. But it is very difficult to explain. Anyone who has worked with molten cast iron, as I have, will immediately object that the molten iron from the blast furnace, flowing into such a large open hearth, without thermal insulation, fuel, or any sort of air blast, will solidify before any significant amount of carbon has been removed.

Most translators and commentators seem unaware of this objection. They explain the passage and illustration in terms of modern open-hearth steelmaking processes, and state that the curious *wu chao ni* would contain iron oxide, FeO, to help remove carbon by the reaction $FeO + C = Fe + CO$, but this would not solve the problem.

The only commentator, as far as I know, who has been aware of the problem was one of the first, the German metallurgist Adolph Ledebur, more than a century ago, and he also proposed a solution. A Japanese friend had shown him a copy of *Tian gong kai wu* and translated the metallurgical sections for him. In his article about it he suggests that the *wu chao ni* spread on the molten iron contained saltpetre (potassium nitrate, KNO_3). It is a powerful oxidising agent (this is its function in gunpowder), and might very well be able to accelerate the oxidisation of the carbon sufficiently to keep the temperature up until the carbon is exhausted and the cast iron is converted to wrought iron. Ledebur adds: 'That a quick conversion of pig iron to wrought iron can be effected by the use of saltpetre was demonstrated two decades ago by the Heaton process.'[85]

Wu chao ni 污潮泥 means (or can mean) something like 'filthy wet loam', and the label in the illustration has the variant *chao ni hui* 潮泥灰, 'wet loam and ashes'. In pre-modern China and Europe, saltpetre was manufactured in 'nitre beds', in which the raw materials were dung, earth, urine, and wood ashes.[86] In China, nitre beds were described as so foul-smelling that birds avoided flying over them.

In the nitre bed fermentation produces calcium nitrate, and treating a solution of this with ashes gives potassium nitrate and a precipitate of calcium carbonate.[87] Without enough information to go into detail it seems possible that the terms 'filthy wet loam' and 'wet loam and ashes' describe something like such a nitre bed. The saltpetre used as a component of gunpowder must be very pure, but perhaps, in the fining process described by Song Yingxing, some much less pure product, containing a small but significant amount of saltpetre, might have been useful.

[85] Ledebur (1885a, p. 192, fn.). Several uses of saltpetre in puddling, including the Heaton process, are described briefly by Wedding (1874, pp. 264–5; 1901, p. 254); see also Gruner (1869). Note also the curious use of saltpetre in traditional Chinese cementation steelmaking, p. 68 above.

[86] Williams (1975); *SCC*, vol. 5, part 4, pp. 188ff.

[87] Alan Williams describes his own experiments with this process as follows: 'A mixture of dung and earth was set up in a pile and urinated on daily for several months. Ammonia (from urea) is oxidised by the air with the aid of various bacteria to form nitrates. Extraction with boiling water yields a very dilute solution of calcium nitrate, which may be treated with wood-ash (containing potassium carbonate) to form potassium nitrate' (Williams, 2003, p. 864, fn. 22).

What is the relation between author and illustrator in this case? The illustration fits the text in almost every detail, so that one definite possibility is that the illustrator simply followed the text without having seen anything himself. One detail tends to contradict this hypothesis: the label *chao ni hui*, 'wet mud and ashes', where the text has *wu chao ni*, 'filthy wet mud'. This might imply that the illustrator had some information about the process without reference to the author; for example he might have heard the term in conversation with the workers. This is not, of course, the only possibility: the text and illustrations were no doubt prepared at different times, and Song Yingxing might on the two occasions have chosen differently among the terms he knew for this substance, whether he knew them from first-hand experience or from written sources.

One point which suggests that Song Yingxing relied on written sources for this process is the curious wall mentioned in the text and seen in the illustration. The text states unambiguously that the workers stand *on* this wall, but why should they do this? If on the other hand they stood *behind* a light waist-high wall it would provide some protection from the flying sparks and intense radiant heat from the hearth. I suggest as one possibility that Song Yingxing misunderstood a written source which mentioned such a protective wall, and the illustrator blindly followed Song Yingxing's text.

Finally Song Yingxing describes a process for making steel. This is clearly what I have called in Section 6(iii) above a 'high-temperature co-fusion process', in which wrought and cast iron are heated together to a temperature above the melting point of cast iron, resulting in a more-or-less homogeneous product with a carbon content between the two.[88] The fact that the text mentions the terms *tuan gang* and *guan gang* suggests that Song Yingxing may have seen Shen Gua's description of a co-fusion process, translated earlier,[89] but the actual description of the process does not obviously owe anything to Shen Gua.

The section on iron ends with a series of brief notes on curious matters which Song Yingxing has heard of. It is reassuring to see that he is often sceptical here, for this suggests that he has looked critically at all of his sources, and has determined that the foregoing material is more reliable. From a modern standpoint we can share his doubt about most of these notes, but quench-hardening steel in oil is very useful to give a slower quench than water, resulting in a tougher blade.[90]

88 Pp. 258–61 above.
89 P. 321.
90 See p. 136 above.

9 SOME CHINESE CONTRIBUTIONS TO MODERN SIDERURGICAL TECHNOLOGY

It was always Joseph Needham's contention that the development of modern science and industry which came to fruition in the West owed a great deal to developments in China, and it has been one of my tasks to investigate this debt in detail. In the following I consider a number of developments, adding technical and economic 'brass tacks' to some discussions which are often rather nebulous. While my results are not by any means conclusive, I hope that the following will open up some new lines of investigation for future studies of these questions.

(i) Indirect Smelting: Blast Furnace + Finery

The indirect process, in which cast iron is produced in a blast furnace, then decarburised to wrought iron by fining, was used very early in China but came late to Europe. The earliest definite evidence of the blast furnace in Europe is at this writing (November 2005) from the +12th–13th centuries, in three places: Sweden, northern Germany, and Italy; further research may well push this date further back, but it may be taken as the time in which the indirect process began to become important. Before this time, we may well imagine that there were ironworks here and there in Europe which used some form of indirect process. Something like this hypothetical situation can be seen in pre-modern Africa, where virtually all iron smelting was by the direct process, but in at least one locality (in North Cameroon), was by an unusual indirect process.[1]

The reason for the rise of indirect iron smelting in widespread parts of Europe in the 12th–14th centuries would seem to be largely economic. In this period, with improved transportation leading to larger markets, and with the first stirrings of a kind of 'embryonic capitalism' in the Hanseatic League and the Italian merchant cities, the economic conditions for large-scale iron production by the indirect process came into force.

This general explanation for the introduction of indirect smelting in Europe does little to explain the particular distribution of the early industry. Why these places and not others? No doubt the answer will lie partly in the comparative advantage of various places and partly in the unaccountable vagaries of history, but a more direct factor is the geography of iron ores in Europe. Nils Björkenstam, an engineer broadly learned in medieval history, has shown that the early indirect process could not deal effectively with phosphorus in iron ore, and that the earliest blast furnaces in Europe were located in regions with plentiful low-phosphorus ores.[2]

[1] David et al. (1989).

[2] Björkenstam (1990; 1995). In writing the following pages I have been indebted to Nils Björkenstam's book, 'Western European iron production in the Middle Ages' (1990), which deserves a translation from Swedish to English. It should be noted, however, that in his occasional remarks about Chinese iron production (pp. 128–9, 170), he is often badly misinformed.

In the following I shall first review the available evidence on the pre-history of indirect iron-smelting in Europe, then consider the three regions of medieval Europe in which indirect iron smelting first became important.

Carolingian blast furnaces?

There is a curious piece of evidence, pointed out by the great metallurgical polymath Otto Johannsen, which suggests that some form of blast-furnace iron smelting may have been known in Europe as early as the +8th century.[3]

The book of recipes *Mappae clavicula* exists in a number of manuscript traditions of both northern and southern Europe, and can in its extant form be securely dated to the late +8th or early 9th century.[4] It is a highly eclectic compilation; a philologist's judgement of one of the manuscripts is that the recipes contained in it cannot today be placed in a particular place or time, except that their origin lies before ca. 800, probably in Europe, perhaps in the Middle East or further east.[5]

There are no recipes for working with iron here, but three which concern the smelting of copper and lead. Johannsen points out that the author of these recipes clearly knew of the techniques only by hearsay. But the author would seem to have had direct knowledge of iron production, and assumed the same knowledge in his readers, for he refers to iron smelting in the recipes. The relevant sentences are:[6]

> [§ 135, on copper smelting from firestone:] set it all on fire and let it stand and cool, so that it does not run like lead, iron, or other metal.

> [§ 225, on lead smelting:] Then it is smelted in the same way that iron is, though lead burns more.

> [§ 226, on lead smelting:] The same ore is not dried, but continually as it is being excavated it is put into an iron furnace with charcoal and a slow fire.

The second and third passages quoted indicate that the author knew something about iron smelting, while the first and second suggest that he had seen iron flow when smelted, like lead and other metals. Thus he seems to have known of some kind of blast furnace.

Johannsen's thesis is weakened when we reflect that the *Mappae clavicula* is an eclectic compilation, and the three recipes therefore need not go back to the same author. Nevertheless we have a hint here of an important point: the production of iron from ore in liquid form may well have been known here and there in very early times, and even occasionally practised, without making much impact before other historical developments brought it to the fore.

[3] Johannsen (1933).
[4] Smith and Hawthorne (1974, pp. 3–4).
[5] Johnson (1939, pp. 88–9); Smith and Hawthorne (1974, p. 17).
[6] Smith and Hawthorne (1974, pp. 47, 62).

Blast furnaces in the Caspian provinces of northern Iran

Otto Johannsen suggested, somewhat hesitantly, that the blast furnace may have come to Europe from the Middle East.[7] It does seem reasonable to suppose that blast furnaces were in use in the Middle East in very early times, for co-fusion steelmaking was in use in Iran by the +10th century,[8] and the cast iron used in this process presumably came from blast furnaces. We lack, however, clear direct evidence on iron-smelting methods here in early times. V. J. Parry has some interesting remarks on the subject, but nothing, as far as I can see, relevant to the question of the blast furnace versus the bloomery.[9] He notes two descriptions of ironworks in the Lebanon: both seem to be very large bloomeries.[10] But further east, in Iran, it seems likely that blast furnaces were in use by the 10th century.

The region of the Elburz Mountains,[11] which lie along the southern coast of the Caspian Sea, has a very different physical geography from the rest of Iran, with plentiful rainfall and rich deciduous forests. In the 10th century, when it first appears in our sources, it was a prosperous region with several flourishing industries, including silk and iron.[12] Italian merchants imported silk from here as early as medieval times.[13]

Through the centuries since then, travellers have often noted this iron industry: al-Qazvini in the 13th century,[14] an English trader, Thomas Barker, in 1618,[15] the German diplomat Adam Olearius in 1635, a French traveller, Jean Chardin, in 1673–79,[16] an English traveller, James B. Fraser, in 1821–22, and others.[17]

The earliest source which makes it moderately clear that blast furnaces were used in the Elburz Mountains is that of Jonas Hanway in 1753.[18] A report by an English diplomat in 1848 makes it explicit that the ore is first calcined, then charged into a water-powered blast furnace:

> The ore is first heated in a furnace with charcoal in alternate layers, after which it is broken with a hammer into small pieces and thrown into a second furnace with charcoal as before in the proportion of one *men* of ore to 3 of charcoal. A blast is effected by means of a large bellows worked by a water wheel and when fused the metal is allowed to run out into a pool and is taken up in long wooden ladles and poured into shot moulds, or it is run into short bars.[19]

In the early 19th century at least thirty ironworks were in operation in the region.[20]

[7] Johannsen (1941, p. 60).
[8] See pp. 264–7 above.
[9] Parry (1970, p. 224).
[10] Parry (1970, p. 224); Seetzen (1854–59, pp. 145, 188); Brocchi (1841–43, vol. 3, pp. 187–94, 283–4).
[11] Modern Azerbaijan and the Iranian provinces of Gilan and Mazandaran (or Ṭabaristān).
[12] Minorsky (1970, pp. 133–7, §§ 32.1, 32.4, 32.9, 32.20, 32.23; pp. 384–91).
[13] Goitein (1967, p. 103); Matthee (1999, pp. 15–16).
[14] Allan and Gilmour (2000, p. 25), quoting al-Qazvini, *Athar al-Bilad*. The passage in question seems not to be available in translation, but note some related passages in Giese's abridged translation (2004, pp. 95, 113, 118) and in Garbers and Weyer (1980, pp. 42–3).
[15] Issawi (1971, p. 263).
[16] Chardin (1927, p. 163).
[17] See Allan and Gilmour (2000, pp. 25–6), to whom I owe most of these references; also Hommaire de Hell (1854–60, vol. 2.1, p. 239); Nabieva (2005, pp. 115–16).
[18] Hanway (1754, vol. 1, p. 196), quoted by Allan and Gilmour (2000, pp. 25–6).
[19] K. E. Abbott, 'Report on a journey to Caspian', 28 April 1948, FO 60/141, quoted by Issawi (1971, p. 284).
[20] Jaubert (1821, pp. 449–51); Böhne (1928, p. 1579).

Box 13 *Description of traditional blast-furnace operation in Mazandaran, northern Iran, translated from Böhne (1928, p. 1579); note also Wertime (1964, p. 392). See Figure 135.*

The blast furnace is situated in an open shingle-roofed shed with a central opening for smoke. Along the long side of the shed are three stalls, one for charcoal and two for ore. The blast furnace, at the centre, is a pyramid of clay about 3 m high. The outer dimensions at half-height are 1.2 × 1.2 m, and the inner dimensions at the mouth are 0.5 × 0.4 m. At the front is the taphole, set back by inset iron bars, and at the side, raised up, is the tuyère.

Connected to the tuyère is a horizontal two-part bellows. The impetus is transmitted directly, with the help of a wooden connecting rod and short iron cranks, by a standing water-wheel, a kind of turbine, as is found in all north Persian mills. On the vertical axle 24 wooden scoops are mounted with carefully fluted blades at an angle of 55°. The removable connecting piece between the bellows and the tuyère is of leather with sheet-iron ends.

In front of the taphole is a sunken forehearth, flat and surrounded by a wall. In front of this is a broad clay floor, and at the side a long wooden trough for the final product.

The iron ore is calcined in the stalls and crushed to nut size. The blast furnace charge per 24 hours is about 440 kg ore (weighed before calcining) mixed with 320 kg charcoal. Every 2½ hours – when the furnace is in good working order, 1½ hours – about 7.5 kg of iron is tapped, together with the slag, into the forehearth. The iron is dipped out of the forehearth with ladles and, under agitation, spread out on the damp clay floor, so that it is broken up into shot. These small balls are stored in the wooden trough, sorted, and sold as shotgun shot at a price of 5 *Schahi* = 0.1 Reichsmark per kg. Daily production is 60–90 kg, when the furnace is in good working order, 120 kg of shot.

It is said that in former times iron for tools and weapons was produced here. This was treated by itinerant smiths in small fineries. Only a few years ago the furnaces of Mazandaran supplied foundry pig to the arsenal in Teheran.

The German mining engineer Erich Böhne, who visited the region in 1927, saw signs that the industry had flourished here from very early times. He found enormous slag heaps, some with entire villages built over them, and numerous ruins of ironworks overgrown with vines.[21] But competition with iron from Russia, and later the Soviet Union, had ruined the industry, and he found only three active ironworks, only one with its blast furnace in blast. His description is translated in Box 13; the furnace seems quite primitive, and it produced only shotgun shot, but he was told that the pig iron produced had in earlier times been fined and used for weapons and tools. Theodore Wertime visited the region in 1962 and again in 1963. He was unable to confirm a rumour that one blast furnace was still in operation, but conversations with workers confirmed Böhne's description.[22]

We have seen in Section 2 above the differential effect of modern competition on the traditional Chinese iron industry,[23] and we seem to see the same phenomenon

[21] Böhne (1928).
[22] Wertime (1964, p. 391).
[23] Pp. 78–9 above.

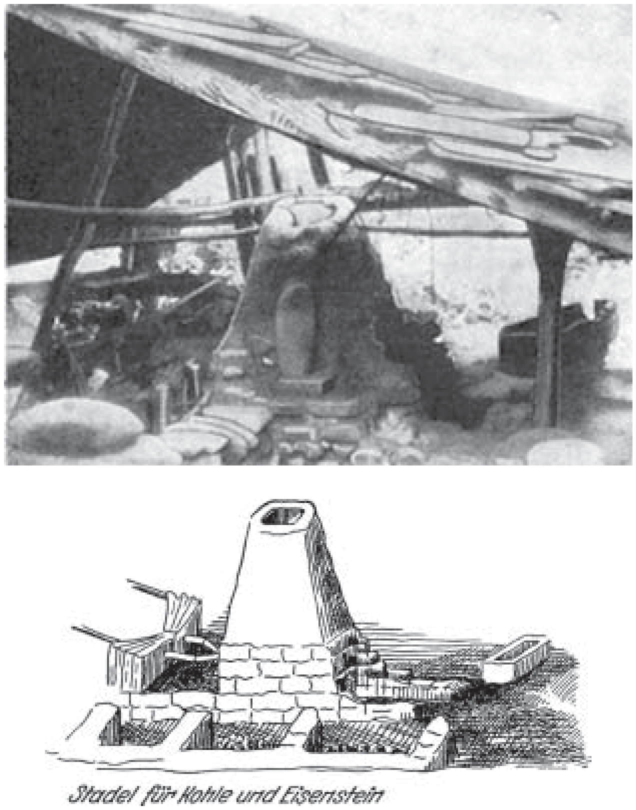


Figure 135 Photograph and sketch of a blast furnace in 'Lawitschtängä', Mazandaran, northern Iran, in 1927, reproduced from Böhne (1928, p. 1579, figs. 3, 4). Height approx 3 m.

here: the most advanced and efficient ironworks, which require significant capital and a large market, cease operations first. What are left are the more primitive works, which are less capital-intensive and produce for local markets. We must not, therefore, assume that Böhne's description is sufficient for an understanding of earlier iron-smelting technology in the region.

Archaeological surveys of the furnace ruins and slag heaps of the Alburz Mountains would probably answer numerous questions concerning the history of iron production in the Islamic world, but we may wonder when, if ever, industrial archaeology will be possible in Iran. It does seem likely that blast furnaces operated here in the +10th century, supplying cast iron to the co-fusion steelmaking centres further east and wrought iron there and to other markets. The early silk industry in the region is a clear sign of Chinese influence, no doubt mediated by merchants, so that a transmission of other economically important technologies, including indirect iron smelting, is a distinct possibility. And the early presence of Italian merchants here provides a plausible route for this technology to Europe.

Austria – the Stuckofen

The Austrian *Stuckofen* – not to be confused with the German *Stückofen*, which was rather different[24] – produced bloomery iron and cast iron in the same discontinuous operation. It was long believed by many to be the precursor of the blast furnace, but recent research, usefully summarised by Nils Björkenstam, has refuted this.[25] The theory was that as production in bloomery furnaces increased, furnaces were made larger, and water power was put to use for the blast, higher temperatures were reached than otherwise had been possible. Cast iron became a by-product of the process, and was fined to wrought iron. As furnaces became larger still, more and more cast iron was produced, until finally the furnaces were producing nothing but cast iron; these were the original blast furnaces.

There is a good deal of technical and historical misunderstanding here. High temperatures are easy to reach in a bloomery, and the furnace master's greatest problem is to maintain the *correct* temperature for his purpose, neither too high nor too low. The significant historical fact seems to be that in this particular region, from very early times, the most important ferrous product was high-quality steel. Bloomeries were operated at higher temperatures than usual in order to put more carbon into the bloom, with the result that some cast iron was incidentally produced. Originally the cast iron was discarded with the slag or recharged into the furnace. About the middle of the 12th century, water power began to be used, furnaces were built larger, and more of this unwanted by-product – called *Graglach* – was produced. Fining was introduced around 1500 in order to make use of it. But this type of furnace continued in use as late as 1775, and was never replaced by the blast furnace. Emanuel Swedenborg visited Vorderberg and Steiermark in Austria in the early 18th century and described the *Stuckofen* process in some detail.[26] He noted that it was terribly inefficient, but was told that the local ore was unsuitable for blast-furnace iron smelting. This was in fact correct. As Nils Björkenstam makes clear, the phosphorus content of the iron ore in the region is too high to make high-quality wrought iron or steel by the indirect process. In bloomery iron smelting, most of the phosphorus in the ore goes into the slag, while in the blast furnace the phosphorus goes into the iron, and is not removed in the finery. Phosphorus in significant quantities makes wrought iron or steel 'cold-short' – brittle at ordinary temperatures – and must be avoided in high-quality products.

Thus the *Stuckofen* was a specialised furnace for producing high-quality steel and wrought iron from a specific local ore. The by-product, cast iron, was fined to produce an inferior, medium-to-high-phosphorus, wrought iron. The last *Stucköfen* seem to have been closed down in about 1775. This was not a primitive precursor of the blast furnace, but a highly developed apparatus for a specialised purpose.

[24] Björkenstam (1990, pp. 108–9). For a general introduction to the economic, social, and technical history of ironmaking in Austria, see Roth (1984).
[25] Björkenstam (1990, pp. 95–107).
[26] Swedenborg (1734; 1762, pp. 106–7); Sjögren (1923, pp. 212–14).

Early blast furnaces in Sweden

Probably the earliest serious study of the history of the blast furnace, anywhere in the world, is from 1791, the introductory chapter of Johan Carl Garney's 'Guide to Swedish blast furnace practice', which may also be the world's oldest technical manual on blast-furnace operation.[27] Garney concluded from documentary evidence that the blast furnace was well established in Sweden by the 14th century.

Later Herman Sundholm, in a more extensive study,[28] came to much the same conclusion, and included in his argumentation a fascinating piece of evidence. Saint Birgitta (1303 to ca. 1370), founder of the Birgittine Order, from Uppland in central Sweden, had a series of revelations, in one of which she saw souls in purgatory being purified in a furnace and transformed to gold. Sundholm points out that the furnace described is instantly recognisable as a blast furnace. And when Birgitta saw the flowing molten gold 'sparkling', she was clearly describing low-silicon cast iron, which is the only metal which throws off sparks when molten. Since Birgitta's father in fact owned an interest in an ironworks, it is clear that she had actually seen a blast furnace in operation, apparently about 1320, and that it had made a deep impression. Later scholars have cast doubt on Sundholm's reading of the text, and on his methodology,[29] but this is still a marvellous example of the way in which seemingly irrelevant sources can cast light in the history of technology when read by technically informed persons.

Sundholm also argued against the then-universal assumption that the blast furnace was introduced in Sweden from Germany by Hanseatic merchants in the 12th or 13th century. In 1941 Otto Johannsen agreed with this assessment, and emphasised the fact that Garney in his 'Guide' describes three types of blast furnace, the 'older Swedish', the 'German', and the 'Walloon'.[30] The older Swedish furnace is quite unlike other European blast furnaces, and would seem to have been in place before the German design was introduced. Garney describes it (seemingly from examination of old ruins) as most often built into a hillside, so that not much of it can be seen above the ground. The outer framework was of timber, and the space between this and the shaft was filled with rubble.[31] It is thus amazingly like some of the Chinese blast furnaces described in Section 7(iii) above.[32]

Excavation of the Lapphyttan ironworks site in Norberg, Sweden, in the early 1980s, made much discussion on the basis of written sources irrelevant.[33] Here the remains of a small blast furnace (see Figure 136), eight fineries, storage sheds, and

[27] *Handledning uti svenska masmästeriet*, Garney (1816, vol. 1, pp. 1–36). Note also Heckscher (1932); Bohm (1972); den Ouden (1981); Rydén (1998).

[28] Sundholm (1930; 1934); note also Tholander (1977).

[29] Holmkvist (1954); Götlind (1990).

[30] Johannsen (1941, pp. 58–60).

[31] Garney (1816, vol. 1, pp. 22–4). Johannsen (1941, T. 32) reproduces two illustrations of what he believes to be examples of the 'older Swedish' furnace, but in fact these appear to be of Garney's 'German' design. Garney (1816, vol. 1, p. 25, fn.) mentions that some older furnaces of this type, still in blast in his time, were timbered in this way.

[32] Pp. 308–11.

[33] Magnusson (1985).

Figure 136 The Lapphyttan blast furnace in Norberg, Sweden, under excavation (Magnusson, 1985, p. 53).

dwellings were found. A few potsherds were found which can be securely dated to the period 1250–1300, and this is earlier than the earliest dates proposed on the basis of documentary evidence for the introduction of the blast furnace in Sweden. Radiocarbon dates for charcoal samples, carefully considered in relation to 'old wood' problems, suggest that the ironworks opened between 1150 and 1200 and remained in operation until the second half of the 14th century. The blast furnace may have been built into a hillside, and in general it seems to have been of Garney's 'old Swedish' type, with a timber frame which has not survived.

Otto Johannsen also quoted with approval a communication from Sundholm in which he suggested that the blast furnace was introduced by Varangian (Swedish Viking) merchants trading through Russia and the Black Sea – and, I will add, the Caspian – with the Orient.[34] This seems even more likely than Sundholm and Johannsen imagined, for we have just seen that there was a major blast-furnace iron industry operating on the southern shores of the Caspian Sea, probably as early as the 10th century.

Germany – the Massofen

A *Massofen* was a furnace which functioned either as a bloomery or as a blast furnace, with only minor adjustment between the two modes of operation.[35] When cast iron was produced, it was fined to wrought iron, for there was no real use for cast iron before the introduction of cast-iron artillery in the late Middle Ages. The *Massofen* is therefore a likely candidate for the rôle of precursor to the blast furnace in Germany. Since the

[34] See e.g. Jones (1984, pp. 241–68); Randsborg (2000, p. 175). On the hypothesis see also Sundholm (1934, pp. 284–5).
[35] My basic source for this discussion is Björkenstam (1990, esp. pp. 108–13). Note also Kempa and Yalçin (1995); Knau (1995); Rehren and Ganzelewski (1995).

word is long obsolete, and the Swedish word for 'blast furnace' is *masugn*, we must also assume that it was the precursor of Garney's 'German' blast furnace in Sweden.

Documentary evidence for the *Massofen* in Germany is not earlier than the 14th century, but archaeological evidence takes it back at least as far as the early 13th century in the Sauerland region of North Rhine–Westphalia, in the Ruhr district of northern Germany. Björkenstam notes that not nearly as much archaeological work has been done in the equally important mining region of Siegerland, just north of here and closer to the Ruhr, where one might expect to find even earlier use of the indirect process.

Italy

There is documentary evidence for the indirect process in northern Italy in 1320, and it may well go back to the early 13th century.[36] There does not seem to be any archaeological evidence on this question.

The best source we have for the construction of an early Italian blast furnace is a 15th-century illustrated description of an ironworks at Ferriere in the Apuan Alps, about 60 km northeast of Genoa, by the sculptor-architect Filarete (Antonio di Piero Averlino, ca. 1400 to ca. 1469).[37] He visited the works in 1463. The blast furnace was built against a mountainside, and thus has a certain resemblance to some Chinese blast furnaces and to Garney's 'old Swedish' blast furnace.

Efforts by Theodore Wertime and Joseph Needham to show an eastern connection for Filarete's blast furnace concentrate almost entirely on the associated water-wheel and bellows. The water-wheel is horizontal (i.e. with a vertical shaft); this arrangement is unusual in Europe but common in both Iran and China,[38] and in particular it was used at the Iranian ironworks described by Böhne. The bellows is vertical (i.e. it opens and closes horizontally). Filarete notes that this is unusual, and for comparison illustrates the typical horizontal bellows used in a Roman hammer-mill. The Iranian ironworks also used a vertical bellows.

Contacts between the Italian city-states, especially Venice and Genoa, and the Black Sea–Caspian region are well documented.[39] It is clear that any Italian merchant who wanted to know about the technology of iron production in Caspian Iran would have been able to. Furthermore Oriental slaves were common in the Italian cities,[40] and an industrialist who wished to introduce the technology might well have been able to import knowledgeable ironworkers from the region. It is therefore a tenable hypothesis that the blast-furnace technology described by Filarete in the 15th century had its origin in Iran and, further back, in China.

36 Sprandel (1965, pp. 295, 315–18; 1984, p. 75); Björkenstam (1990, p. 108).

37 Translated by Spencer (1963; 1965, vol. 1, pp. 220–1, vol. 2, folio 127r); note comments by Smith (1964); Wertime (1964); Needham (1964); Eichner (1964); Spencer (1964); Reti (1965).

38 Wulff (1966, pp. 280–3); Humlum (1959, pp. 314–22); *SCC*, vol. 4, part 2; Wertime (1964); Needham (1964); Reti (1965).

39 See e.g. Lopez (1976, pp. 106–13); Phillips (1988, pp. 102–21); Origo (1955).

40 Origo (1955).

The blast furnace from China to Europe?

The indirect process for iron smelting may well have been known and practised here and there in Europe in very early times, but it became commercially important in about the 12th–14th centuries, when the European economy had advanced to the point that large-scale iron production made commercial sense. This may have happened earlier in Sweden than elsewhere in Europe, for here were excellent ores, easily mined, and not much other industry competing for entrepreneurship, capital, fuel, and labour.

It is virtually certain that the indirect process came to Sweden from elsewhere, and one very likely source for the 'old Swedish' blast furnace was certainly the Caspian provinces of Iran, for Scandinavian merchants had been trading here from the Viking age onward. Perhaps the same occurred in Italy, which also had close trade contacts with the region.

In Germany, on the other hand, the blast furnace seems to have been independently developed from the *Massofen*. The German blast furnace was later introduced in Sweden, apparently by Hanseatic merchants, and replaced the earlier type.

Did the Iranian blast-furnace technology come from China? This seems likely, for both the furnace itself and its horizontal water-wheel resemble some Chinese arrangements. The silk industry of the same region is a clear indication of contacts, direct or indirect, with China, and there are many other signs of Chinese technological contacts in the region.[41] The co-fusion steelmaking technology at Merv is only one of many examples.[42]

(ii) Iron Casting

Certainly the most important and impressive of China's priorities in ferrous metallurgy are blast-furnace iron smelting and iron casting. It is important to note, therefore, that in Europe these are independent innovations. Some writers have assumed that pig iron from a blast furnace is necessary for iron casting, but this, as has already been mentioned, is incorrect, for wrought iron can be carburised and melted in a cupola furnace.[43] Indeed, the earliest European description of iron casting describes exactly this.[44]

On the other hand, other writers assume that production of wrought iron in the blast furnace and finery was not economically viable, and therefore was not practised, until the introduction of iron casting brought an economically important use for pig iron from the blast furnace.[45] This too is incorrect, for we have just seen that wrought iron was being produced in Europe by the indirect process at least two centuries before iron casting became economically important in Europe.

The earliest extant cast-iron products made in Europe seem to be some 20 boundary posts placed in the period 1345–64 by the Order of Saint John of Jerusalem

[41] *SCC*, vol. 1, pp. 220ff.
[42] See pp. 264–7 above.
[43] P. 112 above.
[44] Johannsen (1910).
[45] Rostoker and Bronson (1990, pp. 163–5).

to mark their territory near Schermeisel in Neumark, eastern Germany (modern Trzemeszno Lubuskie, Poland).[46] These are of a very odd alloy, with 2.31 per cent carbon, 0.43 per cent silicon, and 6.20 per cent phosphorus. It would have a low melting point, about 950°C, and therefore be relatively easy to cast using bronze-melting techniques, but would not have good physical properties for more demanding applications. The application of cast iron becomes more important with the introduction of cast-iron artillery. A mortar in the Artillery Museum of Turin, Italy, may be from the late 14th century. By the middle of the 15th century cast-iron guns are commonplace, as evidenced by both textual and artefactual evidence.[47]

Since the Chinese were casting iron for useful products almost two millennia before this, it is natural to suspect a Chinese connection here, but iron casting in itself does not seem difficult to invent. The relevant question is how the European gun-founders developed the necessary techniques to produce castings of the technical quality necessary for a useful gun. It is quite likely that they had some information about how the Chinese gun-founders worked, for Chinese cast-iron artillery is earlier, and was based on a long tradition of other kinds of large iron castings.[48] We are concerned here with a period in which Mongol invaders were making the West aware of the advantages of Chinese military technology, and it is easy to imagine lines of transmission from the Chinese gun-founders to their European counterparts. Joseph Needham has dealt with this question in much greater detail.[49]

(iii) Malleable Cast Iron

An even longer Chinese priority is the technique of annealing iron castings to improve their toughness, making what is called in English *malleable cast iron*.[50] Archaeological evidence shows that this technique was widely used in China by the –3rd century; in the West it was first known in the 17th century, and not widely used until the 19th.

This technique was patented by Prince Rupert (Rupprecht von der Pfalz, 1619–82) in 1670,[51] and was studied systematically by René Antoine Ferchault de Réaumur (1683–1757).[52] Nothing is known of what Prince Rupert intended to use his patented process for, but Réaumur's aim was primarily to soften the surface of an art casting

[46] Niezoldi (1942); Johannsen (1911–17; 1947, p. 41; 1953, p. 141). More recent research has not produced earlier evidence.

[47] Johannsen (1953, pp. 202–3); Hall (1983).

[48] Pp. 289–94 above.

[49] *SCC*, vol. 5, part 7, pp. 568 ff. On Mongol iron-casting technology see Terekhova (1974).

[50] Pp. 159–69 above.

[51] Prince Rupert's original patent was granted on 6 May 1670, but apparently it was never published. It is quoted in Patent no. 164 for 1671, with all technical details omitted. Patent no. 161 for 1670 transfers the rights to this patent from Prince Rupert to 'Hartgill Baron Edmund Hampden and Thomas Stringer'; but Patent no. 164 for 1671 assigns the same rights to the King, Charles II. Patent no. 165 for 1671 is a grant to Prince Rupert and two representatives of the Crown of the right to administer oaths of secrecy to workmen employed in the application of the original patent. These three patents were published at the Great Seal Patent Office, Holborn, 1857; I am grateful to Dr Michael Salt for tracking them down for me. On other early English patents see Lohse (1910, p. 102); Vogel (1917–20, 1918, pp. 1101–2); Schubert (1957, pp. 270–1).

[52] Réaumur (1722); Sisco and Smith (1956).

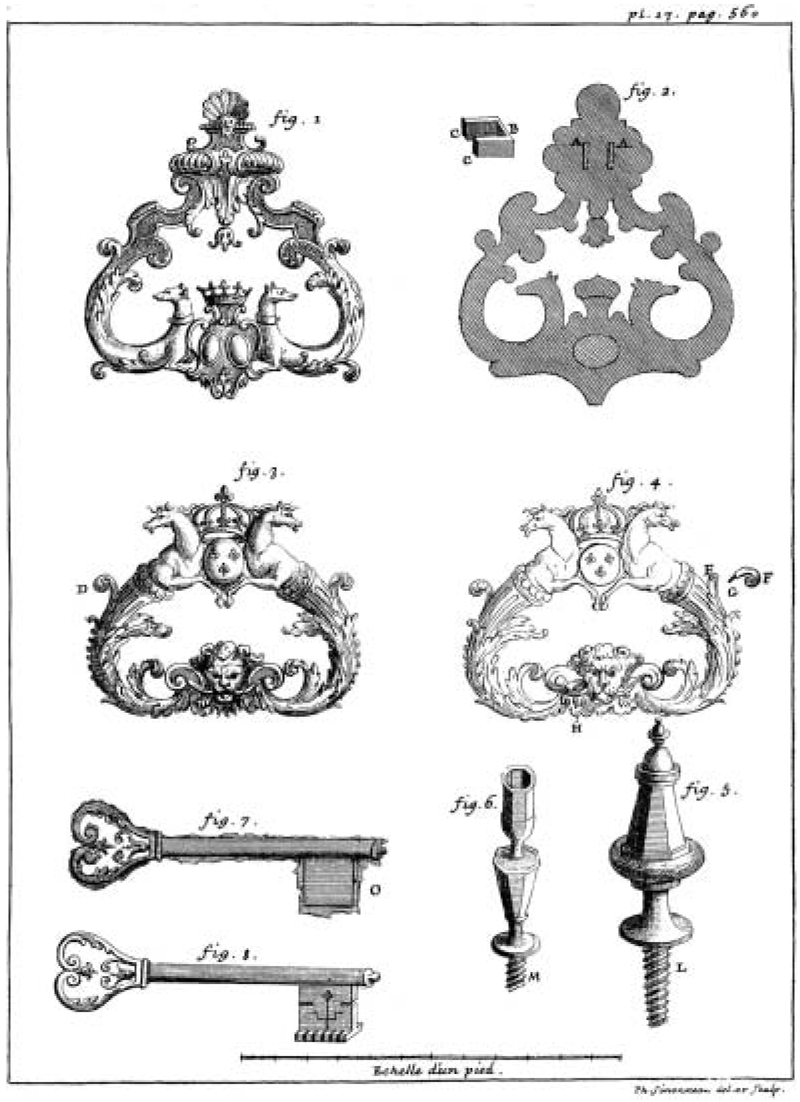


Figure 137 An illustration from Réaumur's treatise on iron (1722). **1–4**. Door knockers. **5**. Part of a fire grate. **6**. Upright part of a candlestick. **7–8**. A key before and after finishing. These are all of malleable cast iron except for the parts marked A, B, C, G, L, and M, which are cast-in pieces of wrought iron. The scale shows one foot, here equal to about 32.5 cm.

so that it could be finished by engraving and filing; Figure 137 shows some of the types of casting he was concerned with. It was only later, in the early 19th century, that the possibility of cheap mass-produced implements with reasonable mechanical properties was exploited. Figure 138 shows some typical examples of malleable castings produced in California in 1884; here malleable cast iron is obviously a cheap substitute for wrought iron worked by smiths.

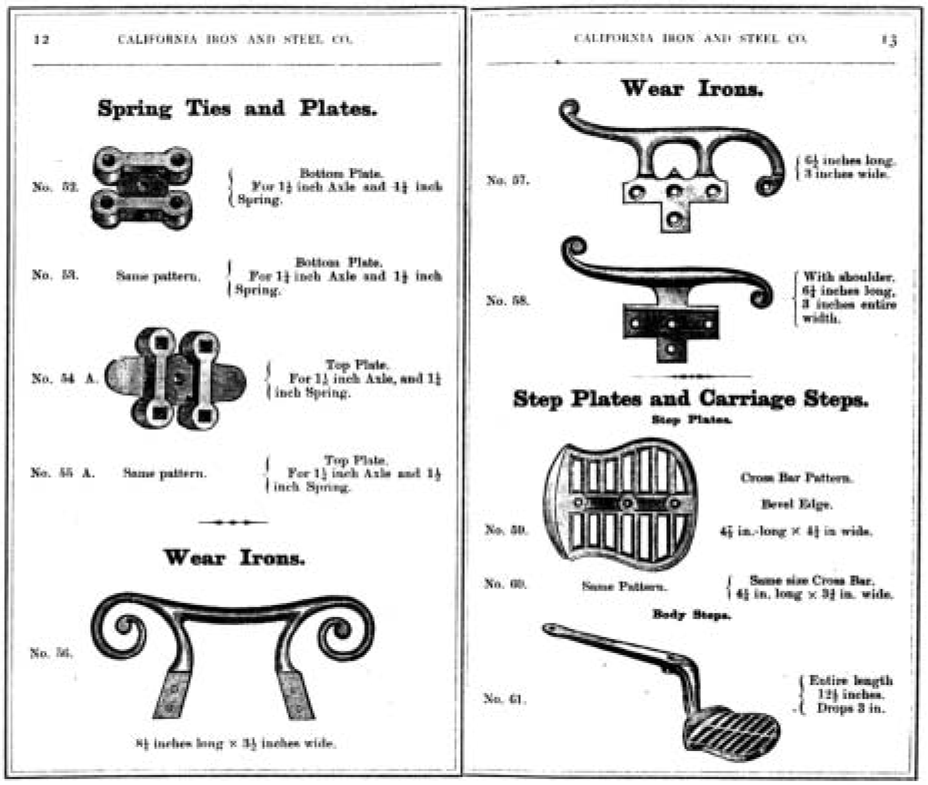


Figure 138 Two pages from a catalogue of the California Iron and Steel Company (Anon., 1884b).

The history of malleable cast iron in the West has not yet been written.[53] It appears that the technique first became industrially important in the early 19th century, in Britain, and spread from there to continental Europe. The period of greatest relative importance of malleable cast iron may have been about the end of the 19th century, after which the falling cost of steel and the rising cost of fuel made it a less attractive alternative; but malleable cast iron still has some importance in industry today.

It was noted in Section 4 above that the latest Chinese malleable cast-iron artefacts known are from the 9th century, but that a related traditional technique was used in both China and Japan as late as the 18th and 19th centuries.[54] John Barrow, who visited China as a member of Lord Macartney's mission, 1793–94, wrote: 'their cast-iron wares appear light and neat, and are annealed in heated ovens, to take off somewhat of their brittleness'.[55] The passage in which he states this appears largely to be based on an account by a member of the same mission, Dr Hugh Gillan, of

[53] Some early descriptions of contemporary malleable foundry practice are given by Strickland (1826), Terhune (1873), Rott (1881), and Guédras (1927–28). Voye (1914), Vogel (1917–20), Maurmann (1923), and Schüz and Stotz (1930, pp. 1–48) give some useful historical notes, mostly on developments in Germany. Deprez (1930) and Davis (1898) discuss early developments in Belgium and the United States respectively.

[54] P. 161.

[55] Barrow (1804, p. 299).

Box 14 *J. J. Rein's description of a traditional Japanese method of malleablising annealing (Rein 1881–86, vol. 2, pp. 518–20; tr. 1889, pp. 434–5; notes added).*

More surprising than the inlaid work on the forged iron armour and the weapons, is its direct employment on cast-iron Tetsu-bin,[a] vases and other articles. As is well known, the cast iron cannot, on account of its hardness and brittleness, be worked with the hammer, chisel and burin. The way in which these properties are lessened by the reduction of the carboniferous contents has been observed by Lehmann and Wagener in Kiôto.[b] It is a peculiar decarburising process, by which the kettle or pot receives a structure like to that of soft iron or steel, and can then be treated in the same way as in the Zogan[c]-work on forged iron.

The process of decarburisation of the surface is called Yakeru[d] (to burn), and is performed with a primitive apparatus. Old damaged rice kettles out of which the bottom has been knocked serve as ovens. These are plastered over on the inside with a fire clay (Oka-saki-tsuchi[e] and sand mixed in equal parts), so that a cylindrical space of the size of the hole in the bottom, remains open. The Kama[f] or kettle thus prepared, is turned over upon a thick plate or slab, three or four centimeters thick, made out of the same fire-proof material, which serves as a grate, and is perforated like a sieve for this purpose. In order to give this plate greater firmness, it is bound around with an iron band. The holes have a width of about 1.5 centimeters. In order to give the air free play, several stones are laid under the edge of the slab. Then the Tetsu-bin to be burned, whose outside has been carefully cleaned beforehand from dust and sand, is placed in the Kama, directly on the grate.

The difference in size between the Kama and the Tetsu-bin must be such that a space of at least five centimeters remains open around the latter. This open space is then filled with the best charcoal in pieces the size of a nut, till the Kama is filled to the rim, when the coal is kindled.

In order to increase the draught, two or three Kamas filled in the same way are set one over the other, forming a kind of chimney. When the coals have ceased glowing, others are put in, and when the second instalment is burned out, the Tetsu-bin are taken out and turned upside down (with the opening underneath), set again in the Kama and burned twice in this position. Under favourable circumstances, the surface is now sufficiently soft and tough, as is ascertained with a file. It is often the case that the furnace must be heated ten times. After the cooling the decorations are then carved as in forged iron, without danger of breaking the edges, or recoil of the burin.

[a] 鐵瓶, 'iron kettle'.
[b] Kyōto 京都.
[c] 象眼.
[d] 燒ける.
[e] 岡崎土.
[f] 釜, 'kettle', or 窯, 'oven'.

'The state of medicine, surgery and chemistry in China',[56] but Gillan does not mention the annealing of cast iron.

In Japan the technique was used, as in Réaumur's case, for surface-softening cast-iron tea-kettles and other art objects preparatory to decoration and inlaying.

[56] Published by Cranmer-Byng (1962, pp. 279ff).

J. J. Rein's brief description, published in 1886, is reproduced in Box 14.[57] Whether the technique was learned from China, or reinvented in Japan, is not clear; it seems too time-consuming for mass production of implements as in ancient China.

Did the European development of malleable cast iron owe anything to a knowledge of this Japanese technique, which might for example have been reported by early Dutch merchants? Prince Rupert grew up in Holland and was educated in Leiden.[58]

The Chinese–Japanese technique was known in Europe as early as 1734. Emanuel Swedenborg has, in his *De ferro*, a very short chapter on siderurgical techniques in 'the Indies', a term which at this time included all of Asia. Here he writes:[59]

> There is also a tradition that the Chinese and the Japanese know an art of bringing iron to a high degree of softness, so that it can receive impressions of figures as easily as lead can; and that they later can give it again its original hardness. Becher[60] seems also to boast that he could do this; this is why I mention the matter. In the following you will learn of the method described by the ingenious Mr Réaumur for softening iron.

What was Swedenborg's source for this information? Did it give any technical details? Could Prince Rupert have seen it before 1670? Further research will be needed to answer these questions, but it seems quite possible that the development of malleable cast iron in Europe was inspired by a knowledge of the Japanese technique.

(iv) The Bessemer Process? Chinese Ironworkers in Western Kentucky, 1854

In the Bessemer process, a strong blast of air is blown through molten cast iron, burning silicon, carbon, and some other alloying elements and raising the temperature sufficiently that molten pure iron is produced. Henry Bessemer patented the process in February 1856, and after some technical problems were solved, by Robert F. Mushet and Sidney Gilchrist Thomas, it largely replaced all other processes for producing wrought iron and steel from cast iron.

In a memoir written in 1890, Bessemer stated that his invention started with a conversation in 1854 with Napoleon III concerning the steel needed for improved artillery. This 'was the spark which kindled one of the greatest revolutions that the present century has to record, for during my solitary ride in a cab that night from Vincennes to Paris, I made up my mind to try what I could to improve the quality of

[57] See also Gowland (1914, pp. 52–4); Wagner (1989, pp. 9–11). Perhaps another reference is Anon. (1779, p. 491). Christopher Dresser (1882) describes several Japanese cast-iron *objets d'art* which seem as if they must have been made using this technique, but he seems to be unaware of the difficulties involved in cutting and incising cast iron.

[58] Vogel (1917–20, 1918, pp. 1101–2).

[59] Swedenborg (1734, p. 194); translated from the Swedish translation, Sjögren (1923, p. 230); note also the French translation, Swedenborg (1762, pp. 115–16).

[60] Johann Joachim Becher (d. ca. 1685), a German alchemist and political economist. He mentions Prince Rupert's invention briefiy in a book entitled *Närrische Weisheit und weise Narrheit,* published in 1682 (Vogel, 1917–20, 1918, p. 1101).

iron in the manufacture of guns'.[61] It was remarks of this kind that prompted *Scientific American* to comment in 1856 on Bessemer's 'knowledge of the properties of the *hot and cold blast*, in its application to the British Press'.[62] But it is incontestable that the Bessemer process, by enormously reducing the price of steel, was a major factor in the Industrial Revolution of the 19th century. Bessemer's entrepreneurship played at least as great a rôle in this revolution as his inventive talent.

Several authors have suggested that Bessemer may have owed something of his invention to East Asian predecessors, and in the following I shall attempt to follow up these claims. They involve a Japanese process, observed in the 17th century, and a group of Chinese ironworkers in western Kentucky in the 1850s.

In his first report of his invention, published in the London *Times* in 1856, Bessemer noted that he had experimented for some time before his entirely new approach occurred to him, after which the development of his process required only 8–9 months.[63] In his public statements Bessemer never, to my knowledge, mentioned any forerunners who might have played a part in his new approach, but in his patent application we find:

> I do not claim injecting streams of air or steam into molten iron for the purpose of refining iron, that being a process known and used before. I claim the conversion of molten crude iron or re-melted pig iron or finery iron[64] into steel, or malleable iron, without the use of fuel for reheating or continuing to heat the crude molten metal, such conversion being effected by forcing into and among the particles of a mass of molten iron, currents of air or gaseous matter containing, or capable of evolving, sufficient oxygen to keep up the combustion of the carbon contained in the iron till the conversion is accomplished.[65]

This statement has confused some writers,[66] for the first sentence seems to a modern reader to disclaim the claim made in the second. But the word *refining*, at this time and in this context, referred to a process by which carbon and silicon were *partially* removed from pig iron preparatory to the complete elimination of carbon by fining.[67] Thus Bessemer was aware of similar, less effective, processes used elsewhere. The essential improvement seems to have been the introduction of a much more powerful blast of air than had otherwise been used, so that combustion occurs quickly enough to keep the iron molten while both silicon and carbon are *completely* burned out of the iron.

. . .

[61] The memoir is reproduced in its entirety by Boucher (1924, pp. 67–76).
[62] *Scientific American*, 27 Sept. 1856, p. 21. Italics in the original.
[63] Bessemer (1856).
[64] Presumably cast iron with reduced carbon and silicon; see Gale (1979, pp. 182–3).
[65] American Patent no. 16082, 11 November 1856, quoted by Boucher (1924, p. 29).
[66] E.g. Boucher (1924, p. 31).
[67] Percy (1864, pp. 579, 625–6); Gale (1979, p. 183). Percy remarks on the terminological absurdity that *refining* should be a process preparatory to *fining*.

One conceivable source of inspiration, for either Bessemer or his predecessors, is a description of a Japanese process by the Dutch traveller Johan Albrecht van Mandelslo, published in English in 1669:

> They have, among others, a particular invention for the melting of iron, without the using of fire, casting it into a tun done about on the inside with about half a foot of earth [ca. 15 cm], where they keep it with continual blowing, and take it out by ladles full, to give it what form they please, much better and more artificially than the inhabitants of Liège are able to do.[68]

Mandelslo's book was well known in 19th-century Britain. He never visited Japan himself, so his report undoubtedly derives from some other Dutch traveller's observations in Japan. As Edward Clibborn noted in 1864, the passage quoted above might well refer to a process similar to Bessemer's, though this is far from the only possible explanation.[69] It is perhaps sufficient to note that a metallurgically informed person, reading the description here and speculating on it, might well come to the idea that the iron is kept molten by the combustion of carbon in a continual blast of air. There are enough *if*s here that we should perhaps not take the possibility too seriously; but it remains an interesting thought.

When *Scientific American* (which at this time was a weekly newsmagazine for inventors) reported Bessemer's patent, in September 1856, there came an immediate response from J. G. Martien of Newark, New Jersey, who had patented a similar process in Britain in September 1855, i.e. five months before Bessemer.[70] He made a somewhat confused accusation that his patent agent in London had filed a narrower claim than Martien had desired, and that this was because the attorney had been corrupted by Bessemer.[71] To my knowledge no historian has investigated Martien's assertion, but on its face it hardly seems likely.[72]

Another American contender was William Kelly of Eddyville, western Kentucky, at that time virtually a frontier region. *Scientific American* published in October 1856 a letter from Kelly in which he described his own experiments with essentially the same process, and suggested that Bessemer could have known something of his work:

> I have reason to believe my discovery was known in England three or four years ago, as a number of English puddlers visited this place to see my new process. Several of them have since returned to England and may have spoken of my invention there.[73]

[68] Olearius (1669, p. 160), quoted by Clibborn (1864, p. 164). A similar Japanese process is described by Geerts (1874, pp. 12–13).
[69] Clibborn (1864); cf. Percy (1864, p. 816).
[70] *Scientific American*, 13 Sept. 1856, p. 6; 27 Sept. 1856, p. 21.
[71] *Scientific American*, 13 Sept. 1856, p. 21.
[72] Note incidentally a letter from this patent agent, John Avery, in the London *Mining Journal*, no. 1047, reprinted in *Journal of the Franklin Institute*, **3** (no. 4), October 1856, p. 285.
[73] *Scientific American*, 18 Oct. 1856, p. 43.

This modest suggestion was later expanded by Kelly's son to the assertion that Henry Bessemer had himself travelled to Eddyville in disguise to spy on Kelly's experiments,[74] and this nonsense has done much harm to Kelly's reputation. The fact remains that, if it is true, as seems likely, that men familiar with the manufacture of iron witnessed Kelly's experiments, and later returned to Britain, it is quite within the realm of possibility that Bessemer's inspiration came through them from William Kelly.

Study of the history of the Bessemer process is hampered by the nature of our sources. Bessemer's iron grip on the British press of his day, and on his admiring biographers ever since,[75] together with the extravagant nonsense propagated by some of Kelly's admirers,[76] places great obstacles to the historian's work.[77] I drop the subject here.

For present purposes what is interesting is a suggestion made in 1899 that William Kelly had direct Chinese help with his invention. After a visit to Eddyville, the engineer William B. Phillips wrote of Kelly:

> Somewhere about 1845 [actually 1854], when he was working on the pneumatic process . . . he imported four Chinamen. He secured them through the American consul in China, and they worked at his iron-furnace. Now, there is an old story that the Chinese had refined iron by blowing air into it a great many years ago, and I have thought that Kelly, in asking for Chinese laborers, would naturally require the services of those who had some knowledge of the iron business. He would have had no use for the ordinary Chinese laborer, since there was, in the region where he operated, no special scarcity of labor of the unskilled sort. May it not be that he was aided by his Chinamen in experimenting with the pneumatic process, and that some knowledge of this method of refining iron was brought into this country first by those men?

There are several errors here, but it is quite true that Kelly had Chinese ironworkers in his employ. Kelly's biography in a reference work published in his lifetime, probably written by himself, has more reliable information:

> In 1854 Mr. Kelly, finding slave labor unsatisfactory,[78] imported through a New York teahouse ten Chinamen to take the place of negroes in his iron-works. This is said to have been the first introduction of that kind of labor in the United States, and it excited much comment. The experiment proved successful, and arrrangements were made for the further importation of fifty Chinamen, when a difficulty between the two nations prevented their coming.[79]

[74] Anon. (1922, pp. 172–3); Boucher (1924, pp. 205–15).

[75] See e.g. Bessemer (1905); James Dredge in *DNB*, Supp. vol. 22, pp. 185–91; Bodsworth (1998).

[76] E.g. Casson (1906, pp. 7–12); Anon. (1922); Boucher (1908, vol. 2, pp. 29–41; 1924). Kelly tells his own story in Swank (1892, pp. 397–9).

[77] Birch (1967, pp. 319–30) says much the same, and gives more documentation, but in more courteous language than I use here. Balanced treatments of the subject are by Percy (1864, pp. 810–24); Hunt (1876); Weeks (1897); Swank (1892, pp. 409–17); Wertime (1961, pp. 284–90); Gordon (1992; 1996, pp. 221–5).

[78] Cf. p. 146 above.

[79] Wilson and Fiske (1887–1900, p. 509).

The US Census for 1860 lists two of these workers, Jim Fo, forgeman, and 'EYOU', painter (artist or house painter?); see Figure 139. Both were born in Beijing, which is very surprising if true, for virtually all 19th-century Chinese immigrants to North America came from Guangdong. Both were literate (in which language?), while Jim Fo's wife Mary, born in Kentucky, was illiterate.

The source of Phillips's 'old story' is something of an enigma, for not much had been published in the West about Chinese iron techniques before 1899. At any rate it is clear that if Kelly's Chinese workers had experience with the Chinese fining methods described in Section 2 above,[80] they would have been intimately familiar with the behaviour of hot or molten cast iron under a blast of air, and they could have given Kelly valuable insights. They would certainly have known that an air blast will raise the temperature of hot cast iron and convert it to wrought iron.

(v) Shanxi Crucible Smelting in Sweden – the Höganäs Process

Readers may feel that the foregoing investigation has given frustratingly little in the way of definite conclusions. It is pleasant, therefore, to end with a story of East–West borrowing which is rather more certain.

By most criteria the most efficient means of producing wrought iron or steel is the indirect process, in which high-carbon cast iron is smelted from ore in a blast furnace, after which it is decarburised, by any of a number of means. However, the indirect process has several drawbacks. The blast furnace is extremely capital-intensive, it is most efficient at high and constant production levels, and it requires high-quality charcoal or coke as fuel. Throughout the 19th and 20th centuries, numerous attempts were made, in Europe and America, to develop new direct processes by which low-carbon iron or steel could be produced directly from ore.[81] The intention was to make iron or steel which is not too much more costly than by the indirect process, but for a smaller or less stable market and with a much smaller investment.

The traditional Chinese iron industry faced the same problems, as we have seen in Section 2 above, and developed two solutions: very small blast furnaces, for example in Guangdong, Hunan, and the Dabieshan region, and the crucible-smelting process in Shanxi.[82] Unfortunately we know virtually nothing of the history of these developments and how or when they occurred, but we must suppose that each required a long period of experimentation before a viable industrial process emerged.

In the West, until the mid-20th century, the only commercially successful direct smelting process was the Höganäs process, patented by Emil Sieurin in 1908.[83] It

[80] Pp. 16–18, 30–4.

[81] See e.g. Husgafvel (1887); Fornander (1923); Tigerschiöld (1932); Durrer (1934; 1938); Dean (1935); Eketorp (1945); Wiberg (1958); Anon. (1979d); Pope (1990). Sieurin (1911, p. 448) notes that from 1855 to 1905, 284 patents were issued in England for direct iron-smelting processes.

[82] Pp. 8–16, 38–44, 47–8, 318.

[83] Sieurin (1911); Fornander (1923, pp. 67–70); Wiberg (1958, pp. 294–8); Anon. (1979d, pp. 316–25).

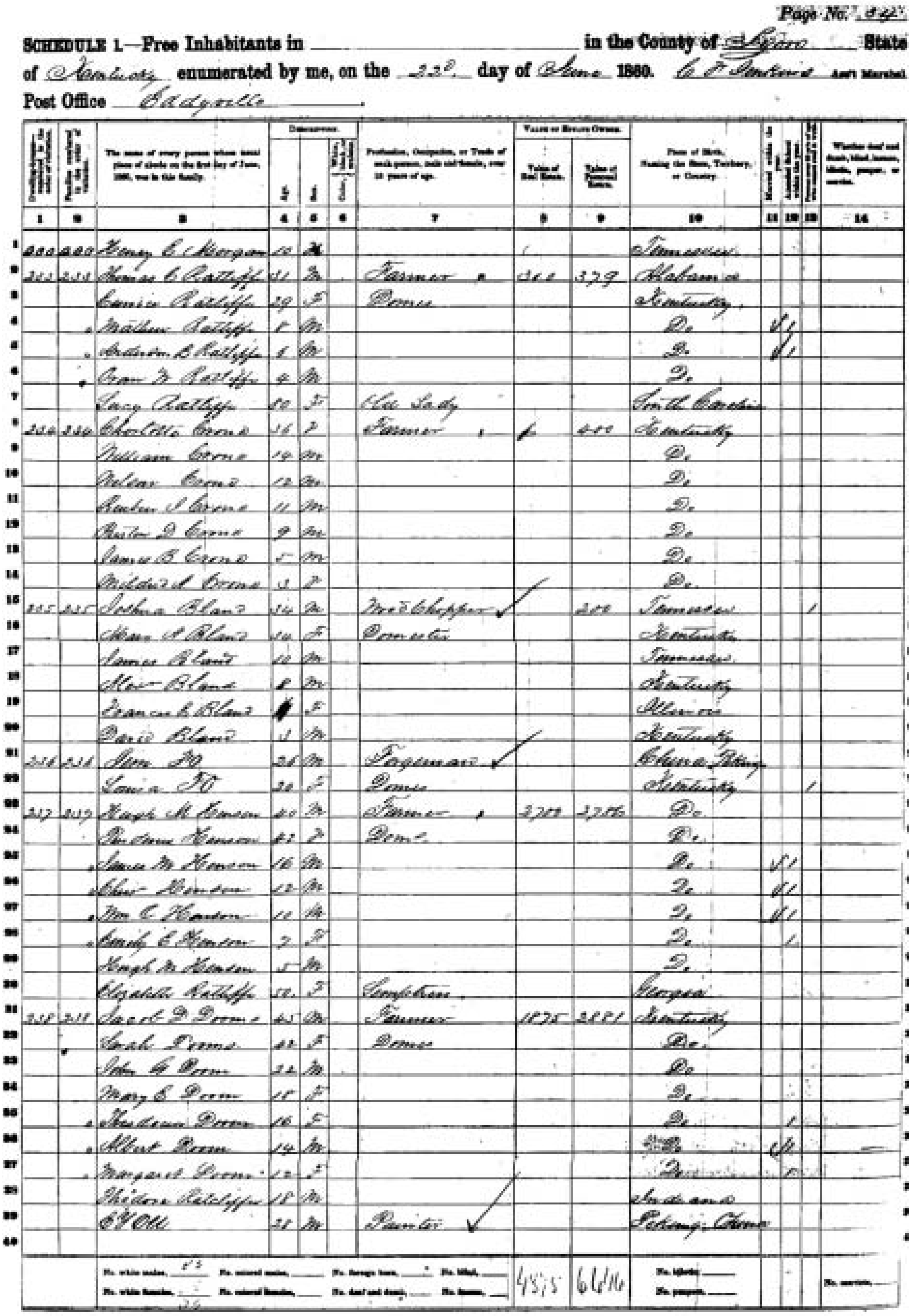


Figure 139 US Census for 1860, Lyon County, Kentucky, page 34. Note entries 21, 22, and 39 for Jim Fo, Louisa Fo, and 'EYOU'. The relevant columns are: (3) Name; (4) Age; (5) Sex; (7) Occupation; (10) Place of birth; (13) Illiterate. (US National Archives and Records Administration, 'Microform 653, Roll 383').

is essentially the same as the crucible-smelting process used in Shanxi, described in Section 2(iii) above.[84] Coal, ore, and flux are packed in long narrow crucibles and heated. The greatest difference is that the Shanxi stall furnaces are replaced with a ring kiln (and later with a tunnel kiln fuelled with natural gas). In 1932 it had been in continuous operation since 1911, and was said to be the only direct process in commercial operation anywhere in the world. In 1945 it was the direct process which had been longest in continual production, and no other direct process had given stable production over a period of years.[85] It also had the special advantage that it could use poor-quality Swedish coal. In 1979 the Höganäs Corporation had three plants in operation using this process, two in Sweden and one in the USA (in Riverton, New Jersey).[86] It appears to be still in use today.[87]

The idea of packing ore and reducing agent in a crucible and heating with an external heat source seems obvious, and in fact numerous attempts had been made since Adrien Chenot in 1855 received a prize for such a process at the International Exhibition in Paris.[88] The only commercial success among all these attempts was Sieurin's, and it is therefore striking that his process is so similar to Shanxi crucible smelting.

Sieurin could easily have known of the Shanxi process from the publications of von Richthofen and Shockley,[89] but he probably had a more direct informant. A young Swedish engineer, Erik T. Nyström, was Professor of Chemistry at Shanxi Imperial University, in Taiyuan, from 1902 to 1931, and wrote extensively on China's mineral resources and traditional industry, especially coal and iron.[90] He maintained his contacts with the Swedish engineering milieu,[91] and he would certainly have been able to answer technical questions concerning the Shanxi process. It is curious that, though he wrote about the traditional iron industries of other parts of China,[92] and wrote a great deal about the coal and iron resources of Shanxi, he never published anything significant about the traditional iron industry of Shanxi. His book, *The coal and mineral resources of Shansi province, China, analytically examined*, includes a photograph of a stall furnace for crucible smelting, but only a very brief description of the process itself.[93] Did he deliberately under-emphasise the process in order to give an advantage to Emil Sieurin?

[84] Pp. 38–44.

[85] Fornander (1923, p. 85); Tigerschiöld (1932, p. 240); Eketorp (1945).

[86] Anon. (1979d, p. 317).

[87] It is difficult to obtain clear technical information from modern industrial firms, but a recent environmental evaluation, read carefully, indicates that the same process is still in use (Axelsson et al., 2004, pp. 24, 31, 38).

[88] Percy (1864, pp. 335–45); Wedding (1901, pp. 205–7); Fornander (1923, esp. pp. 51–6).

[89] von Richthofen (1877–1912, vol. 2, p. 412; 1907, pp. 498ff); Shockley (1904); note also several other early descriptions cited in fn. 121 on p. 42 above.

[90] Available information on Nyström is mostly in his own publications, e.g. Nyström (1913–14; 1956; 1989).

[91] Witness for example his contribution to a Festschrift for his old teacher at the Royal Institute of Technology in Stockholm, Peter Klason, Nyström (1910).

[92] See e.g. p. 16 above on the Dabieshan region.

[93] Nyström (1912, p. 57); note also Nyström (1910, p. 398).

Though we know next to nothing of the early history of Shanxi crucible smelting, it is clear that centuries of experimentation must have preceded the various versions of the process that were used in recent centuries. It would seem that Sieurin built upon this long Chinese development in his own development of an iron-smelting process suited to particular geographic and economic conditions in southern Sweden.

10 EPILOGUE

> 'Begin at the beginning,' the king said, very gravely, 'and go on till you come to the end: then stop.' Lewis Carroll, *Alice in Wonderland*

Readers who have stayed with me so far have seen the technology of iron develop in China from rude beginnings in the early –1st millennium to a major industry in the Ming period. In this history the only major influence from outside was the initial introduction of bloomery iron smelting from the West. From that point onward, development seems to have been largely independent, and to have followed a quite different path from that of the West. Very early innovations – iron casting, blast-furnace smelting, fining, and a range of other techniques – meant that iron production and trade had a very different economic and political significance in China than it had in the West.

On the western end of the Eurasian continent, until late medieval times, iron production was a ubiquitous small-scale operation, and governments had little reason to involve themselves in it. On the eastern end, the Chinese state was confronted with a large-scale iron industry which was both an obvious source of revenue and a potentially dangerous competitor for economic and political power. If there ever was an 'embryonic capitalism' in the Chinese iron industry, the state took steps to abort it, from the Qin regulations through the Han monopoly to the Qing government's attempts to place limits on the size and capitalisation of mining enterprises.[1]

By 1800 things were changing. China was entering a period of deep crisis, while in the West, specifically in Britain, capitalism was in full vigour. The remarkable flood of innovations which together are referred to as the Industrial Revolution was beginning, and the cost of iron and steel was falling drastically. By 1900 China was out of the race, and Western industry dominated the world. It has taken China another century to catch up, and now we may well wonder what another century will mean for Chinese and Western industry.

[1] Sun E-tu Zen (1968); Wei Qingyuan and Lu Su (1983). On 'Embryonic capitalism' see fn. 165 on p. 56.

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ABBREVIATIONS

CSJC	*Cong shu ji cheng* 叢書集成
DZ	*Zheng tong Dao zang* 正統道藏
HWCS	*Han Wei cong shu* 漢魏叢書
QSG	*Quan Shang gu, San dai, Qin, Han, San guo, Liu chao wen* 全上古三代秦漢三國六朝文
SBBY	*Si bu bei yao* 四部備要
SBCK	*Si bu cong kan* 四部叢刊
SKQS	*Si ku quan shu* 四庫全書
SKQSZBC	*Si ku quan shu zhen ben chu ji* 四庫全書珍本初集
SSJZS	*Shi san jing zhu shu* 十三經注疏

Ao bo tu 熬波圖
Illustrated boiling of sea water.
Chen Chun 陳椿 .
Completed +1334.
Editions: (1) *SKQS*; (2) Luo Zhenyu (1914–17).
See Yoshida Tora (1983; 1993); Hara Zenshirō (1989).

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Tang.
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Prose from the Northern Mountain.
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Cheng Ju 程俱 (+1078–1144).
SBCK edn.

Bei shi 北史
Standard history of the Northern Dynasties (+386–618).
Tang, +659.
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Excerpts of books in the Northern Hall.
Sui.
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Facs. repr. of 1888 recut repr. of Song edn, Xinxing Shuju, Taibei, 1971.
See Teng and Biggerstaff (1971, p. 85).

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The great materia medica.
Ming, 1596.
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Writings for elementary instruction.
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See Teng and Biggerstaff (1971, pp. 86–7).

Chun ming meng yu lu 春明夢語錄
A work on Beijing and its environs as it was in the late Ming.
Sun Chengze 孫承澤 (1593–1675).
Written after 1654.
SKQSZBC edn.
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Cong shu ji cheng 叢書集成
Collectaneum of collectanea.
Shangwu Yinshuguan, Shanghai, 1935–37.

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Collected statutes of the Ming dynasty.
Shen Shixing 申時行 (1535–1614).
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Dao zang 道藏
See *Zheng tong Dao zang*.

Dong guan Han ji 東觀漢記
Records of the Han compiled in the Eastern Lodge.
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The essential criteria of antiquities.
Cao Zhao 曹昭.
Ming, +1388.
Tr. + facs. repr. of +1388 edn, David (1971, pp. 344ff); see also Rawson (1975).

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Critical study of the seventeen dynastic histories.
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Extensive records of the Taiping Xingguo 太平興國 reign (+976–984).
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Universal geography of the Taiping Xingguo 太平興國 reign (+976–983).
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Song Yingxing 宋應星, d. ca. 1660.
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Standard history of the Northern Wei dynasty (+386–534).
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Collected works of Wei Su 危素 (+1303–72).
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General investigation on important writings.
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The annals of Wu and Yue, folklore of southeast China.
+1st century.
Yuan Kang 袁康 and Wu Ping 吳平.
SBCK edn.
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Record of an embassy to the West.
Liu Yu 劉郁.
Yuan, +1263.
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Tr. Bretschneider (1937, vol. 1, pp. 122–56).
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The mathematical canon of Xiahou Yang.
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Collection from Fragrant Brook.
Fan Jun 范浚 (+1102–50).
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Newer standard history of the Tang Dynasty, +618–907.
Song, completed +1060.
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Completed +1072.
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Newly revised materia medica.
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Ming, 1462.
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Collected data for a continuation of the 'Comprehensive mirror for aid in government'.
Song, +1183.
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The book of Master Xun.
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Date very uncertain: possibly pre-Han.
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Miscellaneous notes by Zhu Yi 朱翌 (+1098–1167).
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Collection of literature arranged by categories.
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Sea of jade, an encyclopaedia.
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1120 vols., Shangwu Yinshuguan, Shanghai, 1924–26.
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Bao Yanbo 鮑延博 and Bao Zhizu 鮑志祖.
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Zhou shu 周書
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Linghu Defen 令狐德棻 (+583–666).
Tang, +635.
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Zhou yi 周易 (*Yi jing* 易經)
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Zhou, perhaps −4th century.
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Translations: Legge (1872); Couvreur (1914); Watson (1989).
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B/C: MODERN PUBLICATIONS IN ALL LANGUAGES

When the translation of the title of a Chinese or Japanese publication comes from the publication itself, it is given in quotation marks; otherwise not.

ABBREVIATIONS

AI/AO	*Ars Orientalis* (formerly *Ars Islamica*)
AM	*Asia major*
AQ	*Antiquity*
ARM	*Archeomaterials*
BDX	*Beijing Daxue xuebao (Renwen kexue)* 北京大學學報〔人文科學〕(Journal of Beijing University, Humanities Section)
BEFEO	*Bulletin de l'École Française d'Extrême-Orient*
BFWW	*Beifang wenwu* 北方文物 ('Northern Cultural Relics')
BMFEA	*Museum of Far Eastern Antiquities, Bulletin*
BMM/S	*Bulletin of the Metals Museum* (Sendai, Japan)
BSOAS	*Bulletin of the School of Oriental and African Studies, University of London*
CSA	*Chinese Sociology and Anthropology*
CSC	*Chinese Science*
DA	*Der Anschnitt: Zeitschrift für Kunst und Kultur im Bergbau*
DLZZ	*Dalu zazhi* 大陸雜誌 ('The Continent Magazine')
DNWH	*Dongnan wenhua* 東南文化 ('Southeast Culture')
EC	*Early China*
EHR	*Economic History Review*
FEQ	*Far Eastern Quarterly*
FER	*Far Eastern Review*
GBY	*Gugong Bowuyuan yuankan* 故宮博物院院刊 ('Palace Museum Journal')
GDSK	*Guangdong shehui kexue* 廣東社會科學 ('Social Sciences in Guangdong')
GJ	*Geographical Journal*
GT	*Gang tie* 鋼鐵 (Iron and Steel)
GZYJ	*Guangzhou yanjiu* 廣州研究 (Research on Guangzhou)
HJAS	*Harvard Journal of Asiatic Studies*
HXKG	*Huaxia kaogu* 華夏考古 ('Huaxia Archaeology')
JA	*Journal Asiatique*
JAOS	*Journal of the American Oriental Society*
JAS	*Journal of Asian Studies*
JEH	*Journal of Economic History*
JESHO	*Journal of the Economic and Social History of the Orient*
JHKG	*Jiang Han kaogu* 江漢考古 ('Jianghan Archaeology')
JHMS	*Historical Metallurgy: Journal of the Historical Metallurgy Society*
JISI	*Journal of the Iron and Steel Institute* (London)
JRAS	*Journal of the Royal Asiatic Society*
JRAS/MB	*Journal of the Malayan Branch of the Royal Asiatic Society*
JRAS/NCB	*Journal of the North China Branch of the Royal Asiatic Society*
JXWW	*Jiangxi wenwu* 江西文物 (Cultural Relics of Jiangxi)
KG	*Kaogu* 考古 ('Archaeology')
KGTX	*Kaogu tongxun* 考古通訊 (Archaeological Bulletin)
KGXB	*Kaogu xuebao* 考古學報 ('Acta Archaeologia Sinica')
KGXJK	*Kaoguxue jikan* 考古學集刊 ('Papers on Chinese Archaeology')
KGyWW	*Kaogu yu wenwu* 考古與文物 ('Archaeology and Cultural Relics')
KJSW	*Keji shi wenji* 科技史文集 (Studies on the History of Science and Technology)
LSJX	*Lishi jiaoxue* 歷史教學 (History Education)
LSYJ	*Lishi yanjiu* 歷史研究 (Historical Research)
NFWW	*Nanfang wenwu* 南方文物 ('Relics from South')
NYKG	*Nongye kaogu* 農業考古 ('Agricultural Archaeology')

SAM	*Scientific American*
SCWW	*Sichuan wenwu* 四川文物 ('Sichuan Cultural Relics')
SE	*Stahl und Eisen*
SGZS	*Shigaku zasshi* 史學雜誌 (Historical Journal)
SXSY	*Shixueshi yanjiu* 史學史研究 ('Journal of Historiography')
SXYK	*Shixue yuekan* 史學月刊 ('Journal of Historical Science')
TAIME	*Transactions of the American Institute of Mining Engineers*
TCULT	*Technology and Culture*
TGE	*Technikgeschichte*
TNS	*Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*
TP	*T'oung Pao*
TYGH	*Tōyō gakuhō* 東洋學報 (Oriental Studies)
WARC	*World archaeology*
WB	*Wen bo* 文博 ('Relics and Museology')
WSZ	*Wen-shi-zhe* 文史哲 (Literature, History, and Philosophy)
WW	*Wenwu* 文物 ('Cultural Relics')
WWCK	*Wenwu cankao ziliao* 文物参考資料 (Cultural Relics Reference Materials)
WWCQ	*Wenwu chunqiu* 文物春秋 (Annals of Cultural Relics)
WWTD	*Wenwu tiandi* 文物天地 ('Cultural Relics World')
WWZLC	*Wenwu ziliao congkan* 文物資料叢刊 (Cultural Relics Materials Series)
XSYJ	*Xueshu yanjiu* 學術研究 ('Journal of Academic Research')
YJB	*Yejin bao* 冶金報 (Metallurgical News)
ZDGM	*Zeitschrift der Deutschen Morgenländischen Gesellschaft*
ZGNS	*Zhongguo nong shi* 中國農史 ('Agricultural History of China')
ZGQB	*Zhongguo qianbi* 中國錢幣 ('China Numismatics')
ZJSY	*Zhongguo jingji shi yanjiu* 中國經濟史研究 ('Researches in Chinese Economic History')
ZKS	*Zhongguo keji shiliao* 中國科技史料 ('China Historical Materials of Science and Technology')
ZKSY	*Ziran kexueshi yanjiu* 自然科學史研究 ('Studies in the History of Natural Sciences')
ZLBG	*Zhongguo Lishi Bowuguan guankan* 中國歷史博物館館刊 ('Bulletin of the Museum of Chinese History', Beijing)
ZSDX	*Zhongshan Daxue xuebao (Zhexue shehui kexue ban)* 中山大學學報 (哲學社會科學版) ('Journal of Sun Yatsen University: Social Sciences Edition')
ZSJSY	*Zhongguo shehui jingji shi yanjiu* 中國社會經濟史研究 ('Journal of Chinese Social and Economic History')
ZSY	*Zhongguo shi yanjiu* 中國史研究 (Studies in Chinese History)
ZWWB	*Zhongguo wenwu bao* 中國文物報 (Chinese Cultural Relics News)
ZYWW	*Zhongyuan wenwu* 中原文物 ('Cultural Relics from the Central Plains')
ZYYY	*Zhongyang Yanjiuyuan yuankan* 中央研究院院刊 ('Annals of Academia Sinica', Taibei)

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