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The Metallurgy of the American Bloomery Process

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ABSTRACT During the nineteenth century, Americans in New Jersey and the Adirondack region of New York brought the ancient bloomery process for the direct reduction of iron to a high state of technological development. Using this process, they were able to make iron as good as the best Swedish grades. Rich magnetite ore was used; low fuel consumption was achieved by preheating the air blast, and labor productivity was maximized by ore preparation and hearth design that speeded the reduction process. Magnetite grains were reduced to particles of sponge iron in the upper part of the hearth, fell with liquid slag, and agglomerated on rims of iron formed around pieces of charcoal to nucleate the bloom. The hearth was manipulated to form a pool of liquid slag on top of the bloom that served as a trap for descending sponge-iron particles. The iron in the bloom was often partially carburized by entrapped charcoal particles. Although dismissed by some historians as "primitive," the American bloomery process was a sophisticated adaptation of an ancient technology to local resources and economic conditions and was capable of producing grades of iron for special applications not easily made in other ways.

INTRODUCTION

Direct reduction of iron by bloom smelting was practiced from prehistoric times onward throughout much of the world. Europeans developed it most fully as an industrial process in the Catalan forges used in southern France and northern Spain until well into the nineteenth century. The technology of bloom smelting was further refined in the United States and used to make wrought iron in the Adirondack region of New York State from 1801 until 1900. The smelting technology developed there was called the "American bloomery process," and it is of interest today both as a standard for comparison with other methods of bloom smelting and for the light that it sheds on the development of American metallurgical expertise in the early decades of the republic.

HISTORICAL EVIDENCE

Bloom smelting was undertaken by British colonists in North America early in the seventeenth century (Harvey 1988; Mulholland 1981; Swank 1892) and continued for nearly three hundred years. Swank (1892) and other early historians of American metallurgy considered bloom smelting a primitive technology and focused their attention on other branches of ironmaking. In part, this reflects their preoccupation with the quantity of metal produced rather than its quality. In the nineteenth century, most bloomery iron was made for specialized applications, such as crucible steelmaking, where metal of superior quality commanded advanced prices. The archaeological record is also unrepresentative because, while many early blast furnace stacks survive, there are virtually no above-ground remains of bloomeries to be found today, and few excavations of bloomery sites have been undertaken in North America.

At different times and places in the Old World, many alternative bloom smelting procedures and furnaces were used. A few of these have been studied in depth by archaeometallurgists (see, for example, Tylecote 1986; 1987). It is likely that bloomery designs similar to those at Rockley Smithies, Yorkshire, and Muncaster Head, Cumbria, would have been familiar to American colonists who came from Britain. At Rockley Smithies (Crossley and Ashurst 1968), the bloom hearth used between about 1600 and 1640 was a pit approximately 0.4 m. deep with an aperture for tapping the slag. It was blown by a water-powered bellows, but had no power-driven hammer. The forge at Muncaster Head, built in 1636, had a bloom hearth in the form of a pit and was blown by a single tuyere with a water-powered bellows (Tylecote and Cherry 1970). Since furnace bottoms weighing up to 22 kg. were found on the site, it appears that only partial tapping of slag was practiced at Muncaster Head. The blooms made there were forged by a hammer driven by a water wheel that developed 7.5 kw. of power.

Recent excavations show that bloom smelting was probably one of the first enterprises tried by the early Virginia colonists. According to the historical evidence collected by Swank (1892: 113, 148), bloom smelting was carried on in Massachusetts from 1652 and before the early years of the eighteenth century, most of the bloomeries in North America were in New England and New Jersey. Thereafter bloom smelting to serve local needs was undertaken in most of the colonies. Early bloomeries were often built by English colonists (Mulholland 1981: 67) and, while it is likely that they were similar to the ones described above, archaeological excavations are needed to confirm this hypothesis.

In the bloomery process, the iron in the ore serves both as the flux and the source of metal. Fluid slag formed by reaction of gangue minerals with iron oxide is an essential component of the process and, to be liquid at the temperatures at which bloomeries operate, the slag must contain about 50 percent iron. Rich ore is needed for bloomery smelting if all the gangue is to be removed as slag. Some of the richest ores available along the east coast of North America were the magnetite deposits in northern New Jersey and the eastern Adirondacks of New York. Smelting of the magnetite ores in New Jersey began about 1710 (Swank 1892: 147) in bloomeries described by Swank as "Catalan forges of the German type," many blown with a trompe (a device that compresses air with water falling in a tube). It is difficult to interpret this statement because, first, the Catalan bloomery was used in southern France and northern Spain, not Germany, and, second, a larger fall of water was needed to operate a trompe than was commonly available at the bloomery sites in New Jersey. The Catalan forge evolved from the bowl hearth and was fully developed by the early eighteenth century (Percy 1864: 279–280). The hearth was made with metal plates of a particular shape and fitted with a single tuyere blown by a trompe. Both coarse- and fine-grained ores were used in the process. The coarse ore was kept separate from the charcoal and was placed so that reaction with the furnace gases extended through a column of ore as it descended into the hearth. The trompe first appeared in Italy in about 1640 and very few are known in the United States (Alexander 1840: 56–57). By the middle of the nineteenth century, American writers had adopted the term "Catalan forge" to describe any type of bloomery—it is used this way by Daddow and Bannon (1866) in their treatise on American metallurgy, for example—and it appears that Swank followed this usage. Much confusion has arisen from the appropriation of the name of a specific type of bloomery for all variations of the process.

T. Sterry Hunt (1869) offered an interpretation of the origin of the American bloomery in a report written for the Geological Survey of Canada in response to interest in bloomery smelting of magnetite sands found in the St. Lawrence valley. Hunt drew a clear distinction between the American bloomery and the Catalan process, and suggested that the American process originated from the German bloomery described in detail by Karsten in 1816 (but out of use by 1860). He suggested that the American bloomery may have evolved from the metallurgical experience of German immigrants who arrived in the middle Atlantic states in the eighteenth century rather than from that of earlier British colonists. According to Hunt, the German bloomery described by Karsten had an approximately cube-shaped hearth from 14 to 21 inches on a side made of iron plates and a single, horizontal tuyere. Fine ore was placed on the fire at frequent intervals and not separated from the charcoal as in the Catalan hearth.

In 1783 the Swedish traveler, Samuel Hermelin, described a bloomery in New Jersey as having a hearth 20 × 24 inches in plan, 20 inches deep and slightly tapered toward the bottom (Hermelin 1931: 55). A water wheel drove both a bellows for blowing the hearth and a stamp mill for reducing the ore to a fine grain size. The bloom smelter spread ore over the charcoal fire in the hearth at regular intervals until a bloom of the desired size was formed. The similarity of this with the German bloomery suggests that Hunt's interpretation of the origin of the process is correct.

Adventurers began to mine the rich magnetite ore in the eastern Adirondack region of New York (Fig. 1) as early as 1766 and to build bloomery forges in Essex, Clinton, and Franklin counties after 1800. After 1823, they were able to use the canal from Lake Champlain to the Hudson River to carry Adirondack iron out of the wilderness to industrial centers at a great saving in cost. Entrepreneurs found production of bloomery iron for these markets an attractive undertaking and built additional forges (Moravek 1976). Many were financed by landed proprietors of Adirondack estates and operated by professional bloom smelters hired by the owners (Glenn 1977: 239, 265, 325), but others, like the Penfield forge at Ironville (Barker 1969) and the Adirondack forge at Tahawus (Seely 1978: 14, 23, 27, 57), were built by entrepreneurs from outside the region who were well informed about metallurgical technology. At Tahawus, the proprietors of the Adirondack Iron and Steel Company enlisted professional, scientific help in their efforts to make high-quality iron from ore that was later found to be titaniferous magnetite. Numerous chemical analyses of the Tahawus ore were made beginning in 1832; Ebenezer Emmons carried out geological surveys between 1837 and 1841; Walter Johnson (1839) did mechanical tests on the iron made; and the use of a magnetic separator was investigated in 1833.

In the earliest technical account of the bloomery forges used in the Adirondack region, Overman (1850) described a Catalan fire set in a stone hearth some eight feet square with a firebox about 26 inches square and 18 inches deep lined with cast iron plates; there was a single tuyere and a tap hole for slag. Four hundred pounds of ore in the form of coarse sand was used to make a bloom of about 100 pounds. The charcoal was piled two to four feet high over the firebox and the ore stacked on the side opposite the tuyere. Overman's drawing of the forge shows a structure fitted with decorative Doric columns that seem to be out of place in an American metallurgical works. This drawing is very similar to the illustrations of the German bloomery in Karsten's *System der Metallurgie* (1832). We believe that Overman's account was more strongly influenced by his knowledge of German bloom smelting than by direct observation of the American process. He repaired this deficiency within the next few years because the description of the Adirondack bloomery in his *Treatise on Metallurgy* (1852) is different, but contains no suggestion that the process had been changed in the interval. He described the hearth as about 30 inches square in plan, 8 to 11 inches deep below the tuyere, made of iron plates, and fitted with a tap hole for drawing slag. The bottom plate was water cooled; the tuyere entered at the side and a little to the rear. Finely crushed, dressed ore was used. The most novel feature of this bloomery, not seen elsewhere, was the brick stack containing three cast iron pipes to preheat the air blast with waste heat from the forge fire. The difference in the descriptions in Overman's two books might be taken as evidence that the hot blast apparatus had been introduced between 1850 and 1852. However, at least one installation was made as early as 1840 (Seely 1978: 38) and, according to Neilson (1867), hot blast came into general use a few years later. Overman was probably unaware of this development when he wrote his first book. Since Overman remarks that the bloomery could be operated either with hot or cold blast, it may be that in 1852 the hot blast was not yet fully accepted.

Several authors have prepared general accounts of the Adirondack bloomeries (Chahoon 1875; Bixby 1911; Hardy 1985; Linney 1934; Moravek 1976; Glenn 1977; Allen 1983), and three papers on them were

Fig. 1. Map of the Adirondack region of New York. The bloomery forge sites studied are in Essex, Clinton, and the eastern part of Franklin counties. The exact locations are given by Allen and others (1991). (From W. B. Taylor, "Special Report on Coal, State of New York No. 71 in the Senate, March 18, 1865")

written by professional metallurgists from outside the region. In the first of these professional papers, Hunt (1869) gave a general description of bloomery operation primarily on the basis of his visits to the forges at Ausable Forks and New Russia. The other two professional reports were written during a revival of interest in direct reduction processes among metallurgists in the 1870s and 1880s. The most detailed was by Thomas Egleston (1879–1880) of the Columbia School of Mines; the other was written by H. Louis (1880) for John Percy, who planned to include it in the new edition of his *Iron and Steel.* (The new edition was never completed and the manuscript of Louis's report is among Percy's papers in the library of the Institute of Metals in London.) A concise summary of the technical aspects of the American bloomery process based on Hunt's and Egleston's papers was published by Howe in his *Metallurgy of Steel* (1904).

The configuration of the hot blast pipes, tuyere, and hearth of the Adirondack bloomery in its final, fully developed form is shown in Figure 2. Preheating the air blast reduced the consumption of fuel about 20 percent (Hunt 1869: 278). Hearths were limited to the size that a single bloomer could manage and the largest were about 30 inches square and had a working depth of about 17 inches. The blast pressure was about 2 pounds per square inch and the temperature ranged from 550 to 600°F (Hunt 1869: 278) upward to 600 to 800°F (Egleston 1879–1880). The ore was calcined by heating it on wood fires in large pits; it was then crushed to about 3 mm. grain size and passed through magnetic separators or (more commonly) washed with water until it contained about 67 percent metallic iron (Hunt 1869: 276; Egleston 1879–1880). At the more modern forges, the bloomer, working largely alone, made a bloom of about 400 pounds (called a loupe in New York) from approximately 1000 pounds of charcoal and 800 pounds of dressed ore every three hours of a twelve hour shift. About 23 percent of the iron contained in the ore was lost in the slag.

At first, the Adirondack bloomeries supplied the local demand for iron to make nails, agricultural implements, and hand tools; the rest of their product was sold to industrial users downstate. There was little secondary manufacturing that could convert the bloomery iron into finished products in the Adirondack region (Moravek 1976: 83). In the 1830s the Adirondack bloomeries became nationally important as a source of high-quality iron for special ap-

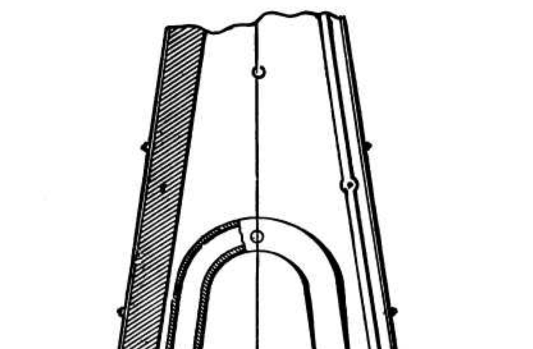

Fig. 2. Front view and section of an American bloomery hearth as used in the Adirondack region in the second half of the nineteenth century. The hearth is made of water-cooled, cast iron plates set in a brick base. The air blast enters on the left through one tuyere. The cast iron pipes for preheating the air blast are placed in a pyramidal brick stack that is topped with a chimney. (After Howe 1904)

plications (such as suspension bridge wire); later, they were a major supplier of low phosphorus iron for the American crucible steel industry. Documentary evidence that the bloomery process could produce superior iron is found in the strength tests conducted by Walter R. Johnson (1839) on samples of bar iron made at the forge at Tahawus. He used the test procedure and machine that he had developed for the study of boiler plate at the Franklin Institute in 1832. Johnson found that ductility, measured as the reduction in area at fracture, was 46 percent (for the two specimens for which these data were reported) and the tensile strength was 56,000 pounds per square inch. This combination of strength and ductility was substantially better than that found in any of the fifteen other kinds of American iron tested in the 1832 Franklin Institute project, and is comparable to the strength properties of Swedish iron of the period (Gordon 1988).

Many examples of preference for Adirondack iron can be found in nineteenth-century records. While searching for sources for iron with which to make wire for suspension bridge cables and wire rope on his trip east in 1846, John A. Roebling found that Champlain iron was often recommended as an alternative to Norway iron (Roebling 1846). Charles Stewart recounted trips to the Adirondacks in the mid-nineteenth century to buy blooms for his wire works in Easton, Pennsylvania, and gave the characteristics of a first-class bloom as "the elongated cut like a horse's under-lip. (The hot loop when finished under the [h]ammer being cut or rather squeezed off by blows of the trip hammer on a dull iron bar); the actual absence of any cross crevices on the lip, the clean, smooth surface of the bloom, indicating its perfect consolidation under the blows of the powerful trip hammer" (Stewart 1986). By 1868, the proprietors of crucible steel works in the vicinity of Pittsburgh were making large purchases of Adirondack iron for use as starting material. It was used as an alternative to the Swedish iron preferred by the English makers of crucible steel (Tweedale 1987: 19). The primary requirement of the iron for this use was a low phosphorus content; Adirondack iron averaged about 0.025 percent phosphorus (Howe 1904: 270). (For comparison, Swedish iron ranged between 0.009 and 0.017 percent P [Barraclough 1984: 70] while the normal phosphorus content of wrought iron used for structural purposes was about 0.15 percent [Aston and Story 1941: table I]).

We have indirect evidence of the strong demand for Adirondack iron in 1867 from Samuel Collins's reminiscences of the attempts of Collins Company, the celebrated makers of axes, to establish their own crucible steel works (Collins 1868: 196). He remarks that, "The first lots of Steel iron that we got from Lake Champlain, some 200 Tons was excellent quality and made good axes. The quality afterwards was much inferior. Not getting any satisfactory explanation by letter we sent up one of our workmen to ascertain the cause, and found that owing to an insufficient supply of Charcoal to meet the great demand for their Iron from Pittsburgh and elsewhere they had been compelled to use bituminous coal and roll the Iron instead of hammering it." He goes on to explain the difficulties that his company had in obtaining adequate supplies of suitable iron from Sweden. In 1882, when the annual output of Champlain iron reached its peak of 48,354 tons (Howe 1904: 271), most of this iron went to the crucible steel makers.

The historical record gives few clues of the origin of the American bloomery process, which was clearly different from the bloomeries used in other countries. It must have gone through a period of major technical development in the United States at a time for which we have little documentary record of the wrought iron component of the American iron industry. That this technical development has been unappreciated is shown by the usual description of American bloomery smelting in economic histories as primitive metallurgy carried on by persons backward in technical practice. Nor does the documentary record tell us much about the reasons for the high productivity of the American bloomery process as compared to other forms of bloom smelting, the skills required, or how they were learned by its practitioners. Archaeological evidence supplies additional information on these points.

FIELD AND LABORATORY EVIDENCE

New York

As bloom smelting came to an end in the Adirondacks late in the nineteenth century, machinery and equipment were removed from the forges and sold. Later, scrap iron and building materials were salvaged from some of the sites. The water power installations at a few forges were used for sawmills, but many bloomery sites remained undisturbed as their associated communities were abandoned. By 1960, the visible evidence of the Adirondack forges had virtually disappeared. Through fieldwork over a period of years, Richard S. Allen relocated the sites of many of the forges. Subsequent explorations by R. F. Allen, J. C. Dawson, M. F. Glenn, and R. W. Ward (Allen et al. 1991) located many more sites. Excavations have been carried out at only one of these, the Caldwell forge at Clayburg (Pollard 1985).

Sites Studied

The bloomeries studied are listed in Table 1; descriptions of the forges and their exact locations are given by Allen and others (1991). Slag is the most abundant artifact at the forge sites, but fragments of wrought iron bars and blooms were found at several of them and there are remains of hearth plates at a few. The amount of slag remaining is not always the amount produced at a site because it has sometimes been removed for blast furnace feed, road metal, or fill. No systematic excavations have been done at these sites and most of the slag samples were collected near the tops of slag piles and so are probably representative of the practice in the last years of forge operation. Consequently, we have listed the sites in Table 1 in the order of their closure dates to provide an approximate chronology of the specimens examined. The microstructures of over seventy-five slag specimens were studied in the laboratory.

TABLE 1. Forges studied

1. North Elba. Cold blast. 1810/c. 1815
2. Brainard's. Cold blast. ca. 1817/1831
3. Higby. ca. 1840/c. 1842
4. Split Rock. Cold blast. 1825/1845
5. Flackville. Cold blast. 1829/ca. 1840
6. Deadwater. 1846/1857
7. Trout Pond. 1847/1857
8. Wilder's. ca. 1825/1857
9. Highlands. 1837/1857
10. North Hudson. 1848/1858
11. Merriam's. 1843/1845/1868
12. Upper Norrisville. Before 1856/1857/ca. 1870
13. Kingdom. 1825/1866/1873
14. Valley Forge. 1845/1873
15. New Russia. 1802/1860/1874
16. Keeseville. 1818/ca. 1880
17. Caldwell. 1844/1853/1881
18. Willsboro. 1801/1850/1862/1883
19. Stower's. 1837/1884
20. Wadham's. 1822/1873/1880/1884
21. Penfield. 1828/1846/1879/1886
22. Clintonville. 1810/1826/1844/1888
23. Woods Falls. 1863/1872/1888
24. Bellmont. 1874/1893

Note: Dates are the years in which the forge was built, rebuilt, and closed. For a full description of the forges and sources of data on them, see Allen and colleagues (1991).

Slag

We can divide the slag found at the forge sites into three types distinguished by size, shape, and texture. The pieces of slag we call *skulls* have convex, relatively smooth bottom surfaces, concave tops with a rough texture, are round to oval in plan, and often have a high iron content revealed by a tendency to weather by rusting. They range from 12 to 28 inches in greatest dimension, weigh from about 25 to 65 pounds, and are usually found complete and unbroken. *Bottoms* have one flat surface that is usually smooth, a strongly developed columnar grain structure extending upwards from this surface, and a concave top surface. They are always found as broken fragments that may range up to as large as 26 inches. The remaining slag is in smaller *fragments*, often of hand specimen size.

Polished thin sections were examined in transmitted and reflected light. The dominant constituents are iron-rich glass and fayalite crystals; wustite dendrites are usually present in amounts ranging from sparse to dense, while droplets of iron and magnetite precipitated from solution are sometimes present. There are ore particles in about half the specimens, usually in the form of fragments of magnetite whose reaction with the slag has been arrested by solidification. The liquid slag had penetrated the magnetite crystals at approximately equally spaced intervals along their perimeters, thereby producing isolated protuberances which subsequently broke off into the slag (Fig. 3). The iron drops present in the slag are usually carbon free; when carburized particles are found, they are always much larger than the carbon-free droplets. Iron labyrinths pseudomorphic after cubic grains of magnetite were found in several specimens. This is illustrated in a sample of slag identified from its shape as having come from the upper part of a skull (Fig. 4). In a few cases, wustite den-

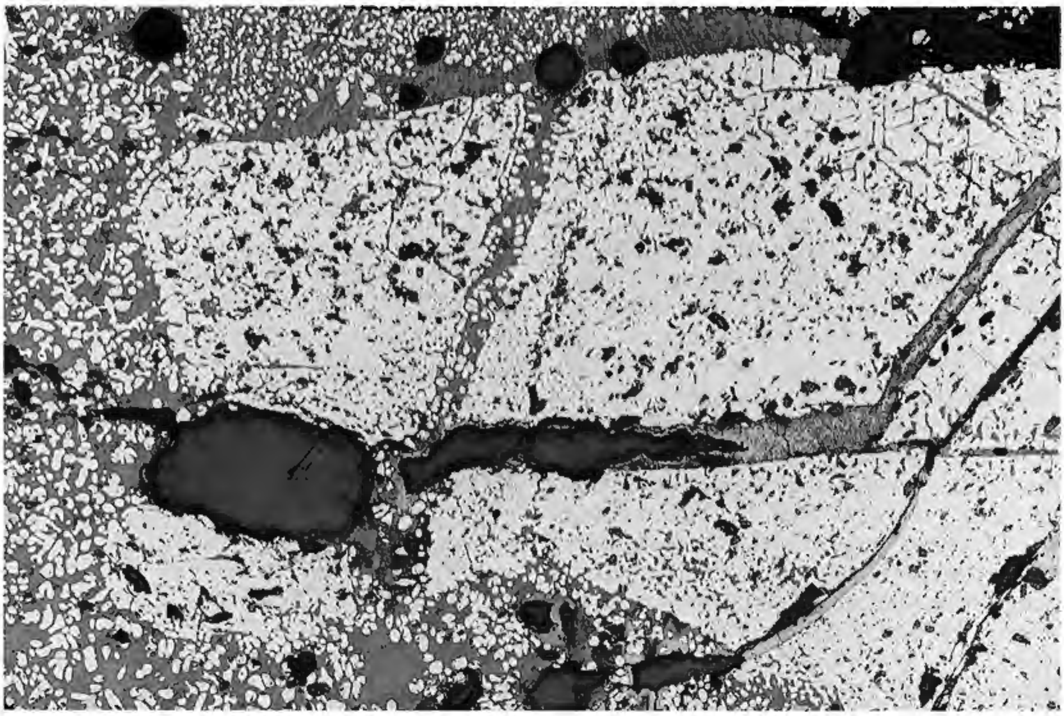

Fig. 3. Magnetite grains of the ore reacting with slag in the bloomery hearth. The reaction is concentrated at approximately equally spaced points along the perimeters of the ore grains, causing small bits of ore to break off and enter the slag. Specimen from Wilder's forge site, collected by R. S. Allen. Length of the area photographed is 1.5 mm.

drites partially reduced to iron metal are present. Other mineral constituents are rarely found.

Although the range of constituents in the slag is small, the range of structures is large and many samples are heterogeneous, even on the scale of a single thin section. Both porous and dense layers, contacts between successive flows, and changes in the concentration and habit of wustite dendrites are often present in the same specimen. This suggests that conditions within the slag in the bloomery hearth were heterogeneous in space and variable in time, and that the resulting variations in the slag were not evened out by subsequent mixing.

Photographs of sections through two skulls are shown in Figure 5. The sample from the Penfield Forge (12.5 × 9 × 5.5 inches, 26.5 pounds) is among the smaller of the skulls found, while that from Caldwell (19 × 14 × 4 inches, 66.6 pounds) is close to the average size. The Penfield sample contains iron particles ranging in size up to 5 mm.; the one from Caldwell has iron particles up to 10 mm. as well as a piece of agglomerated iron. The matrix of both is fayalitic slag that contains bubbles and wustite dendrites in moderate abundance. The included charcoal fragments are often surrounded by rims of iron. The top surface of the example from Caldwell forge has a characteristic rough texture, and examination of the section shows that this is due to magnetite particles that were reduced to sponge iron but not welded together.

Skulls are abundant at the sites where there was large-scale production of iron, such as Clintonville and Penfield. At Clintonville, skulls were used like ashlar blocks to build one wall of the canal that delivered water to the newer of the two forges on the site. At the Penfield forge, there is a pile of skulls at least six feet high and 30 feet long. We estimate that there was a skull for each bloom made.

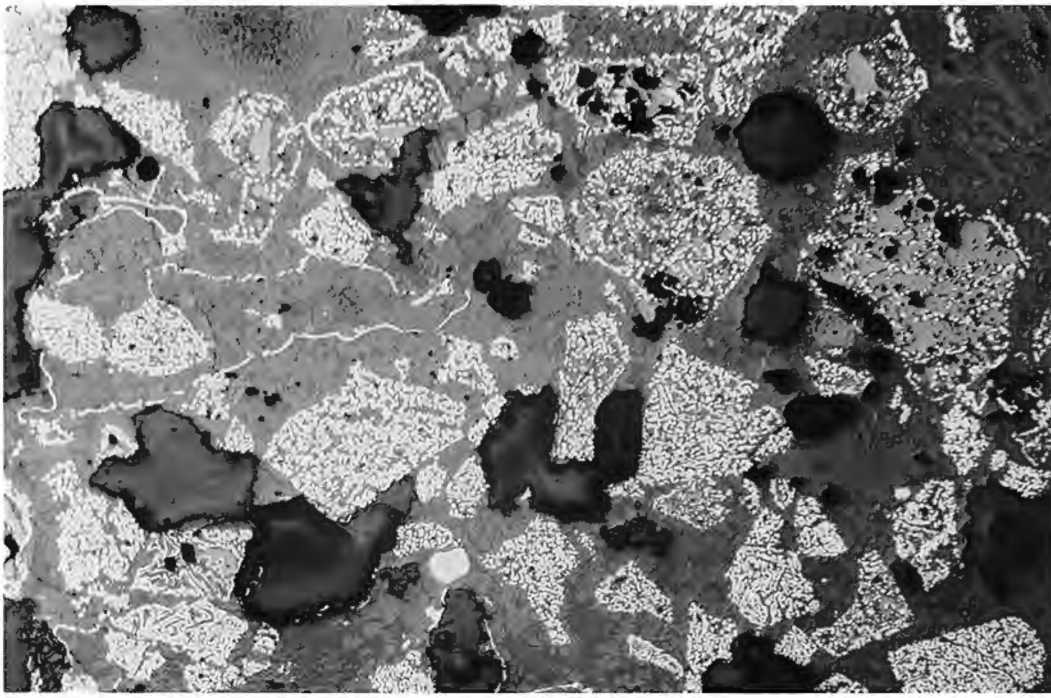

Fig. 4. Magnetite grains reduced to sponge iron. The porous structure results from the decrease in volume as the iron oxide is converted to metal. Length of the area photographed is 4.4 mm. Specimen from the Norrisville forge site, collected by R. S. Allen

Figure 6 shows views taken in the field of the upper and lower surfaces of a broken slag bottom found at the Penfield forge. The upper surface is concave, the bottom surface is flat and has square corners. A nine-inch long section through a fragment of a bottom from the Caldwell forge is shown in Figure 7. The greatest thickness of the section is three inches. The photograph shows how the lower surface is smooth and almost perfectly flat. Long, columnar grains of fayalite are oriented perpendicularly to the lower surface. Charcoal particles found at the top surface are surrounded by thin iron rims, and there are a few agglomerated particles of iron up to 5 mm. long in the slag matrix. Magnetite grains reduced to metal, common in the skulls, are not present, but the wustite content is very great.

Slag bottoms are found at the sites where skulls are found, but in smaller quantities. At the newer forges, they have smooth lower surfaces; at the older, these surfaces are more likely to have small-scale roughness.

The characteristics listed in Table 2 have been used to classify the slag fragments.

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Fig. 5. Sections of slag "skulls" collected at (above) the Penfield forge (Ironville, New York) and (below) the Caldwell forge (Clayburg, New York). The principal component of the slag is fayalite. Also present are free wustite, former magnetite grains reduced to sponge metallic iron (like those in Fig. 4 but not resolved at this magnification), rims of iron surrounding charcoal particles, and larger pieces of iron formed by the agglomeration of particles of sponge iron. The Penfield skull is 12.5 inches long, the Caldwell, 19 inches. (Photographs by William Sacco; the Clayburg sample was collected by Gordon Pollard)

Fig. 6. Two views of a slag "bottom" photographed in the bed of the stream below the Penfield forge site. We interpret the upper photograph as showing approximately half of the piece of slag that occupied the bottom of the forge hearth; the hollow on the top was occupied by the bloom. The length of the measuring rod is 350 mm. The lower photograph shows a cross section of this same "bottom." We interpret the flat surface as the contact between the slag and the bottom plate of the forge hearth. The length of the scale is 12 inches.

Fig. 7. Section of a slag "bottom" from the Caldwell forge site. Columnar fayalite crystals extend upward from the flat bottom surface. Unlike the "skulls," the slag in the "bottom" is free of iron particles, although there are iron rims around some of the pieces of charcoal near the top of the specimen. The length of the section is 230 mm. (Specimen collected by Gordon Pollard; photograph by William Sacco)

When compared to these characteristics, we find that the specimens can be divided into two classes, *plate* and *massive*. The plate slag is characterized by the presence of approximately parallel faces formed upon solidification. One face is usually smooth while the other retains impressions formed by contact with a granular surface. Any of the other features listed in Table 2 may also be present in plate slag. The massive slag has a high concentration of fine porosity and no parallel surfaces formed during solidification. Relatively few of the hand specimens of slag have macroscopic pieces of metal, contact between the rough and smooth surfaces, or rope structure. Multiple flows and pieces of charcoal are about equally likely to be present or absent.

A representative piece of plate slag is shown in Figure 8. It is 0.8 inch thick and, since it is bounded by fracture surfaces, is a fragment from a larger piece. The top was formed by solidification of a free liquid surface, and is pierced in places by bubbles

TABLE 2. Characteristics of hand specimens of slag

1. Thickness, where two parallel surfaces could be identified
2. Impressions of contact with a structure against which the slag solidified
3. Contact of two characteristic surface features preserved on the sample (as distinct from surface features separated by fractured edges)
4. Rope structure, indicating flow of liquid slag of such high viscosity that a level surface could not be formed
5. Smooth surface, formed by fluid sufficiently fluid to make a level surface
6. Multiple flows
7. Charcoal impressions or contained charcoal
8. Ore particles visible on the surface of the slag
9. Impressions of a granular substrate in contact with the slag
10. Columnar structure visible on fractured surfaces
11. Dense slag; material largely free of porosity
12. Large pores or blisters on the surface or within the slag
13. Small pores in the slag
14. Macroscopic pieces of iron present

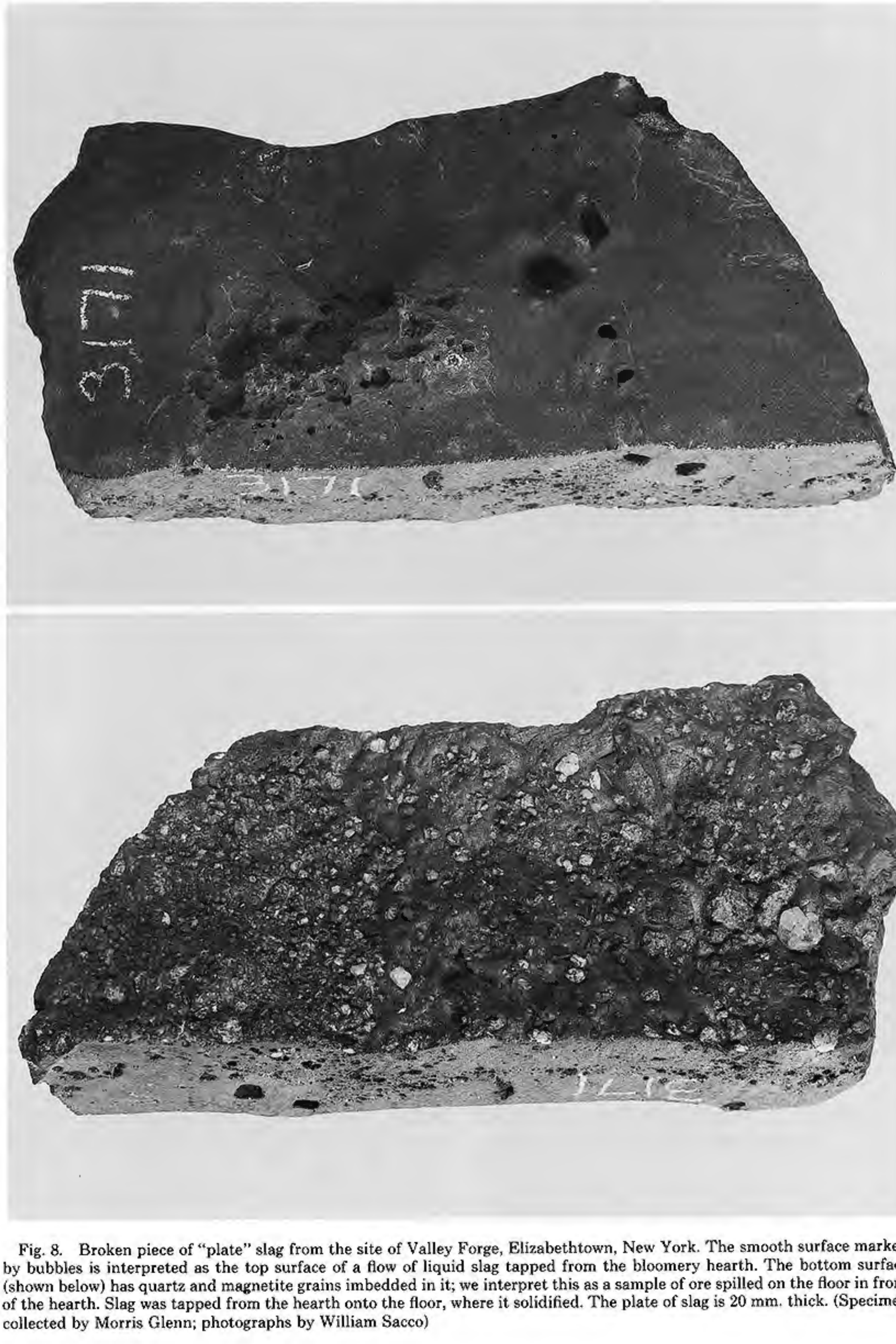

Fig. 8. Broken piece of "plate" slag from the site of Valley Forge, Elizabethtown, New York. The smooth surface marked by bubbles is interpreted as the top surface of a flow of liquid slag tapped from the bloomery hearth. The bottom surface (shown below) has quartz and magnetite grains imbedded in it; we interpret this as a sample of ore spilled on the floor in front of the hearth. Slag was tapped from the hearth onto the floor, where it solidified. The plate of slag is 20 mm. thick. (Specimen collected by Morris Glenn; photographs by William Sacco)

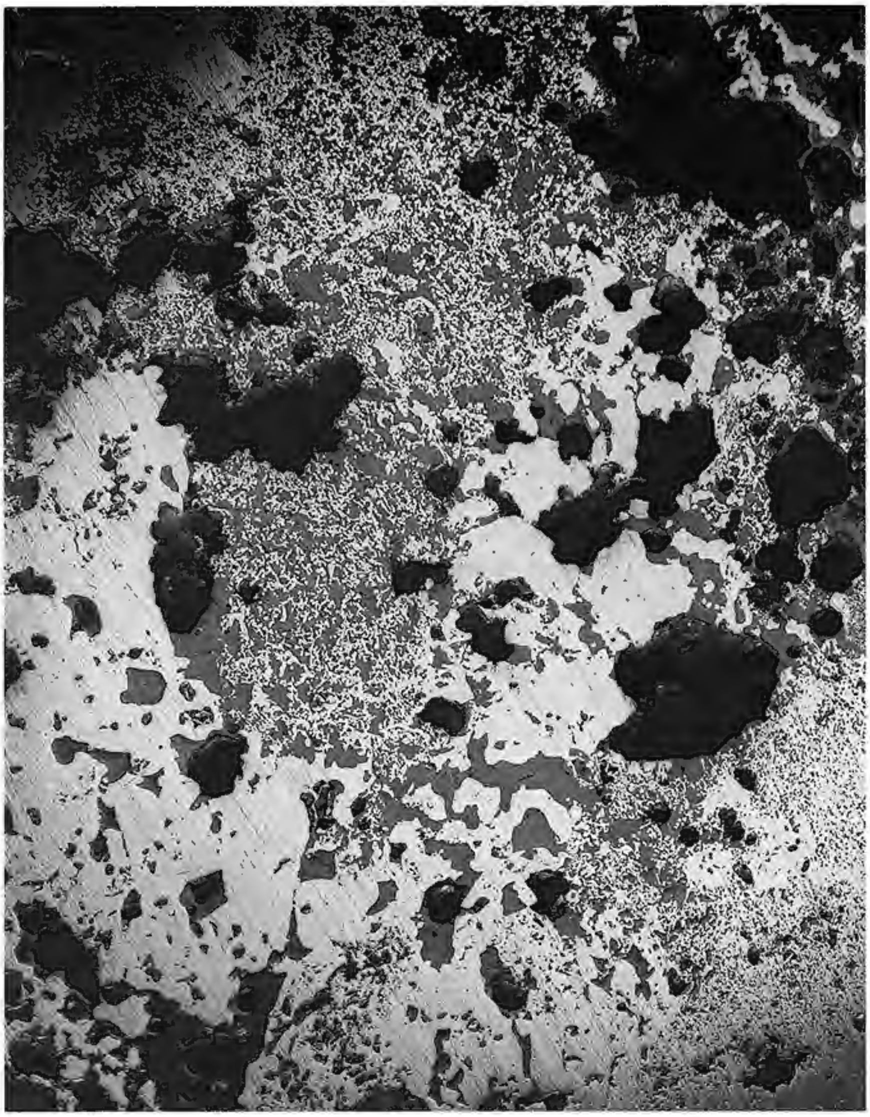

Fig. 9. Fragment of a bloom from the site of the Clintonville Forge. Magnetite grains reduced to sponge iron were settling through liquid slag and agglomerating into solid iron at the time the process was arrested by freezing of the slag. During agglomeration, the small-scale porosity was eliminated by the action of surface tension at the iron-slag interface, but the large-scale porosity remains. The width of the area photographed is 14 mm. (Specimen collected by Morris Glenn; photograph by William Sacco)

that have burst upward through the cooling liquid. The lower surface solidified in contact with a mixture of sand and ore grains, some of which have become imbedded in the slag. The ore particles are cleavage fragments of magnetite about 0.1 inch in size. The microstructure of this slag consists of a glass matrix, wustite dendrites, fayalite crystals that were just beginning to form as solidification took place, and a few microscopic iron drops. Magnetite grains that had been reacting with the liquid slag at the time of solidification are also present.

Metal

Twenty-one metal samples were collected at the forge sites including three bloom fragments, four examples of the primary

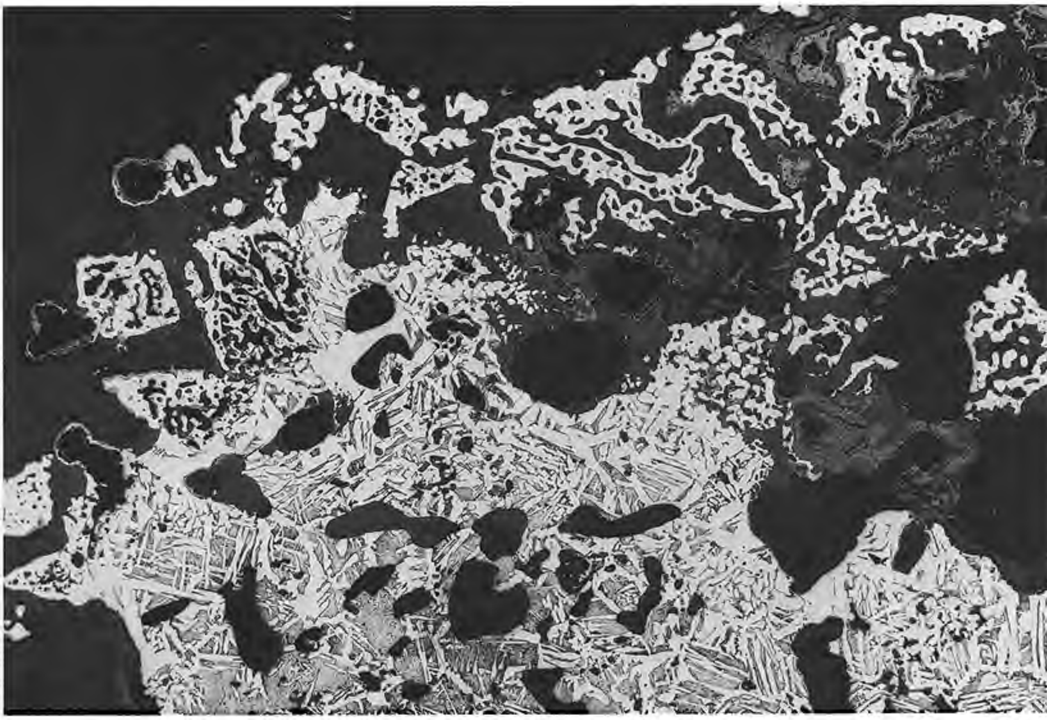

Fig. 10. Agglomeration of sponge iron particles formed by the reduction of magnetite grains into a bloom. As the grains come into contact with the solid iron, the small pores are closed and the slag they contained is expelled. The bloom iron is carburized by the charcoal fragments that it contains. Specimen from the Clintonville forge site. Polished surface etched with 4 percent Nital. Length of the area photographed is 2.8 mm.

product (forged bar), eleven secondary products (such as nail plate), one fragment of a forge plate, and two fragments of forge machinery. Two examples of Champlain iron were placed in the collection of the Metallurgical Museum of Yale College by Professor A. E. Verrill after his visit to the properties of the Essex and Lake Champlain Ore and Iron Company in 1865.

The small number of bloom fragments found suggests that the blooms were sufficiently coherent to hold together while being removed from the hearth, carried to the helve hammer, and forged into bar. Figure 9 is a section through one of the bloom fragments. Magnetite particles that have been reduced to metal are surrounded by slag (top and center of the picture). These grains were agglomerating into coherent metal when the process was arrested by solidification of the slag. The welding of the grains of sponge iron is shown in more detail in Figure 10. The reduced magnetite grains are carbon free and retain their form while they are surrounded by slag and not in contact with other grains. Once they settle on coherent metal, they weld together. Surface tension forces then expel the slag inclusions that are smaller than about 0.1 to 0.2 mm. when these are within a distance of 0.25 to 0.35 mm. of the surface. Larger slag inclusions have to be expelled either by the weight of the metal above or in subsequent hammering. Localized carburization of the iron by included charcoal fragments takes place soon after the iron is consolidated.

The final process carried out at the forges was hammering the blooms into bars. Several examples of remnant parts of forged bars were found, including the end of a two-inch square bar from the Caldwell site (Fig. 11). The lip on the severed end and deformation structure within show that the bar was sheared while still hot, probably as the last step in the forging operation. The con-

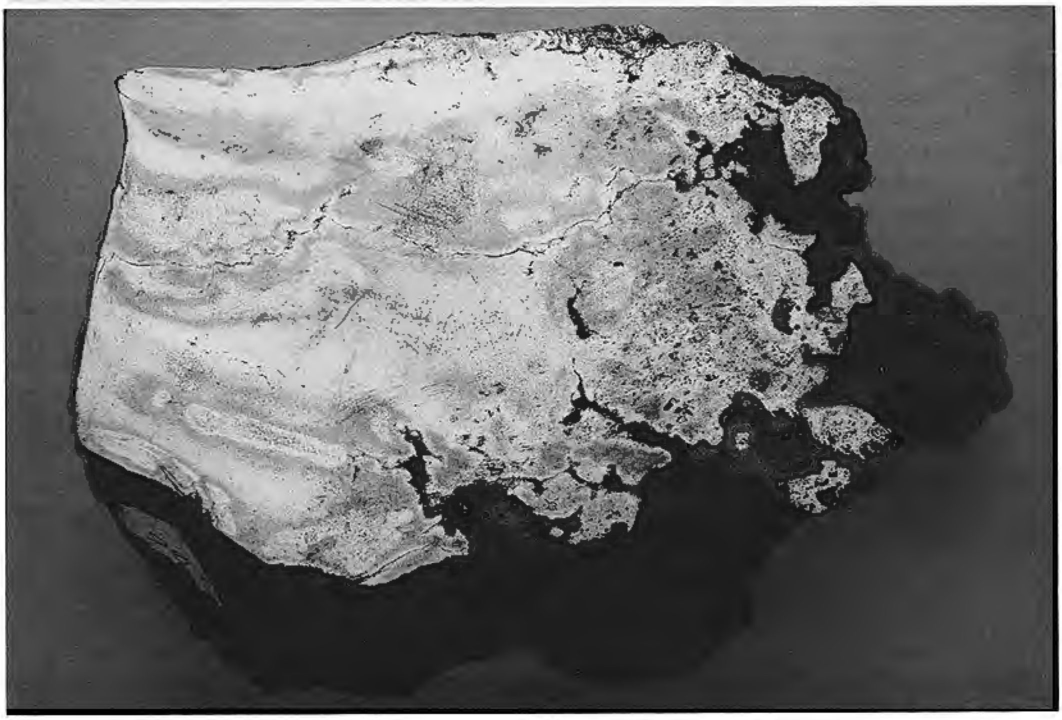

TABLE 3. Properties of iron specimens

Specimen	YS	TS	% Red.	HV	% P
Champlain iron					
Verrill A	34.7	46.3	79	125	0.02
Verrill B	—	—	—	—	0.04
Willsboro Forge	30.1	47.8	20	192	0.38
Bellmont Forge	42.0	56.5	8	217	0.26
Keeseville Forge	36.7	46.1	69	122	—
Swedish iron					
Utansjo	42.8	53.4	78	156	0.13
Skebo	29.2	48.0	32	110	0.02
Gysinge	29.3	44.1	73	101	0.01
Munkfors	31.9	42.0	68	120	0.02

YS = yield strength in 1000 pounds per square inch; TS = tensile strength in 1000 pounds per square inch; % Red. = percentage reduction in area at fracture; HV = Diamond pyramid hardness (100 gram load) of ferrite; Swedish irons are identified by the names of the forges at which they were made, on the basis of marks stamped on the samples.
The low ductility of the Skebo iron sample was caused by slag concentrated in the center part of the test bar and is probably not characteristic of the product of this forge.

cave indentation in the upper surface is the impression of the nose of the forge hammer. The cross section shows how slag was concentrated at the end of the bar during forging. The dark bands visible in the section are mixtures of ferrite and pearlite that surround zones of hypereutectoid steel.

The quality of the bloomery iron was evaluated by metallographic examination, by mechanical tests made according to the method previously used on historic samples (Gordon 1988), and by microprobe analyses for phosphorus in the ferrite. A metallographic section of each broken specimen was examined to be sure that the tensile test results were not vitiated by the presence of large slag particles. Microhardness was measured on undeformed ferrite. The results are shown in Table 3; data for four types of Swedish iron are included for comparison. The Swedish irons were made about 1865 by the finery process and are representative of the imported iron being sold in competition with Adirondack bloomery iron for making crucible steel.

The samples designated "Verrill A" and "Verrill B" are the ones collected by A. E. Verrill in 1865. Verrill A is a bar with cross section 0.520 ± .001 × 1.040 ± .005 inch. Surficial markings and the small variation in dimensions show that this bar was rolled. It is marked as made from "Burt." The Burt mine is located near Mineville, New York, and was operated by the Essex and Lake Champlain Ore and Iron Company in 1865. The mechanical properties of Verrill A are equivalent to those of high-quality Swedish iron. The microstructure consists of uniform, fine-grained ferrite free of pearlite and with a low concentration of slag. The small amount of slag present has been worked into long fibers by the rolling. The phosphorus content is uniformly low. Verrill B is a 2 × 2 inch forged bar of bloomery iron whose microstructure has longitudinal bands with variable carbon content ranging from 0.2 to 0.75 percent. The phosphorus content of the ferrite is nearly as low as that in Verrill A. No tensile test was done because of the variable carbon content of this iron. These samples show that the Champlain bloomery forges were capable of making wrought iron as good as the best Swedish iron, and that there was a solid

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Fig. 11. Half of the end of a two-inch square forged bar from the site of the Caldwell forge (Clayburg, New York). The view of the exterior (above) shows the indentation made by the last blow of the helve hammer and reveals the profile of the blunt nose of the hammer head. The cross section (below) has been etched to show the distribution of carbon in the metal. The dark bands are zones of ferrite and pearlite that surround hypereutectoid steel. As hammering proceeded, slag was concentrated into the end of the bar, which was sheared off and discarded. (Specimen collected by Gordon Pollard, photographs by William Sacco)

basis for the high reputation of this iron that was established in the first half of the nineteenth century.

The other three samples on which mechanical tests were done are all finds. The metal from Keesville, a rolled bar, has slightly lower ductility than Verrill A because of a higher content of slag. The bar from Bellmont forge has a 1¾ × ½ inch cross section and is the discarded end of a forged bar. Its low ductility is due in part to slag that has not been drawn into fine fibers by the forging but, primarily, to its high and variable phosphorus content, ranging up to 0.54 percent, sufficiently high to embrittle bloomery iron. Microprobe analyses of the slag inclusions show the presence of both iron phosphide and iron sulfide. The Bellmont forge operated from 1874 to 1893 and produced iron for the crucible steel industry. For this application, extensive forging to break up slag clumps was not needed, but low phosphorus and sulfur contents were essential. It appears that the operators of the Bellmont forge were compromising the quality of their product by using phosphorus-bearing ore and by mixing mineral coal with charcoal in the bloomery fires.

Of the eleven samples of iron that were too small for mechanical testing, eight contain pearlite. Bands of pearlite with a carbon content of about 0.2 percent are common but two specimens have areas with carbon concentrations ranging well into the hypereutectoid range. The slag content varies from very low to moderate; the slag particles are usually inhomogeneous in size and distribution. None of the iron samples examined shows evidence of having been piled and reforged so as to get a uniform distribution of fine slag such as is found in the best grades of wrought iron. The variable carbon content of the iron samples shows that an Adirondack forge could be operated to produce carbon-free or steely iron, and that close control over carbon content was difficult to achieve. By the late nineteenth century, Champlain iron was no longer being used in applications in which uniform mechanical properties were important, as in wire drawing. In making crucible steel the presence of slag clumps was unimportant and carbon would have made melting easier, but would have made it more difficult to judge the amount of carburizer to be added to the crucible charge.

There is documentary evidence that the iron produced in the Adirondack bloomery forges was of variable quality in the entries in the "Record of Iron Manufactured 1874–1888" for the Peru Steel and Iron Company (Manuscript, Feinberg Library Special Collections 65.10, State University of New York, Plattsburgh). This lists the names of the individual bloomers (designated "firemen") and hammermen, and the iron made by each, week by week. The iron entries are for different grades, such as "Market Billets" or "Cull Billets"; the designations change over the years. Judgments about quality would have been based primarily on the appearance of the iron and its fracture surfaces, methods that were insensitive at the levels of purity required in crucible steelmaking. Inadequate quality control coupled with the apparent use of adulterated charcoal and phosphorus-bearing ore at some forges may have been a factor in the weakened competitive position of Champlain iron relative to Swedish iron, or iron made by puddling.

Forge Plates

A damaged but nearly complete cast iron front plate for a bloomery hearth found at the Bellmont forge site was 34 inches across the top and 20 inches deep. Fragments of forge plates were found at other sites. The microstructure of a fragment from Split Rock consisted of pearlitic gray cast iron in which the pearlite had been almost completely spheroidized by long exposure to high temperature.

New Jersey

Several archaeological reports on bloomery forge sites in New Jersey contain data that can be compared with the results from New York.

Windham Forge was a bloomery built about 1790, rebuilt in 1849, and closed in the 1880s. The layout of the equipment in this forge has been deduced by George Sellmer (1984) from a study of the site and from photographs taken within a decade of its

Fig. 12. This photograph of Windham forge in New Jersey was taken in 1892, about ten years after the forge was abandoned. The blowing engine, with its horizontal cylinder, is on the right. There is an accumulator for maintaining a steady blast pressure on top of the cylinder. The water wheel that drove the blowing engine is in the back. Remains of the bloomery hearth can be seen at the base of the brick stack, which encased the iron pipes of the heat exchanger that preheated the air blast. The remains of the forge hammer and the stamp mill used to pulverize the ore are not visible in this view. (Photograph courtesy George Sellmer)

closure (e.g., Fig. 12). The blowing engine had a horizontal cylinder and was driven by a pitchback waterwheel; another pitchback wheel powered a stamp mill, and a helve hammer was run from an undershot wheel. One of the two forge hearths is visible in the picture. The hearth, about 3 feet wide, was surmounted by a tapered brick stack fitted with a damper at the top. Close study of another photograph shows pipes for preheating the air blast within the stack. We hypothesize that the hot blast apparatus was installed when the forge was rebuilt in 1849.

Another bloomery, Lower Longwood forge, had a hearth with outside dimensions of 8.5 × 7.5 feet and walls about 2 feet thick (Lenik 1970); a photograph of the ruins of this forge discovered by Sellmer shows a tapered stone stack above the hearth that probably housed hot blast apparatus. Bloomingdale Forge was built in 1800, rebuilt in 1839 and 1841, and closed about 1882 (Ransom 1966: 96–99). It had stamps, a hearth stack, and a blowing apparatus similar to that at Windham. The hearths at all these forges are about the same size and shape as the one described by Hermelin (1931: 55) and, therefore, appear to be derived from the German bloomery design used in New Jersey in the eighteenth century. We have no evidence to show whether the use of hot blast originated in New Jersey or in New York, but the fact that a mason and bloomers from New Jersey were brought to Tahawus to set up the hot-blast forge there (Seely 1978: 25, 38, 44) suggests that the technology may have been transferred from New Jersey to the Adirondacks.

INTERPRETATION

The great range of bloomery designs with which iron has been made by different peoples shows that there is substantial latitude in the way the technological requirements of simultaneously attaining a reducing atmosphere and fluid slag can be realized. One objective of the analysis of remains recovered from bloomery sites is to find how smelters adapted the basic process to their needs and preferences. These adaptations could include minimizing the use of fuel, of ore, or of labor at the hearth, or maximizing the production rate, or production of steel rather than iron.

Ore would be used most efficiently in bloomery smelting if all the iron in it except the minimum needed to flux the gangue were converted to metal in the bloom. In the fully developed American bloomery process, the dressed ore contained about 65 percent metallic iron and 4 percent silica (Egleston 1879–1880; Louis 1880) and, if all the gangue were converted to slag by reaction with iron, 175 pounds of ore would be used for each 100 pounds of iron made. All the technical descriptions of the fully developed American bloomery process agree that the ore consumption was about 200 pounds of ore per 100 pounds of iron so, while practice fell somewhat short of the ideal, a high rate of recovery of iron from the ore was achieved. The means by which this was accomplished can be deduced from the historical, field, and laboratory evidence.

The slag samples show that the first step in smelting was the formation of liquid of near-fayalitic composition by reaction of the magnetite and the silica in the ore. Both reactions can be seen in progress in Figure 3. Two competing processes then operated on the remaining magnetite. It could either dissolve in the liquid slag, or the magnetite grains could be reduced to particles of sponge iron that retained the general shape of the parent grains (Fig. 4) but had substantial porosity because of the reduction of volume. Two processes can contribute to the formation of the bloom. First, iron dissolved in the slag in excess of the amount needed to form fayalite could be reduced to metal. Second, grains of iron formed by the direct reduction of magnetite could mechanically agglomerate. Both processes have to be nucleated. Since small clusters of reduced, skeletal iron grains are rarely seen in the slag microstructures, it appears that grains of iron agglomerated best when they made contact with an existing iron surface. The rims of iron found around charcoal particles (see Fig. 7) show that charcoal could nucleate the precipitation of metallic iron from the liquid slag. However, the rims are rarely thicker than about 1 mm., probably because the iron completely surrounded the charcoal and carbon could not diffuse through it fast enough to achieve further reduction at a significant rate. In the American bloomery, the formation of metal from iron dissolved in the slag was slow relative to the time it took the reactants to pass through the hearth, and this mechanism of bloom formation was not effective. The iron rims could, however, serve as nuclei for the initial agglomeration of particles of sponge iron descending from above.

An early stage of bloom formation is shown in Figure 13. Here, a layer of iron grew by the capture of reduced magnetite grains on nuclei consisting of iron rims formed around charcoal particles. The details of the process are visible in Figures 9 and 10. According to this interpretation, the high iron recovery and the rapidity of the Adirondack process were achieved by first minimizing the amount of iron dissolved in the slag and, second, by assuring that all the metal particles in the slag were trapped by the bloom. The bloom was formed rapidly by mechanical capture of iron particles that settled through the slag pool (that later became a skull) on top of the bloom.

Technical descriptions of the bloom smelter's work all agree that the hearth had to be manipulated so that, at an early stage

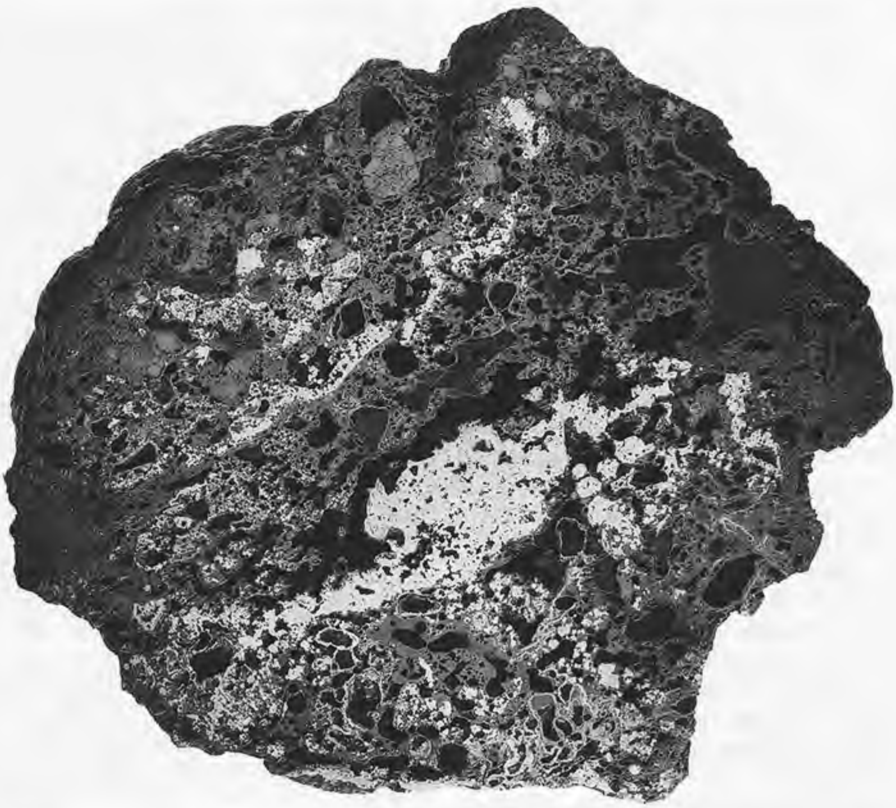

Fig. 13. Section of a lump of slag recovered from the site of Merriam's forge, Westport, New York, showing the early stages of bloom formation. Iron rims have formed around charcoal fragments incorporated in the slag. These rims grow by capturing particles of sponge iron (formed by the reduction of magnetite grains) as they fall through the slag to the bottom of the hearth. The face of the section is 160 mm. across. (Specimen collected by Morris Glenn, photo by William Sacco)

of the process, a lip was formed around the top of the bloom that would retain a pool of slag. This pool was needed as a basin of liquid in which the metal particles were protected from oxidation near the tuyere while they settled onto the top surface of the bloom. Part of the bloom smelter's skill was in the placement of the ore on the hearth so as to form and retain a rim around the edges of the bloom to hold the pool of slag. Ore grains converted to metal in the reducing zone just above the level of the tuyere passed through the oxidizing zone in the descending slag that, being rich in iron oxide, kept them from being decarburized. They then settled through the slag pool and were incorporated into the bloom below. Excess slag spilled over the edge of the bloom and accumulated to the level of the tap holes in the front plate of the hearth, where it could be drawn off from time to time. If the ore were used with maximum efficiency, slag tapped from the hearth should be free of metal particles and of iron oxide in excess of that needed to form fayalite. (Such excess iron oxide would appear as wustite dendrites in the solidified slag.)

The descriptions of the operation of the American bloomery by Louis (1880) and Egleston (1879–1880) do not tell us what happened to this pool of slag when the bloom was removed from the hearth, but they say that, after the blast was turned off and the charcoal raked out, water was thrown on the bloom to cool it. We infer that this cooled the pool of slag enough that, when the bloom was taken from the hearth, the solidified slag could be tipped

*TABLE 4. Composition of ore at Penfield forge**

	Ore	Concentrate
Fe_2O_3	50.3%	66.5%
FeO	22.7	26.6
MnO	0.2	0.2
Al_2O_3	2.0	1.6
CaO	0.9	0.4
MgO	0.1	0.1
SiO_2	23.4	4.1
P_2O_5	0.04	0.02
Fe (metal)	52.9	67.2

* Louis 1880.

off as a solid lump, the material we identify as a skull. In this interpretation, the tapered bottom surface of the skull represents the shape of the dished surface on the top of the bloom.

Further evidence on this interpretation can be obtained from calculations of the weight of slag formed during smelting of a bloom. We take Penfield forge as an example. The composition of the ore as mined and after concentration is shown in Table 4. The analyses show that the beneficiation was primarily effective in removing the silica in the ore. Since the dressed ore contained 67 percent metallic iron and 4.1 percent silica and 1.6 percent alumina, the best that could be achieved in smelting would be to reduce 170 pounds of ore to make 110 pounds of bloom iron and 28 pounds of slag. Egleston (1879–1880) states that for every pound of iron made, two pounds of dressed ore were used; there would then be 30 pounds of slag formed in making 100 pounds bloom iron. Since the usual size of a bloom was 350 pounds, there would be a total of 105 pounds of slag. A typical skull found at the site weighs about 26 pounds, leaving 79 pounds to divide between the bottom and the tap slag formed. We estimate that a complete slag bottom would weigh over 100 pounds so, if the bottom were removed between each heat, there would be little tap slag. We have no documentary information on this aspect of the manipulation of the hearth, but measurement of the volumes of the different kinds of slag at an undisturbed forge site could yield the necessary data. In general, bottoms are much less common than skulls. The accumulated slag was probably removed from the bottom of the hearth only when it reached a height where it would interfere with making a full-size bloom. The less frequently the bottom was removed, the more tap slag there would be.

According to Egleston (1879–1880), the tap slag was run out of the tap hole onto the floor in front of the hearth. It was subsequently broken up and hauled away from time to time. We identify this as plate slag and interpret its granular surface as a sample of whatever was on the floor of the forge shop beneath the fore-plate of the hearth. Often, this was spilled ore.

If the bloomery were run to make the most efficient use of ore, there should be no free iron oxide or iron metal in the tap slag. The microstructures of the samples of tap slag from the forges that operated at a late date show very little of either. We believe that the slag formed by reaction of magnetite with the gangue passed through the reducing zone of the hearth so fast that there was little further solution of magnetite in it. The absence of particles of sponge iron in the tap slag indicates that the capacity of the bloom to collect the descending iron particles was high.

Efficiency of the Fully Developed Process

The efficiency of the smelting operation in a bloomery can be evaluated in terms of

TABLE 5. Efficiency of bloomeries

		Charcoal		Ore	Man hours	Loss
New Jersey	1783	14,000 lb	(800) bu	6000 lb	92	—
Catalan	1843	7180	(410)	6240	109	31%
Tennessee	1881	(14,000)	800	4400	—	—
American	1889	(5425)	310	4000	15	23

Note: Quantities are for 2000 pounds of bloom iron. Data sources are Hermelin (1783) for New Jersey; Percy (1864: 278) quoting François for Catalan; Killebrew (1881: 11) for Tennessee; and Howe (1904: 270) for American. Parentheses indicate derived data. The conversion between pounds and bushels of charcoal is based on Howe's figure of 18 pounds/bushel. Only labor at the hearth is included in the man hours.

the fuel, ore, and labor used per unit of iron made, and the loss of metal in the slag. Data for the American bloomery process as operated in 1889 reported by Howe (1904: 270) are shown in Table 5 and are compared there with data for the Catalan forge process studied in detail by François in 1842 (reported by Percy 1864: 278), a bloomery in New Jersey observed by Hermelin in his tour of 1783 (Hermelin 1931), and bloomeries used to smelt hematite ore in eastern Tennessee (Killebrew 1881: 11). The hours of labor shown in this table are the work done at the hearth and do not include preparation of the ore and fuel or the subsequent hammering of the bloom. When it is remembered that the Catalan forge is often described as the most advanced of the European bloomeries, the technological sophistication of the American bloomery process in achieving a much higher rate of production while at the same time using ore and fuel more efficiently is evident. The data suggest that high productivity by the skilled bloomers needed to operate the forges was the primary objective sought in the development of the Adirondack smelting process.

TABLE 6. Types and dates of hand specimen slag

1. M	North Elba, 1810/1815
2. M	Brainard's, 1817/1831
3. M	Higby, 1840/1842
4. M	Split Rock, 1825/1845
5. M	Flackville, 1829/1840
6. M/P	Deadwater, 1846/1857
7. M/P	Trout Pond, 1847/1857
8. P	Wilder's, ca. 1825/1857
9. P	Highlands, 1837/1857
10. P	North Hudson, 1848/1857
11. —	Merriam's, 1843/1868
12. M/P	Upper Norrisville, 1856/1870
13. P	Kingdom, 1825/1873
14. P	Valley Forge, 1845/1873
15. P	New Russia, 1802/1874
16. P	Keeseville 1818/ca. 1880
17. —	Caldwell, 1844/1881
18. P	Willsboro, 1801/1883
19. P	Wadham's, 1822/1884
20. P	Stower, 1837/1884
21. M/P	Penfield, 1828/1886
22. P	Clintonville, 1810/1888
23. P	Woods Falls, 1863/1888
24. P	Bellmont, 1874/1893

M = massive slag; P = plate slag.

Development of the Process

Some characteristics of the fragmentary slag are much more common among the samples from the forges that operated at an early date than in samples from the forges that operated later. Table 6 shows that most of the massive slag was found at sites of the forges that were worked in the early years of the industry. The slag from these forges has, on average, a higher content of free iron oxide, sponge iron, and ore particles than that from the forges operated later; the fayalite is more likely to be large and massive while that from the later forges is usually fine and needle-like. These differences show that the bloom smelters achieved more complete reduction of the ore and more efficient trapping of the sponge iron particles by the bloom as they gained experience with the design and operation of the bloomery hearths. Less ore was dissolved beyond that needed to flux the gangue, probably because the process was run faster. The spent slag was tapped in smaller quantities and so cooled more rapidly, producing the finer, needle-like fayalite, and contained less gas in solution than at the earlier forges. These developments were largely in place by about 1850.

Further evidence of the improvement in smelting technique can be found in the McLane (1833) report. In 1827 it took 6,000 pounds of ore to make 2,000 pounds of iron; by 1832 this had been reduced to 4,500 pounds of ore; charcoal consumption at this time was 7,800 pounds. The charcoal consumption per ton of blooms in January 1865 at Kingdom Forge was 300 bushels (5,400 pounds) (Verrill 1865). Additional data for charcoal consumption in American bloomeries are: Champlain Ore and Iron Company, 280 bushels/ton; Star Iron Works, 280 bushels/ton; Crown Point Iron Company, 300 bushels/ton; Wilmington Forge, 300 bushels/ton (Hough 1878: 125–126). In Tennessee bloomeries smelting red hematite ore, 800 bushels of charcoal were used to make 2,000 pounds of iron in 1881 (Killebrew 1881: 11). The reduction in fuel use in the American bloomery was largely due to the introduction of hot blast. At this point, the process had been pushed about to the limits set by the physical and chemical constraints under which it operated.

Data on the labor expended in smelting in the McLane (1833) report are given in terms of labor cost rather than hours worked, so cannot be compared with the data in Table 5. The weekly output of a forge in 1833 was 1.25 [long] tons. This can be compared to census data. Before 1845 the output was not above 2.5 tons/week; by 1856 it could be pushed to 10 tons/week working flat out or 6 to 8 tons/week in long-term, steady running, about the same as in 1889 according to Table 5. Thus, it appears that, in agreement with the material evidence, substantial improvements were made in working technique before about 1850, by which time the process had reached the limit of productivity that could be attained in a bloomery hearth.

DISCUSSION

Among all the different varieties of bloomery smelting, the American process achieved unusually high efficiency in the use of ore, fuel, and labor. The technical developments that made this possible were preheating the air blast with waste heat from the hearth, use of finely divided, rich ore, and making the zone in which reduction of the ore occurred very thin. The ore passed rapidly through the reduction zone, was reduced to sponge-iron particles, and reached the bloom before there was much loss of iron beyond that needed to form slag from the gangue in the ore. The quality of the iron made varied with the skill of the bloomer and the care taken with the work. Iron with steely bands in it could be made easily. This was not wanted for uses such as wire drawing and, especially, machining (Northcott 1876: 75), that were important in the early years of the industry; it was acceptable in the market for high-purity iron for crucible-steel making, the principal application of Adirondack iron after 1865. One reason that so much steely iron was made was that by using much charcoal and running the fire hot, the production rate could be increased (Chahoon 1875). The account books of the Peru Steel and Iron Company show that the bloomers were not charged for the charcoal they used and were paid for the weight of iron they produced; hence, the smelters probably made iron with as much carbon content as the forge managers would accept.

The American bloomery process was an adaptation of an old technology to the particular natural resources available in the eastern Adirondack region (high-grade magnetite ore, abundant forests, and swift rivers supplying water power) and the market for grades of wrought iron that could not be made easily by puddling. Compared to the cost of the physical plant needed for the indirect process, an Adirondack bloomery forge plant required a relatively small capital investment, and had the added advantage that the plant could be shut down or started up easily in response to changes in the market for its product, an important factor in the volatile business climate of the late nineteenth century.

None of the other direct-reduction processes tried before 1900 (Howe 1904: 270–275) proved as useful as the American bloomery process. Peak production from the Adirondack bloomeries was reached in 1882, when over 48,000 tons of iron were made. Thereafter production declined. The Adirondack ironmasters tended to blame tariff policy for their financial difficulties but it seems that two other factors were more important. One was the increase in the cost of charcoal from $6.50 per ton of iron in 1860 to $12.50 in 1870 to $21 in 1879. (These data are from the census and Louis [1880]). We have seen that there is evidence that the operators of the Bellmont and Willsboro forges reacted to this by adulterating their fuel with mineral coal, thereby putting their reputations for making high-quality iron at risk. The second factor was the ability of crucible steelworks to make iron of comparable quality at lower cost in puddling furnaces after about 1880.

The historical and archaeological evidence shows that bloomery smelters had brought the American process to its fully developed form by about 1850. We lack evidence on the design of bloomeries first used in the Adirondack region and, if such evidence is to be found, it will probably be from excavation of the earlier, undisturbed forge sites. The erroneous description of the process as Catalan probably originated with the careless use of this term early in the nineteenth century. It is most likely that the American bloomery was developed from the bloom hearth used for smelting magnetite ore in northern New Jersey (Hermelin 1931: 55). On this hypothesis, bloom smelters made the hearth larger in area and shallower to increase the rate of reduction of the ore, and, from about 1844 onward, adopted preheating of the blast with waste heat from the hearth. In France, the air blast for finery forges was being heated with waste heat from the fire from 1834 onward (Crookes and Röhrig 1869: 743). Americans were experimenting with preheating the air blast in bloomeries in the 1840s; a Mr. Swan of the King's Mountain Iron Works in South Carolina used air warmed by the waste heat of a bloomery fire by 1848 and claimed to be able to make 2,000 pounds of blooms with 200 bushels (3,600 pounds) of charcoal (Tuomey 1848: 276). The only other known use of hot blast in bloom smelting was in Catalan forges in Sardinia, where it came into use before 1850 and reduced the consumption of charcoal from 4.35 times the weight of iron made to 2.57 times (Percy 1864: 312). The heat exchanger used in Sardinia was distinctly different from that used in New York, and we have no indication that this technology was transferred to America. We believe, then, that the American bloomery process was developed independently in the United States.

The American bloomery process was developed at a time when metallurgy in the United States has been described as operating "almost exclusively on the basis of traditional technology, despite the very successful new technology in Britain" (Temin 1964: 15) and when bloomery iron has been described as inferior to that made in fineries (Paskoff 1983: 87). In fact, the bloomeries in New York State were operated by entrepreneurs well versed in current science and technology, such as the use of magnetic separators for the beneficiation of ore (Allen 1967), who developed an appropriate and successful technology to supply a specialized market.

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