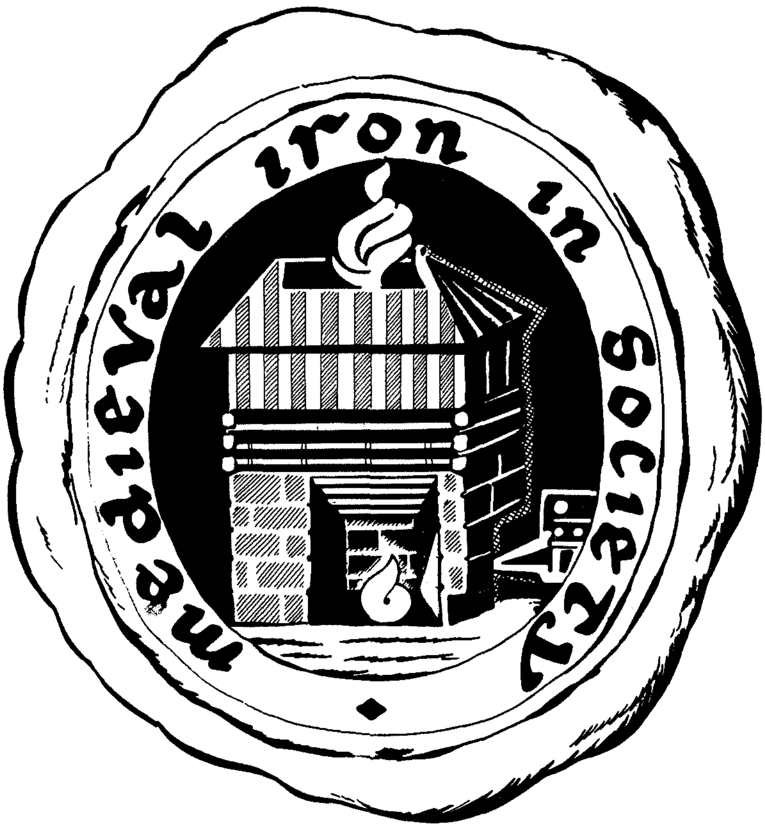
MEDIEVAL IRON IN SOCIETY



Papers presented at the symposium in Norberg

May 6—10, 1985

JERNKONTORET AND RIKSANTIKVARIEÄMBETET

Jernkontorets Forskning H 34

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Foreword

THE ROLE OF THE EARLIEST PROCESS INDUSTRY IN MEDIEVAL SOCIETY

The rise of mining and the introduction of the blast furnace inevitably and profoundly affected the medieval economy throughout Northern Europe.

The mining district in the middle of Sweden - Bergslagen - constitutes a uniquely developed region for studying metallurgy and settlement during the period 1100-1500. One of the hundreds of sites for iron production - Lapphyttan - has been archaeologically excavated and has proved to be a complete iron manufacturing site with iron ore deposits, a roasting pit, a blast furnace with waterdriven bellows, eight finery hearths and large slagheaps. This blast furnace has been in use from the middle of the 12th century and until the mid-14th century.

The development, function and social impact of mining and metal working had manifold effects on life in certain parts of Northern Europe during the medieval period. In terms of production technology, a change took place from small-scale to more large-scale operations. The older technique of producing iron in rudimentary small bloomery furnaces with relatively small yields did not require any elaborate organization and was perfectly compatible with the agrarian scheme of production. The advent of mining and blast furnace technology involved completely new demands in the way of social organization and economic resources. This technology required investment capital and the excess local production required a market.

It is in these terms that we have to discuss the iron industry and the role of the early process industry in early medieval society, because it was this period which laid the foundations of modern society. This was the time when the preconditions were established of the national state with its defined frontiers, complete with a power of state represented by the crown and with the kingdom divided up territorially for administrative purposes.

During this same period in the towns of Northern Germany, trading factories - the Hanseatic League - were established with an efficient entrepreneurial organization and with new cargo vessels that were heavy by the standard of the time, fundamentally transforming the export trade of Northern Europe. This probably also boosted the development of agrarian production and economics in Southern Scandinavia , which in turn made possible markets and the earliest urbanisation process in Northern Europe. Thus the agrarian heartland of Southern Scandinavia probably became linked already in the 12th century with mining operations in Central Sweden, as Lapphyttan seems to confirm. In this way an economic system evolved which included an extensive trade in primary materials, both by land and by sea.

The forgeable osmund iron manufactured from the pig iron proudced in the furnaces developed, together with copper, from the early Middle Ages onwards into a major Swedish export commodity - a quality product which dominated the European iron trade.

We are very happy to note the great interest these questions have aroused among scientists all over Europe and in the USA. The papers in this preprint cover developments in nearly all the European countries where iron production has been of any major importance for economic development. Some of the old and traditional questions concerning technical standard will be answered, but new and different questions will naturally arise concerning the early process industry and its impact on medieval society.

We sincerely hope that this symposium will be a dialogue with the future about the past, the foundation of contemporary society.

Erik Höök   Roland Pålsson

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Session 3 - Socio-economic consequences

INTRODUCTORY COMMENTS ON THE IRON DISTRICT OF NORBERG

by SVEN FORNANDER

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SUMMARY

In the first part of the paper a few characteristic features of the history of iron in Sweden are described. For a period of time in the 18th century Sweden was the leading iron producer of the world. By 1630 the industry was put under rigid state control. A special legislation and jurisdiction was introduced, the main purpose of which was to preserve the forests. A Ministry for mining and metallurgy was instituted, the preserved archives of which are of great value to historians. Later, the Ministry's technical activities were partly taken over by Jernkontoret. A rather extensive metallurgical literature has been published since the 1730ies.

The latter part of the paper gives information about the Norberg district, A short account is given of the origin and geology of the iron ores. The waterfalls came into being during the last glacial period. A short scetch of the history of the forests is presented. The hard winters were of great aid in solving the transport problem of the Middle Ages. In the 16th century a very large number of blast furnaces was in operation. Ever since the number has been decreasing, and nowadays none of them remains.

1. The history of iron in Sweden - a few characteristic features.

About 200 years ago Sweden was the leading iron producing country in the world. It is estimated that Sweden provided the western world with at least one third of its total demand of iron in the middle of the 18th century. Nowadays there is no nation that has anything near such a high share of the world market.

It took a long time, however, before the country could reach this unique position. The development can be followed in the royal ordinations which have been issued since the 14th century onwards. Their purpose was to control and - not least - to impose taxes on the iron industry. One of the very first ordinations, issued in 1354, concerns Norberg. It contains regulations about the organisation of the work in the ore mines (1).

In 1540 the first lists were compiled of all the real estates in the country. In one of these lists one finds the names of all blast furnaces in the Norberg district. They were no less than 62 in number. How they were situated is shown on the map in fig. 1 (2).

The year 1630 is important in the history of Swedish iron, because then the government decided to set up a central department for mining and metallurgy. A few years later it was named the Board of Mining. As its president was a member of the government it became in reality Sweden's first professional ministry. For the sake of simplicity I shall refer to it as the Ministry in the following. At the same time a special legislation for mining and metallurgy was introduced, the main purpose of which was to preserve the forests. It was not allowed to build new blast furnaces and hammer works without special permission. In existing works the production of wrought iron was restricted and special licence was required for the operation. A particular kind of law court was established in every mining district. These courts had to pass judgments upon all cases concerning the operation of ore mines, blast furnaces and hammer works. Fig 2 is a map of middle Sweden, which shows the areas of jurisdiction of each one of the courts. Within these areas all the main iron ores of middle Sweden are situated.

The judge of a court also acted as supervisor of the industry in his district, and in this capacity he had to provide the Ministry with annual reports describing the situation in his district. The Ministry existed for more than 200 years. Its rather extensive archives, which are still preserved, contain a lot of information valuable to historians. Whatever opinion one might have about state control of private enterprise one has to admit one thing: bureaucracy improves the historic material.

In the 16th century the ore mines and blast furnaces were run cooperatively by groups of so called *bergsmän* ("mining men"). These people performed the work needed at the production units, and they were part owners of those. Later on, when the furnaces had grown in size and the production had increased, the "mining men" met with difficulties in trying to acquire the capital needed for operation and investments. From the middle of the 17th century and onwards the blast furnaces were gradually taken over by a new group of people, the works owners, who had enough capital to erect hammer works also. In these plants the pig iron was refined into wrought iron that was forged under hammers to a new kind of product called *bar iron*. - Today, of course, all iron- and steelplants are operated by companies, one of which is owned by the state.

In the year 1767 an interesting calculation was published (4). It concerned the amount of work that was required in each one of the different stages in the production process, see fig. 3. For the total production of the country - 55000 tons of bar iron per annum - 26000 whole-time workers were needed. The two stages, which demanded most of the labour effort, were the ore mining and the charcoal-making. The two raw materials required more than 80 percent of the total work. The blast furnace work was not more than 8 percent of the total, and the share of the forging work was also low: only 9 percent. - The consumption of energy in the form of charcoal was enormously high, about

10 times higher than nowadays. There is reason to believe that the legislation to preserve the forests was justified.

Several of the works owners and metallurgists in the 18th century were learned men, who had studied at the university and who were authors of dissertations and books. One of the first text-books of metallurgy (5) was published in 1734. It was written in Latin by SWEDENBORG, and its title was DE FERRO (6). A few of the officers of the Ministry devoted their time to "trials and findings" in chemistry and mineralogy at the laboratory. It is worth mentioning that no less than 4 new chemical elements, metals all of them, were discovered (7) by Swedish metallurgists, see fig. 4.

The works owners were people of good social standing. Some of them were members of r i k s d a g e n (parliament), a few were members of the government. The first prime minister, who did not belong to the nobility, C.J.THYSELIUS, was chairman of the board of Jernkontoret; this was as late as in the 1870ies.

In 1747 J e r n k o n t o r e t (verbal translation: The Iron Office) was instituted with the works owners as its shareholders. Already in 1751 Jernkontoret appointed its first technical officers. Their task was to give advice to the works owners in technical matters. As a result the technical leadership of the industry was transferred from the Ministry to Jernkontoret. The great name in this context is SVEN RINMAN. As Jernkontorets "director of forging" he devoted an untiring effort to the erection of new blast furnaces and hammer works and to the modernizing of old plants. Towards the end of his life he summarized his experience in four books of which his Bergverks-Lexicon (9) is the most well-known. This work, which had the great French encyclopedia as its prototype, consists of over 2000 pages and contains a detailed account of the fundamental and technical knowledge of the whole field of mining and metallurgy.

Towards the end of the 18th century, when new processes for iron- and steelmaking were introduced in Britain, in which coke and coal were utilized, Sweden's leading position on the world market came to an end. Today, our country's share of the market is less than 1%. Nowadays, the only thing that is remarkable about Sweden is, that such a large part of our production consists of special steels - perhaps a larger part than that in any other country.

2. The iron district of Norberg (Norbergs Bergslag).

In order to be able to make iron, people in the Middle Ages required access to three resources, which they could obtain from Nature. Iron ore, mined from the rock, was utilized early. The only reducing agent, which was known to them, was charcoal, and that was needed in large quantities, because charcoal consumption was very high in those days. A third natural resource, viz. mechanical energy to drive the furnace bellows, was also necessary. Water power was the only form of mechanical energy that was known.

In the Norberg district all these natural resources were in ample supply.

Fig. 5 is a geological map (10,11) of the area around Norberg, where the iron ores are to be found. The area is about 14 km in length and 7 km in width. Diagonally through the area there is a rather wide strip of a kind of rocks which are called leptites. Embedded in the leptites there are iron ore bodies in great number. The bodies are in the shape of fairly wide slabs or slices; many of them are deformed. The ore slabs are strongly tilted and reach down to a depth of several hundred meters below the surface.

The ore bodies as well as the leptites are part of one of the oldest geological formations on Earth. The ores were formed about 2 milliards of years ago as layers of precipitates of iron compounds on the bottom of the sea. These layers, which were horizontal to begin with, later became tilted by so called folding. This is a very slow process even if it is measured on a geological time-scale. As a result of it the ore slabs are now nearly vertical. From a practical point of view this is very important, because it made it possible for the ore slabs to reach the surface - otherwise they would not have been detected.

In contrast to the iron ore the water power came into being rather late. This occurred during the last glacial period, which ended recently, as measured on the geological time-scale - some 10000 years ago. At that time Sweden had been covered by a huge deposit of ice for a period of at least 100000 years. Because the ice had a thickness of something like 3 kilometers, it exerted an enormous pressure on the underlying rock surface. In addition the ice moved slowly like the glaciers do nowadays. The rock became heavily eroded, and large cavities were dug out in it. Many of these cavities remain today as lakes. In the brooks and streams between the lakes there are plenty of waterfalls, which provided the power needed for the furnace bellows.

The third natural resource, the forest, has a history of its own also (12). A few thousand years ago when the climate was milder than it is now, the forests consisted of broadleafed trees such as the oak, the beech and the elm. The first coniferous tree that made its way into this country, was the (Scots) pine, which came from the continent in the south. The (Norway) spruce came in much later, from the east. The type of coniferous forest, which is dominant in Middle Sweden in our time was not fully developed until relatively late, something like 1500 years ago. It consists mainly of two kinds of tree only, the pine and the spruce, but of course also other kinds can be found in it, e.g. the birch.

In the Middle Ages the transport of raw materials and finished products must have been difficult. The roads were few and very poor. In this context one could talk about a natural resource number four: the hard and long winters. In winter-time when the many lakes and moors are frozen and the ground is covered with snow, it is easy to do the transport work by sledges. Such winter transports were in general use up to only a few decades ago.

Norberg is mentioned in a document for the first time in 1303. There it is referred to as an "iron and steel mountain". This indicates that iron ore mining took place here in the 13th century and probably earlier. According to a document from the 17th century ore mining was performed in several different ore fields and the number of open pits which had been worked until then could be counted in hundreds. When mining reached a depth of some 10 meters the ground water began to present a problem. Therefore the work was moved to a new site. An important stage in the mining method used was that the rock was heated up with large wooden fires to make it brittle and easier to break loose. Blasting with powder was introduced as late as in the 1720ies. A detailed description of the technical development has been published (14).

As mentioned earlier there were 62 blast furnaces in operation in the district in the year 1539, see fig. 1. An inventory of the furnace sites has been made (2), in which 60 of the old sites were localized, often by means of slag heaps. Since the 16th century a permanent concentration of the operation has taken place. More and more of the furnace units have been closed down. In 1820 there were 20 units in operation. In 1896 the number had decreased to 6. The diagram in fig. 6 shows the production figures for each one of the blast furnace plants in operation in Sweden that year. They were 121 in number. The six furnaces in the Norberg district are marked with arrows. The last furnace in the district, Spännarhyttan, ceased to operate in 1982. Today there are only two blast furnace plants remaining in the country.

Fig. 7 shows, very approximately, how furnace dimensions and furnace production has changed since the Middle Ages. Lapphyttan had a hight of (probably) 3 meters and its production could have been something like 0,1 tons per day. In RINMAN's time (1780) the height of the furnace had grown to 9 metres and its production to approximately 3 tons per day. The last furnace in operation at Norberg produced ca 700 tons per day.

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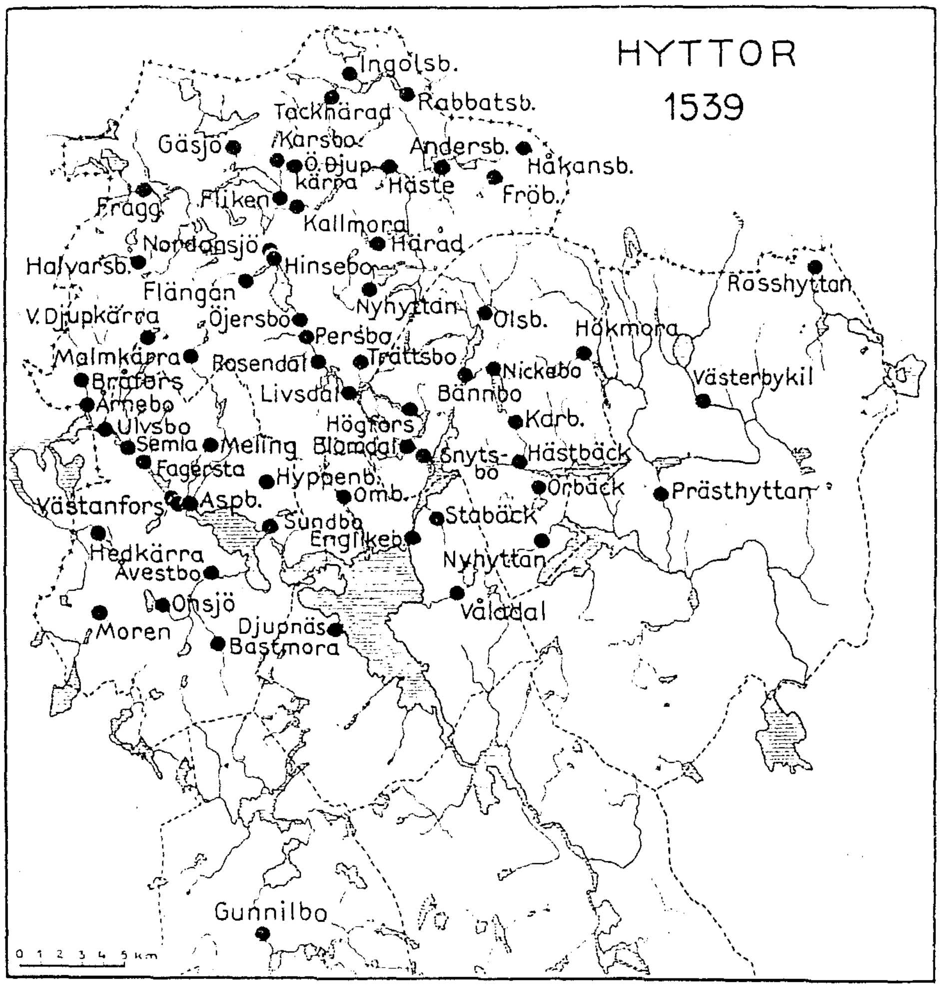
Fig. 1



HYTTOR
1539
Ingolsb.
Rabbatsb.
Tackhärad
Gäsjö
Karsbo
Andersb.
Håkansb.
Ö.Djup-
kärra
Häste
Fröb.
Frägg
Fliken
Kallmora
Nordansjö
Härad
Halvarsb.
Hinsebo
Flängan
Rosshyttan
V.Djupkärra
Öjersbo
Nyhyttan
Olsb.
Hökmora
Persbo
Malmkärra
Rosendal
Trättsbo
Nickebo
Västerbykil
Bråfors
Livsdal
Bännbo
Arnebo
Karb.
Ulvsbo
Högfors
Semla
Meling
Blomdal
Snyts-
bo
Hästbäck
Fagersta
Hyppenb.
Örbäck
Prästhyttan
Västanfors
Aspb.
Omb.
Stabäck
Sundbo
Englikeb.
Hedkärra
Nyhyttan
Avestbo
Onsjö
Våladal
Moren
Djupnäs
Bastmora
Gunnilbo
0 1 2 3 4 5 km

Fig. 2

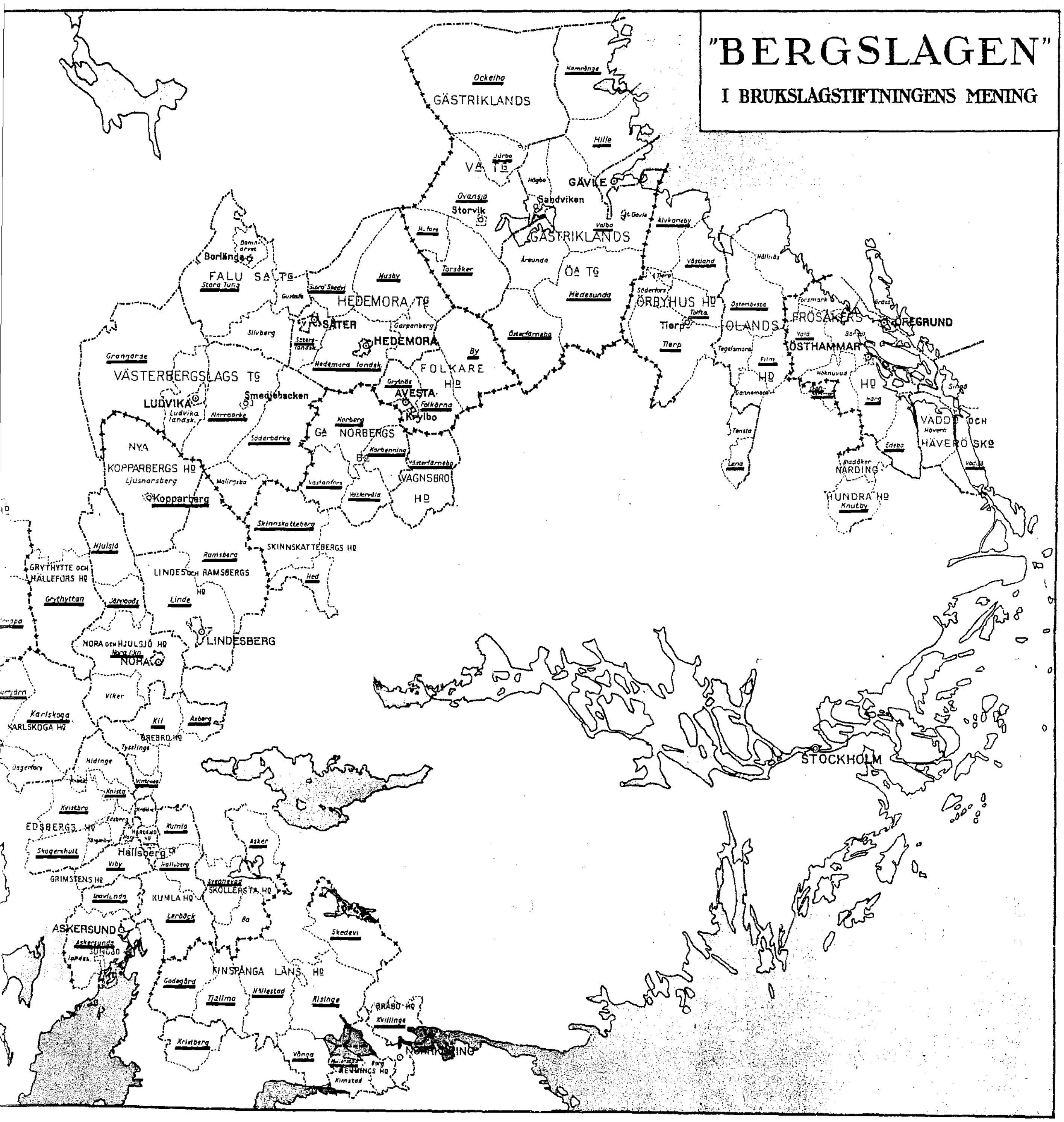

"BERGSLAGEN"
I BRUKSLAGSTIFTNINGENS MENING
GÄSTRIKLANDS
GÄVLE
Sandviken
Storvik
GÄSTRIKLANDS
ÖA TG
HEDEMORA TG
SÄTER
HEDEMORA
Borlänge
FALU SA TG
VÄSTERBERGSLAGS TG
LUDVIKA
Smedjebacken
FOLKARE HD
AVESTA
Krylbo
NORBERGS
VAGNSBRO HD
NYA KOPPARBERGS HD
Kopparberg
SKINNSKATTEBERGS HD
LINDES OCH RAMSBERGS HD
LINDESBERG
NORA OCH HJULSJÖ HD
NORA
KARLSKOGA HD
ÖREBRO HD
EDSBERGS HD
Hallsberg
GRIMSTENS HD
KUMLA HD
SKÖLLERSTA HD
ASKERSUND
FINSPÅNGA LÄNS HD
BRÅBO HD
NORRKÖPING
ÖRBYHUS HD
Tierp
OLANDS HD
FRÖSÅKERS
ÖREGRUND
ÖSTHAMMAR
VADDÖ OCH HÄVERÖ SKD
NARDING
HUNDRA HD
STOCKHOLM

Fig. 3

STOCKENSTRÖM's estimate 1767.

Bar iron production in realm, total = 400 000 S@ = 54400 tons/annum.

Charcoal consumption = 2 772 000 m^3 = ~ 416 000 ton = ~ 7600 kg/ton

No. of workers required (250 working days per man annualy):

	No. of workers		Percent
Iron ore mining	4000	6400	25,0
Iron ore transport to blast furnace	1800		
Mining of lime + transport	600		
Forest work + charcoal-burning	10 800	14800	57,8
Charcoal transport	4000		
Pig iron making	2000	2000	7,8
Bar iron making	2400	2400	9,4
	25,600	25,600	100,0

Fig. 4

Chemical elements discovered by Swedish metallurgists

Nickel	Ni	discovered by	A.F. CRONSTEDT	in 1751
Manganese	Mn	-"- "	J. G. GAHN	" 1774
Cerium	Ce	-"- "	W. HISINGER	" 1804
Vanadium	V	-"- "	N. G. SEFSTRÖM	" 1830

Source: Handbook of Chemistry and Physics, 51st Ed.

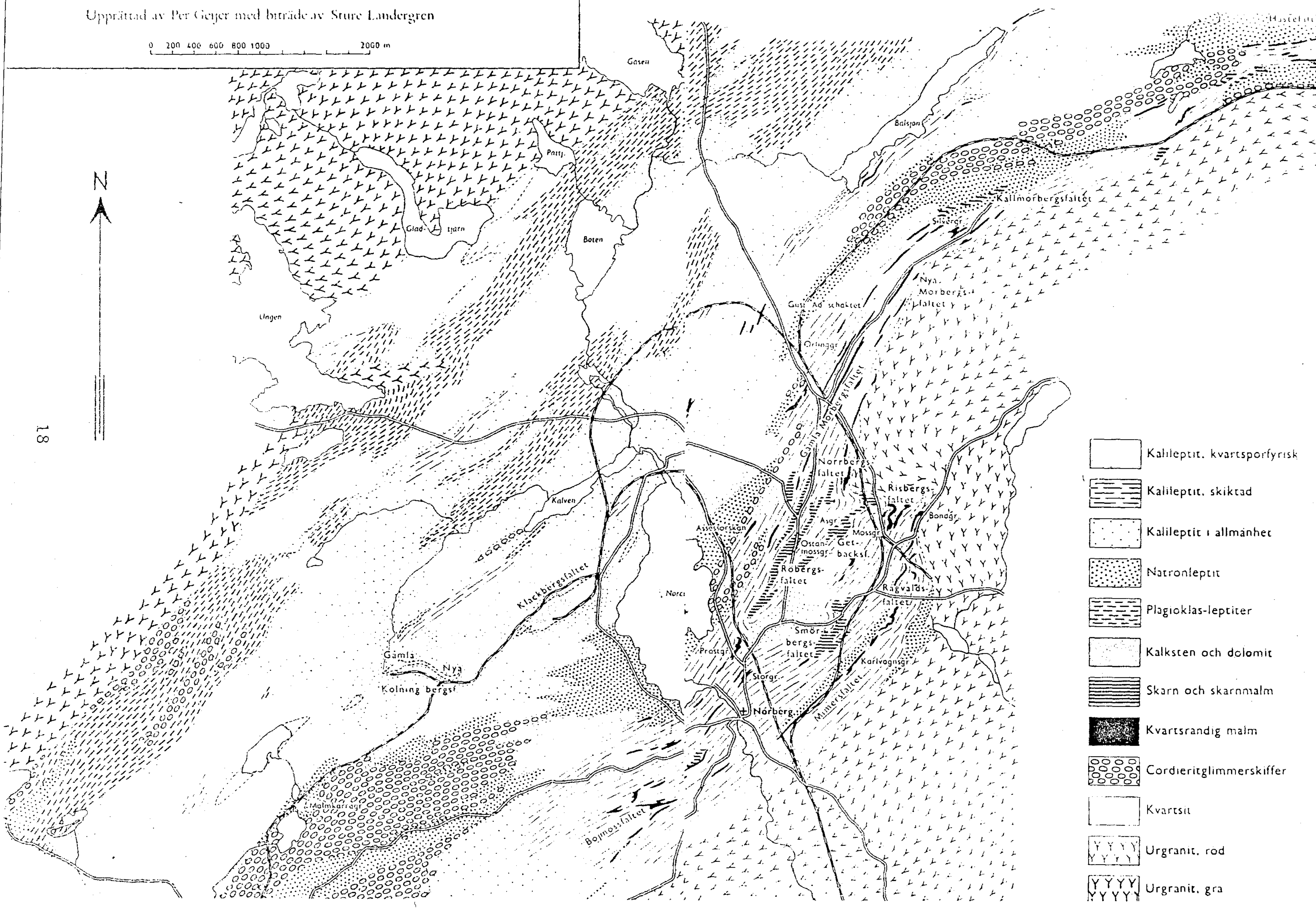

Upprättad av Per Geijer med biträde av Sture Landergren
0 200 400 600 800 1000 2000 m
N
Gasen
Balsjön
Patt.
Glad- tjärn
Boten
Ungen
Kallmorbergsfältet
Silvergr.
Nya Morbergsfältet
Gust. Ad. schaktet
Orlinggr.
Gamla Morbergsfältet
Norrbergsfältet
Risbergsfältet
Bonagr.
Kalven
Assessorskan
Åsgr.
Mossgr.
Östanmossgr.
Getbacksf.
Robergsfältet
Ragvaldsfältet
Klackbergsfältet
Norrn
Smörbergsfältet
Prostgr.
Storgr.
Karlvagnsgr.
Gamla Nya
Kolning bergsf.
Norberg
Mimersfältet
Malmkärrsgr.
Bojmossfältet
Kalileptit, kvartsporfyrisk
Kalileptit, skiktad
Kalileptit i allmänhet
Natronleptit
Plagioklas-leptiter
Kalksten och dolomit
Skarn och skarnmalm
Kvartsrandig malm
Cordieritglimmerskiffer
Kvartsit
Urgranit, röd
Urgranit, grå

Fig. 5

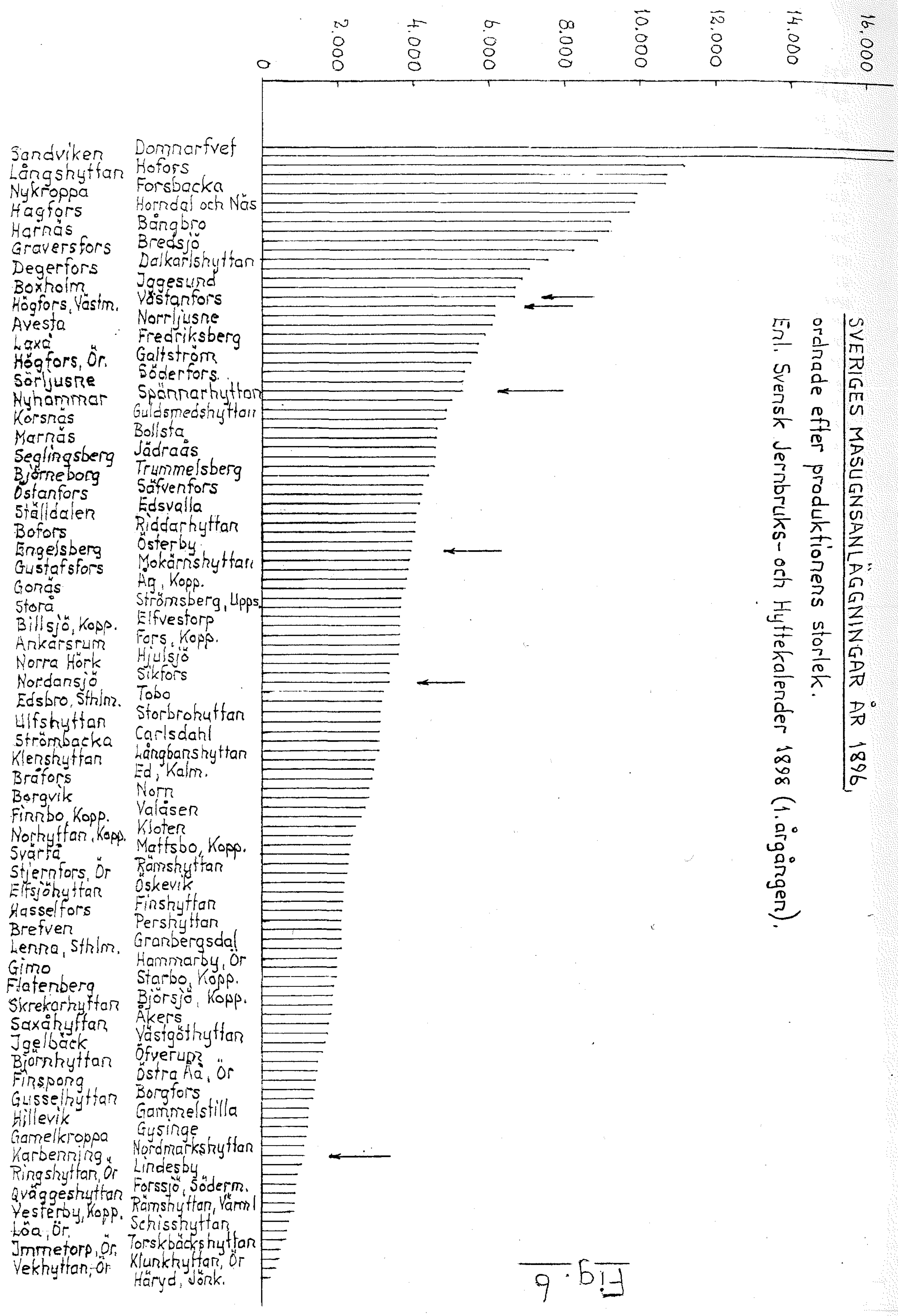

SVERIGES MASUGNSANLÄGGNINGAR ÅR 1896
ordnade efter produktionens storlek.
Enl. Svensk Jernbruks- och Hyttekalender 1898 (1. årgången).
Årstillverkning, tackjärn + gjutgods, ton
0
2.000
4.000
6.000
8.000
10.000
12.000
14.000
16.000
Sandviken
Domnarfvet
Långshyttan
Hofors
Nykroppa
Forsbacka
Hagfors
Horndal och Näs
Harnäs
Bångbro
Graversfors
Bredsjö
Degerfors
Dalkarlshyttan
Boxholm
Iggesund
Högfors, Västm.
Västanfors
Avesta
Norrljusne
Laxå
Fredriksberg
Högfors, Ör.
Galtström
Sörljusne
Söderfors.
Nyhammar
Spännarhyttan
Korsnäs
Guldsmedshyttan
Marnäs
Bollsta
Seglingsberg
Jädraås
Björneborg
Trummelsberg
Östanfors
Säfvenfors
Ställdalen
Edsvalla
Bofors
Riddarhyttan
Engelsberg
Österby
Gustafsfors
Mokärnshyttan
Gonäs
Åg, Kopp.
Stora
Strömsberg, Upps.
Billsjö, Kopp.
Elfvestorp
Ankarsrum
Fors, Kopp.
Norra Hörk
Hjulsjö
Nordansjö
Sikfors
Edsbro, Sthlm.
Tobo
Ulfshyttan
Storbrohyttan
Strömbacka
Carlsdahl
Klenshyttan
Långbanshyttan
Bråfors
Ed, Kalm.
Bergvik
Norn
Finnbo, Kopp.
Valåsen
Norhyttan, Kopp.
Kloten
Svartå
Mattsbo, Kopp.
Stjernfors, Ör
Rämshyttan
Elfsjöhyttan
Öskevik
Hasselfors
Finshyttan
Brefven
Pershyttan
Lenna, Sthlm.
Granbergsdal
Gimo
Hammarby, Ör
Flatenberg
Starbo, Kopp.
Skrekarhyttan
Björsjö, Kopp.
Saxåhyttan
Åkers
Igelbäck
Västgöthyttan
Björnhyttan
Öfverum
Finspong
Östra Ån, Ör
Gusselhyttan
Borgfors
Hillevik
Gammelstilla
Gamelkroppa
Gysinge
Karbenning
Nordmarkshyttan
Ringshyttan, Ör
Lindesby
Qväggeshyttan
Forssjö, Söderm.
Vesterby, Kopp.
Rämshyttan, Värml
Löa, Ör.
Schisshyttan
Immetorp, Ör.
Torskbäckshyttan
Vekhyttan, Ör
Klunkhyttan, Ör
Häryd, Jönk.

Fig. 6

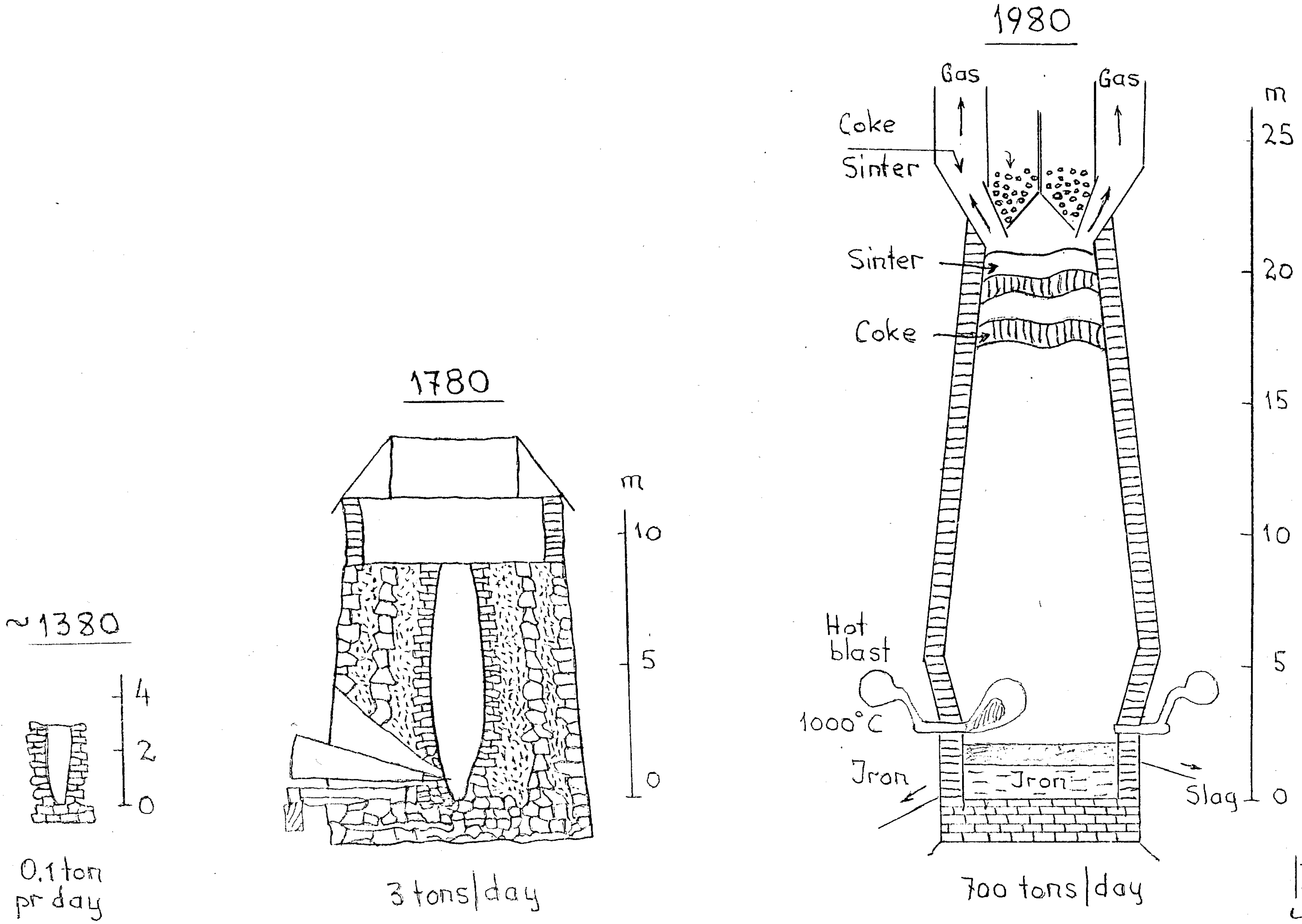

~1380
4
2
0
0,1 ton
pr day
1780
m
10
5
0
3 tons|day
1980
Gas
Gas
Coke
Sinter
Sinter
Coke
Hot
blast
1000°C
Iron
Iron
Slag
m
25
20
15
10
5
0
700 tons|day

Fig. 5

LAPPHYTTAN - AN EXAMPLE OF MEDIEVAL IRON PRODUCTION

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SUMMARY

The introduction of industrialised mining has had a crucial bearing on our understanding of medieval Scandinavian history. It was the foundation of the dualism and polarisation which, from the 14th century onwards, came to characterise political developments in Scandinavia.

The written sources have been discussed by a succession of eminent historical researchers, and they have probably little left to tell us; new source material is needed, and it is forthcoming in the form of archaeological sources, i.e. the remains of long-abandoned furnaces in our Bergslag regions.

Independent initiatives resulted in Lapphyttan becoming the subject of a major investigation at the end of the 1970s. Field work on the furnace site was completed in 1983 and has been followed by analysis of the finds under the aegis of a project group at Jernkontoret and the Central Board of National Antiquities.

The findings have made possible the complete reconstruction of a smelting and manufacturing facility from the 13th and 14th centuries. During the period in which Lapphyttan was in use, pig iron was manufactured by means of a continuous blast furnace process. The furnace site at Lapphyttan began to be used during the latter half of the 12th century and was probably closed down some time in the mid-14th. This makes Lapphyttan the <u>oldest known</u> surviving furnace site in Scandinavia.

The Norberg mining district (<u>bergslag</u>) occupies a special position in research into the history of the iron industry, as being the oldest medieval ironworking district mentioned in our written sources. It crops up as early as 1303 in the record of a purchase and exchange transaction between the then king, Birger Magnusson, and his lord high constable, Torgils Knutsson. This document is important in many respects. For one thing it shows that the leading personages of Sweden at that time had interests in Bergslagen and its iron industry. And just over 50 years later, Norberg became the subject of special legislation in the form of a charter, conferred by King Magnus Eriksson in 1354 and regulating relations between different groups of the population and proprietory rights in furnaces and mines. This marked the beginning of a distinctly Swedish process, observed by Kjell Kumlien and several other writers, whereby rights in the furnace were the governing factor. At the same time these early documents show that Norberg possessed great importance extending beyond its own boundaries. The mine proprietors of the Norberg Bergslag were to play a crucial part in the high politics of late medieval Scandinavia, throughout the great crises which included the Engelbrekt rebellion.

This hastily sketched background is necessary in order to understand the significance of Norberg Bergslag when attempting to answer questions about medieval iron production and mining. The written sources have been thoroughly researched, above all by Kjell Kumlien, Allan Weinhagen and Ulla Stahre (Kumlien 1958, p. 152 et seq., Weinhagen 1947, Stahre 1958, p. 244 et seq). It is no great exaggeration to say that we can hardly hope to make any further progress on the strength of the written material. Another kind of source material is needed to elucidate those points which the written records cannot reach. One such source is the archaeological material, which of course mainly consists of industrial remains. It is immediate in character, being so close to everyday life. The first really general presentation of archaeological source material for the study of medieval ironworking was Åke Hyenstrand's study "Hyttor och järnframställningsplatser". (Hyenstrand 1977) This work is not without its precursors, but most of them were more extensively based on the written sources, from which forays were then made to the individual sites.

The strength of the archaeological source material lies in its palpable demonstration of human activity. In most cases it has not been manipulated in the manner which the written sources are liable to be. This important aspect of source criticism has above all been pointed out by Mats Malmer (Malmer 1963, p. 12 et seq.). Using waste, facilities and mislaid objects, it is possible to trace former activities directly and on the spot. This involves a qualitative criterion. It is of the utmost importance to find a site which was abandoned as early as possible. The site must not have been used afterwards, because any subsequent use will transform it. This is particularly important when dealing with such a heavy industry as a blast furnace. The written records tell us of many medieval blast furnaces in the Norberg Bergslag, but most of the sites remained in use for a long time afterwards. In all probability, the subsequent furnace was erected on the same site as the earlier one, thus obliterating all previous traces. This is the case, for example, with Olsbenning Blast Furnace. The remains visible today are those of the 19th century furnace. The medieval facilities have long since been obliterated, although they may possibly remain in the form of severely disrupted strata beneath the present ground level or to one side of the late blast furnace building. All the furnaces needed water power, and so the actual blast furnace was bound to be positioned on a fall in the stream or river.

Clearly, then, a medieval furnace surviving intact is a very unusual relic. In the Parish of Karbenning we know of two furnace sites, apart from Lapphyttan, which were abandoned at an early stage, namely Mats Mikael's Furnace and the furnace at Hyttjärn. Altogether about 30 other medieval furnace sites are estimated to be extant in the Swedish mining districts.

BACKGROUND TO THE LAPPHYTTAN STUDY

During the early 1970s, the Municipality of Norberg published a description of the Parish of Norberg with the aim of making residents more conscious of local history. The initiative was taken by Karl Björzén, M.P. This description was subsequently followed by a presentation of the other parish, Karbenning, which also formed part of the Municipality of Norberg. The arrangement of this second description was somewhat differently conceived by Björzén. He had the idea of describing the route taken by iron along the Svartån River. This made it natural to start with iron manufacturing in the Norberg Bergslag. Björzén got in touch with Nils Björkestam and Sven Fornander and they consulted the Västerås County Antiquarian, Henry Simonsson.

In 1976, Åke Hyenstrand, Henry Simonsson and Karl Björzén explored the Parish of Karbenning to compile a C_{14} series of eligible furnace sites, their aim being to find a ruined furnace in a good state of preservation. The three sites already mentioned were dated, and Lapphyttan proved to be the oldest of them. This made Lapphyttan the obvious choice for a study of the medieval iron industry in Bergslagen.

Lapphyttan has always been known to the inhabitants of Olsbenning. The first written evidence of its name occurs in 18th century national survey maps. By that time the furnace area had been turned into a meadow.

During the early 1960s, the Parish of Karbenning came up for the regular survey of ancient monuments for the official economic map of Sweden. This led to the recording of several sites with traces of abandoned furnace workings. There were 22 sites altogether, most of which could be variously dated to the medieval period. All of them are described in the ancient monuments register of the Central Board of National Antiquities.

COMMENCEMENT AND COURSE OF THE INVESTIGATION

The original aims of the investigation were modest enough, the actual furnace mound being subjected to a limited investigation to elucidate various points concerning the construction of the furnace.

Medieval mining and iron manufacturing have been a topic of intense debate since the 1960s, above all within the Metallurgical History Group of Jernkontoret. Two main schools of thought crystallised out in this connection.

1. Blast furnaces already existed in Sweden during the early medieval period. The large export trade in Osmund iron from 1250 onwards was based on pig iron production in continuously operated furnaces. This pig iron was subsequently refined into the malleable iron called Osmund.

An important hypothesis on this subject propounded a long time ago by Sten Lindroth was that the blast furnace might be a Bergslagen invention and of Scandinavian origin. He maintained that the idea was derived from the copper industry. Norberg, of course, is close to the Falun copper mine, which did not become a really important factor in the Swedish economy until the 16th century (Lindroth 1955, p. 73).

2. The blast furnace was introduced in Sweden from Germany during the 16th century. The medieval Swedish iron industry was based on direct production of forgeable iron in non-continuously operated furnaces, otherwise known as stückofen, based on Continental models. Furnaces of this type were already known on the Continent in the 12th century and must have been introduced into the Swedish mining industry subsequently. Swedish iron exports during the medieval period, accordingly, were based on iron produced directly in large lumps and then broken up into Osmund pieces.

What type of furnace once stood on the mound at Lapphyttan and what type of iron did it produce. Pig iron or lump?

Inquiries during the early years focused entirely on the furnace mound. After three seasons' work, the remains of a blast furnace were successfully uncovered together with a stack, partly intact, a blowing arch and a tapping arch, and traces of a waterwheel attachment. The surviving fragments indicated that the structure was a timber-clad furnace.

While work was in progress on the ruins of the actual furnace, the site was cleared of some of the recent woodland growing on it. It soon became clear that we were dealing with a medieval furnace site which has survived completely intact. This suddenly opened up the possibility of investigating a complete medieval ironworking, but a more comprehensive investigation did not actually become feasible until 1981. The closure of the last steelworks at Spännarhyttan created an employment crisis in Norberg, and the National Labour Market Board (AMS) therefore needed job creation projects. Lapphyttan made a suitable assignment and a more comprehensive investigation now became possible. The site was completely unturfed and examined in detail for three years. All the facilities which a furnace site ought to incorporate were discovered. They comprised the ruins of a furnace, a roasting pit, seven slag heaps, eight fineries, about 20 stores in heaps, traces of a charcoal shed, an iron store, a dwelling house, a subterranean iron store, traces of a stable, two drainage ditches, a main pond and a pen pond. There were also traces of latter-day facilities in the form of two charcoal pits and a charcoal burner's hut.

Compared with the prehistoric process of direct iron production, the blast furnace process and its subsequent refining of the pig iron can be termed an industrialised sequence of operations. So far Lapphyttan has proved to be the oldest known complete industrial site in this technological chain.

More than 8,000 different finds were salvaged in the course of the investigation. The overwhelming majority of these were iron at various stages of production, but there were also a number of other finds, viz pottery, glass and some bronze objects. Then again there are large collections of specimens of slags, ores, furnace linings and charcoal etc. A great deal of this material is of a very special archaeological quality.

THE RESEARCH PROJECT

This archaeological material was found to require extensive further processing in many ways in order to shed light on the details of the various technical processes used at Lapphyttan. What had been the role of Lapphyttan in the medieval community?

To tackle this assignment, Jernkontoret and the Central Board of National Antiquities set up a research group numbering just over 30 representatives of various fields of knowledge. During the very first season's investigations, a small reference group had existed comprising Nils Björkenstam, Sven Fornander, Karl Björzén, Inga Serning, Boris Serning, Henry Simonsson, Krister Ström, Erik Ljung and Åke Hyenstrand. A grant from the Bank of Sweden Tercentenary Fund made it possible for this group to be established on a formal footing and for a larger number of experts to be co-opted. The material could now be processed on a wide front. Apart from archaeologists, the experts represented also include historians, metallurgists, metallographers, mining specialists, potters, geologists, paleobotanists, quaternary geologists, osteologists, dendro-anatomists, thermoluminescence specialists etc.

From the very outset, this work has been of an interdisciplinary nature and has been based on co-operation between the Västmanland State County Administration and County Museum, the Municipality of Norberg, AMS, Jernkontoret and the Central Board of National Antiquities.

The plan is for the work of the research project to be concluded during the autumn of 1985 and findings published in 1986.

THE INDIVIDUAL FACILITIES

The furnace ruin

The furnace ruin is the focal point of Lapphyttan and was, of course, the fons origo of the whole inquiry. Excavation work on this ruin has proceeded throughout the study, and it has involved very great archaeological problems. There have been no previous investigation reports or other reference material available for consultation. Every stage in the investigation of the ruined furnace has been recorded in detail. In many cases, e.g. when digging in the rubble surrounding the actual furnace ruin, this was perhaps unnecessary, but all the time we were uncertain as to whereabouts in this rubble we might come upon the original structures.

A great deal of the ruin was in a good state of preservation. The furnace had one tap-hole for iron and slag pointing towards the stream which flows in front of it. This was the weakest part of the furnace structure, which explains why it collapsed outwards. This is in fact a common feature with several furnace ruins of more recent date which are to be seen in Bergslagen. The furnace was partly let into the sloping bank of the stream, which provided a certain measure of support for its rear wall. The blowing wall was intact here up to 1.9 m above the bottom of the hearth. The other two walls are slightly lower. They too have been partly pushed outwards as a result of ground frost movements and the general process of decay.

The hearth has been torn out, as was the usual practice in all blown-down blast furnaces. When the furnace was taken off blast, some of the iron and slag would solidify and accumulate on the bed and walls of the hearth, forming what is known as "the bear". This contained enough iron to be worth salvaging. At all events, the hearth always had to be rebuilt on account of the extensive melting which invariably took place. The bear was broken out and extracted through the tap-hole. Part of the bottom and walls of the hearth were removed in the process. Unfortunately this made it impossible to reconstruct the original, operational appearance of the tap-hole.

The furnace's one and only blast tuyère for blowing in blast air was located upstream, at right angles to the tap-hole. The blowing wall was in a good state of preservation and showed traces of repeated repairs during the period when the furnace was in use. It was heavily scorched, due to the high temperature of the blast flame in this part of the furnace. As mentioned above, the hearth was broken up after every blowing down. At the same time as it was rebuilt for the next charge, the blast wall was also repaired if necessary. The damaged area of the blowing wall was mended with suitable fire-proof material. In the surviving blowing wall one can distinguish at least five repairs.

It is impossible to tell at present on the strength of the surviving remains how long the different campaigns at Lapphyttan can have lasted. On this subject we are thrown back on written records from the 17th century, but these can only support a hypothesis concerning the duration of the blowing time. During the 17th century, the average blowing time throughout the Norberg Bergslag was no more than 22 days. The number of blowing days per furnace could vary between 5 and 70. At Olsbenning Furnace, not far away, blowing times varied between 20 and 40 days (Weinhagen 1947, p. 65 et seq.). Considering the available water power and the service life of the furnace lining, blowing at Lapphyttan may perhaps have lasted for about 10 days. Another possibility, of course, is that blowing took place during both spring and autumn, which would have substantially augmented the output. This would mean laying in sufficient stocks of charcoal and ore.

The outer walls of the furnace were supported by a dry stone platform about 1.2 m high and 4.6 m across. The northern part of this platform rests directly on the gravel of the slope overlooking the stream, while the southwestern corner is built on a specially prepared bed of roasted ore, charcoal and soot.

The furnace shaft occupies a central position in the structure and was square in shape with sides about 1 m thick and 3 m high of fire-proof natural stone, a micaceous sandstone. On the outside of the inner shaft wall there is a retaining wall of the same mica schist. The outer walls of the upper part of the installation were of timber. The outer wall and stack wall were separated by an infill of topsoil, burned clay and crushed stones from burned-out stack walls. Nothing remains of the outermost timbering. This probably lay uppermost when the furnace decayed and thus rotted away completely during the centuries that followed. On the charge side, opposite the tapping arch, a partially decayed log from some previous conversion of the furnace was found in the débris of charcoal and roasted ore.

To convey the blast air to the tuyère and to the tap-hole, arches had to be built to carry the outer walls. The foundation stones of the tapping arch were still in situ. This arch had an outer width of 3.4 m and extended 1.7 m towards the blowing wall. The position of the tap-hole could be established and with it the positions of the furnace floor and the working floor in the arch as far as the stream running parallel to the furnace; at this point the stream was lined with timber.

The blowing arch was upstream, at right-angles to the tap-hole. It was severely dilapidated but quite possible to reconstruct. The floor in this arch could be seen to consist of a thin, compressed layer of soot and dust. This arch was a simple aperture in a cavity wall which, being of a much weaker structure than the tapping arch, had collapsed more completely. The arch had in all probability been about 1.1 m wide and 1.7 m deep. The blast tuyère shaft had been positioned in the blowing wall. Two pairs of bellows had probably opened into the blast tuyère. There were probably two sets of bellows, operating alternately so as to produce a steady airstream. These bellows were driven by cams on an extended waterwheel shaft.

As in all blast furnaces, the shaft tapered towards the hearth, which, judging by the position of the bed floor, the level of the tuyère and the furnace generally, cannot have exceeded about 0.5 x 0.3 m and cannot have been more than 0.23 m deep.

WATER POWER

The furnace is very strategically positioned beside the slight waterfall at this very point. The maximum drop was utilised, which made it possible to work with relatively small quantities of water. Journal stones and an iron cotter pin from a waterwheel were found immediately upstream of the furnace. The water was conveyed to the waterwheel by means of a channel from the small main pond at the top of the hill. The main pond was lined with a timbered stone caisson, of which the bottom log of a hatch have survived. Above the main pond are traces of another pond - a larger pen pond. This pond is contained by an earth dam, partly reinforced with timber and partly lined at the edges with stones and timbers measuring 0.3-0.5 m in length.

THE ROASTING PIT

Three main types of ore have been discovered on the furnace site:

1. Carbonacious, manganese-bearing iron ore of the Klackberg type.

2. Silicious, manganese-bearing iron ore of the Häste type.

3. Quartzite, low-manganese iron ore of the Bondgruve type.

These ores were determined by the Iron Ore Subcommittee of the Jernkontoret Mining History Committee. The Klackberg ores are the commonest and the Bondgruve ores the least common of those recovered. Sven Fornander and Nils Björkenstam will be dealing at greater length with these ores in their lecture on Wednesday, and so I do not propose to go into the matter any further at present.

Just a few words, though, about where and how the ore was discovered on the site. It is in principle possible to study the entire sequence of operations which the ore passed through before being put into the furnace.

Scattered throughout the southern part of the site there are numerous large pieces of ore, measuring 0.2-0.3 m. We have taken these blocks to indicate the size in which ore was delivered from the mine. These pieces fell off the ore sledges and for some reason were never salvaged.

The other size, measuring about an inch, is the broken ore. This is scattered round about the roasting pit, within the perimeter of the ore sheds and round about the furnace. It occurs in both the roasted and unroasted states, which shows that the ore was broken before being roasted in the roasting pit.

The roasting pit was a simple bunker measuring 2.6 x 1.8 m and 1 m deep, with dry-stone walls. The bottom was lined with a 1 dm thick layer of roasted ore.

The roasted ore was then stored in heaps. Our investigations have revealed about 20 of these ore sheds, mostly in the southern part of the site.

THE CHARCOAL SHED

There must have been several charcoal sheds at the site, but the latter-day charcoal stacks were so unfortunately positioned as to be directly superimposed on that part of the site where the charcoal sheds logically ought to have been located. On the edge of one of the charcoal beds, however, there are traces of a building which may have been a charcoal shed. It measured 5 x 4 m and was roofed with slag; this is what enabled us to record it.

THE FINERIES

The eight fineries are among the more remarkable installation finds at this site. The number in itself is remarkable, and I shall be elaborating this point in due course. The fineries are scattered over almost the entire area. Seven of them have been excavated, and an eighth has been saved for future research.

Structurally speaking, the fineries can be roughly divided into two groups. I refer here to the shape of the actual hearth. The normal hearth is 50-60 cm long, 40-48 cm wide and 20-25 cm deep. Two hearths do not conform to this description. They are 85 and 90 cm long respectively, 40 cm wide and 25 cm deep. They appear to have been open at one end. They are positioned somewhat asymmetrically in a dry-stone platform measuring 1.8 x 1.9 or 3 x 2 m. The area round the actual hearth was originally level and on two sides the hearth had a low rear wall, about 0.2-0.3 m high. This was probably designed to protect the bellows. All eight hearths are positioned in such a way in relation to the furnace site that their bellows cannot possibly have been water-powered.

It is worth noting that large and numerous slag heaps are only to be found round three of the fineries. The other five have practically no slag heaps at all. One has a feeling that they were commissioned only a short time before Lapphyttan closed down. Quite heavy investments seem to have been made at Lapphyttan just before it was abandoned. Fineries A15 and A14, together with A21, seem to have been original features. Subsequently five more were constructed, just before the furnace went out of business.

It is very interesting that there should be just eight fineries. It seems as if the prevailing legislation, known to us in its earliest form from the charter conferred by Magnus Eriksson in 1354, was closely complied with here. That charter made each <u>bergsman</u> personally responsible for the quality of the iron he produced. Work at the furnace itself was collective, with individual elements. Every <u>bergsman</u> blew his own ore shed, but blowing in and blowing down were the collective tasks of the furnace team. After smelting, when the iron had to be refined from pig iron to malleable iron, the individual <u>bergsman</u> was personally responsible for this work and for the good quality of the refined iron. There is clear evidence of this working organisation from the 17th century (Granlund 1945). The Lapphyttan finds incline us to date this furnace team organisation back to the medieval period, and above all, as things now stand, to the 13th century. Looking at the number of fineries, we are immediately reminded of the words of King Magnus Eriksson's charter, issued 600 years ago:

"Furthermore, if any ironmaster holds less than one-eighth of a furnace, that same holding shall belong to the King in perpetuity, unless he assign it to some other person within one month after being lawfully called upon to do so." (Stahre 1958, p. 136 et. seq.)

This means, quite simply, that nobody could own less than one-eighth of a furnace. Lapphyttan, clearly, was already divided according to this pattern during the 14th century. In this particular case, one-eighth of a furnace corresponded to a complete farm.

The finds from the fineries are very similar to those made at the furnace. The overwhelming majority consist of iron shot. Some of them are refined, while others have never seen a finery. In several of the fineries one also comes across a considerable amount of forging waste and iron objects. These hearths seem to have been used both for refining and for repairing the most important implements needed for work in the furnace.

TRACES OF DWELLINGS

Immediately adjoining the site, there are traces of a dwelling house, two stables and two iron sheds. One of the stables and one of the iron sheds can only be identified by compiling complete distribution maps of the finds from the site. Certain types of objects suggest that there may have been one more stable and one more iron shed.

The dwelling house was a single-roomed building with a gabled front porch. The fireplace, constructed of stone and clay, stood in one corner of the one and only room and was of the type to be found in the homes of country people until quite recently. It had a corner bar of iron or wood, inserted between two stones in the hearth. The entire building was timbered. Unfortunately we know nothing about the roof structure, but it was probably turf-clad.

The finds from the dwelling house are more personal in character than those from other parts of the site. Sherds have been discovered from imported earthenware vessels of the redware I type and a bronze ring inscribed with a star, a number of knives and - perhaps the most amusing of all - a small musical instrument, a type of jew's harp. Scattered inside the dwelling house and outdoors were sporadic mealtime traces in the form of mutton, beef and pork bones.

The dwelling house mainly served as overnight accommodation for furnace workers, but it must also have been used as a mess and dining room. We were not able to find any traces of permanent settlement at Lapphyttan. The permanent agrarian community adjoined the nearby village of Olsbenning instead. Pollen analyses from the furnace pond and the lake downstream indicate that Olsbenning was colonised at the same time. We have employed both traditional archaeological inventory and extensive phosphate charting in an attempt to find traces of a permanent settlement at Lapphyttan, but without any positive results.

THE IRON SHEDS

The facilities identified at the furnace site include one resembling an latter-day mattamore. This is accompanied by a heavy concentration of numerous lumps of iron within a small area, close to a number of stone courses which might possibly have supported another timber building. Innumerable cut-up pieces of iron have been found at both points, and this is what leads us to believe that these facilities were sheds used for storing the iron pending shipment by way of such important export harbours as Västerås and Stockholm.

DATING

One of the essential aims of the Lapphyttan inquiry was to date the site accurately, and a highly comprehensive dating programme was devised for this purpose. We used several different dating methods: artefact dating, thermoluminescence dating, dendrochronology and also the dating of certain horizons in nearby wetlands. The historical significance of Lapphyttan is to a great extent bound up with its dating, the essential point being to verify that it is a genuine source of information about a period concerning which sources are otherwise lacking.

The few objects from the furnace site which can be used for dating purposes, mainly comprising pottery (early red earthenware), indicate the period between 1250 and 1300.

We have at present a C_{14} series of 26 analysed specimens from the various facilities of the Lapphyttan furnace site. C_{14} dating is extremely difficult to use in a case like this, due to the considerable factors of uncertainty involved by the specimens we have obtained from various strata of the various facilities. We had to bear in mind that when Lapphyttan was originally established, the furnace site must have been cleared in an ageing forest. Consequently there must be great chronological variations even in each individual tree used for charcoal burning. Towards the close of the Lapphyttan epoch, the forest must have been exhausted, in which case a larger proportion of younger trees would have been used for charcoal burning. It follows that the terminal phase is more amenable to C_{14} dating than the introductory phase. For present purposes I have chosen to amalgamate all datings into one graph and reweight them collectively. This procedure indicates that activities at Lapphyttan began some time between 1150 and 1200 and were discontinued between 1375 and 1425, which indicates that the workings were in use for up to 175 or 250 years. There are great factors of uncertainty involved, but we still have some indication of the chronological context.

Thermoluminescence datings partly corroborate the C_{14} datings. These TL datings come above all during the latter phase, mainly because this is the phase from which we have the best TL dating specimens. One specimen taken straight from the tuyère comes between 1270 and 1390, and this is a good indication of the period during which the closure of the site must have occurred.

Unfortunately the dendrochronological specimens had insufficient annual rings, and so nothing could be ascertained this way.

CONCLUSION

Our inquiries at Lapphyttan have contributed completely new source material to discussions of the introductory phase of medieval mining and ironworking and the technical level and social environment of which it was both the product and the cause.

The Lapphyttan datings indicate that the furnace site was open some time between 1150 and 1200 and remained in use until the second half of the 14th century.

During the earlier phase of its history, the furnace site appears to have been organised on an individual pattern or initiative, while during its terminal phase it was adapted to some form of team organisation and social requirements. This, possibly, is our first encounter with the furnace team of the <u>bergsmen</u>, a form of collective, joint-stock proprietorship of the facilities. This is probably the team organisation reflected by the few 13th and 14th century written sources and partly expressed in the charter of 1354. This organisational model was fully evolved in the 17th century.

The place names in Norberg Bergslag, and especially those ending with Benning, are predominantly Scandinavian. In other words, the alleged German influence during the initial phase of the mining industry is not apparent here in Norberg Bergslag.

It has also been conjectured that the introduction of the blast furnace was an innovation sponsored by the upper classes. Looking at the cadastre material of the 16th century, one finds that all the furnaces were predominantly owned by bergsmen. I believe that the conversion of the Bergslag area from wilderness to industrial community was very much the work of the individual bergsmen, whose technical skill and social vision laid the foundations of prosperous development. This capacity for social organisation has been very dramatically expressed later on in the Engelbrekt rebellion, one of the few medieval rebellions of the common people to have succeeded, resulting as it did in the deposition of the ruler of the Kalmar Union, King Erik of Pomerania.

Mats Malmer once broached the idea of two poles of medieval Scandinavian history. Following on from this, one can say that there were two essential poles of medieval Scandinavian history. One of them was the feudal agrarian economy, with its natural emphasis on the former Danish provinces, and the other is the dynamic early industrial development of the Mälar Valley area. During the 13th century this doubtless resulted in a heavy urbanisation of the Mälar region and a shift of the political centre of gravity in this direction from the more prosperous agricultural communities of Östergötland and Västergötland. This achieved its supreme manifestation in the foundation of the national capital, Stockholm, during the 13th century.

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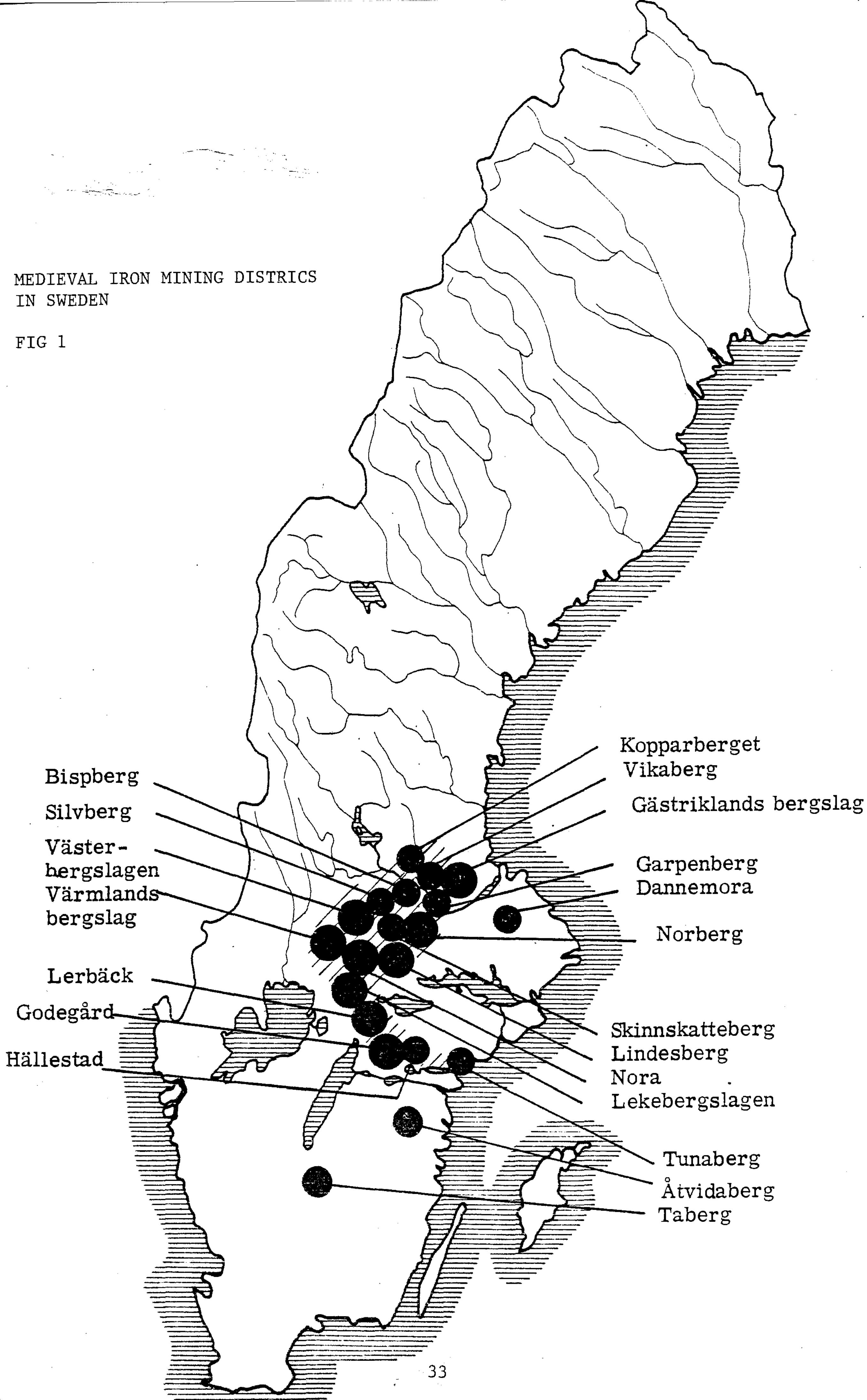
MEDIEVAL IRON MINING DISTRICS
IN SWEDEN

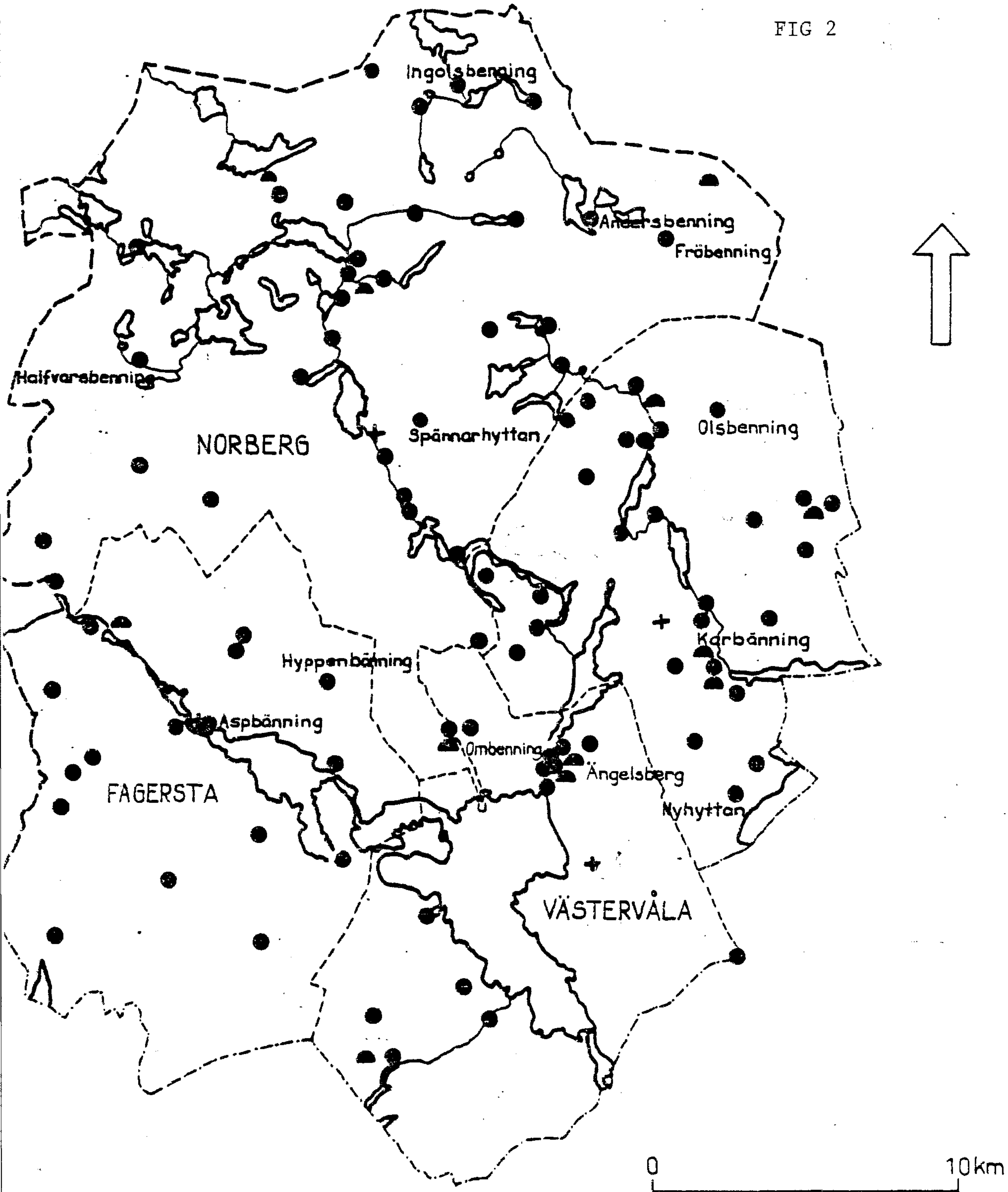
FIG 1



Norbergs bergslag

NORBERG MINING DISTRICT

FIG 2



NORBERG MINING DISTRICT IN VÄSTMANLAND

● BLAST FURNACES
▲ FORGES

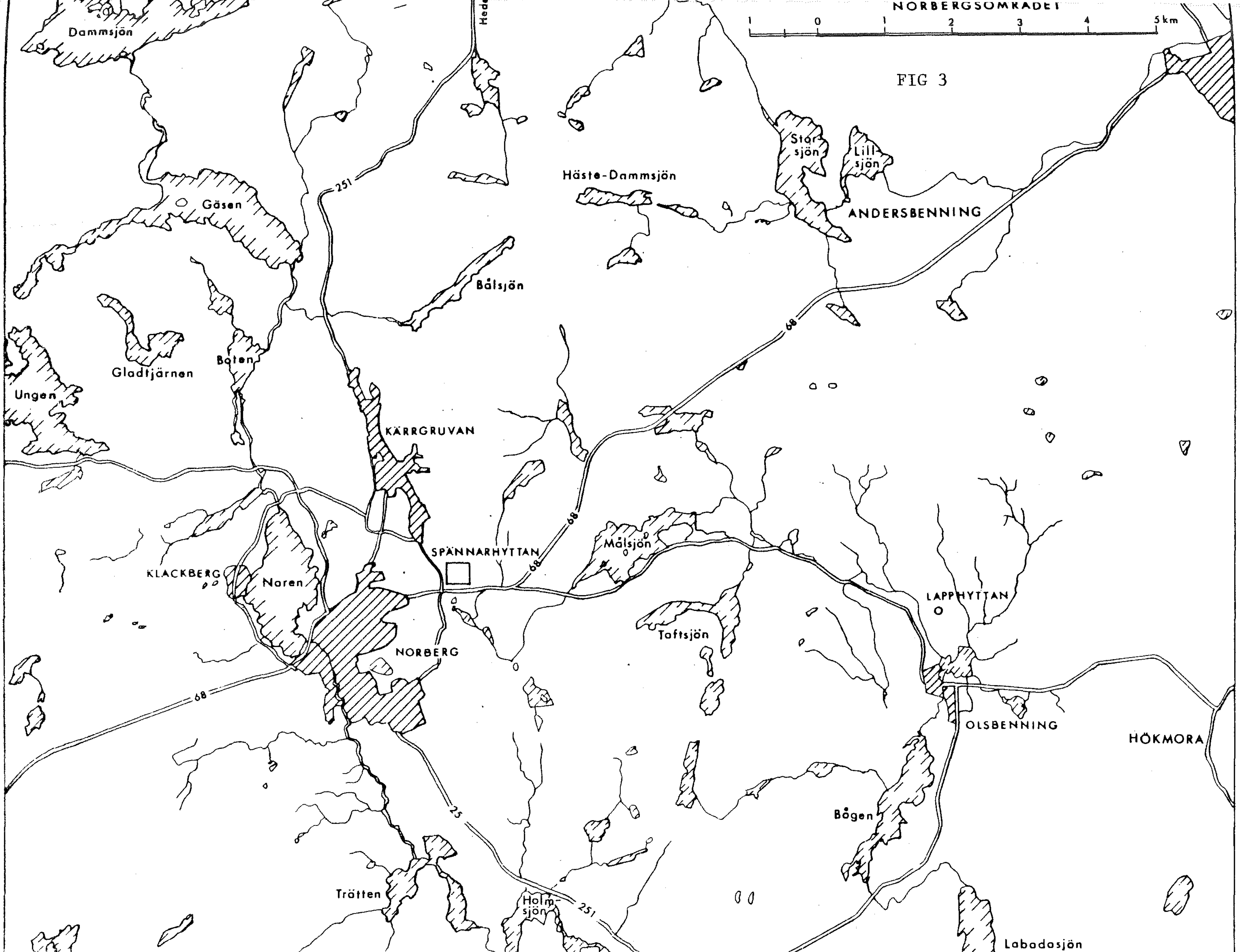
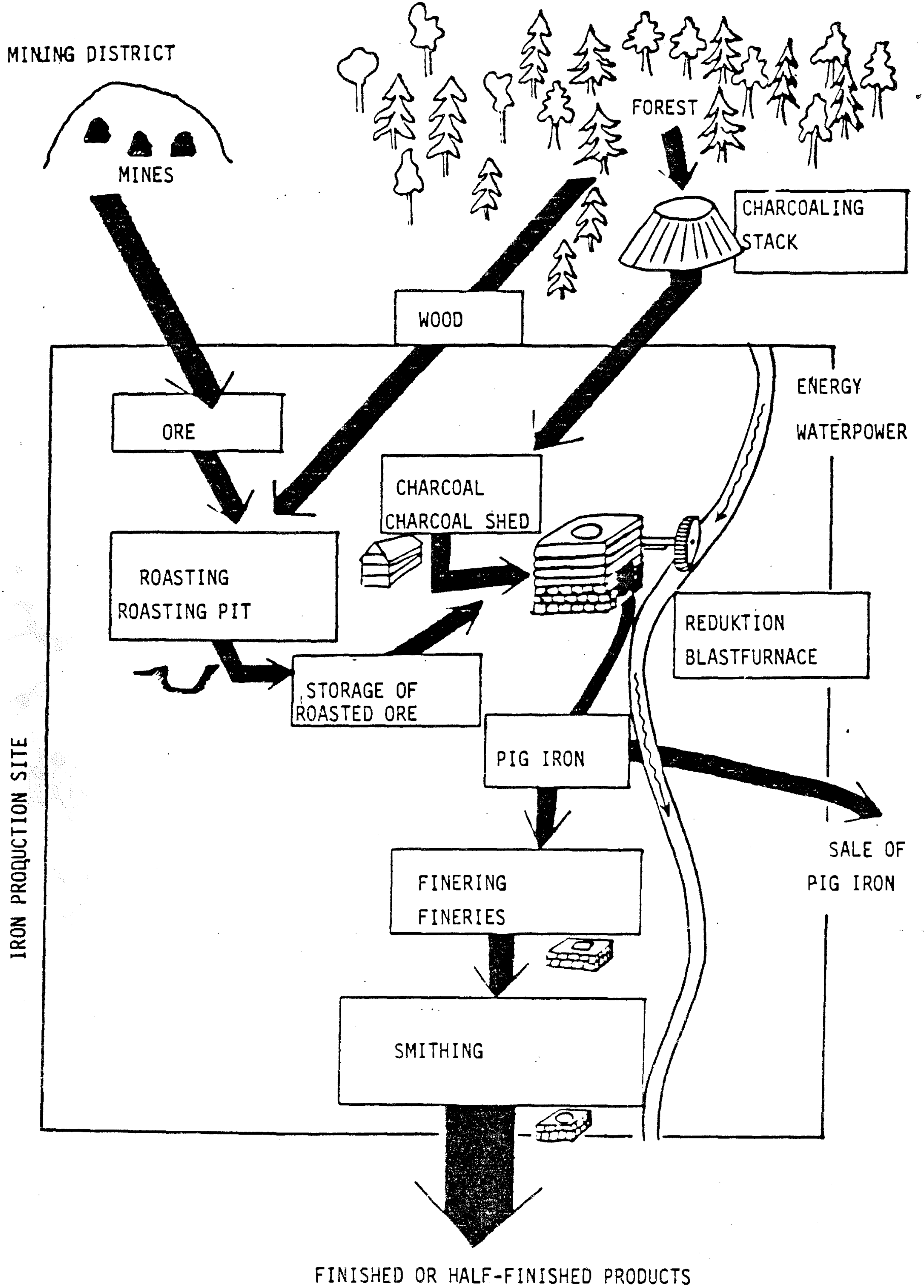
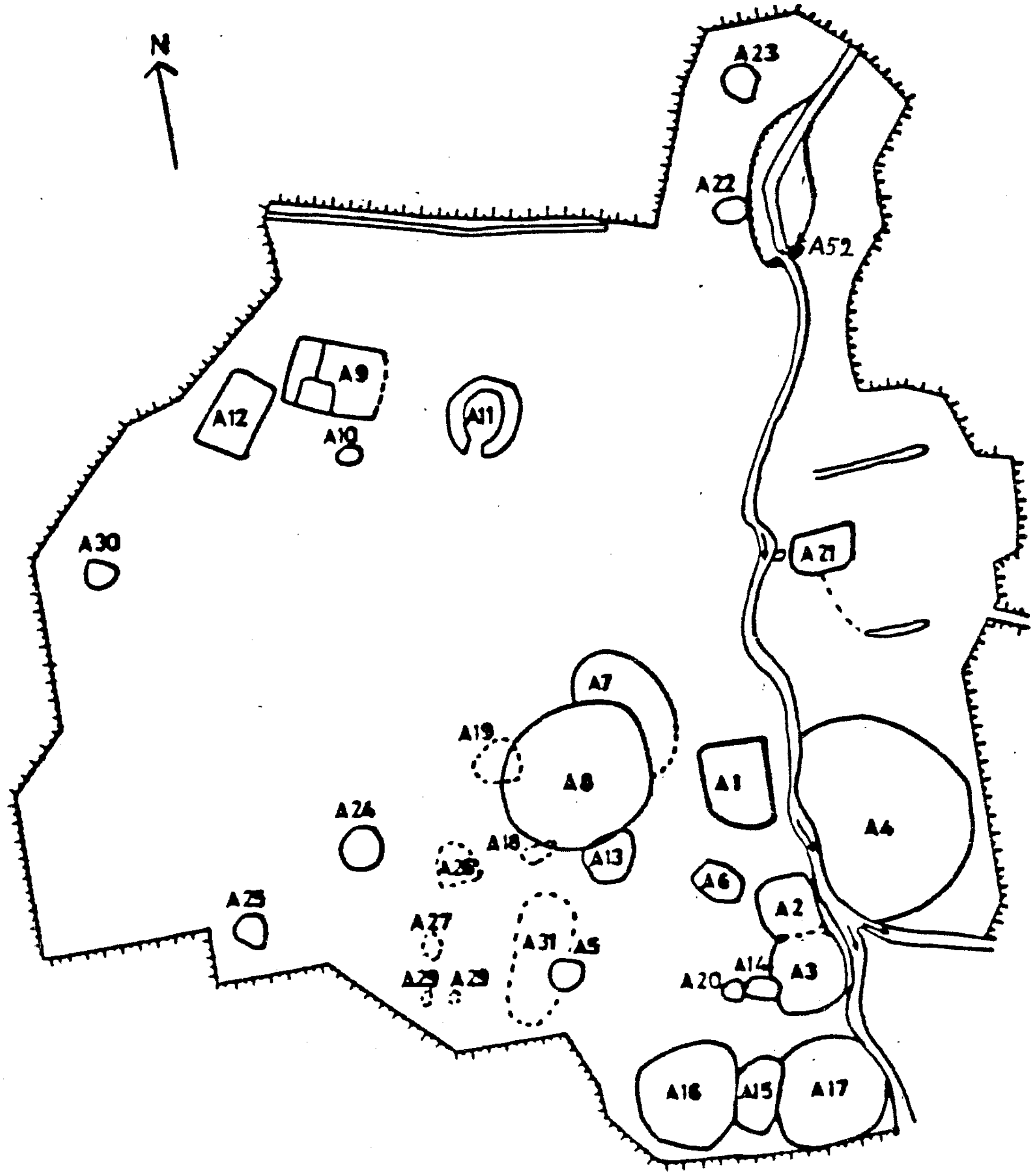

NORBERGSOMRADET
1 0 1 2 3 4 5 km
Dammsjön
Gäsen
Häste-Dammsjön
Starsjön
Lillsjön
ANDERSBENNING
Bålsjön
Boten
Gladtjärnen
Ungen
KÄRRGRUVAN
SPÄNNARHYTTAN
Målsjön
KLACKBERG
Noren
NORBERG
Toftsjön
LAPPHYTTAN
OLSBENNING
HÖKMORA
Bågen
Trötten
Holmsjön
Labadosjön
251
68
25

FIG 3



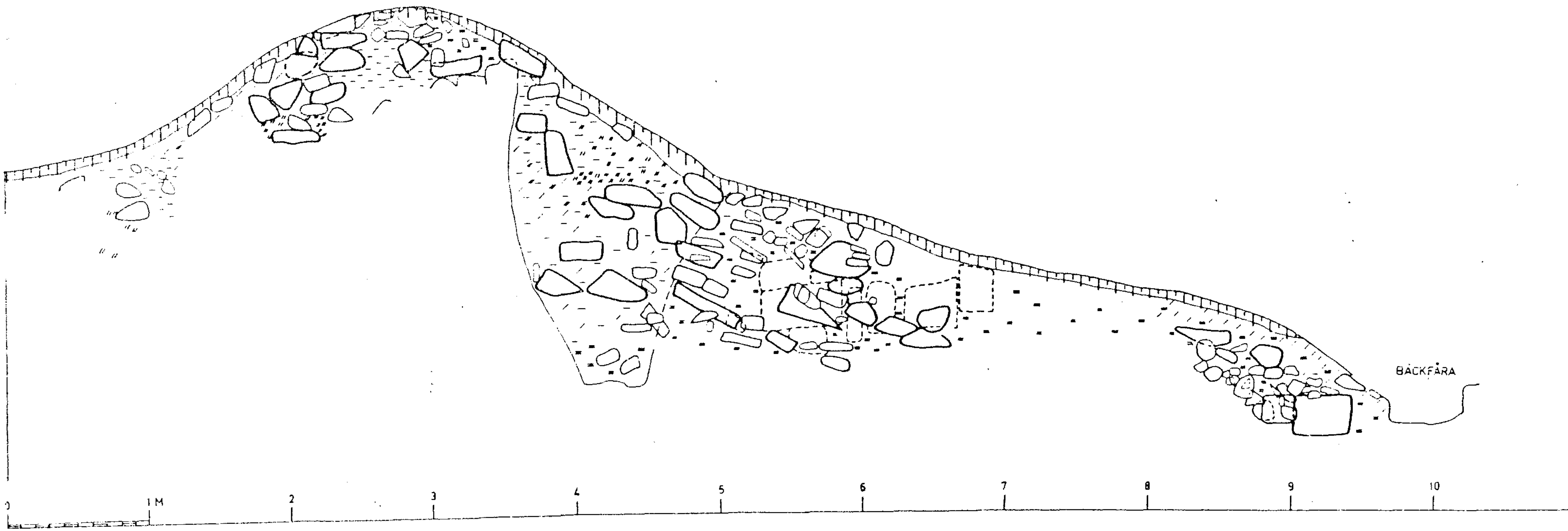
MODEL OF AN IRON PRODUCTION SITE

FIG 4



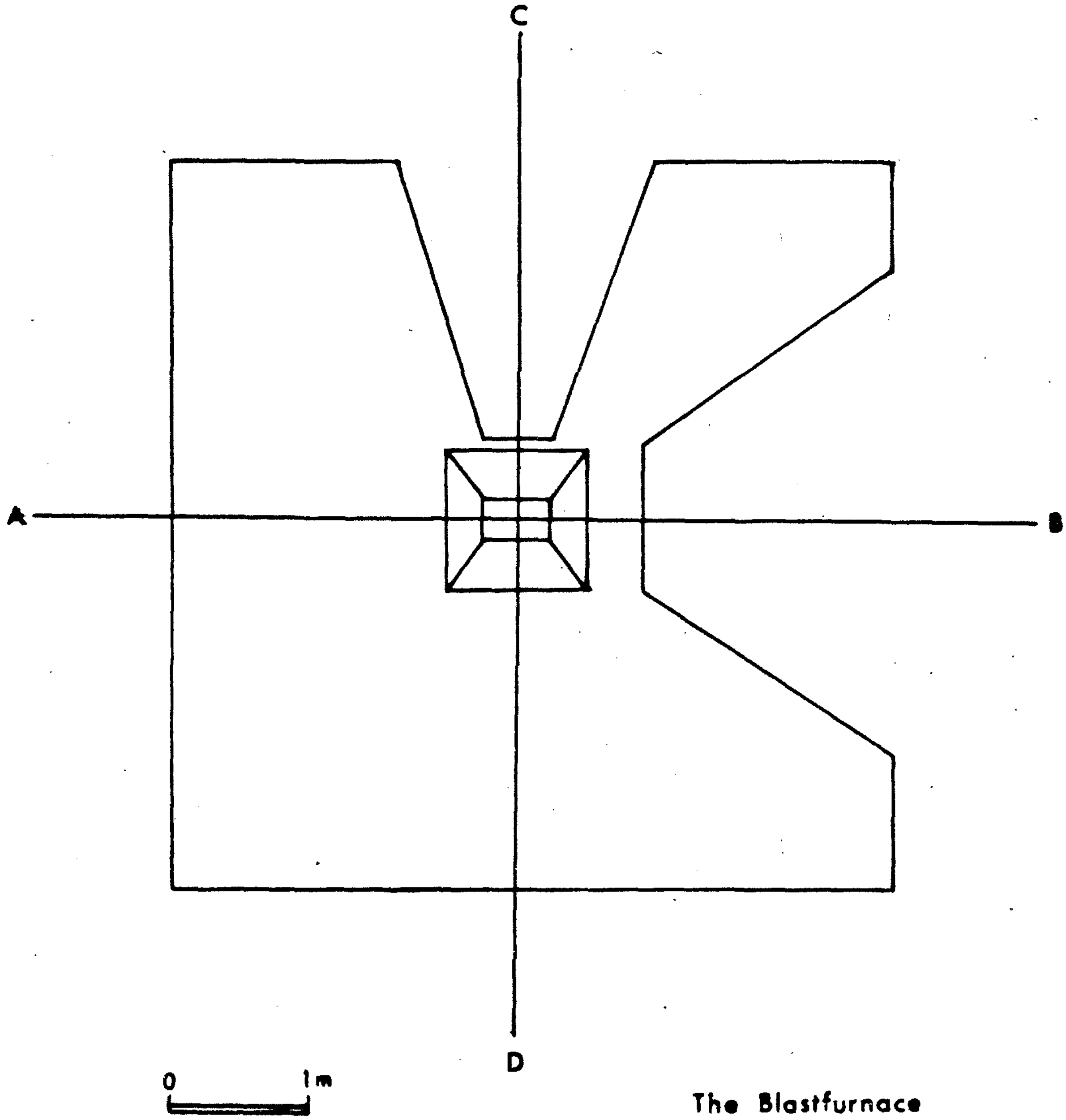
A I = Blast furnace ruin
A 2 = Slag heap
A 3 = Slag heap
A 4 = Slag heap
A 5 = Slag pieces
A 6 = Roasting pit
A 7 = Charcoal stack
A 8 = Charcoal stack
A 9 = Dwelling house
AI0 = Hearth
AII = Iron shed
AI2 = Stable
AI3 = Charcoal shed
AI4 = Finery
AI5 = Finery
AI6 = Slag heap
AI7 = Slag heap
AI8 = Heap of ore
AI9 = Heap of ore
A20 = Slag heap
A2I = Finery
A22 = Finery
A23 = Finery
A24 = Finery
A25 = Finery
A26-A29 = Heaps of ore
A30 = Finery
A3I-A5I = Heaps of ore
A52 = Pond and timbered stone caisson

FIG 5



AI BLAST FURNACE, PROFILE E-W

FIG 6



The Blastfurnace
Reconstruction
FIG 7

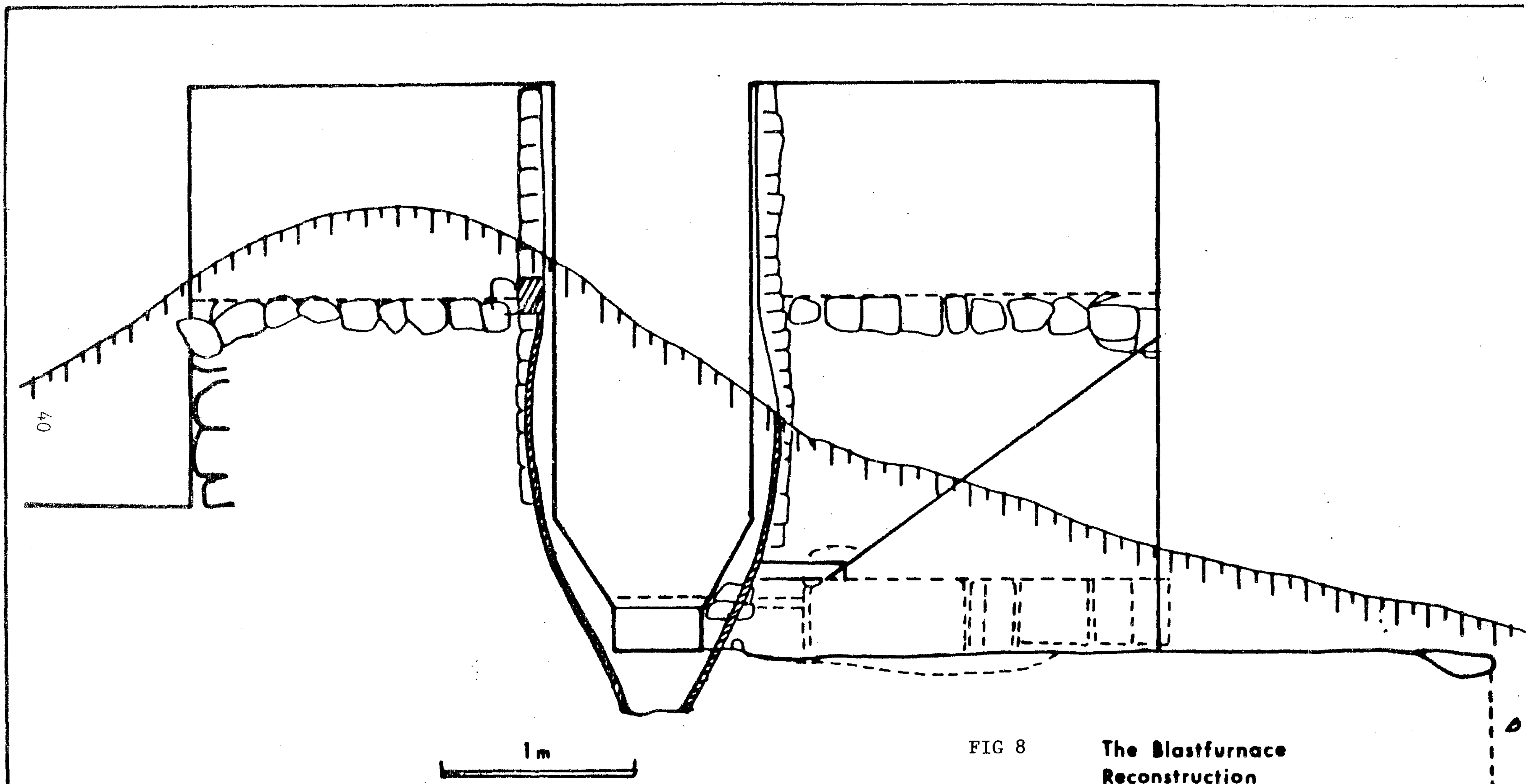


FIG 8 The Blastfurnace Reconstruction Lapphyttan Profile A-B

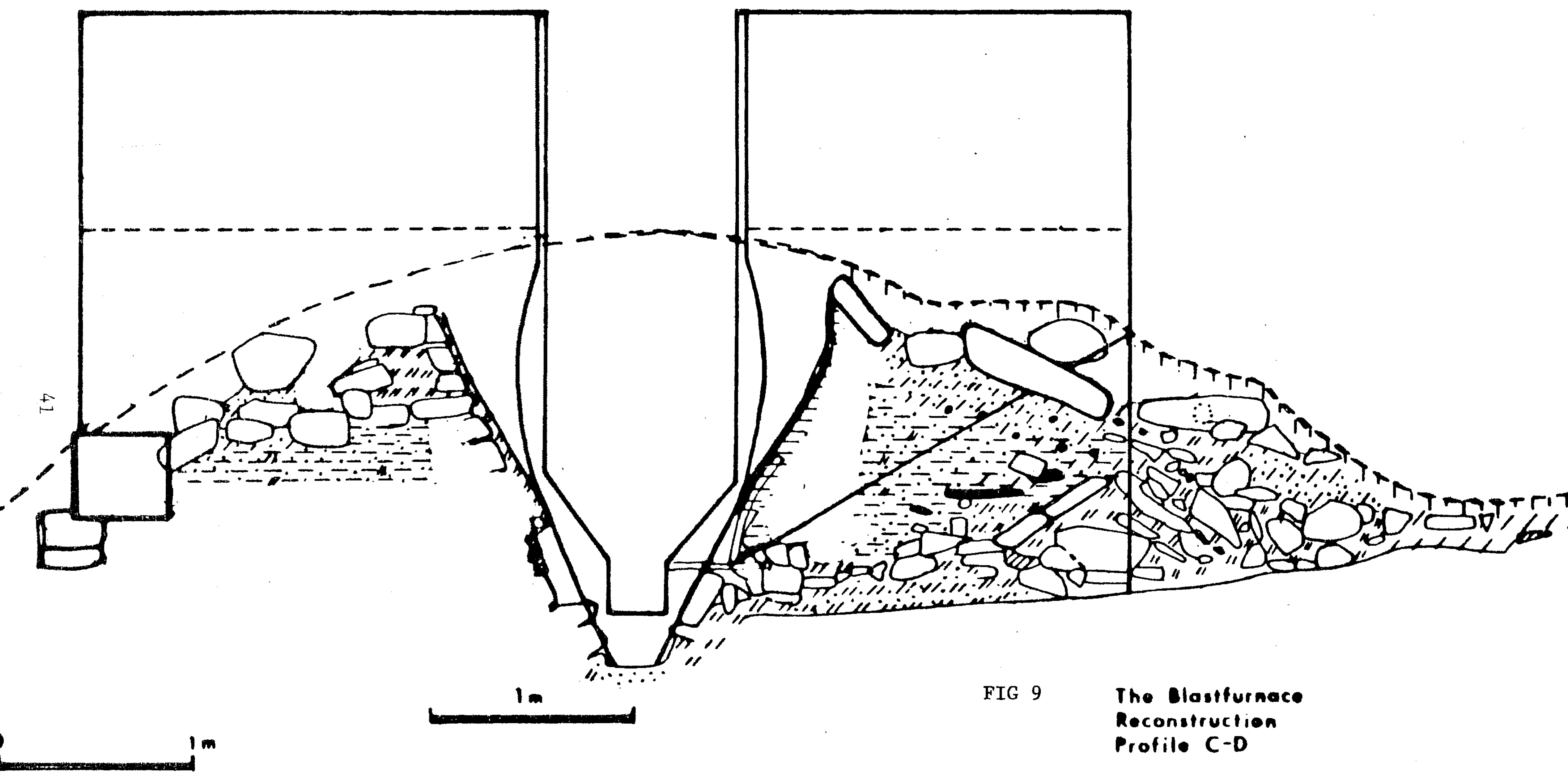


FIG 9 The Blastfurnace Reconstruction Profile C-D

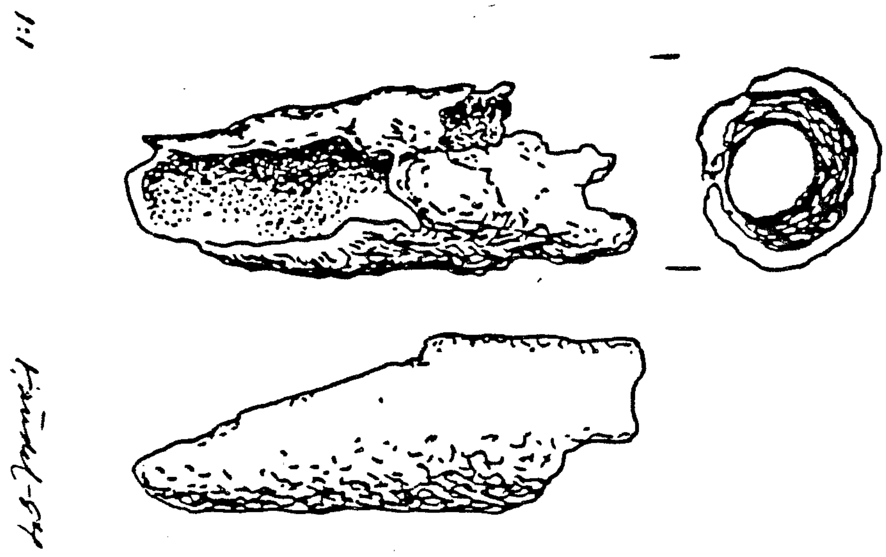
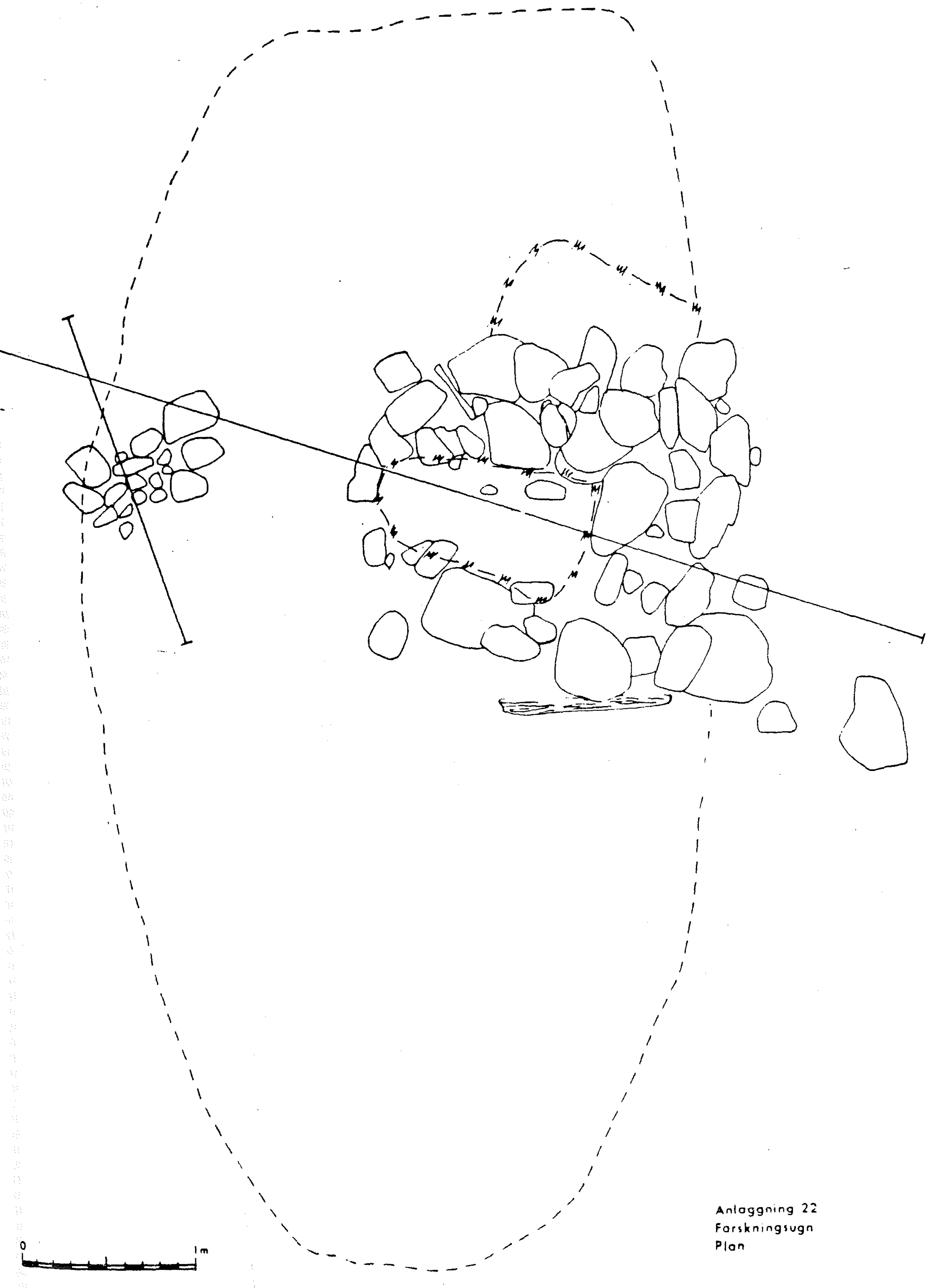
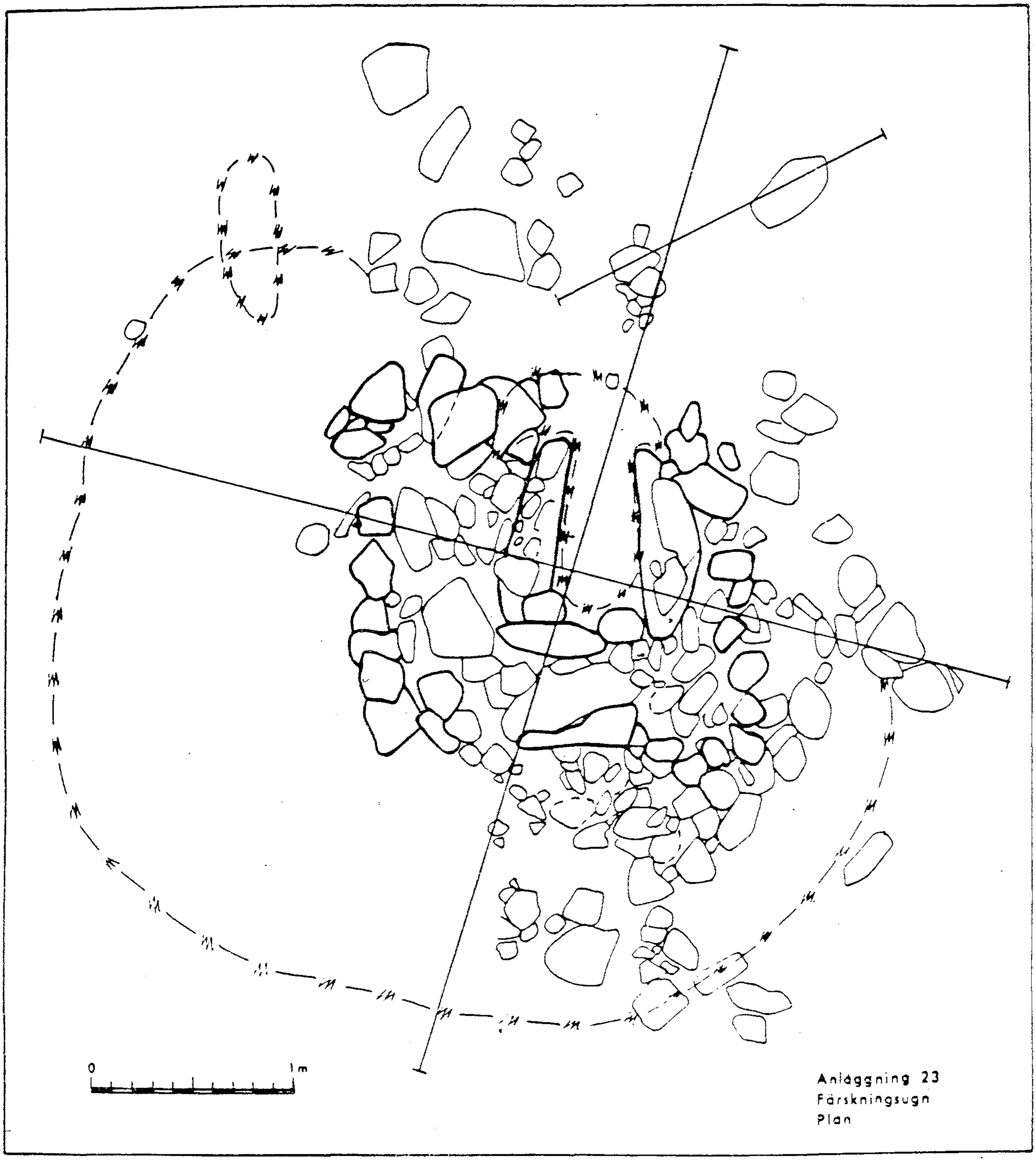


FIG 10 A TUYERE FROM LAPPHYTTAN

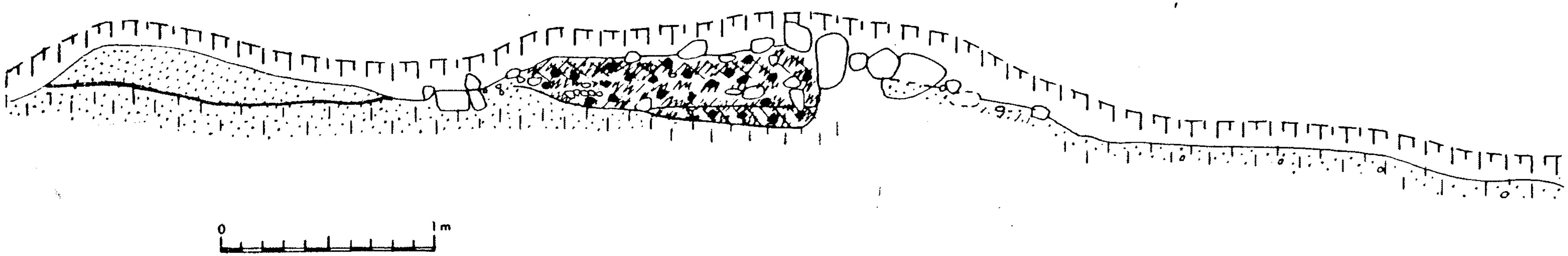


A22 FINERY
FIG 11

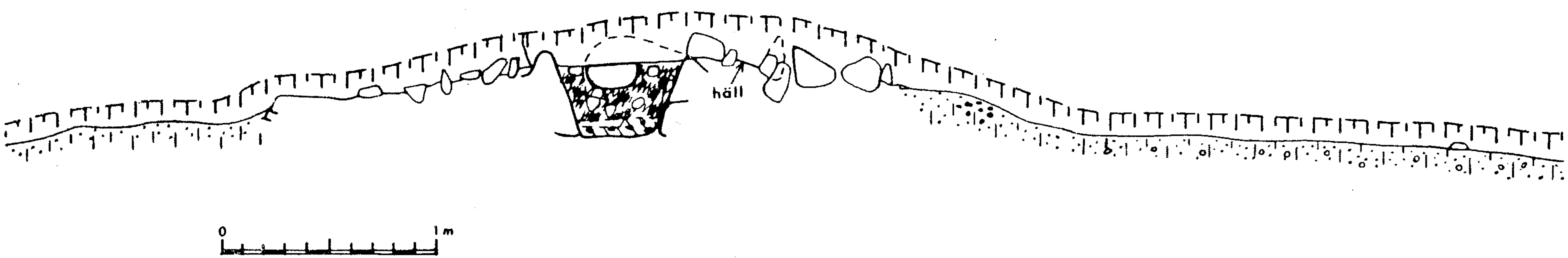


A23 FINERY

FIG 12

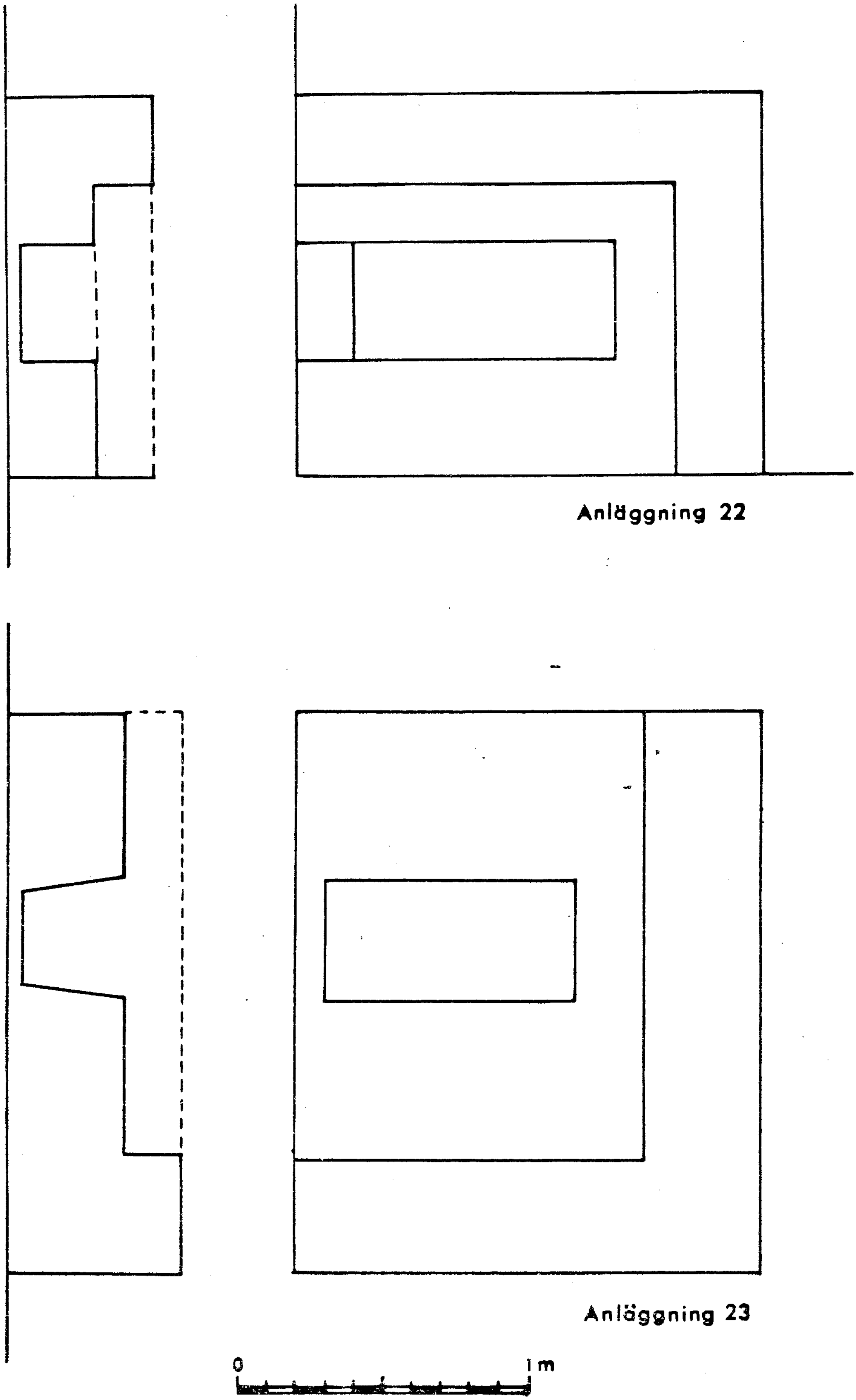


Profil N-S



Profil Ö-V

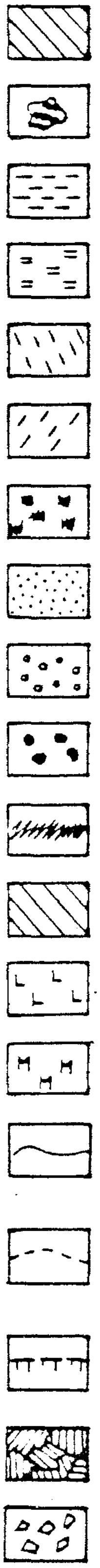
A23 FINERY
FIG 13



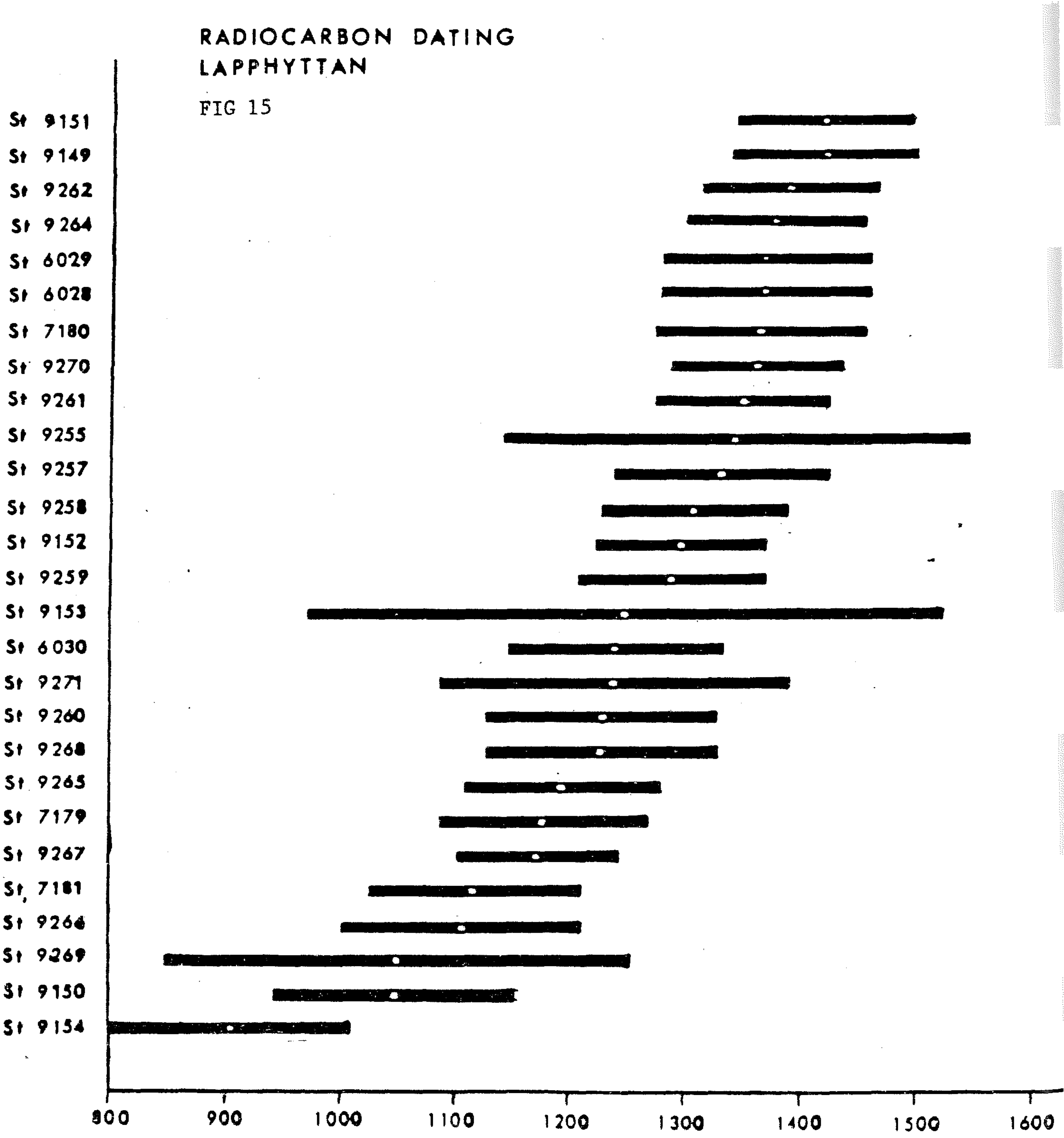
A 22, A 23 FINERIES RECONSTRUCTIONS

FIG 14

LEGEND



- SLAG
- PIECE OF SLAG
- CLAY
- BURNED CLAY
- SANDY SOIL
- TOP SOIL
- CHARCOAL
- SAND
- GRAVEL
- PIECE OF CHARCOAL
- SOOT
- IN PLAN SLAG
- CLAY IN PLAN
- ORE IN PROFILE
- SOLID LINE SHOWS CLEARLY DEFINED LAYERS
- BROKEN LINE SHOWS DIFFUSE LAYERS, ALSO USED IN SHOWING THE LOWER EXCAVATION LIMIT
- RECONSTRUCTED TURF LAYER
- PRECIPITATIONS IN THE STREAM
- PLAN: ORE


RADIOCARBON DATING
LAPPHYTTAN
FIG 15
St 9151
St 9149
St 9262
St 9264
St 6029
St 6028
St 7180
St 9270
St 9261
St 9255
St 9257
St 9258
St 9152
St 9259
St 9153
St 6030
St 9271
St 9260
St 9268
St 9265
St 7179
St 9267
St 7181
St 9266
St 9269
St 9150
St 9154
800
900
1000
1100
1200
1300
1400
1500
1600

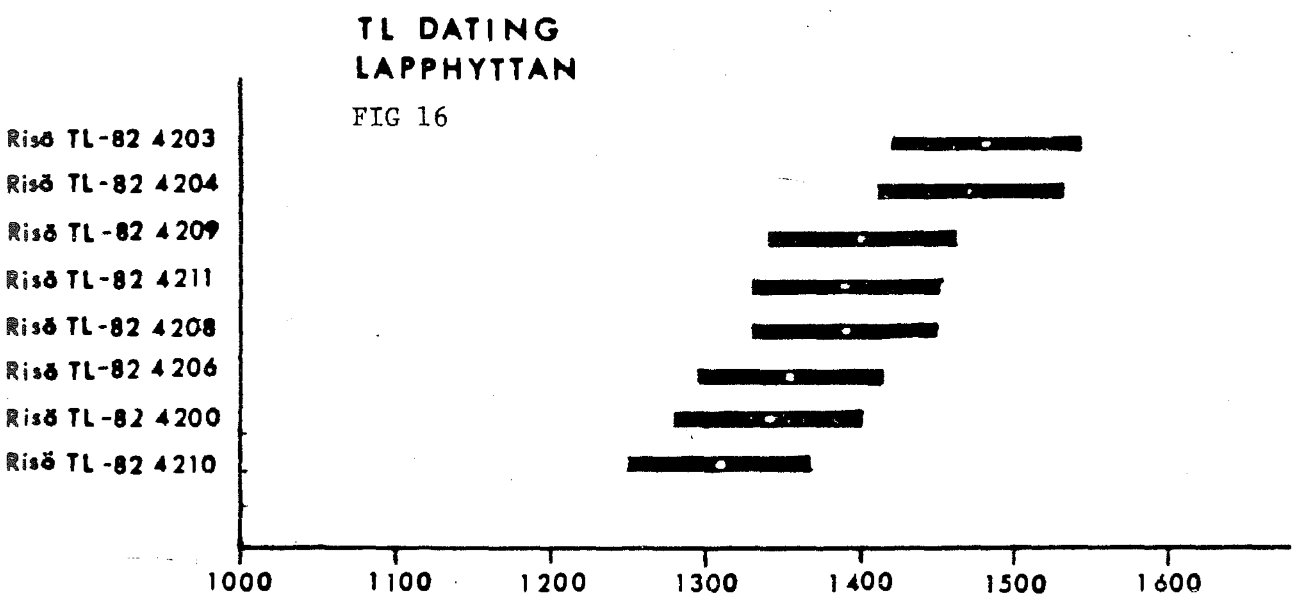
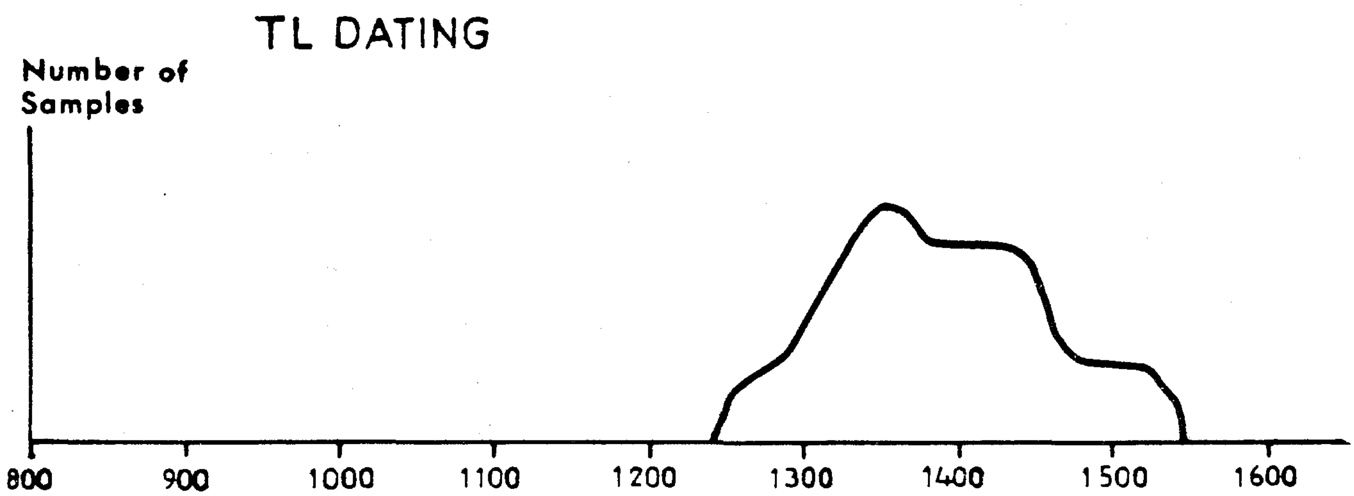
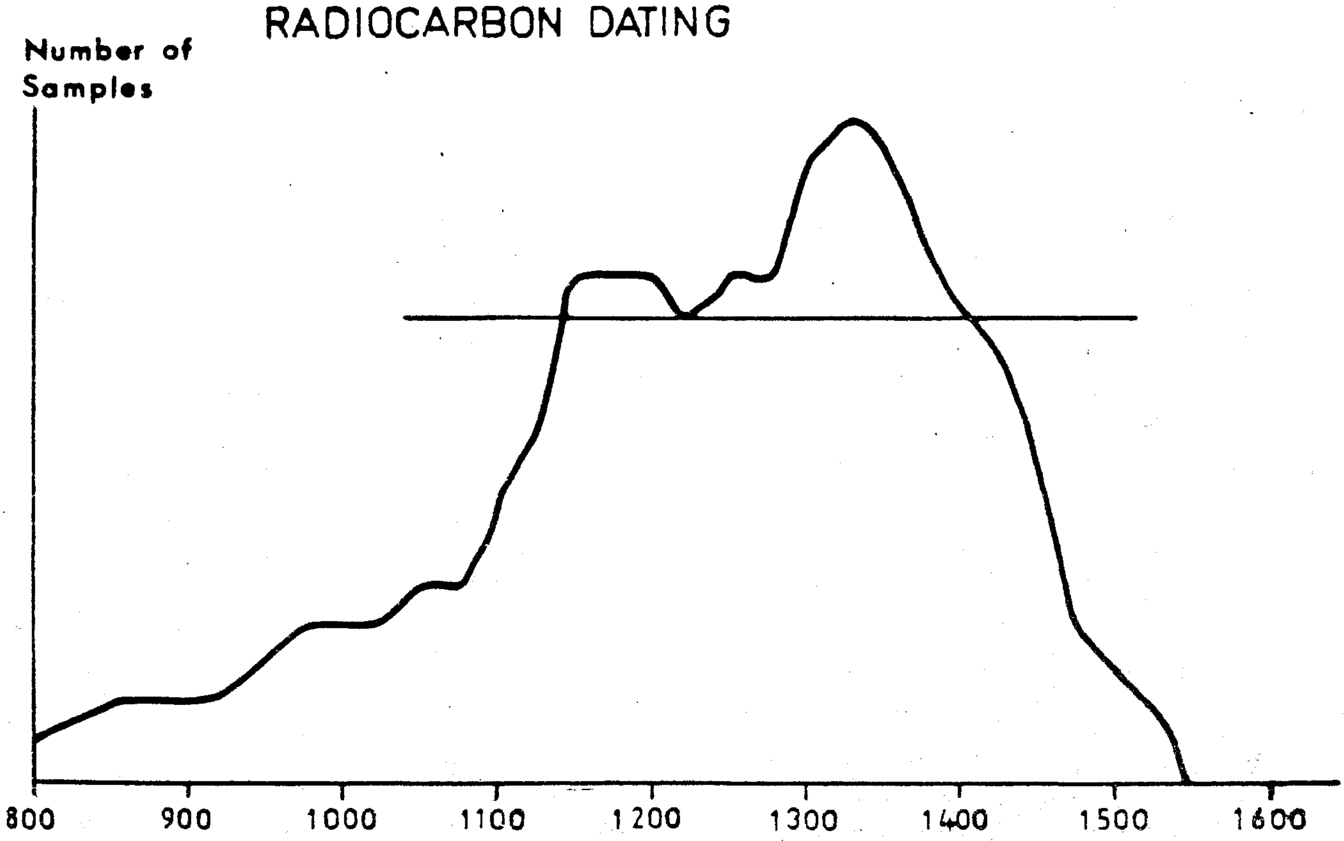

TL DATING
LAPPHYTTAN
Risö TL-82 4203
Risö TL-82 4204
Risö TL-82 4209
Risö TL-82 4211
Risö TL-82 4208
Risö TL-82 4206
Risö TL-82 4200
Risö TL-82 4210
1000
1100
1200
1300
1400
1500
1600

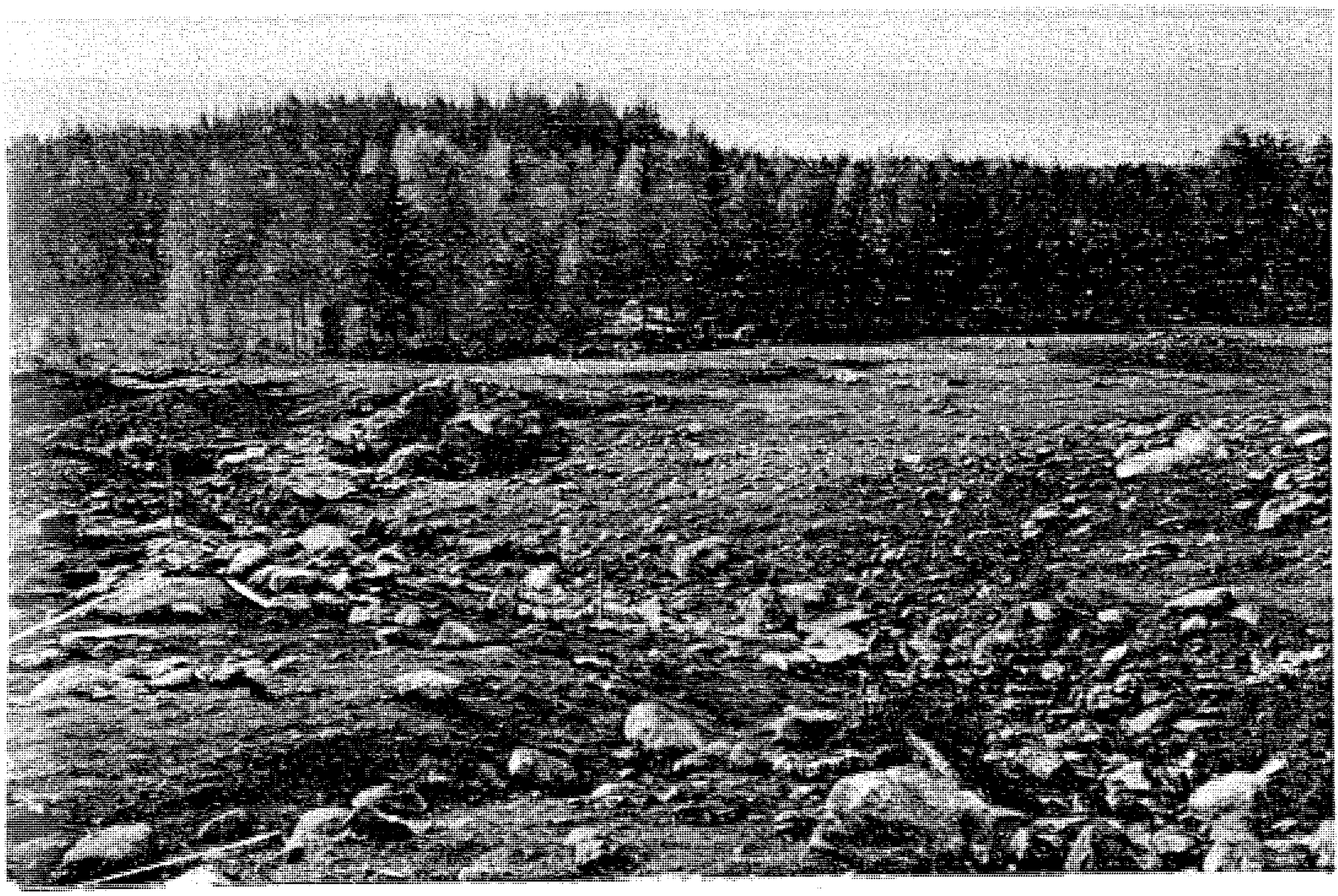
FIG 16





LAPPHYTTAN

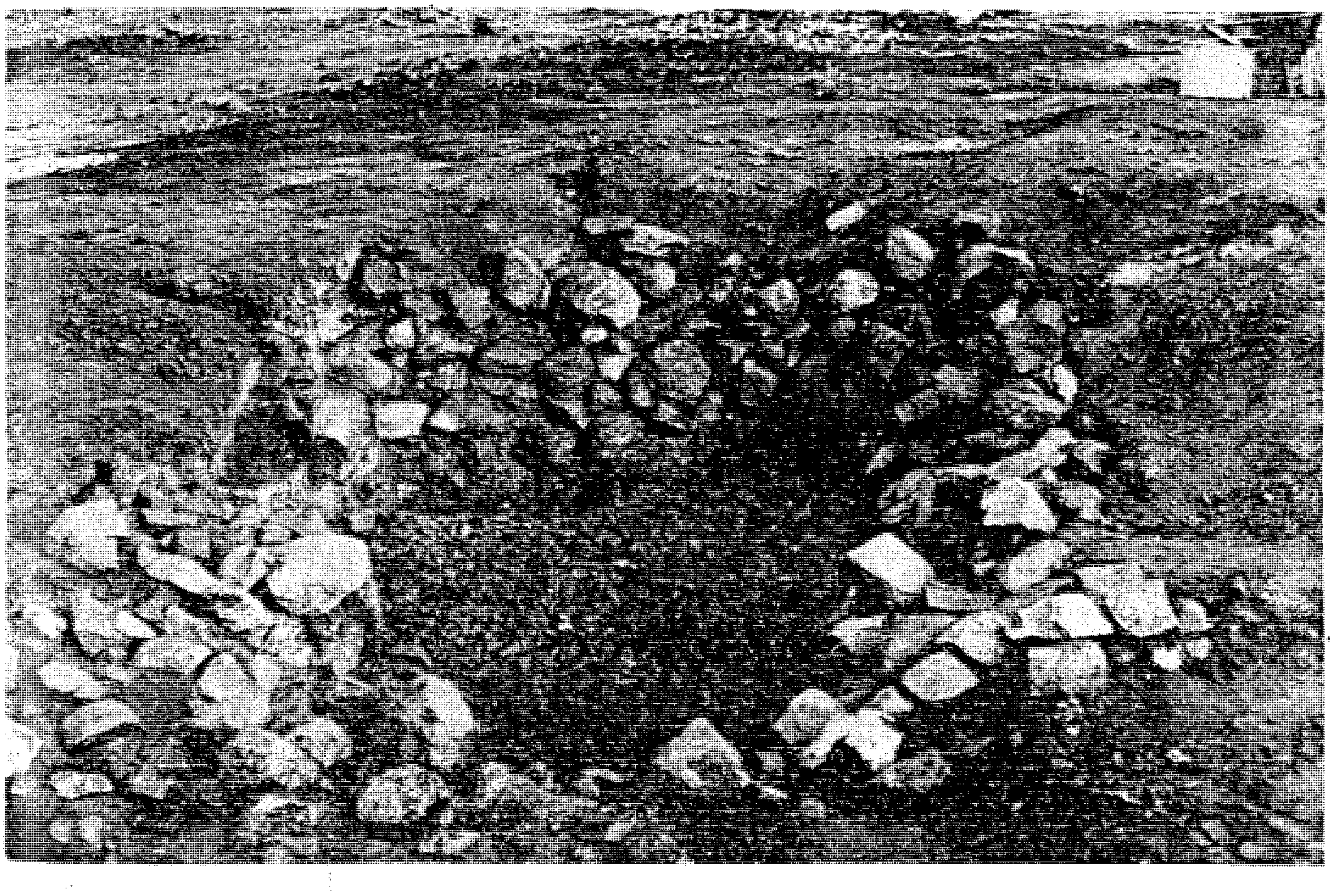
FIG 17



THE SITE

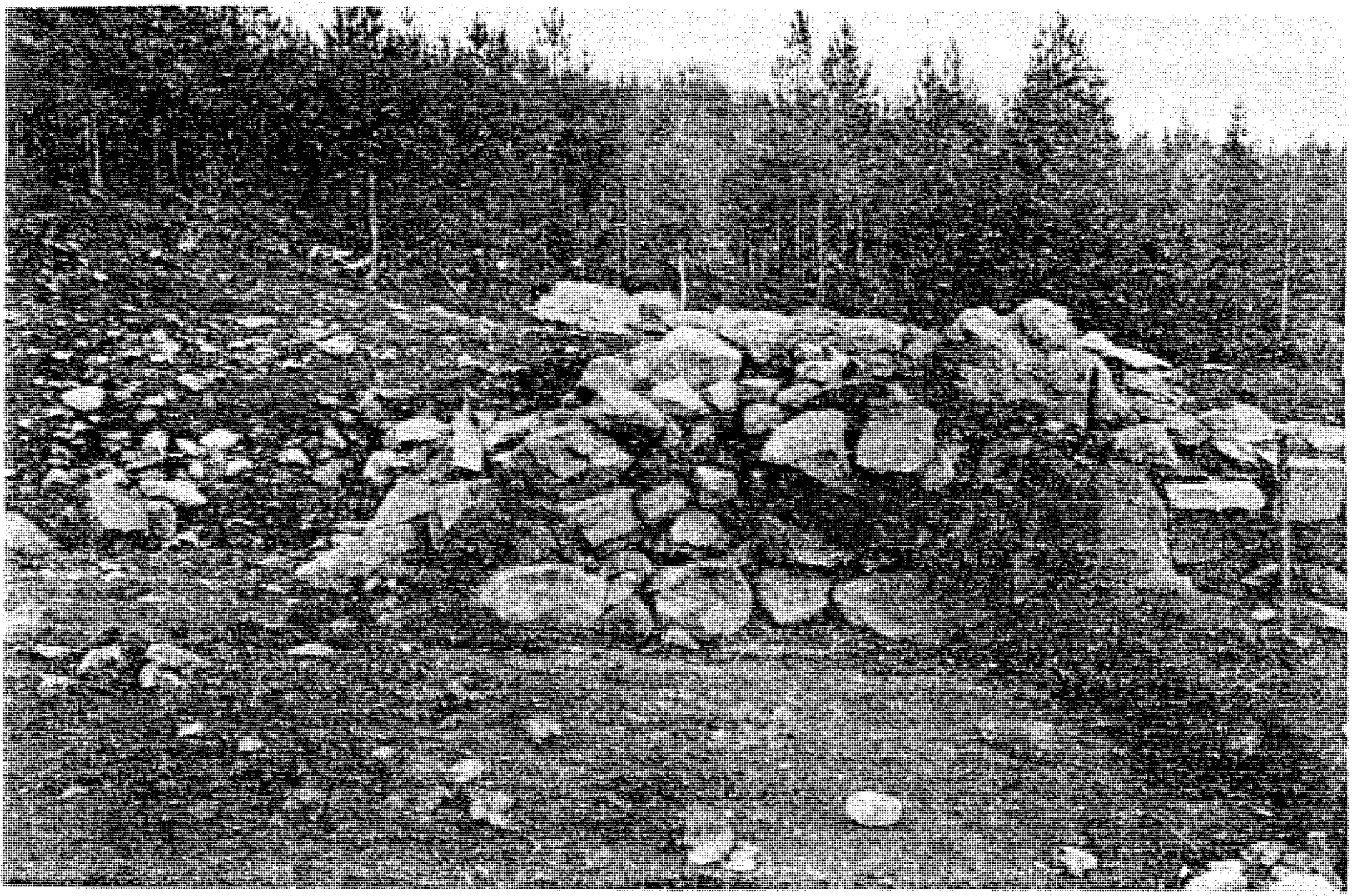
THE SITE

A52 POND AND TIMBERED STONE CAISSON



A6 ROASTING PIT

AI THE BLAST FURNACE RUIN



AI THE BLAST FURNACE, WESTERN WALL

AI BLOWING WALL

AI BLOWING WALL

A22 FINERY

A23 FINERY

AII IRON SHED

SESSION 1

WATER POWER

IRON AND WATER: TECHNOLOGICAL CONTEXT AND THE ORIGINS OF THE WATER-POWERED IRON MILL

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Michigan Technological University
Houghton, Michigan, United States of America

SUMMARY

The application of water power to iron production at the iron mill is generally regarded as one of the key technical innovations of the medieval period. Despite its importance, however, the origins of the iron mill are obscure because the early evidence relating to the application of water power to iron working is ambiguous, often suggesting rather than proving the existence of iron mills. Moreover, the available evidence comes from widely separated areas. Strong cases can be made for at least five regions as the origins of the iron mill--Sweden, England, Catalonia, the Alps, and the regions surrounding Bohemia.

One way of determining, in spite of the confusion of available evidence, which of these regions saw the birth of the iron mill is to look at the iron mill in its technological context. The hydraulic hammers and hydraulic bellows of this mill were just two of a dozen industrial processes which, in the medieval West, required transforming the natural rotary motion of the water wheel into linear motion. Of the remaining ten, surviving evidence indicates that six probably emerged in or near Alpine Europe and two others possibly did. In brief, the technological context of the water-powered iron mill (the use of water power to produce linear motion) suggests the Alps as the iron mill's birthplace.

TEXT

Historians of technology have generally agreed that the application of water power to the iron forge and iron furnace was one of the major metallurgical innovations of medieval Europe. [1] The earliest extant illustrations of the hydraulic iron hammer and the hydraulic bellows date from the mid-fifteenth century and show clearly how water power was adapted to these devices. At the water-powered forge a small projection, or cam, mounted on the axle of a water wheel, was rotated against a similar projection (tappet) mounted on either a vertically-situated hammer or a pivoted recumbent hammer. The rotation of the cam lifted the hammer and then dropped it as the cam passed out of contact. The hydraulic bellows operated in a similar manner. A cam mounted on a water wheel axle lifted the upper leaf of a bellows, drawing in air. The weight of that leaf, after the cam had rotated out of contact with the leaf, would then close the bellows, pushing out the air. [2]

In the Greco-Roman era such devices had been unknown. The hammers and bellows used in iron production had been invariably powered by muscle. But by the fifteenth century, when the first extant illustrations of iron mills appear, the use of water power was well on its way to becoming standard in European iron districts. In 1492, for instance, all of the smelting works, bloomeries, pig iron works, and steel making forges in the Siegen area of Westphalia used water power. [3] Shortly after, in 1540, the Italian metallurgist Biringuccio maintained that the availability of water power was essential for smelting works of all kinds. [4] Moreover, the seventeenth century accounts of the iron industry of the Swedish traveller Abraham Cronström and the Polish iron master and poet Walenty Roździeński provide additional evidence that European ferrous metallurgy had become heavily dependent on water power by the early modern era. [5]

The application of water power clearly had major repercussions on the iron industry. It tied iron production to streams of water, where it was to remain until freed by the introduction of the steam engine. [6] It increased the capital requirements for entering and remaining in the industry, promoting the growth of larger enterprises and, presumably, a growing division between capital and labor. [7] Water-powered hammers increased production and lowered iron prices by permitting larger blooms to be worked and decreasing labor requirements. [8] Water-powered bellows, likewise, decreased the labor requirements for iron working and, in addition, contributed to the evolution of the blast furnace and the indirect method of producing wrought iron. [9]

EARLY EUROPEAN IRON MILLS

But even though the development of the water-powered iron mill was one of the key innovations in medieval iron production, the region in which the iron mill originated is uncertain. Strong claims could be developed for at least five regions: (1) Sweden, (2) England, (3) Catalonia, (4) the Alps, and (5) Bohemia and adjacent areas (the Oberpfalz, Saxony, Moravia, etc.). Let us briefly review the evidence for early iron mills in each of these areas.

Sweden

The earliest clear and unambiguous evidence of an iron mill comes from Sweden. A document of 1224 lists, among the possessions of the Danish Cistercian monastery of Søro, the village of Toaker (Tvååker) in southern Sweden (Halland), which included a mill to make iron (*de molendino ubi fabricatur ferrum*). [10] Sweden's potential claim to being the home of the iron mill has received recent reinforcement from excavations carried out at Lapphyttan, near Norberg, in central Sweden. These excavations have uncovered an extensive medieval iron works, including a water storage reservoir and remains suggesting the existence of a water wheel in a stream beside the site. The excavators' believe that the use of water-powered bellows for a blast furnace at the location may date back to as early as the mid-twelfth century. [11]

England

The claims of other regions seemingly rest on more tenuous bases. For instance, the foundation for any English claim for the origins of the iron mill must be based on a reference in the Domesday Book of William the Conqueror, dating from 1086, nearly a century and a half before the iron mill at Toaker in southern Sweden. The Domesday Book includes four watermills at three places around Lexworthy in Somersetshire, southwestern England, which paid rents in blooms of iron. [12] None of the other 5624 Domesday mills and no known contemporary continental watermill paid dues in this coin. [13] It is, therefore, quite possible that these four mills were iron mills and not the usual flour mills. [14] Even if these were not, England may well have had an iron mill in Yorkshire in northern England, shortly before the Swedish mill at Toaker. At Kirkstall Abbey, near Leeds, Cistercian monks erected iron works around 1150-1160. Around 1200 they constructed a five-foot (1.5 m) wide canal which led water from a nearby stream past their workshops. [15] Although no document specifically indicates that the water in this canal was used to drive hydraulic hammers or bellows, the possibility that this was the case is increased by archeological excavations in the Bewl Valley in southeastern England which have yielded a wheel race and wheel pits dating from around 1300 at an ironworks site. [16]

Catalonia

Another region which may have pioneered the adoption of water power for working iron was Catalonia, in northeastern Spain. In their history of Catalonian iron, Antoni Gallardo i Garriga and Santiago Rubio i Tuduri cite several large forges along Catalonian streams in documents dating from 1104, 1138, and 1155. The coexistence of streams and forges here may, as at Kirkstall forge in England, suggest the possible application of water power, but it does not make it certain. However, Garriga and Tuduri also refer to an act of 1190, from the regin of Alfonso II of Aragon, which associates forges with mills on the Llobregat River near Barcelona, providing us with a much more certain indication of water-powered iron processing. [17] Unfortunately, the authors provide no manuscript references for their citations, leaving the validity of the documents they cite in some doubt. [18] Another document from northern Spain, dating from 1073, and cited by Rolf Sprandel, refers to a molinum fornacinum, which could be interpreted to mean a furnace mill, implying the use of water-powered bellows. [19] If these documents are confirmed, water-powered iron mills were in operation in Catalonia shortly before 1200, more than a quarter century before the mill in southern Sweden.

The Catalonian hypothesis for the origin of the iron mill gains further plausibility from the fact that the eastern

Pyrenees had been a major iron producing center since Roman times. It is, therefore, not surprising that the Catalan claim has been occasionally accepted by historians. [20]

The Alps

The case for the Alpine region of Europe as the birthplace of the European iron mill rests on a significant number of documents which suggest, but do not prove, the use of water power for forges or bellows in the twelfth and early thirteenth centuries. For example, Hubert and Georges Bourgin's history of the French iron industry before the French Revolution cites documents which indicate that an iron works in Franche-Comté might have dated back to 1119. The works were called Moulin-Martin, which certainly implies a water-powered hammer. They were owned by the monastery of Bellevaux, founded in 1119. [21] On the opposite side of the Alps, a document of 1135 refers to a watermill and a stamp (molendinum unum et stanf unum) owned by a monastery at Admont, in the iron producing region of Styria. [22] A similar document from the same place, dating from 1175, also mentions a mill and a stamp. [23] These documents have usually been interpreted to be the earliest extant references to water-powered ore stamping mills, [24] but they could also be interpreted to mean hydraulic forges.

Other documents from the Alpine region from the late twelfth and early thirteenth centuries may also refer to iron mills. In the western Alps, the monastery of Chartreuse de Saint-Hugon, long known for its iron works, had forges in operation on the banks of the River Bens in 1170, [25] and other iron works are reported along streams near Allmond in Dauphiné in 1226 [26]. But these documents do not indicate the use of water power for certain; forges sometimes located along streams for other reasons than power.

In the eastern Alps, G. Heckenast, in an article unfortunately devoid of documentation, asserts that water-powered hammers and bellows were known in Styria between 1227 and 1262 and that the use of water-powered iron works had passed into western Hungary from Styria around 1260. He also asserts that water power was used in iron production in Carinthia a little before 1266. [27]

In the Alps just to the north of the Italian peninsula there is further evidence of early iron mills. An 1179 document from the Bishop of Bergamo mentions the right to make use of a river in conjunction with an iron furnace, suggesting the application of water power to bellows. [28] In 1214 a document refers to a monastery near Trent, where wheels (rotae), presumably water powered, were used in conjunction with silver-smelting furnaces. [29] Although these wheels were not positively water powered, they probably were, and no modification of apparatus would have been necessary to apply the bellows to iron furnaces. Moreover, other documents from northern Italy only a few years later certainly refer to water-powered iron mills. For example, a 1226 document from Bormio lists, in conjunction with an iron furnace, a water wheel and a canal.[30] Another document from the same area and dating from 1251 mentions iron production in conjunction with an aqueduct [31].

The Bohemian Region

A fifth area in which the iron mill could have originated is the mountainous zone surrounding Bohemia and Moravia, including Saxony, the Oberpfalz, Silesia, and western Slovakia. On that region's eastern edge, in the German Oberpfalz, a monastic document dating from the period 1006 to 1028 refers to a village on the River Vils named "Smidimulni."[32] This, of course, suggests the existence of water-driven hammers at the site, but it could conceivably have been named for a smith who also leased or owned a flour mill or for an assortment of other non-iron related reasons.

Other, but much later, documents indicate the coexistence of iron works and streams near or in the region, without referring specifically to iron mills. Examples come from the Harz near Goslar (1174-1195) and from near Freiberg (1278). [33] The earliest certain reference to an iron mill in the area comes from southern Poland in 1261, when the Duke of Cracow ceded to the Polish monastery at Jedrzejow a mill at Rudnyki which worked iron (molendino, quod ibiden materiam ferri massam in quam sive metallum molit). [34] Shortly after water-powered bellows are mentioned in a 1269 document from the monastery of Hradish in Moravia. [35]

Figure 1 summarizes the data outlined in the preceding paragraphs. Clearly, the resulting picture is confusing to anyone attempting to pinpoint the region where water power was first applied to iron production. Because of the geographical diversity and ambiguity of many of the early documents, which region one inclines toward is likely to depend, if not on national origin, on how strictly or how loosely one is willing to interpret the documents. It is even possible to argue for multiple origins.

TECHNOLOGICAL CONTEXT

I believe, however, that a close look at the technological context of the iron mill can provide us with a means of identifying the region in which water power was first applied to the iron industry. Let me explain the approach I propose to take by analogy. Suppose one were presented with a typewriter dating from between 1850 and 1900 which had at least some interchangeable or nearly interchangeable parts. If one had to identify the region where such a typewriter first emerged, a logical choice would be the United States, since that country pioneered in the introduction of elements of interchangeability to a whole host of devices in the 1840 to 1940 period, including firearms, bicycles, agricultural machinery, watches, clocks, sewing machines, and automobiles. In other words, the technological context (machines with interchangeable parts) would suggest the United States as the region in which a typewriter with

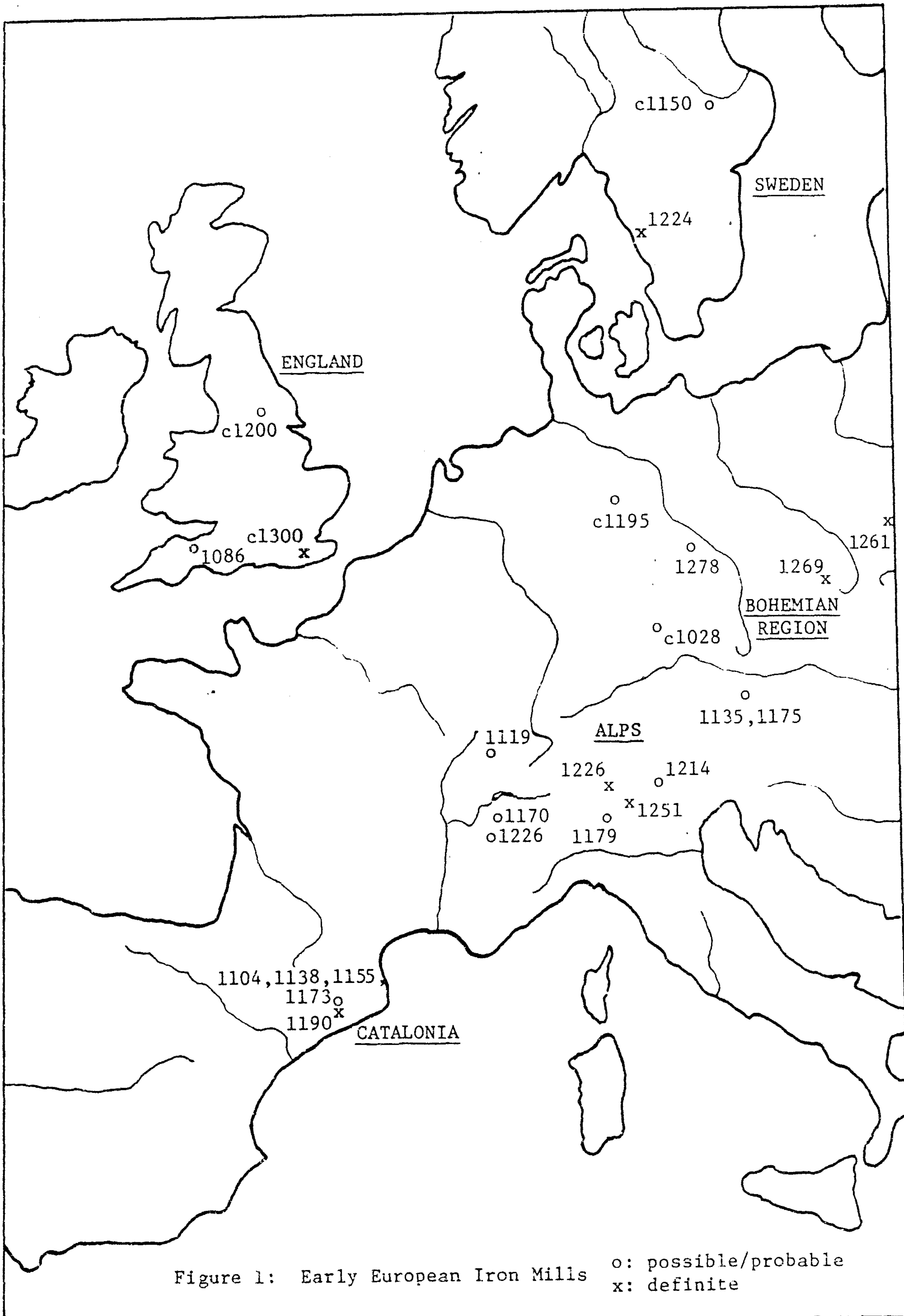

Figure 1: Early European Iron Mills

interchangeable parts first emerged, even if we did not know that this was, in fact, the case. [36]

What would be an analogous technological context for the iron mill? The use of water to lift hammers or pump bellows was certainly the element which separated the iron mill from older iron works. By 1500 medieval European craftsmen, in fact, had adapted the water wheel to nearly fifty tasks, most, however, involving rotary motion, like turning millstones, not the linear motion required for moving bellows and hammers. [37] Nonetheless, a dozen of the processes adapted to water power did involve the transformation of the natural rotary motion of the water wheel into linear motion.

Of these dozen, lifting hammers and pumping bellows in iron mills were but two. The other ten included preparing beer mash for brewing, separating hemp fibers from their plants, fulling, making paper, preparing tanning bark, preparing the ingredients of mortar, crushing oil-producing seeds, crushing ore, sawing wood, and drawing wire. These linear-motion activities to which water power was applied in medieval Europe provide a technological context for the emergence of the iron mill analogous to that provided by interchangeable parts for the manufacture of typewriters in the late nineteenth century. If, therefore, it can be demonstrated that the bulk of the water-powered industries which modified the watermill to produce linear motion emerged in one of the regions outlined above, I believe it reasonable to assert that this region was also the birthplace of the water-powered iron mill.

Beer Mills

The earliest process which used the water wheel and cam to produce linear motion was apparently the preparation of mash for brewing. An idealized plan for the monastery of St. Gall, prepared around 820, and apparently drawn to scale, contains a room on the outer edge of the monastic premises which has within it sketches of hammer-like objects labelled *pilae* (). [38] Several factors suggest that these *pilae*, or hammers, were water powered. First, their room is adjacent to another room which contains two round objects labelled *molae*, presumably millstones, and considerable evidence indicates that water power was commonly used in monasteries by the ninth century for grinding grain. Second, Walter Horn and Ernest Born have convincingly argued that the plan of St. Gall is drawn to scale. [39] If this is so, than the *pilae* are too large to have been moved by hand. Thus, in view of the heavy monastic use of water power in the period, the location of the hammers, and their size, water-powered hammers are the most likely explanation. Finally, medieval artistic conventions generally called for depicting objects in the plane that best revealed their action, even if it meant mixing planes in the same drawing. A pivoted trip hammer would be best shown in side view, and the sketches on the plan look very much like a crude side view of a water wheel axle and pivoted trip hammer. Walter Horn, who has studied the plan most closely, has concluded that there is "no doubt" in his mind that the *pilae* of the plan of St. Gall are water-powered, cam-activated, recumbent trip hammers, probably, in view of the location of the pilae room across the hall from the brew room, used to produce beer mash. [40] Further support for this conjecture comes from a document dating from around 900 and associated with St. Gall which refers to mills with hammers (molinis vel pilis). [41]

Hemp and Fulling Mills

Around A.D. 1000 technicians working with two other industrial processes--hemp production and fulling--applied the combination of water wheel, cam, and trip hammer in similar fashion to secure needed linear action. In the hemp industry stamps were used to beat hemp stalks. This freed the fibers in the stems for use in making rope and cord. In the fulling process, hammers or stamps were used to agitate wool cloth in a cleansing solution. The pounding action, carried out manually in antiquity, served three functions. It cleansed the cloth, shrunk it in preparation for sewing, and felted the wool fibers to strengthen the weave.

There is considerable confusion in the terms early used to refer to hemp and fulling mills, with different regions, especially in France, using different terms, and not all such terms clearly indicating the use of water power. [42] While this confusion casts a shadow over attempts to identify the earliest use of water power in the hemp and fulling processes, both appear to have begun to use hydraulic energy around 1000 in Alpine France or Italy. The earliest identifiable hemp mill was at the monastery of Saint-Bernard de Romans in Dauphiné, for this monastery had a mill with a pounder, or beater (molenario et batedorios), around 990 and was in a hemp growing region. [43] Additional documents which refer to mills with pounders in the hemp growing regions of Dauphiné come shortly after this, in the early eleventh century. [44]

Documents referring to fulling mills date from a few years later. A monastic document from Lodi, in northern Italy, from around 1040, mentions a watermill and fulling in a context indicating a connection between the two. [45] A few years after, documents refer to fulling mills in other locations in northern Italy and in eastern and central France, as well as in northern France. [46]

Paper Mills

Another important medieval industry to use water-activated trip hammers was the paper industry. In the paper mill batteries of hydraulic hammers, activated by cams, were used to beat rags into a pulp. The pulp was then drawn off in a frame with wire mesh. After the water had drained off, the remaining pulp fibers would form a sheet of paper.

Although it is conceivable that some of the Arab papermaking installations in north Africa or Spain were water powered, there is no indication that they were. Documents which definitely refer to water-powered paper mills appear first, almost simultaneously, in northern Italy and Spain. A 1276 deed from Montefano, near Fabriano, in central Italy refers to a fulling and paper mill (molino cum gualchis et cartere) [47]. Only slightly later, in 1280, a Spanish document uses one of the standard terms for watermill (molendino) in conjunction with paper making activities at Xativa, near Valencia, long a center of paper making activity in Spain. [48]

Tanning Mills

In some manufacturing processes surviving documents indicate that both rotary millstones and mechanical hammers were used. The tanning mill, which ground or pounded the bark from certain trees, usually oak, into a powder, from which the tanning agent, tannin, was extracted for processing leather, is an example. According to Bautier's study of French documents dealing with the tanning mill, both grindstones and pounders were used, and which an individual mill used is often impossible to determine. She found the earliest extant document relating to a tanning mill to be one referring to such a mill at Charment, not far from Paris, in 1138. Most of the other early documents citing tanning mills came either from that region or from further west, around Normandy. [49]

Mortar Mills

The mortar mill, used to grind limestone to prepare mortar, like the tanning mill, could have used either some type of rotary millstone or hammers. Few extant documents mention mortar mills, but the earliest refers to a "Maurmühle" in the south German city of Augsburg in 1321. [50]

Oil Mills

The oil mill, a mill used to press oils from the seeds of oleaginous plants, like the tanning and mortar mill, could use either rotary or linear processes. The oil presses of the Romans, for example, used edge roller stones. And when illustrations of watermills become common in the sixteenth century this process had clearly been adapted to water power. [51] But stamps may also have been used. W. A. McCutcheon, for instance, claims that the oil mills used in northwestern Europe in the fifteenth and sixteenth centuries to crush olive, flax, rape, groundnut, and soy seed were stamping mills rather than edge-runner mills. Some of these crushed directly by hydraulic hammer and mortar; some crushed indirectly through the intermediary of wedges and blocks--the hammers drove the wedges, which pushed blocks against sacks of seed. [52] It is, therefore, quite possible that the earliest references to oil mills refer to the stamp rather than the edge-roller variety.

The earliest reports of oil mills come from southeastern France around 1100. Thérèse Sclafert says they were in operation in Dauphiné in the eleventh century; R. J. Forbes reports one on the Vaucluse Canal in nearby Provence in 1101. [53] Neither, however, provides documentation for his claim. Archeological evidence indicates oil milling at the monastery of Poblet in Catalonia before 1300, and Sclafert does cite a document from 1316 which mentions an oil mill at La Paute in Dauphiné. [54]

Ore Stamps

Hydraulic hammers were sometimes used for metallurgical purposes other than pounding iron or moving bellows. Bradford Blaine and several other authorities have accepted the water-mill and stamp (molendinum unum et stanf unum) at the Styrian monastery of Admont in the eastern Alps as providing the "earliest known example of a stamping-mill" for crushing ore. [55] John Nef, moreover, claims that water power was used to crush and break ore in the southern Tyrol, near Trent, around 1310, but does not document the claim. [56] The first document clearly indicating ore preparation by water power does not appear until 1317, when an ore mill (erzmulen) is mentioned in conjunction with iron mines around Plauen in Saxony. [57]

Sawmills

Two medieval manufacturing processes--sawing and wire drawing--used water power to produce linear motion, but did not use hydraulic stamps. The more important of the two was sawing.

Early illustrations of European sawmills indicate that the prevailing type of saw was an up-and-down saw, where cams attached to the axle of a water wheel were used to depress the saw, with some type of counterweight or counterforce (such as a spring pole) in use to raise the saw for the next stroke. It is possible that the hydraulic saw appeared in Roman Europe, for the Roman poet Ausonius in the fourth century mentioned a water-powered marble saw on a small tributary of the Moselle, the Ruwar. [58] The authenticity of this poem is still under debate. [59] But even if the poem is authentic, it seems certain that the technique used on the Ruwar, whether rotary or linear sawing by water power, was lost for some centuries after the collapse of Roman power. The first medieval document citing a sawmill dates only from 1204 and refers to a plank mill (molendina de planchia) at Évreux in Normandy. [60] Shortly after, around 1235, the architect Villard de Honnecourt, who came from the same region, sketched a water-powered sawmill in his notebooks. [61]

Wire Mills

A second medieval manufacturing process which used the water wheel to produce linear motion for something other than hammers was wire drawing. Wire mills, moreover, appear to have used the crankshaft, rather than the more usual camshaft, as the implement to convert rotary to linear motion. The earliest clear illustration of the operation of a wire mill comes from Biringuccio's Pirotechnia of 1540, which shows how the combination of water wheel, crankshaft, attached gripper, and draw plate was used to form wire at the desired size. [62]

Bradford Blaine, in his comprehensive review of the use of water power in medieval Europe, thinks that there is a "strong indication" that water power was used in manufacturing wire at Augsburg as early as 1351, when city records contain an entry referring to a "Tratmul" or "Draht Mühle," especially since wire and nail production were common in that city by 1400.

The earliest definite evidence of a water-powered wire mill, however, is a drawing by Albrecht Dürer from around 1490, showing the exterior of a wire mill (Trotszich Müll) near Nuremberg. [63]

CONCLUSION

If one plots the locations of the earliest references to the application of water power to the ten processes we have just reviewed (see Figure 2), the Alpine region stands out as the likely center for the emergence of innovations involving water power combined with linear motion. Four of the ten processes--production of beer mash, production of hemp fibers, fulling, and preparation of mortar--seem definitely to have emerged in or very near the Alps. In addition, it is highly probable that at least two additional processes--water-powered ore crushing and wire drawing--had Alpine origins. While the earliest indisputable references to these two activities appear somewhat outside the Alpine region, documents exist which very strongly suggest the earlier application of water power to these processes in or near the Alps.

What, then, of the other four activities--the use of water power to crush seeds to produce oil, to beat pulp for paper, to saw wood, and to prepare tanning substances? In two of these cases, there is sufficient evidence to suggest the possibility of an Alpine origin. For example, if Sclafert's undocumented claim of oil mills in eleventh-century Dauphiné is true, oil milling in Alpine France antedates the emergence of oil mills in Catalonia. And, in any case, documented cases of oil mills in or near the French Alps date from only a short time after the reported Catalonian oil mill.

A strong case can also be made for the possible Alpine origins of the sawmill. As noted earlier, the earliest known documents referring to sawmills come from Normandy early in the thirteenth century. But sawmills appear at several points on the western fringes of the Alps before the end of that century. For instance, a contract from 1268 indicates sawmills near Basel. Moreover, Thérèse Sclafert cites documents indicating that sawmills on streams around Vizille in Dauphiné were so numerous at the end of the century that they had caused serious deforestation, resulting in a prohibition against the use of hydraulic saws. This, at the least, suggests the possibility that sawmills had had, by this date, a very long history in Dauphiné, a history perhaps antedating the sawmills in northwestern France. [64]

For tanning mills and paper mills the cases for an Alpine origin are weaker. The earliest medieval document relating to a tanning mill, as noted, comes from the Paris region in 1138. And most known medieval documents citing tanning mills come from northwestern France. The Italian historian Umberto Forti, however, claims that the tanning mill was known in Italy as early as 1154. [65] Unfortunately, Forti provides no documentary reference to support his claim. If it is valid, the

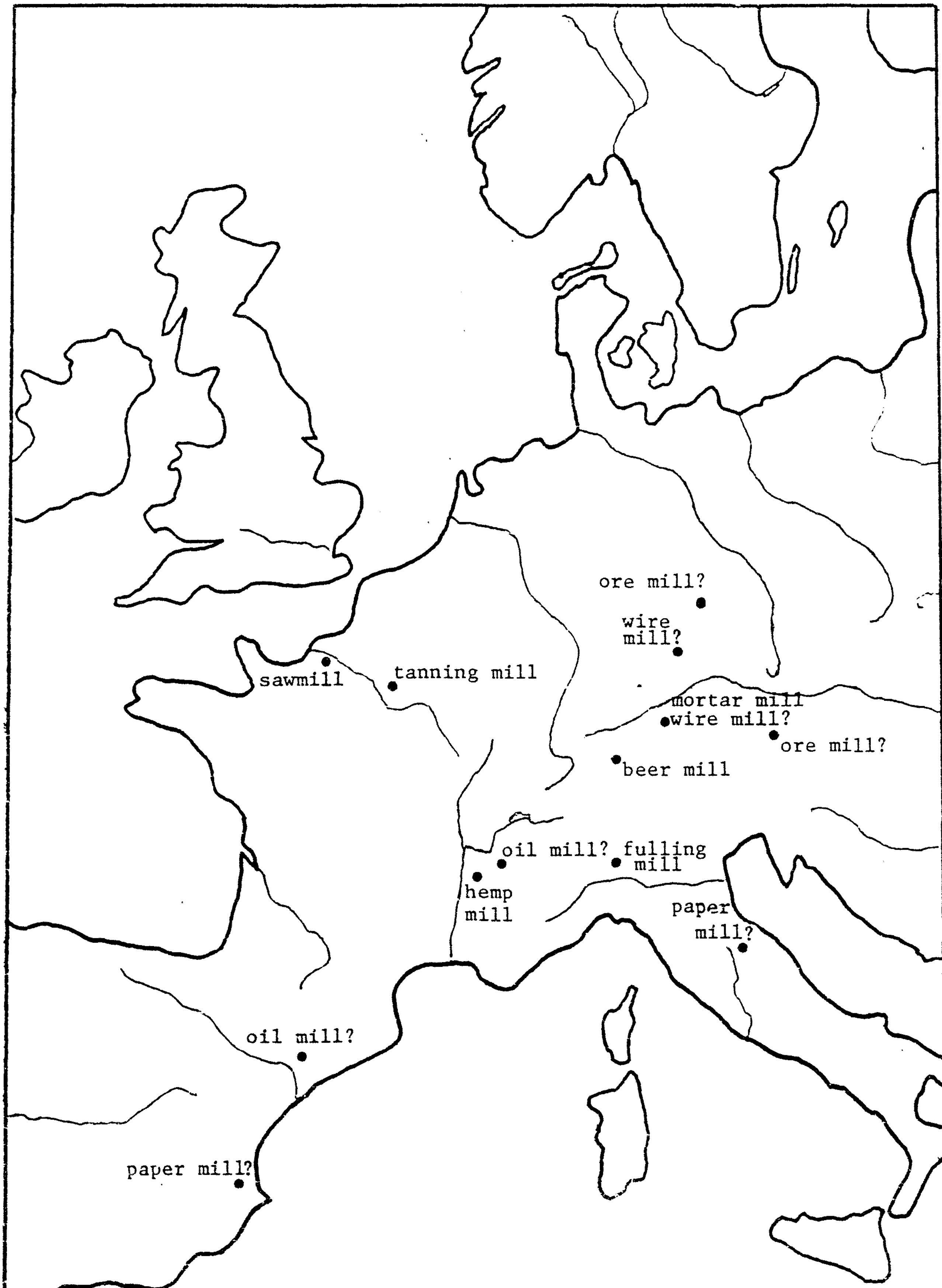

Figure 2: Earliest Evidence of the Application of Water Power to Industrial Processes Requiring Linear Motion

strength of an argument for the Alpine origin of the tanning mill would increase significantly.

There is no evidence that the water-powered paper mill originated in the Alps, but one of the two possible origins--Fabriano in central Italy--is close enough to the Alps to permit one to argue that the process could have been influenced by Alpine developments.

In brief, six of the ten medieval industrial processes, other than those involved in iron production, which applied water power to produce linear motion probably originated in the Alps. Of the remaining four, good cases for the possibility of an Alpine origin can be made for two, and of an Alpine influence for one (paper). Thus the technological context of the iron mill leads me to conclude that it first emerged in the Alpine region of Europe.

While I regard the argument from technological context to be the critical one for determining the origins of the iron mill, some additional evidence from the diffusion of the iron mill seems to support this conjecture. Of all countries, we have perhaps the most complete and detailed record of early iron mills for France. In Figure 3, I have plotted the approximate locations of early (pre-1350) French iron mills. A pattern of steadily later dates moving from the south towards the north would have suggested a Catalan origin for the iron mill; a pattern of steadily later dates moving from the northwest towards the south or southeast would have suggested an English or, perhaps, Scandinavian origin. However, with the exception of a possible early iron mill in French Hainault and undocumented reports of similar mills around Bayonne, the pattern of diffusion seems to be from the French Alps and associated ranges towards the southwest and northwest. Thus, diffusion data, too, seem to indicate an Alpine origin for the medieval European iron mill.

Dating the origins of the iron mill is plagued with much the same problems and uncertainties as locating its origins. The technological context--the use of water power to produce linear motion--suggests that water-powered forges could have emerged in or near the Alps by the late tenth or early eleventh century. This early origin would account for the ambiguous references to possible iron mills in the eleventh century, for example, the possible Domesday iron mills in England, Smidimulni in the Oberpfalz, and Moulin-Martin in eastern France. But the widespread use and diffusion of water power in iron production seems to have occurred only during the thirteenth century, when documents which may or do refer to iron mills suddenly become numerous.

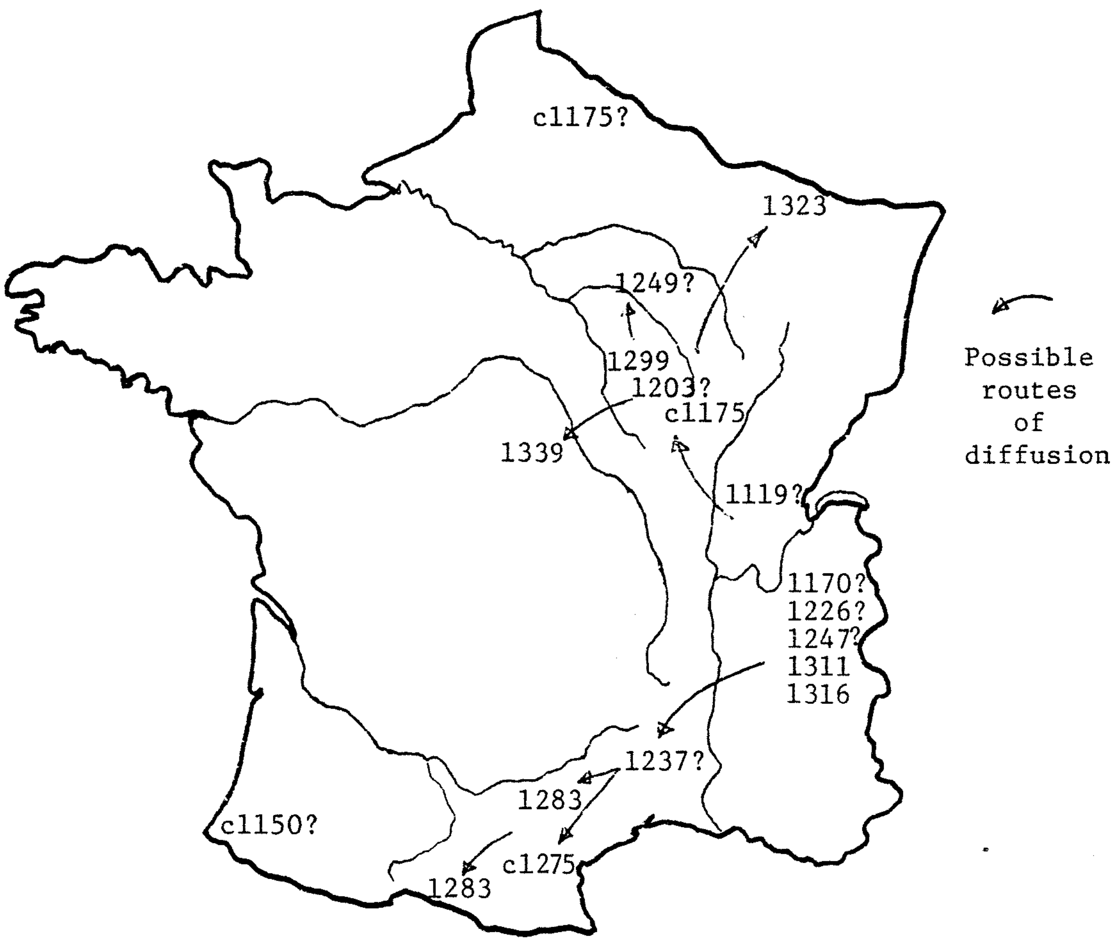

Figure 3: Iron Mills in France before 1350

Based on pre-1350 iron mills noted by:

Anne-Marie Bautier, "Les plus anciennes mentions de moulins hydrauliques industriels et de moulins à vent," Bulletin philologique et historique, 2 (1960) 603-606. Bautier warns of possible confusion between mills used to power bellows or work hammers at iron works and mills used to sharpen or polish iron. I have attempted to exclude the mills in the latter categories where possible since they utilized rotary motion, not linear motion.

Bradford Blaine, "The Application of Water-Power to Industry during the Middle Ages," Ph.D. dissertation, University of California, Los Angeles, 1966, 123-124, 126-128.

Bertrand Gille, "Les Origines de moulin à fer," Revue d'histoire de la sidérurgie, 1 (1960-63) 23-26.

Bertrand Gille, "Les Origines de la grande industrie métallurgique en France (Paris, 1947) 13-15.

Bertrand Gille, "Cartulaire de la sidérurgie française," Revue d'histoire de la sidérurgie, 3 (1962) 241-252; 4 (1963) 27-34, 119-125, 179-182.

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2. The earliest extant illustration of a water-powered iron hammer is in Hugo Spechtshart, Flores musicae (Strasbourg, 1488), reproduced in Friedrich Klemm, A History of Western Technology (Cambridge, Mass., 1964) 104; the earliest extant illustration of a water-powered bellows is in Mariano Taccola, Liber Tertius de Ingeneis [c1430], ed. by J.H. Beck (Milan, 1969) f 30v. In dealing with the iron mill I will ignore the question of whether references to early iron mills imply water-powered hammers, water-powered bellows, or both.
3. R.J. Forbes, "Metallurgy," in Charles Singer, et al., eds., A History of Technology, 2 (Oxford, 1956) 74.
4. Vannoccio Biringuccio, Pirotechnia [1540], transl. C.S. Smith and M. T. Gnudi (Cambridge, Mass., and London, 1966) 22, 145, 147.
5. [Abraham Cronström], Iron and Steel in the European Market in the 17th Century: A Contemporary Swedish Account of Production Forms and Marketing (Stockholm, 1982) 156, 158, 161, 166, 205, 224, 225; Walenty Roździeński, Officina Ferraria: A Polish Poem of 1612 describing the Noble Craft of Ironwork, transl. S. Płuszczewski; ed. Wacław Różański and C.S. Smith (Cambridge, Mass., and London, 1976) 64, 83-85.
6. R.F. Tylecote, J.N. Austin, A.E. Wraith, "The Mechanism of the Bloomery Process in Shaft Furnaces," Journal of the Iron and Steel Institute, 209 (1971) 343; Leslie Aitchison, History of Metals, 2 (New York, 1960) 343; Wertime, Steel, 59, 61-62.
7. John U. Nef, The Conquest of the Material World (Cleveland and New York, 1967) 45-52, for example.
8. Crossley, "Medieval Iron Smelting," 35, 36; R.F. Tylecote, A History of Metallurgy (London, 1976) 65; Tylecote et al., "Mechanism of Bloomery Process," 343; G. Heckenast, "Le développement de l'entrainement par route hydraulique dans la sidérurgie hongroise," Revue d'histoire de la sidérurgie, 8 (1967) 84; R.A. Mott, "English Bloomeries (1329-1589)," Journal of the Iron and Steel Institute, 198 (1961) 149; Rolf Sprandel, "La production du fer au Moyen Age," Annales. Économies, Sociétés, Civilisations, 24 (1969) 318 and tab. 4; Fontana Economic History of Europe, 2, 209-211.
9. Tylecote, History, 65; Sprandel, "Production du fer," 312-313, 320-321; Tylecote, Metallurgy in Archaeology (London, 1962) 273; M.S. Giuseppi, "Some Fourteenth-

Century Accounts of Ironworks at Tudeley, Kent.," Archaeologia, 64 (1912-13) 154.

10. P.F. Suhna, ed., Scriptores rerum danicarum medii aevi, 4 (Copenhagen, 1776) cxxi, 471. Among those citing this as the first indisputable reference to an iron mill are Bradford Blaine, "The Application of Water-Power to Industry during the Middle Ages," Ph.D. dissertation, University of California, Los Angeles, 1966, 117-118, and "The Enigmatic Water-Mill," in Bert S. Hall and Delno C. West, eds., On Pre-Modern Technology and Science (Malibu, Calif., 1976) 169; Rolf Sprandel, Das Eisengewebe im Mittelalter (Stuttgart, 1968) 361, 372; Anne-Marie Bautier, "Les plus anciennes mentions de moulins hydrauliques industriels et de moulins à vent," Bulletin philologique et historique, 2 (1960) 606 n. 1; and Gille, "L'Évolution," 150. A document referring to an iron mill in Berry and dating from 1116, sometimes cited as the earliest extant reference to an iron mill, is of suspicious authenticity. See Bautier, "Anciennes mentions," 596 n. 6.
11. Marie Nisser, "Industrial archaeology in the Nordic Countries, viewed from Sweden," World Archaeology, 15 (1983) 140.
12. H.C. Darby and R. Welldon Finn, eds., The Domesday Geography of South-West England (Cambridge, 1967) 190, 211.
13. Schubert, British Iron Industry, 89.
14. Among those assuming the Domesday mills to be iron mills are Wertime, Steel, 63; Tylecote, History, 64; Lynn White, Medieval Technology and Social Change (Oxford, 1962) 84; and Otto Johannsen, Geschichte des Eisens (Dusseldorf, 1953) 93.
15. Rodney F. Butler, The History of Kirkstall Forge, 2nd ed. (York, 1954) 1.
16. David Crosseley, The Bewl Valley Ironworks, Kent, c1300-1730 (Leeds, 1975) 2, 7.
17. Antoni Gallardo i Garriga and Santiago Rubio i Tuduri, La farga catalana [Barcelona, 1930] 42-44, 59.
18. For example, Blaine, "Applications," 122-123; Gille, "L'Évolution," 150; and Gille, "Les origines du moulin à fer," Revue d'histoire de la sidérurgie, 1, no. 3 (1960) 24, note the need for more work to establish the validity of the Catalan documents.
19. Sprandel, Eisengewerbe, 223 n. 12.
20. Bertrand Gille, "The Medieval Age of the West," in Maurice Daumas, ed., A History of Technology & Invention (New York, 1969) 456, and "Le moulin à eau: Une révolution technique médiévale," Techniques et civilisations, 3 (1954) 11; and Alphonse Gillard, L'Industrie du fer dans les localités du Comté de Namur et de l'Entre-Sambre-et-Meuse de 1345 à 1600 (Brussels, 1971) 40. Gille was more cautious in other works.
21. Hubert Bourgin and Georges Bourgin, L'Industrie sidérurgique en France au début de la Révolution (Paris, 1920) 131, citing Archives nationales, F12 680 (Franche-Comté).
22. Josef von Zahn, ed., Urkundenbuch des Herzogthums Steiermark, 1 (Graz, 1875) 170, no. 171.

23. Ibid., 544, no. 575.
24. Blaine, "Applications," 140-141; Johannsen, Geschichte des Eisens, p. 93; Mott, "English Bloomeries," 149, and Ludwig Beck, Geschichte des Eisens, 1 (Brunswick, 1891) 956 n. 4.
25. August Bouchayer, Les Chartreux, maitres de forges (Grenoble, 1927) 56-57, citing Archives de Société des Hauts-Fourneaux et Forges d'Allevard, Mémoire des Chartreux contre de Barral.
26. André Allix, L'Oisans au moyen âge: Étude de géographie historique en haute montagne (Paris, 1929) 126, citing Archives départementales de l'Isère, B 3009, f 363.
27. Heckenast, "Développement de l'entrainement," 84-86.
28. Sprandel, Eisengewerbe, 223 n. 12 (potestas utendi fluminibus . . . levandi furnos ferri) In this work and in "Production du fer," 312, Sprandel argues that water power was first applied to the blast furnace in the Alpine valleys of Italy.
29. Rudolf Kink, ed., Urkundenbuch des Hochstiftes Trient (Codex Wangianus) (Vienna, 1852) 453-454, no. 242, cited by Blaine, "Applications," 125, who points out that the taxes charged for these wheels were high enough to suggest that water power rather than tread power was being used.
30. E. Besta, "L'Estrazione e la lavorazione dei metalli nella Valtellina medioevale," Atti e memorie del terzo congresso storico lombardo (1938) 359 , cited by Sprandel, Eisengewerbe, 372.
31. G. Finazzi, "Sulle antiche miniere di Bergamo," Annali universali di statistica 1860, 37, cited by Sprandel, Eisengewerbe, 373.
32. Bernhard Pez, "Codex thaditionum Sanct-Emmerammensium," lvx, col. 114-115, in Thesaurus anecdotorum novissimus, 1, pt. III (Augsburg, 1721), cited by Blaine, "Applications," 120-121. The existence of the place name "Smidimulni" has been accepted as evidence of the early use of the water-powered hammer for iron working by several authorities, including Blaine, "Applications," 120-121, and "Enigmatic Water-Mill," 169; White, Medieval Technology, 83-84; and Gimpel, Medieval Machine, 14.
33. For Goslar see George Bode, ed., Urkundenbuch der stadt Goslar, 1 (Halle, 1893) 322, no. 301. Johannsen, Geschichte des Eisens, 93 and "Die erste Anwendung des Wasserkraft im Hüttenwesen," Stahl und Eisen, 36 (1916) 1226-1227 accepts this as an early iron mill. For Freiberg see Hubert Ermisch, ed., Urkundenbuch der stadt Freiberg in Sachsen, 2 (Leipzig, 1886) 3, no. 868, cited by Johannsen, "Wasserkraft," 1227, and Blaine, "Applications," 129.
34. Sprandel, Eisengewerbe, 362, 373, citing Cod. dipl. Poloniae III, no. 38; Roździeński, Officina Ferraria, 22-23.
35. Antonius Boczek, ed., Codex diplomaticus et epistolaris Moraviae, 4 (Olmütz, 1845) 37, no. 30.
36. For the American tradition of manufacture with interchangeable parts see David A. Hounshell, From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States (Baltimore

and London, 1984) and Donald Hoke, "Ingenious Yankees: The Rise of the American System of Manufactures in the Private Sector," Ph.D. dissertation, University of Wisconsin-Madison, 1984.

37. The best guide to evidence relating to the application of water power to industry in the medieval West is Bradford Blaine's dissertation, cited in note 10 above. I have consulted his work on numerous occasions in preparing this paper and hope that he will eventually find time to update his research and publish it. See also my book, *Stronger Than a Hundred Men: A History of the Vertical Water Wheel* (Baltimore and London, 1983) and Bertrand Gille, "Le Moulin à eau: Une Révolution technique médiévale," *Techniques et civilisations*, 3 (1954) 1-15. Many medieval Western applications of water power, including its application to metallurgy, of course, were anticipated by the Chinese, as Joseph Needham points out in *Science and Civilisation in China*, 4, pt. 2 (Cambridge, 1965) 369-406 *passim*.

38. Walter Horn, "Water Power and the Plan of St. Gall," *Journal of Medieval History*, 1 (1975) 220, 228, 229, for views of the plan generally and the *pilae* room in particular.

39. Walter Horn and Ernest Born, "The 'Dimensional Inconsistencies' of the Plan of Saint Gall and the Problem of the Scale of the Plan," *Art Bulletin*, 48 (1966) 285-308.

40. Horn, "Water Power," 246, 252.

41. K. Zeumer, ed., *Formulae Sangallenses miscellaneae*, in *Monumenta Germanae Historica*, *Leges*, 5 (Hanover, 1886) 385.

42. Bautier, "Anciennes mentions," 571-601, esp. 571-578.

43. *Ibid.*, 572 n. 2; Paul-Émile Giraud, *Essai historique sur l'abbaye de S. Bernard et sur la ville de Romans: Complément textuel du cartulaire* (Lyon, 1866) 13, no. 95.

44. Bautier, "Anciennes mentions," 572-576.

45. Georgio Giulini, *Memorie spettanti alla storia, al governo ed alla descrizione della cittá, e della compagna di Milano*, 3 (Milan, 1760) 67, 502 (*fictum de molendinis omnibus vel fullis* and *totum fictum molendinorum seu fullorum*). Blaine, "Applications," 85, and White, *Medieval Technology*, 83, accept this as the earliest fulling mill.

46. Blaine, "Applications," 85-89; Bautier, "Anciennes mentions," 576-578.

47. Aurelio Zonghi, "Le antiche carte Fabrienesi," in E.J. Labarre, ed., *Zonghi's Watermarks* (Hilversum, 1960) 114. Blaine, "Applications," 103, considers this the "earliest firm example" of a water-powered paper mill. The text reads: *molino cum gualchis et cartere*.

48. Augustin Blanchet, *Essai sur l'histoire du papier et de sa fabrication* (Paris, 1900) 52-53, citing Archivo general de la Corona de Aragon en Barcelona Registrao, no. 46, f 16 (del reg. Pedro III el Grande). Blaine, "Applications," 101-115 reviews the literature on the emergence of the paper mill in some detail.

49. Bautier, "Anciennes mentions," 595-601; Blaine, "Applications," 94-96.
50. Paul von Stettin, *Kunst-Gewerbe und Handwerks Geschichte der Reichs-Stadt Augsburg*, 1 (Augsburg, 1779) 141, cited by Blaine, "Applications," 160-161.
51. Blaine reviews the early references to oil mills in "Applications," 75-77. He notes that the crushing device used in medieval oil mills is uncertain but inclines toward edge-rollers.
52. W.A. McCutcheon, *The Industrial Archaeology of Northern Ireland* (Rutherford, etc., 1984) 249-250.
53. Thérèse Sclafert, *Le Haut-Dauphiné au Moyen Age* (Paris, 1926) 369; Forbes, "Power," in Singer, *History*, 2, 610.
54. Luis Domenech y Montaner, *Historia y arquitectura del monasterio de Poblet*, 2nd ed. (Barcelona, 1928) 8, 10, citing Archivio de Reus armario II (Codices de Poblet) f 148, doc. ccxxvii, and f 219, doc. cccxxxiv; Sclafert, *Haut-Dauphiné*, 519, citing Archives départementales de l'Isère, B 3020, f 4.
55. See note 22. Blaine, "Applications," 140, and Johannsen, *Geschichte der Eisens*, 93.
56. Nef, *Conquest of the Material World*, 34, claims that in the first decade of the thirteenth century around Trent "water-driven machinery was frequently employed for breaking and crushing the ores" of silver.
57. Adolf Zycha, Das böhmische Bergrecht des Mittelalters auf Grundlage des Bergrechts von Iglau, 1 (Berlin, 1900) 181, n. 1 (*erzmulen*). Blaine, "Applications," 141, indicates this as the earliest definite indication. T.A.P. Greeves, "The Archaeological Potential of the Devon Tin Industry," in Crossley, ed., *Medieval Industry*, 94, says that the earliest documented ore stamping mills date from the late 1400s in central Europe, citing J. Majer, "Die Hauptzüge der Bergbautechnik des Böhmischen Zinnbergbaus im 16 Jahrhundert" in Majer, ed., *Cin v Dějinách Vědy, Techniky a Umění*, 2, 15.
58. Ausonius, *Mosella*, 361-364.
59. Karl-Heinz Ludwig, "Die technikgeschichtlichen Zweifel an der 'Mosella' des Ausonius sind unbegründet," *Technikgeschichte*, 48 (1981) 131-134; D.L. Sims, "Water-driven Saws, Ausonius, and the Authenticity of the *Mosella*," *Technology and Culture*, 24 (1983) 635-643; and White, *Medieval Technology*, 82-83, 369.
60. Léopold Delisle, ed., "Cartulaire normand de Philippe Auguste, Louis VIII, Saint Louis et Philippe-le Hardi," in *Mémoires de la Société des antiquaires de Normandie*, 16 (1852) 288, no. 1079.
61. Villard de Honnecourt, *Sketchbook of Villard de Honnecourt*, ed. Theodore Bowie (Bloomington, Ind., 1959) 129, pl. 59.
62. Biringuccio, *Pirotechnia*, ed. cit., 380.
63. Stettin, *Augsburg*, 1, 223; Blaine, "Applications," 146. Dürer's drawing is reproduced in John Canaday, "Albrecht Dürer," *Horizon*, 6, no. 3 (summer 1964) 19.
64. Alfred Ribeaud, *Le moulin féodal: Étude de droit et d'histoire sur la principauté épiscopale de Bâle* (Lausanne, 1920) 11 (*tria molendina et unam serram, cum*

areis ibidem contiguis) for the 1268 contract; Sclafert, *Haut-Dauphiné*, 435, citing Archives départementales de l'Isère, H 820 and H 787.

65. Umberto Forti, *Storia della tecnica italiana alle origini della vita moderna* (Florence, 1940) 91.

HYDROLOGICAL ANALYSIS OF WATER POWER USED AT MEDIEVAL IRONWORKS

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SUMMARY

The performance of water power systems used in the medieval iron industry is examined by calculation of the operating characteristics at works for which archaeological data are available. The water power system consists of the drainage basin which supplies the water used, the civil engineering works that supply the water motors, the hydraulic machinery, and the tail race which carries off the waste water. The power requirements of bloomeries, forges and blast furnaces can be evaluated from archaeological evidence of the machinery that was used. Once the machinery used is known and fall of water available at a site is determined, the stream flow required to sustain a given schedule of production can be calculated.

The mean flow available at a site is determined from the drainage basin area, the rainfall, and the evapotranspiration. The variability of the flow is described with the aid of a flow-duration curve. It is necessary to use modern hydrological data. A review of available evidence on climatic change shows that there were probably significant changes in the rate of growth of trees and in the water yield of drainage basins in Northern Europe in medieval times; both were lower in the Little Optimum and increased during the Little Ice Age. Changes in land use also cause changes in the water yield of drainage basins; deforestation increases the yield significantly. However, it appears that modern hydrological data can be used to obtain useful results about medieval water supplies.

Sites in England active between 1200 and 1700 AD for which archaeological reports are available were studied. Most of the forges could have been operated on a seasonal basis only. The sites used lacked potential for expansion of production and none were located so as to provide a generous water supply. Operation of the earliest blast furnaces (early 16th century) would have been restricted to no more than half the year; later furnaces could have smelted throughout most of the year. The forges and early blast furnaces appear to have been built with minimum capital investment and lacked power capacity for sustained use or for expansion of production. Later blast furnaces appear to have been intended for more nearly continuous operation. Shortage of water resources does not seem to have placed a limit on the development of the iron industry in this period.

INTRODUCTION

The performance of the water power systems used at medieval ironworks - bloomeries, forges, and blast furnaces - is examined in this paper. Emphasis is placed on the hydrological aspects of the water power systems used and on long term effects that may alter the performance of a water power installation such as may arise from changes in land use, accumulation of silt, or climatic change.

The results obtained bear on the extent to which medieval iron production was limited by the technical skills in using water resources then available, by the capital investment needed to obtain the requisite service from water power systems, and by scarcity of the necessary natural resources of wood and water. They also show how the geographical distribution of ironworks may have been influenced by the availability of suitable sites for the generation of water power.

Documentary evidence on the use of water power at medieval ironworks is quite limited. Available records, which have been summarized by Blaine (1), often do no more than state that water power was in use at a works in a given place and time, frequently without specifying the purpose it was used for. Some sort of modeling must be used to find out about the actual operation of water power facilities at medieval ironworks. Physical reconstruction and operation of a works is possible in principle and has provèd a useful technique for some small-scale operations, such as the hand-powered bloomery, but the amount of land required and the cost of building and operating a water-powered iron works would be large. The analysis of the operation of water power systems presented here uses engineering and hydrological data for specific sites in the following steps:,

1. Calculate the amount of power required, and the time over which it is required, at the various types of works of interest.

2. Infer the machinery and civil engineering works that would have been used to provide the requisite power from available documentary and archaeological evidence,

3. Compute the flow of water needed to generate the power required at the site being investigated, and

4. Compare this flow with that deduced from the meteorological and hydrological characteristics of the site.

Once adequate machinery was built, the success of the operation of the water power system would depend primarily on the adequacy of the water supply - if there were sufficient flow available when required, the requisite power would be available. Other factors of importance are the frequency and magnitude of floods, which could not only stop the operation of a water wheel but also damage the dams and leets used to deliver the water and the effects of changes in land use (such as deforestation) and climate or of sedimentation on the operation of the water power system.

In carrying through the analysis modern meteorological and hydrological data are used. Several problems may arise with this. First, there have been significant changes in climate since medieval times. Changes in land use change stream flow characteristics and allowance must be made for both of these factors. Finally, the requisite hydrological data are frequently not available for the sites of interest and have to be inferred from other data. It is important, therefore, to consider the sensitivity of any results obtained to changes in the assumptions made in the modeling.

The method of analysis used here was developed for the study of 19th century water power systems for industrial use (2,3) and will be described briefly here. The geographical unit used is the drainage basin, the area of land that supplies water to a stream above the site of interest. The power potential of a drainage basin is the amount of power that could be developed if all of the runoff of water from the basin were passed through hydraulic machinery. It is determined by the distribution of rainfall and elevation in the basin, the amount of work done in throughflow, and by the amount of water lost by evapotranspiration. The power potential becomes a bound on the water power developed in a drainage basin only if all of its water power resources were fully developed. Capital costs generally insure that this never happens.

The principal cost involved in the use of water power is the capital cost of the machinery and engineering works needed. Once this investment is made, subsequent costs are limited primarily to maintenance costs. The capital cost is strongly influenced by geographical and geological factors. The amount of economically useful water power that can be developed in a given drainage basin can be found from a cost function which shows the cost of each unit of power developed as a function of the percentage of the power potential utilized. Cost functions for direct-drive (as distinct from hydroelectric) water power have been determined for a number of drainage basins and are found to be highly non-linear (2). Power can be developed at lowest cost at sites where there is a sharp fall of the stream bed immediately downstream of a reach of the stream with a small gradient because at such places the dam required to provide the needed water storage can be built at relatively low cost. In any drainage basin there will be a number of sites at which power can be produced at relatively low cost; in the basins studied these account for 20 to 50 % of the basin power potential. Once these sites are developed, the cost of using more of the power potential of the basin increases very rapidly.

Analysis of the water resources for industrial power in New England and Great Britain showed that even at the height of the use of water power for manufacturing in the 19th century the low-cost part of the power potential of the industrialized drainage basins was never fully utilized with very few exceptions. Was this also the case in medieval times? The Domesday survey of English mills shows many presumably small mills clustered in the upper reaches of drainage basins, where sites suitable for the development of small amounts of power with a small capital investment would be most numerous (4). A detailed analysis of some of these basins would be required to determine what proportion of the possible mill sites were really used. Reports of disputes about water rights suggest that the proportion may have been fairly high, but such evidence can be misleading - quantitative examination usually shows that there was much unused potential power in drainage basins that 19th century entrepreneurs complained of as being crowded.

Examination of the experience of 19th century American manufacturers with their water power systems shows that they frequently encountered unsatisfactory performance because their systems were not properly designed to allow for the variability of stream flow and because sites were chosen that did not allow for future expansion of power required for their growing enterprises (3). These conclusions were reached by comparing the amount of water required for their manufacturing operations with a computation of the amount that was available at each site by modern engineering methods and hydrological data. Similar comparison for medieval ironworks will be made here.

II. METHODS

Power Requirments

Good estimates of the power required to operate various types of medieval ironmaking equipment can be made.

Bloomery. An indication of the power required to blow a small bloomery can be obtained from studies that have been made of the operation of the bloomeries that were operated in central Africa until the of the first quarter of the 20th century. The technical characteristics of these bloomeries are probably similar to those used in northern Europe in the early medieval period. (In central Africa shaft furnaces with natural draft are sometimes used in the first stage of smelting but the product is usually iron of such low quality that a second smelting operation in a forced draft furnace is required.) A bloomery blown by bellows is required therefore. A bloomery which can produce 10 lbs of iron per day requires a team of up to 6 men to operate the bellows; they are relieved every few hours.

A bloomery producing 100 to 150 lbs of iron per day requires mechanical power. One analysis suggests about 1 HP to operate the bellows, which has an efficiency of only about 10% (5). There must be sufficient water available to provide for continuous operation during the time required to form the bloom, perhaps about 10 hours. According to experiments done by Rankine in the 19th century, a man operating a pump for 10 hours per day can do work at the rate of 0.06 HP. At least seventeen men pumping hand operated bellows would be needed to operate a large bloomery.

Forge. The power required to operate a forge hammer can be calculated from the weight of the hammer head, the height through which it must be lifted for each stroke and the number of strokes it delivers per minute. Tylecote and Cherry (5) estimate that the efficiency of the machinery at a water-powered forge was about 50%. The power required for a small forge hammer would be about 1.5 HP and, for the largest, about 5 HP. Since a forge could be put into or out of operation easily, there would not be a continuity requirement for the water flow as there would for a furnace, but the sufficient flow to operate the machinery would have to be available for a sufficient number of days in the year to meet production requirements.

Blast Furnace. Archaeological evidence and calculations show that the power required to blow a medieval blast furnace was about 1 HP. The necessary flow to supply this power must be available at the wheel during the entire campaign of the furnace, which might be as long as 20 weeks. Continuity of supply during the period of operation of the furnace is essential but, when a long interval between campaigns was allowed for repairs and the collection of fuel and ore, it may have been possible to choose the season of the year in which the furnace was to operate so as to obtain the most favorable hydrological conditions.

Engineering Capabilities

The basic machinery required to produce rotary motion from the fall of water was well known in the Roman world and was widely used for milling grain. Water power was used for milling in medieval Europe from at least the 9th century onwards (6) and mills had become common by the 11th century - the Domesday survey showed one mill per 50 households in southeastern England in 1086 AD (4). The cam for obtaining reciprocating motion from a water wheel was introduced in Europe first for fulling and was subsequently adapted to the requirements of actuating bellows and forge hammers. The efficiency of the various designs of water wheel were determined by Smeaton.

The civil engineering works required for a water power installation are a dam or weir, a leet to deliver water to the wheel, and a tail race. The dam can serve either to provide storage of water (called "pondage" if it is at the location where power is generated) or to increase the fall available at a site. Substantial dams had been built by the Romans and in the Moslem countries before medieval times. By the 12th century considerable skill in dam construction had developed in some parts of Europe - an earth dam built in 1189 AD at Ariesford, England, is still in place, for example and the large dam built on the Garonne at Barbagel is well known. The requisite skills were not known everywhere, however, as is shown by the collapse of the large dam built at Siena, Italy, in the late 15th century (7).

The necessary technical skills for the construction of both the machinery and the engineering works needed to adapt water power to the production of iron were available when required in medieval Europe. Difficulties with this aspect of water power systems were probably related to the large capital expense required for the works; this may have encouraged short-cuts that later resulted in unsatisfactory service.

Hydrological Analysis

To evaluate how well a water power system met the requirements of an ironworks, we need to know the fall at the site of interest, the mean flow, and the variability of the flow during the year. (The annual variation is the largest approximately periodic characteristic of stream flow.) The fall is determined by the topography of the site chosen and may be altered to only a limited degree by the design of the dam used. It is the easiest characteristic to estimate.

Mean Flow. The mean flow is determined by the drainage area above the site, the rainfall in the drainage basin, the evapotranspiration (the loss of water by evaporation from exposed water surfaces and through transpiration by plants), and by diversion of the flow out of the basin above the site of interest. Locating the drainage basin requires finding the region where ground water and throughflow reach the stream. Since this is subsurface flow, it has to be inferred from the topography but experience has shown that basin boundaries drawn with the aid of an accurate topographic map of appropriate scale are usually quite reliable.

Rainfall is strongly dependent on altitude and there can be considerable local variation within a drainage basin. Rain gage networks have been deployed in a number of European countries for long enough to provide good rainfall data. (The need for correction for climatic changes will be discussed below.)

In the North Atlantic countries the evapotranspiration is usually at least 50% of the rainfall and is sensitive to land use. Forest cover results is large transpiration losses because of the roots of trees reach water deep in the ground. The large loss of water from drainage basins caused by forests was not known or appreciated until the 1930's (the 1934 paper by Hoyt and Troxell (8) appears to have been the first to show this.) Clearance of forest cover results in wetter soil and more runoff. The most useful data for our purposes is from experimental forest plots in North Carolina (9); these show that clearcutting increases the average runoff by about 30%. Consumption of nearby forests for fuel at an ironworks could substantially increase the flow of water in the summer and late fall, since the transpiration loss is greatest in the summer and there is typically a delay of one to two months in the response of stream flow to changes in evapotranspiration. Changes in the amount of water lost by evaporation are a greater source of uncertainty in using modern hydrological data for the analysis of medieval water power installations than are differences in rainfall.

The runoff reaching a given site may be diminished by diversion of flow to other uses outside of a drainage basin. Diversions of water were locally important and controversial in medieval times and are well represented in written records since they provoked legal and governmental actions, but they are probably not an important factor in the hydrological analysis. (Large diversions of water from drainage basins to meet the requirements of municipal water supply became important in 19th century Europe.)

Variation of Flow. A certain minimum flow of water would be required to turn the machinery at an ironworks and, to evaluate the operation of the power system at the works, we want to know the number of days per year that this flow is available. Data from a discharge gage over a period of years are required to describe the annual variation of river flow and it is only in recent times that such data have been accumulated on most rivers. Gage records are used to make a flow-duration curve, a plot showing the percentage of the year that each different discharge, expressed as a ratio to the mean flow, is exceeded. The number of days during which there will be on average sufficient water to operate a water power installation can be read directly from the flow-duration curve.

In addition to the information contained in the flow-duration curve, it will be helpful to know the season in which low flow occurs and the magnitude of the departures from the average behavior represented by the flow-duration curve that may be expected from year to year. Another important characteristic of the drainage basin is the flood frequency curve, which expresses the probability that the greatest discharge in a given year exceeds a certain magnitude. This will show the likelihood of the works being damaged by flood or the cost of the engineering structures required to sustain large flow without damage.

These hydrological factors have to be evaluated from modern streamflow data and it is necessary to consider how applicable these may be to the past. The most important factors to consider are changes in climate and in land use. In addition to the long term changes that may influence the applicability of modern data, changes that may have occurred during medieval times and which would have affected the operation of ironworks are also of interest. These could affect the rate of growth of trees, the degree of difficulty encountered in draining mines, or the operation of transportation systems.

Changes In Climate

Growth of Trees. Almost all information on changes in climate in medieval times and between medieval and modern times comes from proxy data since there are no instrumental records from this period.

However, some data on the rate of growth of trees in medieval times, which have a direct bearing on the supply of fuel for iron production, are available for red oak from central Germany (10). Two tree ring series show that the growth rate was only about half of the long term average in the period 900-1080 AD due to drought and summer warmth. In 1080-1160 AD growth increased to about half again as much as it had been because of the more frequent incidence of mild summers with adequate moisture. The return of wetter conditions after 1080 would therefore substantially increased the rate at which wood cut for fuel could be replaced, which would have favored enterprises involved in sustained iron production.

Climate Change. It is difficult to interpret changes in the growth rate of trees in terms of temperature, rainfall or other measures of climate except where a given species is marginal and sensitive to a particular climatic variable. All manner of indirect indications of climate change have been studied - the results are summarized by Lamb ((10) - and the main aspects of climate change in medieval times in Europe are established. During the "Little Optimum" of 1000-1200 AD warm weather with moderate rainfall was common and settlements along the northern fringe of the North Atlantic (including Greenland) expanded and throve. The "Little Ice Age" began in 13th century and was well developed in the 14th; summers were cold and wet, there was more storminess and settlements in northern regions suffered from inadequate food production. The adverse climatic conditions encountered by many parts of the European community during the Little Ice Age were not necessarily adverse for the iron industry, however.

Changes in Runoff. The rather slim evidence available suggests that the years 750-900 AD were wet. We infer that there would have been diminished stream flow in drought years of 900-1000 AD because of reduced rainfall and high summer temperatures that would have caused increased evaporation. In the 11th century there was higher rainfall with mild, wet winters and more frequent floods and drought but a smaller percentage of the annual precipitation in the summer months. These conditions probably offered no advantage to the iron industry because of the greater variability of stream flow that probably resulted. However, from about 1200 AD onwards cold summers with a greater proportion of the annual rainfall in the summer would have resulted in substantially greater streamflow and wetter ground. Mine drainage became more difficult (although this was probably less important to the ferrous as to the non-ferrous industries), low flow in the summer would have been less of a problem, and transportation on rivers wold have been easier. These conditions would have favored the operation of ironworks, particularly the blast furnace, where continuity of water supply was particularly important.

The climatic changes described above cannot be made quantitative yet. The change in annual rainfall, a deviation of less than 5% either way of the modern mean, was not great but we anticipate a much larger change in evapotranspiration and, hence, in stream flow. Except in regions where there has been a large change in forest cover, there was probably somewhat more water available in streams than the amount we calculate with modern data.

APPLICATION AND RESULTS

Sites Studied

Sites of English ironworks operated in medieval or early post-medieval times for which there are archaeological reports were examined in a trial of the method of analysis of water power systems described here. The sites studied and the sources of information used are listed in Table I.

The study has been confined to sites in England so far because the necessary hydrological and geological data are more easily obtained than for other European countries. An important limitation, however, is that, with very few exceptions, the gaging of rivers and streams in England began only about 35 years ago; the long records needed to construct reliable flow-duration curves are not available. Part of this difficulty is now being overcome through the use of alternative sources of data. Jones (11) has computed the frequency of periods of low river flow for years back to 1860 for a number of rivers from rain gage data while Jones, Briffa and Pilcher (12) have extended the time series of river discharges back to 1755 with the aid of tree ring sequences. These new results are helpful in the analysis of water power in the industrial period but they do not as yet extend to the time period of interest here. We have to use flow-duration curves constructed from modern data without direct correction for past climate. Since there are no gage data for the streams on which the sites studied are located, an averaged flow-duration curve for several rivers has been used; the sensitivity of the results to the differences between rivers is indicated.

Hydrological Calculations

Available Flow.The sites were located on the 1:50 000 Ordnance survey topographic sheets (or, where sites are now flooded by reservoirs, on older sheets of similar scale). The drainage basin boundary above each site was constructed from the topography. The average rainfall in the basin was found from the rainfall map included on the Hydrogeological Map of England and Wales except for sites where more detailed maps are available from other sources. The average annual evapotranspiration was found by comparison of the measured discharge of the nearest gaged stream and the rainfall in its drainage basin. The average annual discharge, Q_a at the site of interest can then be computed.

Computed Operating Time. The flow of water, Q, required to operate the power system at a site is determined from the power requirement of the machinery found by the archaeological examination to have been used there and the fall of water available. The fall can usually be found from the archaeological reports or from the topography of the site. Where the excavations failed to identify what machinery was used, estimates were made for alternative sets of equipment. The percentage of the year during which there would be sufficient stream flow to operate in the run-of-the-river mode (i. e., without drawing water from storage), %t, can then be read from the flow-duration curve. At those sites where the archaeological reports show that there was a pond, it is assumed that the pond would have been used to supplement the flow during periods of low water. Where the slope of the flow-duration curve is low, as it usually is when %t is greater than about 60%, small amounts of water drawn from a pond can extend the operating time a great deal. The amount that a pond can be drawn down is limited by the loss of head which results and it has been assumed that the drawdown is limited to 10% of the fall at each site. Once the area of the pond is known, the increment of %t due to pondage can be determined from the flow-duration curve by integration.

The use of the hydrological data could be extended by finding the probability of the works being damaged by flood, but this has not yet been attempted.

The final step in the analysis is determination of the length of time the works could be operated before being impeded by siltation. The sediment yield of the drainage basins used is estimated from reports of the siltation rates in the closest reservoirs for which data are available. (Most of these data are for central and northern England.) The efficiency at which a pond traps silt-clay sediment depends on the ratio the pond volume to the annual flow of water through it; this relation has been found experimentally from observations on many reservoirs. It is assumed that there are no upstream sediment traps and the pond siltation rate is found found from the product of the sediment yield of the drainage basin and the trapping efficiency of the pond. (A caution is necessary here; if coarse sediment enters the stream, as from land clearance or construction work in the basin, the trapping efficiency and, hence, the siltation rate, may be much higher than that calculated.) A pond in which drawdown is limited so as to avoid head loss can deeply silted and still remain serviceable.

Forges. The results obtained for the forge sites studied are listed in Table II. At Kirkstall Forge there is no information about what equipment might have been used at the site. If a small bloomery is assumed, it is found that there is sufficient water available to operate a bloom heath bellows and a small hammer during about 90% of the year. The excavations at Chingley did not reveal how the forge was equipped during Stage I of its use but the power available would have been sufficient to operate a bellows at a bloom hearth for only about 70% of the year; if a hammer were used, operation would have been restricted to less than a third of the year. The excavations at Byrkeknott and Muncaster Head give a much more complete picture of the equipment operated. At Byrkeknott the flow would have been sufficient to run the bellows for the two bloom hearths throughout most of the year. At Muncaster Head, even with a generous estimate of the flow available, it seems that the amount of water would have been sufficient for only about three quarters of the year at most. The pondage available at all of these forge sites was too small to have any effect on the fraction of the year that the works could be run.

The results show that none of the sites examined had a generous supply of water and that operations at two of the four would have been restricted by want of water during an appreciable part of the year. There was no margin for the expansion of operations at any of the sites. The lack of pondage, the use of simple leets to deliver water to the wheels, and the small capacity of the sites used all suggest installations made to achieve an immediate purpose with minimum capital expendature and no requirement for special technical expertise. The frequent complaints about inadequate water that appear in documents relating to medieval forges would be a consequence of this mode of establishing works; the complaints suggest that the difficulties that would arise from selection of a site with inadequate power potential were not foreseen by their proprietors.

The topography of much of England lends itself to an abundance of sites suitable for the construction of small water-powered works with minimum capital expendature. To know whether or not the supply was greater than the demand, a complete inventory of all the water-using industrial works in a given watershed at a given time is needed; some such data are available for the 18th century and show that power potentials available at low marginal cost were far from fully utilized (2).

Blast Furnaces. The results for the blast furnace sites studied are summarized in Table III. It is assumed that an overshot waterwheel was used to drive the blowing bellows at each furnace since overshot wheels were found at all of the sites where there was any evidence of the type of wheel used.These wheels would have an efficiency of about 60%. At the two earliest furnaces the water supply was adequate for operation during only about half the year. The additional water that could be drawn from the furnace ponds was sufficient to extend the period of operation for a few weeks when the flow was just too small for run-of-the-river operation. This could certainly be most helpful in extending the campaign of a furnace in successful blast but was no substitute for the selection of a site with a better power potential. Smelting at these furnaces would have to be seasonal, perhaps limited to a single campaign a year. This suggest the erection of works at minimum capital cost and selection of sites based on considerations other than the provision of a reliable water supply.

The later furnaces were better situated and approached the possibility of year-round operation. This was achieved by the use of larger drainage basins rather than the provision of larger ponds, which would have been a more costly alternative. Suitable sites for the year-round operation of blast furnaces may have been in more limited supply than sites with smaller power potential - inventories of all the water-powered works in the drainage basins used would be needed to settle this question - but, again, the results of such analyses for the industrial use of water power in England in the 19th and 19th centuries suggests that no geographical or physical shortage of sites acted as a barrier to the expansion of blast furnace operations (2).

For comparison, the operating characteristics of a large, charcoal-fired, water-blown blast furnace which produced iron in Connecticut throughout the first quarter of the 20th century are shown at the bottom of Table III. It is of interest that they are not very different from those of the Pippingford furnace (when a single furnace was run at this site).

Several cautions apply to the results presented in Tables II and III: They are based on inferred rather than measured flow-duration curves; as the %t approaches 70% or more, errors in the low-flow part of the curve can change the estimated operating times by large amounts. We can be fairly confident that climatic change has not caused significant changes in the amount of water available but changes in land use could be important. If the forest cover were less at the time the furnaces were in operation than it is now, the mean flows would have been larger in the summer months and could have extended the smelting season. The estimates could be improved by more complete study of local conditions.

Pond Siltation. The sediment yield of drainage basins in central and northern England tends to be low, as it is in the glaciated parts of North America (13). If these results can be applied to all of the blast furnace sites studied, then the estimated pond siltation rates are found to be only about a few millimeters per year. It is expected, then, that in most cases other factors would have reduced the economic viability of a blast furnace before pond siltation became a serious problem. This estimate could be upset if some event in the drainage basin used released coarse-grained sediment. In modern times, road construction and housing development are common causes of greatly increased siltation rates in power ponds. Such release is unlikely from land that is kept in forest or pasture. Silt accumulation could be a nuisance in wheel pits or tail races but was unlikely to cause the loss of power at a blast furnace site.

The general conclusion to be drawn from these results is that water power resources were probably never a limiting factor in the growth of the medieval or post-medieval iron industry (though they could be a very severe limitation to expansion of works at a specific site), and that poor site selection and lack of adequate capital expendature often resulted in the construction of water power systems whose performance was a source of difficult to their proprietors.

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Table I

SITES STUDIED

Site	Date	Reference
Forges		
Kirkstall Forge	1200 AD	1
Chingley Forge (Phase 1)	1300	2
Byrkeknott Forge	1408	3
Muncaster Head	1636	4
Blast Furnaces		
Panningridge	1542	5
Chingley	1558	2
Scarlets	1580	6
Sharpley Pool	1650	7
Pippingford	c.1700	8

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Table II

OPERATING CHARACTERISTICS OF FORGES

Name	Date	Q_a	Fall	Q	Q/Q_a	%t	Equipment
Kirkstall	c.1200	13.5	[10]	[3.5]	0.3	90	a
				[13.5]	1.0	35	b
Chingley	c.1300	6.9	8	[6.9]	1.0	34	c
				[2.7]	0.4	62-70	d
Byrkeknott	1408	11	15	3.3	0.3	72-92	e
Muncaster Head	1636	98	7	38	0.4	62-72	f

Notes

Units: Fall in feet, Q in cubic feet per second.

Quantities in [ ] are hypothetical values assumed for illustration where data are not available.

a. Small hammer and hearth.

b. Large hammer and hearth.

c. Small hammer and hearth.

d. Bloom hearth only.

e. Two bloom hearths.

f. Three bloom hearths and hammer.

Table III

OPERATING CHARACTERISTICS OF BLAST FURNACES

Name	Date	Q	Fall	Q	Q/Q_a	%t(a)	%t(b)
Panningridge	1542	2.6	10	1.5	0.55	51	-
Chingley	1558	2.4	11	1.3	0.55	51	56
Scarlets	1580	5.0	9	1.6	0.33	67-75	70-78
Sharpley Pool	c.1650	3.7	10	1.5	0.40	62-72	-
Pippingford (2 furnaces)	c.1770	9.5	10	1.5 3.0	0.16 0.32	87-95 72-92	90-100 75-95
******							
E. Canaan	1880	78.4	15	12.9	0.16	87-95	-

Notes

Units: Fall in feet, Q in cubic feet per second.

a. Operating time per year without use of the pond.

b. Operating time per year with 10% drawdown on pond.

TRADITIONS OF THE WATER WHEEL IN ITALY

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SUMMARY

The exploitation of water power in Italy for production purposes was already practised in Roman times: Vitruvius describes several devices for the raising of water from streams and also describes the main characteristics of water driven grain mills.

In recent times, a few important archaeological discoveries (the Roman water mill in the Athenian Agora and the Roman water mill in the Baths of Caracalla) have made it possible to verify the reliability of the written sources.

To ascertain whether there is any relation between the Vitruvian pattern and the water powered mills that still survive in Italy, dating back to past centuries, it was thought worthwhile to conduct a survey on those primitive grain mills which still exist in Northern Italy. This report takes as an example a grain mill still in operation in Bienno (Brescia), which probably dates back to the 17th century. Since, in past centuries, Bienno was also the seat of several water driven iron forging works, a blacksmith's workshop is described as well in this report.

From the results of the survey, it would appear that the characteristics of water mills have remained substantially unaltered over the centuries, only a few technical improvements having been made.

The data that can be acquired by the study of primitive works still in operation are of fundamental importance to the archaeologist since he is thus given bases of comparison for the evaluation of structures brought to light during archaeological excavations.

It is to be hoped that evidence of primitive working processes, of whatever type and wherever they may be found, be made the subject of study in the very near future, before they vanish forever, obliterated by the advent of modern technology.

" Fiunt etiam in fluminibus rotae....
" Eadem ratione etiam versantur hydraletae, in quibus eadem sunt omnia,
" praeterquam quod in uno capite axis tympanum dentatum est inclusum. Id
" autem ad perpendiculum conlocatum in cultrum versatur cum rota pariter.
" Secundum id tympanum maius item dentatum planum est conlocatum, quo
" continetur. Ita dentes tympani eius, quod est in axe inclusum, inpellendo
" dentes tympani plani cogunt fieri molarum circinationem. In qua machina
" impendens infundibulum subministrat molis frumentum et eadem versatione
" subigitur farina " .

In De Architectura, X,5,1-2, Vitruvius describes various devices which were used to collect water from streams and to raise it to a higher level, examples of which are "tympanum" (a compartment wheel), "rota...duplex ferrea catena" (a bucket wheel), and "cochlea" (a wooden screw revolving in a hollow cylinder).

Vitruvius also mentions the possibility of exploiting the force of the river for grain milling, and even though his description is rather meagre and has given rise to various interpretations (1), it explains the working of a water powered flour mill with sufficient clarity.

The water wheel is constructed in such a manner that its shaft ("axis") is of the right size to meet the height requirements. Paddles ("pinnae") are fixed around the rim of the wheel, and, when subjected to the force of the current of the river, are set in motion, thus causing the wheel to turn. A toothed drum ("tympanum") is secured to one end of the shaft of the water wheel and turns with it. Adjoining this, a second and larger toothed drum ("tympanum dentatum planum"), laid horizontally, is engaged by the teeth of the "tympanum", so that the millstones are made to revolve, thus grinding the wheat. (De Arch., X,4,3 - X,5,1-2)

It is generally accepted that Vitruvius describes a water wheel of the undershot type, i.e. a wheel placed in a vertical position, with horizontal shaft, set in motion by the water which flows past the paddles. Compared to the most primitive "Greek mill" (also called "Norse mill" or "vertical mill"), (2), the Vitruvian mill (also called "horizontal mill") was far more efficient. It could be built anywhere a small but steady and rapid flow of water was available, not necessarily requiring either dams or mill-races. Although installation and utilization costs were low, there were several drawbacks due to the variations in the level of the water. During summer the weak flow of water could jeopardize the working or put the mill out of action altogether, whilst high water levels in the stream, due to heavy spring rainfalls or to autumn storms, could have wrought such damage to the wheel as to make it inutilizable. This type of wheel was not, therefore, suitable for the major rivers of Italy since, for most of the year, the seasonal variations of the water level would have compromised the working of the mill.

Although the Vitruvian mill was an improvement on previous types of mills, high production was not attainable since the millstones turned slowly (usually once per each revolution of the water wheel). The power output depended on the velocity of the water flow as well as on how efficiently the water hit the paddles.

At the beginning of this century, a few lucky archaeological discoveries made it possible to verify Vitruvius's description (3).

The discovery of the water mill of the Athenian Agora and of the water mill in the Baths of Caracalla in Rome are particularly important. The former was brought to light in 1933, and a full report was published by Arthur W. Parsons in 1936 (4). The latter, discovered in 1912, was not published scientifically until 1983, when two Scandinavian archaeologists, Thorkild Schiøler and Orjan Wikander, provided a clear and convincing reconstruction of the mill (5).

The Athens mill, located in the area of the Stoa of Attalos, dates back to the V century A.D. and, when uncovered, was found to be in a state of near distruction. The water was brought from the south through a long mill-race, from where it fell onto the wheel, making it revolve. Traces left in the heavy lime deposit have made it possible to calculate the diameter of the wheel as 3.24 m. The shaft of the wheel (c. 3.50 m long) caused the "tympanum dentatum" (Ø 1.11 m) to revolve, and this, in turn, engaged the teeth of the horizontal "tympanum" (Ø 1.36 m). The millstones were set directly above the horizontal "tympanum": some of them are fairly well preserved, they have a diameter of c. 0.80 m, their thickness being only 0.08 m. Such a limited thickness is rather perplexing, when consider ing the material in question, that is, stone.

The Athenian Agora mill was very close to the Vitruvian pattern: the horizontal "tympanum" was larger than the vertical "tympanum", just as Vitruvius prescribes. Such an arrangement caused a loss of speed, as the grindstones revolved more slowly than the water wheel, but it might have been suitable enough for a mill-race which had a low volume of water, but a rapid and constant flow. The only striking difference between the Vitruvian plan and the Athens mill is that the water wheel was not undershot but was overshot, that is to say, it was struck by the force of the water from above instead of from below.

The two water wheels of the mill discovered in the Baths of Caracalla were also overshot. The mill is located in the subterranean system of rooms and corridors under the court of the Baths, close to the Mithraeum, and dates back to the III-IV century A.D. Although partly destroyed, what remained was sufficient to make a good reconstruction of the mill machinery.

The water was brought to the mill from the Baths, and it is presumed that water drained from the Baths was re-utilized. It was conveyed to the wheels through one or probably two channels, and fell onto the wheels from wooden mill-races. The diameter of each water wheel is estimated to have been between 1.95 and 2.10 m, the diameter of the pit-wheel ("tympanum") about 0.95 m ,the diameter of the lantern pinion about 0.35 m. The diameter of the grindstones was calculated to be c. 0.65 m. Here again, as in the Athens mill, the water wheels were of the overshot type, thus constituting a variation of Vitruvius's general rules.

From the point of view of efficiency and power output, the overshot wheel (6) gives better results than the undershot wheel, but is has higher constructional and operational costs. In fact, the overshot type requires a carefully regulated water supply. Water from rivers and streams is collected behind dams and conveyed through a sluice to a mill-race from which it falls upon the wheel. The system is expensive since a certain amount of engineering is required to raise the water to the necessary height and to convey it to the mill-race. The power output depends on the rate of water flow and on the height of the fall.

As a general rule, the water wheel is coupled by the shaft to a vertical toothed drum ("tympanum"), so that they turn together at the same speed. The "tympanum" is geared to a horizontal pinion which is smaller, and thus revolves more rapidly than the wheel by which it is driven (this is another variation of the Vitruvian pattern).

The grindstones are set directly above the horizontal pinion, whose axle, transmitting the power to the upper grindstone, makes it revolve on the lower stone, which is fixed to a platform. It has been estimated that in Roman water mills of the overshot type the ratio of the grindstone revolutions to those of the water wheel was 5:1 (7). In the water mill of the Baths of Caracalla the gear ratio was estimated to be circa 3:1 (8).

The substantial similarities between Vitruvius's description and the mills brought to light by archaeological excavations prompted me to verify whether there might also be some relation with the water mills still existent in Italy. A comparison between the main characteristics of the mills of Roman times and those of the mills which were active until recent times might help to determine a "common thread" in the iterative sense, and might also be a way of ascertaining whether the suppositions made on the working techniques of Roman mills are reliable.

The survey on mills which exploit hydraulic energy has been carried out in many places in Northern Italy. Most of the mills date back to the 16th, 17th and 18th centuries; unhappily, most of them are no longer working, many are in ruins, the very few that survive are on their way to extinction.

As an example of the survey, this report covers the "Valle dei Mulini" at Bienno, where a grain mill and five iron forging works are still to be found. These are small family concerns which still make use of rudimentary machinery and traditional techniques, not yet contaminated by modern innovations.

Bienno is a village in the province of Brescia, located at 1500 m above sea level and surrounded by mountains; it is in a valley which branches off from Val Camonica, known from prehistoric times for its iron ore mines, as demonstrated by the renowned engravings on its rocks. The mines in Val Camonica and those in the nearby Val Trompia produced a mineral (siderite) devoid of sulphur and naturally rich in manganese which made it possible to obtain a very high quality metal.

The Grigna (a mountain stream which empties into one of the main tributaries of the river Po, i.e. the river Oglio), flows in the neighbourhood of Bienno. A 5 km long meandering adduction canal, built in medieval times, conveys water from the Grigna stream to the village. This duct, which was widened and improved upon in the 16th and 17th centuries, flows partly in an excavated trench and partly through a wooden duct, supported by large wooden piles embedded in the ground, which, in some places, is more than 6 m above ground level. This duct is named "Vaso Re" and is still used, some of its parts having been renovated over the years, and some piles having been reconstructed in concrete.

At the beginning of this century, hydraulic energy was still exploited by more than 100 workshops, including saw-mills, iron works and grain mills. Each of these workshops had one or more water take-off from the duct for the activation of the water wheels. Maintenance of the duct was the responsibility of the owners of the various workshops: each of them had to clean and to maintain the efficiency of the part of the duct from which he took the water.

In modern times, electricity and industrial concentration have gradually emarginated the small production units which used hydraulic energy and have caused them to disappear. In Bienno, only five water driven iron works are left, and only one mill which grinds cereals still survives.

The grain mill is situated in the central part of the village, on sloping ground, positioned in such a way that the water wheel is directly underneath the duct "Vaso Re" (about 5 m below it). The mill is inside an old stonehouse, the oldest parts of which in all likelihood date back to the 17th century. The interior of the house consists of a single large room with a very high ceiling, in which all the grain grinding machinery is installed. The floor is of compacted earth; a stone bench runs along the whole length of one wall. All the mill machinery is of wood and can reasonably be assumed to be original, at least as far as the main parts are concerned. Nowadays, the mill is only used occasionally and it is expected that it will shortly be closed altogether.

The water wheel has a diameter of c. 3 m, width c. 0.50 m, and is provided with 24 boxes. It is of the overshot type: the water falls from above, through a take-off in the duct, regulated by the opening and closing of a sluice gate, and is conveyed onto the water wheel by a sharply slanted chute. The wheel makes about 22 rotations per minute, its speed of rotation being a consequence of the weight of the wheel and of the water in the boxes, as well as of the rate at which the flow of water falls. Were it wished to calculate the power output of the mill, the high energy losses due to friction and to the faulty centering of the wheel and its component parts should be taken into consideration. In any case, the results would probably be inexact since it would be almost impossible to take all the variable factors of such a primitive mill into account.

The axle of the wheel is a large wooden shaft about 6 m long and 0.30-0.40 m in diameter, and rotates a vertical toothed wheel which has an outside diameter of 1.4 m (the mesh diameter is 1.2 m), and a width of c. 0.20 m. This wheel has 40 teeth which engage the 16 teeth of a horizontal pinion (diameter c. 0.40 m). The grindstones are placed above the pinion: the axle of the pinion passes through a bearing in the lower grindstone and turns the upper grindstone. The latter has a diameter of 1.20 m and a thickness of c. 0.20 m; it rotates at about 65 r.p.m. Therefore, the ratio of rotation of the grindstone to the water wheel is approximately 3:1 (which is very close to the calculations made with regard to the Roman mill discovered in the Baths of Caracalla (9)).

A hopper ("infundibulum") containing the wheat to be ground is suspended above the grindstones by means of ropes fixed to the ceiling. The hopper is slightly tilted and the wheat grains stream slowly out of it through a small outlet. To ensure a continous stream of grains,the hopper must be kept in motion, and the miller worked out a clever arrangement: from the hopper hang two strips of wood, one end of which rests upon the grindstone which, rotating, joggles them. The resultant vibration is transmitted to the hopper, thus causing the grains to pour slowly out.

The two grindstones, both the upper stone which rotates and the lower stone which is fixed to a wooden platform, are of rough, grey, compact sandstone, and have grooves cut into their inner surfaces. The flour is gradually pushed outwards by the rotation through the grooves towards the outer edge of the grindstones and thence falls into a wooden chute which channels it into a sieve, after which the fine flour is put into bags.

The production of the mill is about 25 kg per hour. To achieve a higher productivity, the grindstones would have to be replaced or at least re-grooved (this is practically impossible today owing to the lack of craftsmen able to do this kind of work).

In general, it should be borne in mind that hourly production of a mill is affected by many factors: friction causes high energy losses, and the general conditions of the milling equipment, in particular those of the grindstones, are determinative.

If the weight of the grindstones is not proportionate to the diameter, if the inner surfaces of the stones have been worn smooth, or if the grooves have not ben properly cut into the stone, grinding will not be perfect and the yield will decrease.

The type and the conditions of the cereals to be ground also affect efficiency: if the grain is damp, grinding is slower since there is a tendency towards the formation of a paste, instead of flour. The degree of fineness of the ground product is also important, and, in this respect, the clearance between the two stones must be properly regulated. If the clearance is too large, the flour will be coarse. If the grindstones are too close together, there is direct friction between the stones themselves; the insufficient heat dispersal causes the flour to burn and blacken.

On the basis of the data collected during the survey carried out in Bienno and in other villages in Northern Italy, it would seem that the average production per hour of a water driven mill of the most traditional and primitive type ranges between 25 and 50 kg/hour, under normal conditions. This value is much lower than the 150 kg/hour which, according to Forbes, would have been possible in a mill in Roman times (10).

Again on the basis of information gathered during the survey (perhaps, in this case, it would be more correct to say: "on the basis of the recollections of old millers"), it would seem that grinding went on continuously, that is, day and night. Grinding knew no interruption, and the mill stopped neither during the night nor on feast-days. Milling came to a halt only when the water wheel stopped, i.e. when the grindstones or gears were overhauled, in summertime and during droughts, when there was not enough water to work the mill.

When making calculations referred to antiquity, the working conditions as well as the many variables inherent to such primitive mills, each with its own particular characteristics, must be kept in mind, since, otherwise, there exists the risk that the calculations will be unrealistic.

For instance, a production of 28 tons in ten working hours was calculated for the Barbegal mill (11). Had it been kept in mind that the working hours were twentyfour, and not ten, the result would have been a total of 67 tons per day, a value which, even at a glance, is obviously excessive.

As an appendix to these considerations on grain mills, in view of the fact that this Symposium on Medieval Iron is dedicated both to water power and to metallurgical processes, it might be of interest to include a brief description of one of the five iron forging works still in existence in Bienno, which utilize hydraulic energy to drive the hammer.

The forge held to be the oldest in the village will be used as an example in this report: the construction, according to the engraving on the lintel above the entry, dates back to 1643. The forge is located in the lower part of the village, where the duct "Vaso Re" finishes, after having been exploited by all the workshops of the village.

Inside the stone building, a single large room houses the forging hammer and all the other equipment used by the blacksmith. The forge hammer is a helve-hammer (in Italian, "tipo ad altalena"), and is the one used originally, whilst most of the other equipment dates back to the 19th century and will therefore not be described in this report.

The water wheel that drives the forge hammer is of the overshot type. The water falls from above through a take-off in the duct "Vaso Re" which, in this stretch, is elevated and runs more or less at the forge roof height. A sharply inclined chute conveys the water from the take-off onto the wheel, and the water flow may be regulated through a sluice gate.

The water wheel has a diameter of 2.10 m, a width of 0.70 m, and is provided with 20 boxes. When driving the hammer, its speed is 50/55 r.p.m., and when idling the number of revolutions per minute can reach 150. The drive shaft is a large chestnut trunk, 6 m long and with a maximum diameter of 0.70 m, which transmits intermittent motion through a 4 cam-gear (in Italian, "tamburo a 4 palmole") to another shaft that holds the forge hammer and that is positioned orthogonally to the drive shaft. The hammer shaft is 3 m long, is supported by two large blocks of granite embedded in the ground and connected to each other by two heavy wooden tie-beams. The hammer head is of iron and weighs about 210 kg to which are to be added the weight of the blocking wedges, which bring the total weight to about 250 kg.

When in action, the number of hammer strokes per minute is about 200 (that is, 50 r.p.m. of the water wheel multiplied by the 4 cams of the gear). The number of strokes per minute is regulated according to the type of forging work : the blacksmith avails himself of a particular device connected to the sluice gate to reduce or increase the flow of water falling onto the water wheel, thus regulating its speed.

The anvil, which is positioned directly below the hammer, is a heavy wooden block topped by a rugged iron plate on which the blacksmith places, ready for hammering, the incandescent metal object extracted from the forge furnace.

Various implements, in particular shovels, spades and hoes are forged in the shop. Taking the forging of a shovel as an example, the main working phases are as follows.

- a block of iron (nowadays purchased ready for use from the foundry) is cut to a size and weight suitable for the shovel to be forged.

- the block is heated in the forge furnace until it is red hot, then hammered to lengthen and flatten it, and to form the tang.

- the block is re-heated and re-hammered for further lengthening and flattening, for shaping and for formation of the central rib of the shovel.

- third heating and hammering phase in which the tang is tapered and flattened, whereafter it is shaped to form the handle socket.

- fourth heating and hammering phase for surface levelling and smoothing.

- shear trimming to shape shovel edges. A small hole is made in the handle socket, through which the nail holding the wooden handle in place will be driven.

- finishing and polishing.

Hand forging has a great many advantages in that the repeated heating and cooling phases have excellent hardening effects, and the iron itself is strain-hardened by the forge hammer blows, thus optimizing the characteristics of the finished product. In the specific case of the shovel, the use of a forge hammer makes it possible to form a solid central rib, whereas, on the contrary, shovels made from sheet metal have a hollow rib. Furthermore, since the thickness of the metal can be regulated as wished, the part of the shovel subjected to greatest stress during use (i.e. the part around the handle socket) can be left thicker than the rest of the shovel, thus rendering it stronger and more resistant to wear.

After this digression on the utilization of hydraulic energy in metallurgical processes, which is intended as an acknowledgement of the rôle played by The Swedish Ironmasters' Association in this Symposium, we shall now return to the main topic of the report, that is the exploitation of the water wheel in grain milling.

The conclusions that can be drawn from this survey, limited though it may be, is that the water wheel has remained unaltered through the centuries. There is a substantial conformity between the general principles described by Vitruvius, the layout of the mills of Roman times brought to light during archaeological excavations, and the features of the traditional mills which have been active until recent times.

Taking into specific consideration the Bienno mills, the height from which the water falls improves the functioning of the water wheel; the drop between the duct "Vaso Re" and the wheel provides the high degree of energy required to activate the heavy forge hammers.

A survey such as that described herein can, in my opinion, back up the theory whereby the awareness of traditional working conditions and of primitive equipment may be of use to the archaeologist for a better understanding of archaeological finds. In fact, comparison with data gathered in situ may be of aid to him in the formulation of reliable hypotheses concerning both the working and the efficiency of mills in antiquity.

In this regard, there is a point which I believe to be worthy of mention: traditional craftsmanship in its most primitive form, of whatever type and in whatever country, is rapidly vanishing, ousted and crushed by modern technology. It is therefore a matter of great urgency that as much data as possible on these traditional working techniques be collected, data which, in the future, will not only be precious as historical evidence but also as a basis of comparison for archaeological studies.

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7. R.J.FORBES, op.cit. p.91

8. T.SCHIØLER-O.WIKANDER, op.cit. p. 54

9. Ibidem, p. 54

10. R.J.FORBES, op.cit. p. 93 : ".. the millstones performing 46 revolutions per minute could grind 150 kgrs. of corn per hour ".

11. R.J.FORBES, op.cit. p. 94.
It should be noted that on page 90 of the first edition of Forbes' publication (1955), a figure of 150 kg is given (Venafro grain mill), whilst the figure given on page 91 is : "15-20 kgrs." (Barbegal flour-factory).
In the second edition of the volume (1965), the former figure was still "150 kgrs.", whilst the second figure had been corrected as follows:
".... the capacity was 150-200 kgrs of corn per set of stones, or a
" total capacity of 2400-3200 kgrs per hour" (p. 94).
Both the 1955 and the 1965 editions state:
"..Even in a ten-hour day this would mean 28 tons of flour" (p. 91 and p. 94 respectively).

Two further comments are to be added:

a) the paper on the Barbegal mill written by the French archaeologist who made the excavation runs as follows:
"...la seule meule qui soit complete...mesure près de 0 m 90 de
" diamètre sur 0 m 45 de hauteur " (p.59)
"...L'évaluation approximative...montre que des meules du diamètre
" de celles-ci avaient une production très faible, de 15 a 20
" kilogrammes de farine à l'heure, soit 240 à 320 kilogrammes pour
" les 16 chambres de meunerie, en supposant que chaque moteur
" n'entrainait qu'une meule " (p.63)
F.BENOIT, L'usine de meunerie hydraulique de Barbegal (Arles) in "Revue Archéologique", 6,XV,1940, pp. 19-80.

b) the figure of 150 kg/hour has been accepted without reserve by other authors, for instance: K.D.WHITE, op.cit. p. 197.

THE CONSTRUCTION AND INSTALLATION OF WATER WHEELS : MEDIEVAL TO POST-MEDIEVAL

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SUMMARY

In the past twenty years vertical water wheels have been found during excavations of ironworks and corn mills in Britain. The methods of construction are reviewed, together with those of emplacements in which the wheels were mounted. Consideration is also given to aspects of the impounding of water noted during field surveys.

1. INTRODUCTION

The methods of building and installing water-wheels found in the mills of the Middle Ages have a life which extends beyond the medieval centuries. There is little to distinguish the 17th-century water-wheel from its 14th-century predecessor, nor do means of impounding or control of water undergo significant changes. The stage when innovations become clear is essentially in the 18th century, so it is realistic to consider examples from before that time as one group.

One warning at the outset is that the physical remains of mills, whether excavated or visible as earthworks, are often difficult to interpret unless the full circumstances of their construction are known. The millwright faced more than the obvious variables of terrain, water-supply and availability of materials. How he tackled the questions of siting and construction could be constrained by property boundaries, resulting in weirs reservoirs or channels being placed in positions other than those seeming most logical to a modern observer. He might also be influenced by the form of tenure of the mill site, particularly if a lease was short enough for durability of construction to be a secondary consideration. Availability of materials might also be affected by tenurial arrangements, for example if timber or a quarry lay on the leased ground, even though the quality of materials might not be ideal. The balance of first cost against maintenance charges could also be affected, if one or the other could be subsidised out of estate resources or out of some form of customary service.

Nevertheless, the pressure to concentrate upon making the best use of water grew. Particularly where circumstances favoured industrial mills, the intensity of use of streams increased. In some areas overcrowding is clear by the 16th century; in many the problem is present by the 18th, leading to investigations into the efficiency of water-wheels.

2. THE CONSTRUCTION OF WATER-WHEELS

An important group of water-wheel fragments have been found during excavations in Britain over the last 20 years, and this is a suitable opportunity to take stock of their design-features. All are from vertical wheels, and all the evidence points to their having been overshot.

It is not proposed to discuss horizontal wheels here. There have been no significant developments since the last surveys (1) and the details of the one recent excavated example, Tamworth, are now well known. The problems of the distribution, chronology and use of the horizontal wheel remain, particularly in England,and France north of Provence, and this topic is an important priority for further research, not least as to whether this type of wheel was used in Europe for purposes other than milling and crushing.

The vertical wheels listed in Table 1 all belong to a common tradition of construction in oak. All but two come from south-east England: the exceptions, from Yorkshire, correspond in their features with the southern group, so we are led so far to think in terms of a tradition of mill-wrighting which covers a wide area of England. Although early water wheels are relatively rare discoveries in archaeology, due to replacement during the re-use of sites, they were a common artefact in the Middle Ages and beyond, the total of mills in England being given as 5624 in the Domesday survey (2). It is not surprising therefore that a general uniformity of design had emerged by 1500. It is also notable that these wheels resemble the examples seen in Flemish landscape paintings, and contrast in many details with those illustrated by Agricola (3), which appear to represent a different, Central European, pattern.

TABLE 1 : EXCAVATED WATER-WHEELS

Size	Date	outside diameter	width overall	Source (4)
Batsford Mill Sussex	mid-14th century	2.60	0.30	Bedwin 1980 (i) 194, 198
Batsford Furnace Sussex	1571 (+)	3.90	0.45	Bedwin 1980 (ii) 101-3
Chingley Mill/Forge Kent	mid-14th century	2.50	0.32	Crossley 1975, 10
Chingley Furnace Kent	1558 (+)	3.40	0.32	Crossley 1975, 34
Chingley Forge Kent	Late 17th century (+)	2.40	0.58	Crossley 1975, 27
Maynards Gate Furnace Sussex	c.1562 - before 1653	2.50	-	Bedwin 1978, 169
Panningridge Furnace (1) Sussex	1542 (+)	3.65	0.30	Crossley 1972, 50
Panninridge Furnace (2) Sussex	c.1563-1580	3.05	0.40	Crossley 1972, 52-4
Rockley Forge (1) Yorkshire	c.1500-c.1630	3.05	0.30	Crossley and Ashurst 1968, 23, 35
Rockley Forge (2) Yorkshire	c.1500-c.1630	3.20	0.35	Crossley and Ashurst 1968, 23, 35
Scarlets Furnace Kent	c.1588-c.1700	2.90	0.72	Crossley 1979, 244

Constructional Details (Fig. 1)

There are no surviving examples of wheel hubs, and only at Chingley furnace was a fragment of a shaft found. This was a piece of the bellows cam-shaft bearing the cam-mortices, and its diameter (0.40m) was not necessarily the same where the wheel was mounted. Exact methods of fixing wheel spokes are therefore not known, but it is clear that all these wheels were of compass rather than clasp design. The best spokes remaining were at Batsford Mill (120 x 80 m/m section), Panningridge furnace 1 (200 x 100) and Chingley furnace (200 x 150, max). Two adjacent spokes survived at Batsford, showing that there had been four spokes in all. At Panningridge and Chingley only one spoke was present in each case, but measurement of the sole-boards showed that it was unlikely that either wheel could have had more than six spokes. At Rockley, mortices in the sole-boards showed that the wheels each had eight spokes.

The sole-boards on these wheels were formed from pieces of wood 70-110 mm thick, shaped to the necessary radius with an adze. The lengths ranged up to 2 metres, restricted by the dimensions of the trees from which they were cut. The spokes, ending in tenons, were set in mortices in the sole-boards. It was normal for the tenon to pass through the sole, and to be pegged on the outside. The wheels at Batsford mill and Chingley furnace had particularly well-preserved examples of such a fixing. At Chingley and Panningridge the sole had been left thicker round the mortice.

The shrouds or side-boards of these wheels were in every case nailed to the sides of the sole. Only at Chingley forge was caulking found, of tar and cow-hair, on the late 17th century wheel. Shroud length varied according to available timber, up to 2.40 m. in one case at Chingley furnace. The breadth was typically 0.40-0.50 m., and the thickness 25-30 mm. The lengths of shroud were either plain-butted together or, more often, fastened by scarf joints and nails.

The greatest detail variation among this group of wheels was in the fitting of the bucket boards. It was common for these to be fixed against the sides, although at Batsford furnace grooves had been cut in the side-boards to improve the location of the buckets. Nails or dowels were used as fixings. The fourteenth-century wheel at Chingley had dowels set on either side of the bucket boards, which were prevented from sliding between the dowels by small nails through the shrouds. At Chingley furnace each bucket had a dowel passing through the breadth of the board, projecting at each side through the shroud. At Batsford mill each bucket lay against two dowels, but they appear to have needed nails in addition: these did not survive. The bucket boards were straight in every wheel except

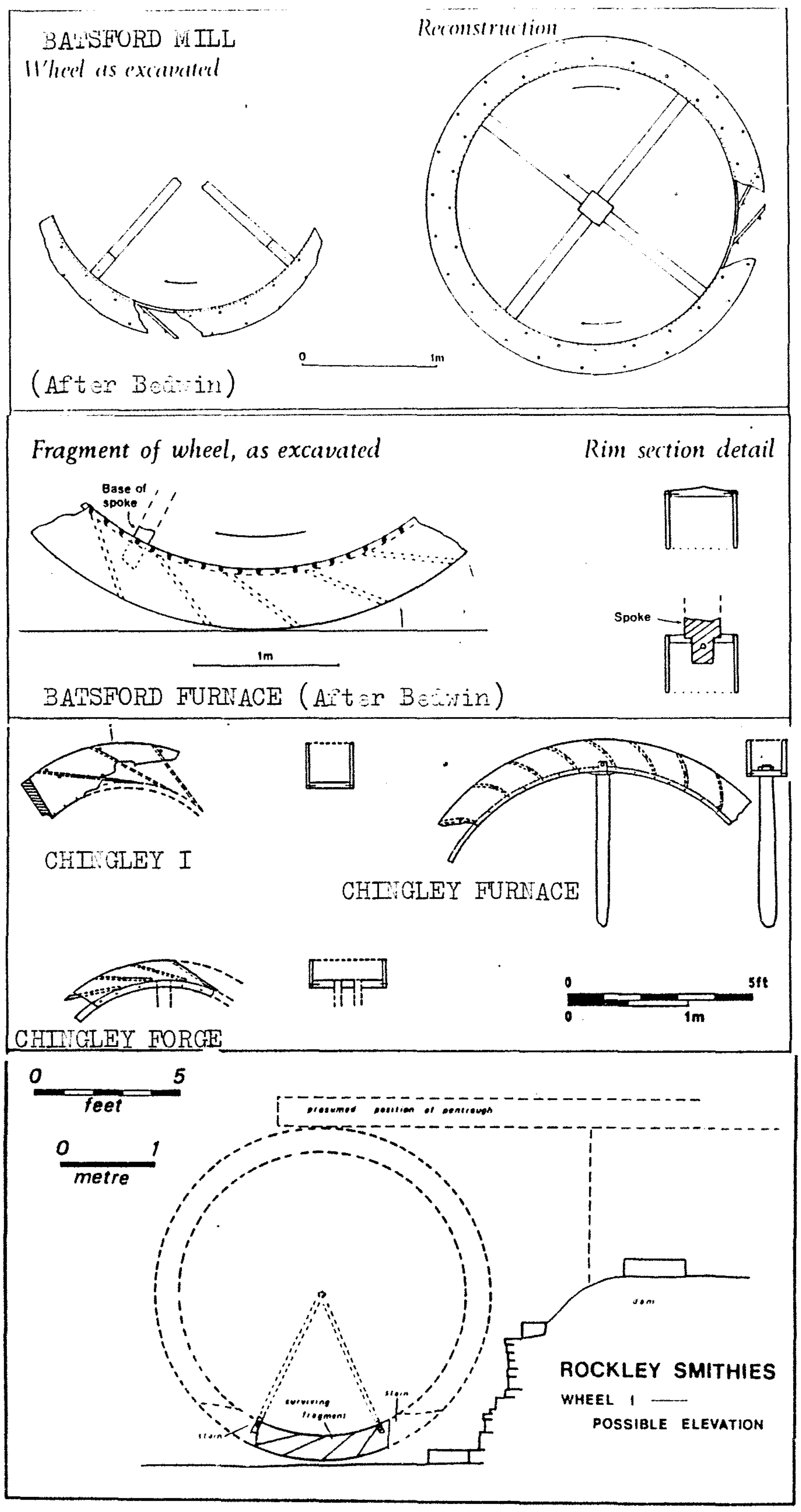


Fig. 1. Excavated Water Wheels.

one. This, at Chingley furnace, was of particular interest, a mid-16th-century wheel with curved buckets, a feature normally thought of as a later innovation.

The resemblance to the wheels portrayed by artists such as Henri Bles is striking. Although the Flemish landscapes do not reveal details of construction, the proportions of the wheels are made very clear, emphasising their delicate, even flimsy appearance. The narrow cross-section characteristic of the English wheels is seen, and it is to be expected that what appears to be a feature of English wheels, the longitudinal sole, would be repeated in the Flemish mills. This contrasts with the cross-planked soles of the broader Central European wheels drawn by Agricola. Also contrasting with Agricola's wheels is the housing of spokes in the centre of the sole, rather than joints to the inner edges of the shrouds.

Given this type of construction, it is not surprising that these wheels required frequent repair. In the case of iron-works, particularly blast furnaces, wheels were apt to remain stationary for appreciable periods, some parts being left dry, others damp due to rain-water filling buckets, or a sector of the wheel being immersed in the wheel pit. An all-wood wheel was also liable to stress in use, particularly when driving bellows or hammers. In contrast to the steady load of a corn mill, such equipment represented an intermittent load, with stresses concentrated on the spokes and their joints.

In most excavations of wheel-pits, discarded wheel parts can be found. In the medieval levels at Chingley, three substantial shroud pieces had been used to patch the side of the wheel-pit. At Chingley furnace, bucket boards different in detail from those on the wheel were found in the tail-race. At Scarlets a number of discarded parts were found in the tail-race. At Batsford mill, evidence of repair was found on a spoke, where it joined the sole, and the repair of water-wheels is an interesting aspect of the accounts of the Sussex ironworks of the Sidney family, extant for the years 1542-73 (5). These include the excavated furnace at Panningridge, and show both that patching was frequent, and that a completely new wheel was required only twelve years after the furnace was built. At the companion forge, Robertsbridge, repair entries are also common with examples such as: 'scooping of the hammer wheel and mending of the gudgeon' (1555). Such repairs often add information missing from the archaeological record: in particular, the references to bearings (gudgeons) are valuable, for these have in every case disappeared. The nearest approach is the timber bearing-block which survived at Chingley furnace, at the end of the bellows camshaft remote from the water wheel: this object was usefully similar to those portrayed by Agricola.

THE INSTALLATION OF WATER-WHEELS (Fig. 2)

Despite the attention which the excavated fragments of water-wheels naturally attract, their emplacements and water-feeds required equal skill in construction if the wheels were to be effective. During the Middle Ages, timber wheel-pit frames developed into impressive examples of structural carpentry, integrated into the foundations of the mills which their wheels powered.

The earliest excavated examples are at Tamworth and Old Windsor. The Tamworth mill foundation has received thorough treatment in print (6), and is illustrated in Professor Tylecote's paper for this conference. This, and the second phase at Old Windsor, housed horizontal wheels. The first phase at Old Windsor was marked by well-preserved timbers, which had housed three vertical wheels in the ninth century A.D. It is regrettable that this important site has not been adequately published, but it is assumed from what has appeared in print that this was an emplacement for under-shot wheels (7). Housings for undershot wheels have recently been briefly noted, without illustration, for the 13th-century fulling mill at Fountains Abbey, Yorkshire, and for a mill, considered to be medieval, in Gallowgate, Glasgow (8).

For overshot wheels in timber wheel pits, it appears to have been usual to construct a box frame, to house the wheel and to form the first section of the tailrace. The base-frame for this box was set in the bottom of a ditch excavated against the down-stream side of the dam. Substantial posts were tenoned into the frame, and to these were secured the edge-set planks forming the wheel pit. On the vertical members was mounted a second horizontal frame. This was a much larger structure. It enclosed the wheel, supported the penstock which fed water from the dam to the wheel, and was extended to the side to form the foundation for the mill and its equipment.

Such systems were used at Batsford and Chingley in the 14th century, with virtually identical details of carpentry, and, less complete, at Bordesley Abbey, c.1300 (9). At Batsford and Bordesley these structures formed the foundations of corn mills. At Chingley the function was less clear: small quantities of tap-slag from iron smelting were found, too small, it was thought, to indicate smelting in the immediate vicinity.

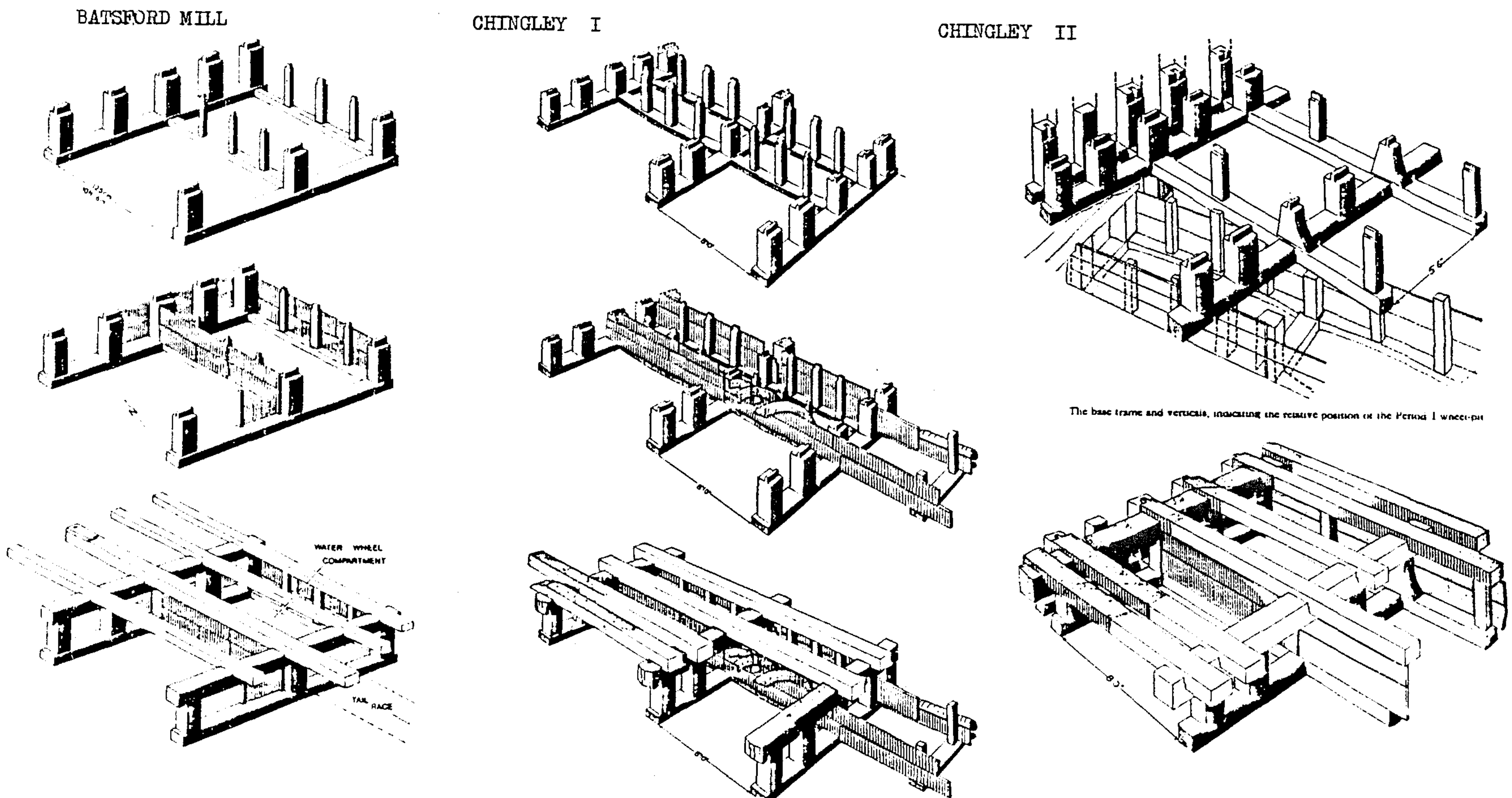


Fig. 2. BOX FRAME WHEEL-PITS

Yet the quantities of charcoal in the occupation levels, and metal artefacts and scrap in the wheel pit silts suggested use as a forge. Current thinking about this site is that some change of use occurred within the 14th century: parts of a wooden gear wheel, similar to those found at Batsford, were present adjacent to the wheel pit, suggesting a right-angle drive for a corn mill. The ground-level timbers, though much decayed, resembled those at Batsford mill but would, equally, have provided an adequate foundation for a forge hammer. Any medieval anvil-pit had been obscured by later re-use of the site.

Box-frame wheel-pit structures following this tradition have been found during excavations at post-medieval ironworks. At Panningridge furnace (1542) the wheel-pit comprised a simple box, of square-section oak members, with horizontal boards nailed to the exterior. The box was not integrated with the timbers of the bellows building or the equipment which it contained. This structure can be compared with the generally similar timber wheel-pit at Chingley furnace (c.1559). Here a box frame was also used, but an extension survived which formed a culverted tail-race beneath the casting floor. It is likely that this had originally been the case at Panningridge, the culvert being destroyed in subsequent rebuilding later in the 16th century. The Chingley furnace wheel-pit differed from the earlier examples in having a planked floor. This would assist the free flow of water from the wheel: in the medieval wheel-pits there were no traces of planking, and the exposed cross-sleepers in the pit bottoms would create a turbulent flow.

A remarkable variant within this group of box-frame wheel-pits is the structure associated with the documented late-16th century phase at Chingley Forge. Here a massive frame enclosed a wheel-pit and formed an adjacent foundation at the contemporary ground level. The striking feature was that the area enclosed by planking comprised two adjacent compartments. These had been separated by framing whose position could be established by empty mortices. There must be some doubt about how this structure was used. The most likely explanation is that there were two wheels, set side by side. The wheel-bearing positions were indicated by exceptionally substantial vertical supports: however, what could not be established was whether two wheels rotated separately or on a common spindle. There is certainly a tradition of double mills in England. The excavation of the 17th-century double mill at Caldecotte, Buckinghamshire, provides an example, and the use of double mills has been investigated in Gloucestershire (10). At Chingley, however, one would have expected that if wheels had rotated independently, there would have been ground-level foundations on each side of the wheel-pit framing. In fact such timbers were only present on one side, and there was no evidence at all of equipment being mounted opposite.

Hence the conclusion that the wheels ran on a common spindle, an arrangement which allowed two compact wheels rather than one broad wheel, which would have been vulnerable to decay and damage, given the traditional methods of construction.

The final example of a wooden wheel-pit structure lies rather too far from the medieval to be a real part of this study. It is the final-phase structure at Chingley forge, in use into the 18th century. There is no firm construction date, which could lie as early as 1650, or as late as the early years of the 18th century. It is noteworthy for two reasons. One is the timber breast, a feature more often found built of stone, and normally associated with the early-to-middle 18th century development of the breast wheel and its close-fitting housing. This example raises the possibility that such features originated before 1700. The other point of interest is that the pit-casing was built in the form of a trough, mounted on cross-sleepers. It was found that the whole unit could be removed, leaving virtually no trace, and this has implications for excavations on sites where the location of a water-wheel has been hard to establish.

Stone wheel-pits have been found on fewer excavations in Britain. No medieval examples have yet been reported upon, and the earliest is probably at the 16th-17th-century bloomery at Rockley, Yorkshire. Here there were three pits, set along a stone-faced dam, with culverted tailraces and an overflow channel. This complex operated until the second quarter of the 17th century, but excavated and documentary evidence take the site back to c.1500. The best preserved features were a pair of stone-lined pits for overshot wheels, separated by a stone wall but with a common tail-race. Adjacent to each pit was a bellows building, one for a bloom-hearth, the other for a string-hearth.

Stone-walled wheel-pits can be found at ironworks in the Weald from the second half of the 16th century, notably at Maynards Gate furnace (c.1574 onwards). Scarlets furnace (1588-9 onwards) and an early 17th-century phase at Chingley forge. Of these three, only at Chingley was there a stone-flagged floor. At the other two, planks were used, the timbers being set beneath the stone side walls, an arrangement which made replacement peculiarly difficult.

The Supply of Water to the Wheel

The archaeological record is initially silent on the subject of the supply and direction of water on to the wheel. Whereas the timbers of wheel-pit frames survive, below the water-table, elevated troughs and shoots have vanished. At Chingley furnace a beam-slot was recorded, crossing the dam and aligned with the wheel pit. The vertical timbers at the back corners of the wheel-pit had rotted as they rose to meet the line of this slot. The back of the double wheel-pit at Chingley forge was formed of two rows of massive vertical posts, cut down when the pit went out of use, but originally supporting a water-feed. But neither in these examples nor in the medieval mills is it clear what kind of structure such timbers supported. Only at a much later site, Pippingford furnace, Sussex (1696) has a trough been found (11). This was a hollowed-out piece of oak 5.5m long, which had been re-used as part of a tail-race floor. The Flemish landscape painters portray simple open shoots not unlike this example at Pippingford, with some form of shuttle operated at the dam rather than in a box over the wheel. These troughs were set at a shallow slope, contrasting with Alpine, notably Italian feeds. By contrast Agricola's illustrations show water regulation taking place much closer to the wheel, more similar to systems illustrated and surviving from the mid-18th century onwards. What is not clear is which form was indicated by the term 'penstock' in the 16th century. The word was certainly in use, as shown by entries in the accounts for Panningridge furnace for the years 1542 and 1549.

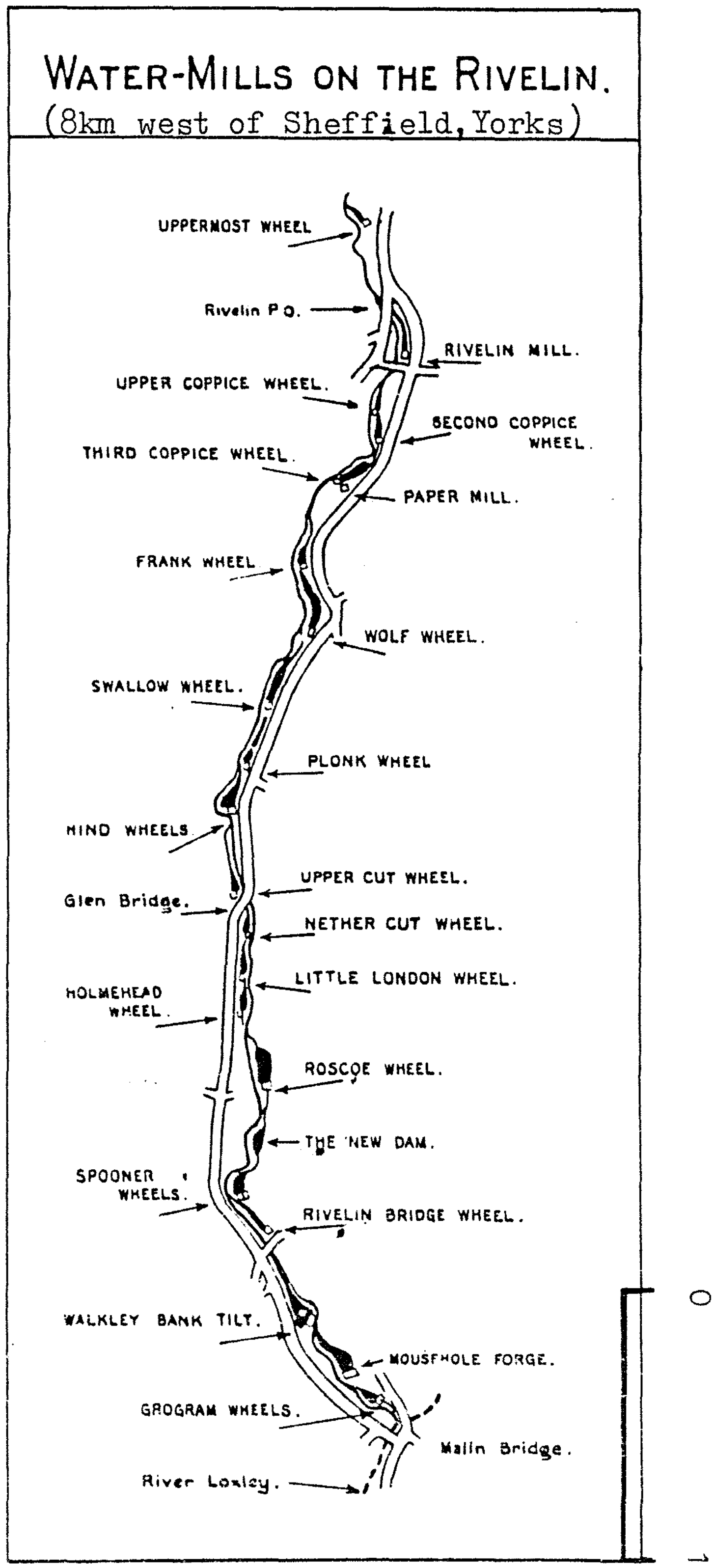
The failure of penstocks to survive has posed difficulties in attempting to calculate the power output of excavated wheels. It has proved virtually impossible to determine the head of water available above the wheel, thus removing an important variable in estimating the rate of flow into the wheel-buckets.

4. IMPOUNDING OF WATER (Figs 3 & 4)

a) The diversion of water into a channel parallel with the river served to provide reservoirs and a head of supply, as well as isolating water-wheels from seasonal variations in river levels. The documentary and archaeological evidence for systems of this kind is good. Descriptions of river-weirs diverting water into supply channels range from Gregory of Tours' well-known account of the weir and channel built for the Abbot of Loches in the 6th century to Fitzherbert's description of a weir in his Surveying of1539 (12).

On the ground, many weirs survive, often in positions used since the Middle Ages. In many parts of upland Britain and France there are weirs constructed of pitched stones, set between masonry or wooden kerbs (13). The use of wood can be explained by the need to set fish-traps in mortice slots in the lower kerb, and wash-boards, adjusting the height of the weir, at

Fig. 3. Series of by-pass ponds.



the top. Many such kerbs have survived remarkably well, in damp conditions, although the frequent maintenance which any weir requires inevitably means that few parts will date back to the Middle Ages. Stone kerbs naturally survive more readily, particularly when linked by iron staples, set into the stones with lead. Observation of deteriorating weirs has emphasised the maintenance costs faced by mill owners. Flood damage is an obvious risk, although minimised by the construction of weirs on a diagonal line across the river, spreading the load of storm water and debris. As significant is the action of tree roots. This is due to the accumulation of silt in the slow-flowing stream above the weir. Vegetation and eventually trees become established, and roots enter the structure of the weir, dislodging the stonework.

Many weirs have disappeared in the course of improvement of rivers for navigation. Their positions have to be inferred from those of surviving channels. This applies in the case of the Saxon corn mill at Old Windsor, on the Thames, where it would seem likely that a weir would be required to divert water into the lengthy head-race traced at the time of the excavation of the mill.

Sluice-gates, or shuttles, leading into head-races, have also been affected by later changes. Survivors have been re-equipped with modern parts, usually incorporating cast-iron racks and gears. Many have been obliterated, again by post-medieval river improvement, which has involved the construction of flood-banks and tow-paths.

Most head-races were no more than open ditches, at best revetted with stone walls or wooden piles, and often acting as land drains, gaining extra water. However, where space was limited, races were set along hillsides and here it was important for waterproof clay to be laid in the bed of the channel.

Tail-races should be considered at the same time, not least because as water became more intensively used, successive mills were fed with water direct from their upstream neighbours, forming in effect a power canal, without intermediate return to or supplement from the main stream. The tail-race had to allow free flow of water from the wheel-pit without impeding the rotation of the wheel. This was a real risk if the gradient were insufficient, or if obstructions were formed downstream. There are examples in the Sheffield area where tail-race flow was retarded due to the raising of downstream weirs, and at Panningridge, Sussex, the problem is graphically illustrated by the raising of the whole furnace and wheel-pit in about

1563, due to silting of the original race after the construction of Ashburnham furnace, downstream, about 1550.

Some mills had tail-races of remarkable length. There are examples in the Sussex iron region of channels several hundred metres long. One reason was that wheels were given maximum head of water by being set at a low level in relation to the adjacent river. To secure an outflow, a long tail-race was needed, at a gradient rather less sharp than that of the river itself. There are also excellent examples at Yorkshire forges; in one case, indeed, on the river Porter, close to Sheffield, the wheel-pit was set so low that the tail-race could actually be tunnelled under the river before emerging in a lengthy open ditch on the far side from the mill.

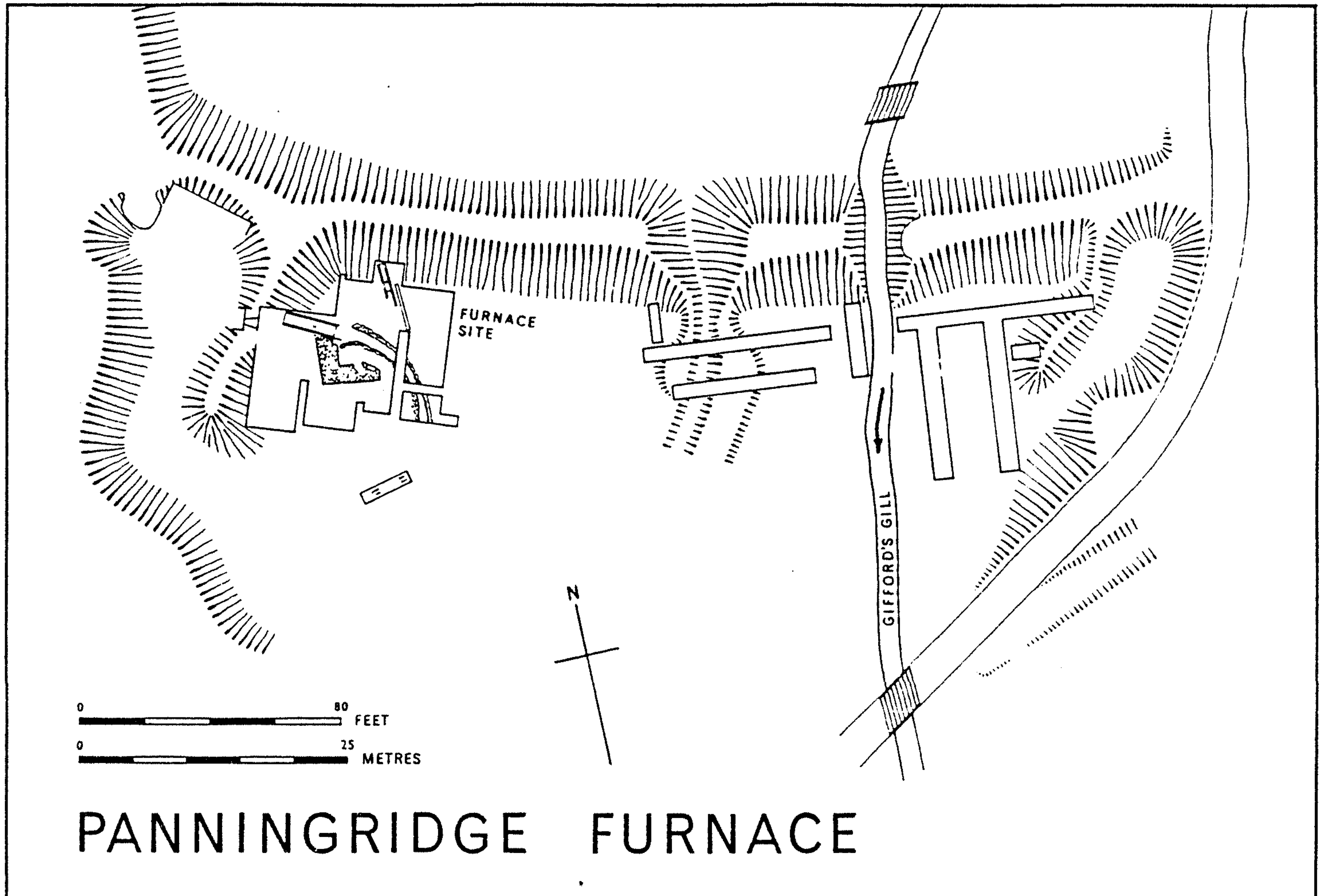
b) Cross-valley dams.

In certain districts it was more common for the water of a stream to be totally impounded, by means of a dam stretching from one side of a valley to the other. This method was favoured in areas of low rainfall, and is rarely found in the uplands. The iron region of south-east England is a good example where the cross-valley dam was in general use, except where valleys were too wide for the system to be feasible.

The system presents the field-worker with problems. When mills with dams of this kind passed out of use, ponds were often drained, either deliberately or as a result of erosion. The dams have often disappeared, except where preserved as road causeways or field boundaries. The extent of ponds, similarly, is hard to gauge except where fossilised in boundaries of fields reminiscent of those which William Camden saw converted into ironworks ponds at the end of the 16th century (14). These ephemeral remains contrast with those of the abandoned by-pass pond which, set on a shelf on the hillside, lies silting, but unaffected by the centuries' storm water which carries away its valley-bottom counterpart.

These problems reflect the difficulties which the original builders faced. A cross-valley dam had to withstand the heaviest flows, requiring one or more overflow sluices. Such storm overflows had to be routed clear of the furnace, forge or mill. There was a tendency for patterns of flow within the pond to erode certain lengths of the dam and to deposit silt against others. In one case piling was required, in the other dredging was necessary, particularly if a season's disuse had led to silting adjacent to the feed to the wheel.

Fig. 4. TYPICAL WEALDEN CROSS-VALLEY DAM



c) Dam Construction

The methods of building medieval and later dams have received limited attention, for in few excavations has it been possible to cut appropriate sections. At Panningridge furnace it was found that logs had been laid before the clay and earth of the bank was deposited. At Maynards Gate furnace the old topsoil had been stripped, and clay and sand laid without a foundation. At Chingley forge there were three successive earth dams laid between the 14th and the 17th centuries. An example of a stone-built dam-core was found at the furnace at Sheffield Park (Sussex), exposed during pipe-laying.

Material for dams was generally taken from the fringesof the pond: on a by-pass system quarried material from the hillside was carried to form the bank between the new pond and the river, creating a terrace which had to be waterproofed with puddled clay before impounding began. When additional capacity was required, dams were raised, as shown at Panningridge and Maynards Gate. Slags from ironworks were often used and additional support provided by revetments of timber or stone. At Westfield forge, Sussex,piles were set on both sides of the dam: at Wassell forge sandstone blocks have been exposed on the pond side, and at Huggetts furnace there is a stone wall on each side (15).

5. CONCLUSION

Although this group of examples shed considerable light on the methods and problems of the medieval mill-wright, the gaps in our coverage of this subject are all too obvious. The cases described are from one country, and it is hoped that excavated examples will be forthcoming elsewhere in Europe. Although the 16th-century iron industry and its use of water power is satisfactorily covered, much is left to be discovered about how earlier ironworks were powered. In particular, there is as yet no indication of whether the horizontal wheel had, in the west, any application beyond milling and crushing.

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SESSION 2

METALLURGICAL PROCESSES

THE TECHNOLOGY OF IRONMAKING

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SUMMARY

The technology of ironmaking is discussed with particular reference to pre-Roman times in terms of the ingredients used in the production (ore, charcoal, flux), the furnace arrangement and the methods used in attaining the required temperatures. It is shown how the underlying physicochemical principles determine the outcome of the smelting and how the early ironmakers empirically knew what conditions satisfied the physicochemical principles, i.e., yielded iron.

Ironmaking evolved differently in China than in the Old World. The technology used in China, based primarily upon the use of cast iron, is described and the more recent discoveries for both ironmaking and the manufacture of iron objects are mentioned.

Although this symposium has as its main theme medieval iron in society with particular emphasis on water power, metallurgical processes and the socio-economic consequences, I have been assigned the task of reviewing the technology of ironmaking in antiquity.

Ironmaking is taken as meaning the technology of both the smelting and fashioning of iron objects. The principles of ironmaking, that is, the physical chemistry of the reduction of iron minerals with charcoal as a fuel are, of course, independent of time.

How, when and where iron was first smelted are not known although some good guesses may be made about the how it was first made and identified. The dates and locations of the first smelted iron in the Eastern Mediterranean are discussed in detail by Waldbaum (1). Although the Iron Age is considered to have begun in the Eastern Mediterranean by 1200 BC, she documents a considerable number of iron objects prior to this time excavated from wide areas throughout this region, some as early as the 3rd millennium BC.

The identification of early iron as the smelted product is not difficult provided elemental and metallographic analysis on the objects are allowed and conducted. A good example of these types of analyses is described in a 1976 publication by Li Chung (2). Briefly, if the nickel content is between about four and 20 per cent and certain metallographic features, such as Neumann bands, a Widmanstatten structure or a fine grain size are present (depending upon the amount of nickel) an unambiguous identification may be made. Other characteristics such as the nickel-cobalt ratio and the presence and identification of non-metallic inclusions add to the certainty of differentiating smelted from meteoritic iron.

One suggestion of how iron was first "produced" comes from the technology of copper smelting. In the smelting of a copper ore containing silicious minerals as part of the gangue a flux such as hematite is considered to have been added to the charge in order to remove the silicious material. The hematite combined with the silicious material to form part of a slag (fayalite); the slag in addition to removing the gangue protected the smelted metal from oxidation and removed many harmful impurities from the ore. However, in the use of copper sulfide ores, reduction of the oxidized sulfides, dependent as it was on the oxygen pressure in the furnace, which in turn was dependent upon the supply of air from the manually operated bellows, a combination of iron with copper rather than copper alone often resulted. The thermodynamics of these reactions may be seen in App. A) reproduced from the studies by Yazawa (3). This illustration shows the relationship between the oxygen and sulfur pressures at 1300 deg. C. At low pressures of both oxygen and sulfur the equilibrium phase of the gamma iron results and gives way at higher oxygen pressure to copper; at higher sulfur pressure the slag and matte phases are in equilibrium. High oxygen pressure results in the production of magnetite. Since copper dissolves only a small amount of iron (less than 0.1 % at room temperature), in a mixture of copper and iron the iron precipitates from solution at the high temperature where it is soluble and may be recognizable as a distinctly different metal from the copper when the mass of the iron far exceeds that of the copper as is often the case. There are numerous reported cases of "magnetic coppers", as first pointed out by Aschenbrenner and Cooke (4). An example of this effect may be seen in the piece of "copper" from Sardinian nuragic context (Sa Sedda 'e Sos Carros in the district of Oliena, Nuoro Province) shown in App. B). This is a piece of copper-colored metal which, upon cutting, exhibited a solid core of iron. The copper, with its iron core may have resulted from an "uncontrolled" copper smelt. The detailed analysis of this and other such objects are outside the scope of this lecture; the point, however, is that iron most likely appeared first in this form.

Still another guess to account for the first "production" of iron would be what I believe were the continuing attempts at smelting any rock suspected of yielding metal. Once the idea that a colored or perhaps heavy brittle rock would, upon being heated with charcoal, yield a ductile, dense and fashionable material was known it would have set off somewhat of a frantic effort to smelt almost anything that was colored and/or heavy. This sort of experimental attempt may account for the curious piece of speiss excavated from the 14th century (BC) Hittite city of Hattusas. The piece of speiss indicates the attempt at smelting an "improper" mineral (in this case, one high in arsenic)(5). See, for example, App. C) which shows the analysis of what must have been a discarded result of a "poor smelt". Trial and error thereafter refined the smelting of the first "homogeneous" iron ore to a state where further development resulted in bloomery iron. An experimental phase in the development of iron technology must have occurred since the technology to produce a usable product was so different from the technology in practice for more than three millennia, i.e., the iron "did not liquefy" during the smelting. Iron was reduced from the mineral in the solid state, unlike copper, which was liquid at the smelting temperature as was silver and lead. Then, after it had been reduced it was not usable until the slag had been squeezed out with laborious effort. Both of these steps required a new technology. I expect that many years were spent in learning to develop these techniques.

In antiquity the smelting of a mineral required ore, fuel, refractories, flux, a furnace to hold the charge and a source of a forced air supply to attain and sustain temperatures in the vicinity of about 1150 or 1200 deg. C for about three or four hours.

Iron, after oxygen, silicon and aluminum is the most abundant element in the earth's crust; it is 715 times more abundant than copper, 1250 times more abundant than tin, 10,000 times more than arsenic, 500,000 times more than silver and 10,000,000 more abundant than gold.

Iron ores are of four types; oxide, sulfide, carbonate and silicate. The oxide minerals are:

Hematite (Fe_2O_3) containing when pure 69.9% Fe.

Magnetite (Fe_3O_4) containing when pure 72.4% Fe.

Limonite with variable iron content up to 62.9% (goethite). Limonite is the name given generally to various mixtures of the minerals goethite ($HFeO_2$) and lepidocrocite (FeO (OH)).

The limonites are hydrous iron oxides. These include the bog ores.

Ilmenite ($FeTiO_3$) contains 36.8% Fe with 31.6% Ti and found usually in association with magnetite.

The sulfide minerals are:

Pyrite (FeS_2) containing when pure 46.6% Fe.

Marcasite (FeS_2)(white iron pyrite) containing when pure 46.6% Fe.

Pyrrhotite (FeS)(magnetic iron pyrite) with 60% Fe when pure.

The carbonate mineral is:

Siderite ($FeCO_3$) containing when pure 48.3% Fe.

The silicate minerals, such as chamosite, stilpnomelane, greenalite, minnesotaite and grunerite, are chemically complex with little importance in antiquity except where they had weathered to the iron oxides.

Iron ores have a wide range of formation in geologic times found among the oldest known rocks as well as in various subsequent ages. Their distribution is wide with many thousands of deposits known with the size of a few tons to millions of tons. Their distribution in Europe and Turkey are shown in App. D).

The definition of an ore contains an economic element in that the composite, the mineral part of the conglomerate diluted by a "worthless" substance (known as the gangue), is an ore when it can be mined and smelted at a profit. Another aspect of the description of an ore concerns its proximity to the smelter. These two factors may have played a role in ancient times as they do today in that the early miner probably mined those sources richest and closest to his smelter.

Mining the iron would not have presented a difficult problem since they were most likely picked up from outcropings and hand-sorted to pick out the more concentrated minerals. Additional treatment may have been practiced by breaking the larger rocks into sizes found by experiment to be more productive in producing iron. We know this today as a way of permitting the hot reducing gases to permeate the charge of ore, fuel and flux; too large a size would result in incompletely reduced minerals while too small a size would reduce or even cut off the flow of the reducing gases. The early iron smelters would have soon discovered the optimum size of the ingredients to be added.

The fuel was almost always charcoal produced by the thermal decomposition of wood generally accomplished by heating of wood piled so as to allow a limited amount of air to circulate throughout the pile. Such a pile is seen in App. E) as the process is practiced in present day Crete. With the volatile gases (hydrocarbons, water vapor, carbon dioxide among others) removed, the result is essentially carbon containing some impurities that, in general, do not harm the smelted iron.

Since the various woods have different caloric value with oak being among the best, forests of oak were the first to be depleted soon followed by other trees. Various scholars have estimated the consumption of trees used in the smelting of iron. For example, Rostoker has estimated that it took about 125 trees to produce 100 kg of iron (6). This means that, as an example, the more than 6000 pieces of iron armaments excavated from the Urartian building destroyed at Hasanlu in the 7th century BC required on the order of thousands of trees. It is no wonder that, by the 15th century AD, the felling of trees for fuel for the production of iron was forbidden when the recently developed new fuel, coal became available. Coal, however, produced an inferior and mostly unusable cast iron for the cannon of Her Majesty's navy and charcoal was permitted just for that purpose until the technology for producing usable iron using coal was perfected (7).

Quite often, the charcoal was mixed with matter such as dung and straw. This mixture increased the caloric output of the fuel and produced a harder product by adding nitrogen to the iron. In parts of the world where oak was not readily available acacia, tamarisk and other trees or shrubs indigenous to the area were used.

Refractories for construction of the lining of the furnace and for the tuyeres had to be able to withstand temperatures of about 1200 degrees C as well as to withstand erosion during the time at the high temperatures. The outside stone layer must have been covered by clay probably applied to the stones as a paste. Much fuel would have had to be used to dry out the clay slowly to prevent cracks from forming due to shrinkage after which additional clay would have been added to build up the furnace to the desired size. I suspect that the success of a smelt required that the furnace be thoroughly heated before the charge of ore, fuel and flux was added otherwise attaining the smelting temperature would have been most difficult if not impossible.

Clays, the usual refractories in use in early times, are of different compositions which have a large effect on their refractory properties. For example, clays with fair amounts of soda and potash fuse at low temperatures while clays with large amounts of silica or alumina can withstand higher temperatures. It is likely, therefore, that suitable deposits of clay were recognized, and, hence, became as valuable as the ore deposits. Clays high in kaolin were the most desirable.

In the early days of iron smelting when bowl-type furnaces are considered to have been used, the refractory used in the lining was not required to have unusual strength; but as the height of the furnace increased, however, the refractories had to possess good mechanical strength to withstand the increased load of the charge.

Even with careful hand-sorting the minerals could not have been separated from the worthless component (the gangue) of the ore to produce a pure mineral by the techniques known in those times, such as gravity separation using water as the medium. Smelting is not only the chemical separation of the metal from the mineral at an elevated temperature but also the removal of this worthless component. These impurities are usually of a refractory character and, if not removed, would interfere with the production of the iron. A flux is added to render the gangue more fusible and thus permit the separation of the metal. As it turns out some impurities reduced with the iron are more soluble in the fused gangue-flux product, i.e., slag, so that the slag provides a medium with which the impurities can combine or in which they can dissolve. We know today that fluxes are classed either as basic or acidic and that a basic flux is needed to add to a iron ore with an acidic character or an acid flux for a basic ore. Consequently, crushed limestone would be added to a silicious iron ore while some form of silica such as sand or chert would be added to counteract a basic iron ore. The product of the chemical combination at high temperature of the gangue and flux produces the slag. A slag consisting of pure iron silicate (fayalite) mixed with pure wustite (iron oxide) would solidify at 1177 degrees C and would be very viscous at 1200. Ancient furnaces operated no higher than about 1200; hence, the slag would not separate from the reduced iron during smelting. Attempts were made early in the history of smelting to produce a more fluid slag by adding various products to the flux. For example, the addition of crushed bone to the flux substantially reduced the solidification point (the glass forming temperature in the case of the addition of a substance that prevented complete crystallisation of the slag) of the slag in some cases to as low a temperature as 900-850. In 1974 Gaskell and I added five per cent crushed and desiccated bovine bone to a lime-kaoline mixture and found that the solidification temperature (in this case the glass forming temperature) was reduced by as much as 300 degrees. We further found that the fluidity at 1200 was considerably improved (8). There are numerous reports of excavated crushed bone pits at iron as well as copper smelting sites (9). Seldom, however, were the ancient slags pure mixtures of fayalite and wustite; consequently, the solidification temperature was below the eutectic temperature of 1177. This was fortunate since the blacksmith could remove the slag from the bloom by hammering out the slag at temperatures below 1177, a most difficult temperature to attain in those days. Furthermore, a pure fayalite-wustite eutectic mixture, once solidified, could not be squeezed out at temperatures below 1177 deg. since the pure fayalite/wustite eutectic is brittle below 1177 and hence would shatter on hammering.

The volume of slag produced per kg of iron has been estimated by both Tylecote (10) and Rostoker (6). These estimates suggest that the ratio of slag to iron was about 3.5. Using our example of the Hasanlu hoard we would have to account for more than ca 10,000 kg of slag in this case alone to account for the armaments excavated.

Although there have been numerous reports of the discovery of iron smelting furnaces or sites in the Eastern Mediterranean, these usually have turned out to be incorrect interpretations. Often these furnaces were later identified as kilns or blacksmith hearths.

Smelting of an iron mineral can occur theoretically at any temperature but yields significant amounts in reasonable times only at temperatures in excess of about 1100 degrees. These temperatures are difficult to attain with charcoal as a fuel in small volumes such as crucibles. The furnace must have a minimum size to permit the heat of the carbon combustion to be retained within the volume of the furnace. This requires sufficient refractory mass to prevent loss of heat through the walls and reflect the heat back into the charge. Although some heat is lost through the furnace walls, most of it is lost by the exiting combustion gases, CO_2 and CO. Putting a roof on the furnace such as was done in the kiln would reflect much of these losses but that seems not to have been done in the early smelting furnaces. By restricting the furnace opening at the top a sort of reflecting surface results and this appears to have been done in the development of the early copper shaft furnaces in China (I will discuss this in greater detail below as it applied to the early iron production in China).

The reconstruction of the earliest iron smelting furnaces are based upon adaptations of copper smelting arrangements. Many of these are shown in the volume by Coghlan (10) and Tylecote (10). App. F) shows a few suggested configurations (11). It is likely that the first iron smelting furnaces were, like their earlier copper counterparts, simple bowl-shaped cavities lined with stone and covered with a refractory lining. Ceramic tuyeres were inserted from the top of the furnace or fed in from holes in the sides of the furnace. Since the product of the smelt was a solid iron sponge the interstices of which were filled with slag it would have been difficult to remove the mass from the top although this could have done by using green poles. It is more likely that the furnace was permitted to cool after which the furnace was destroyed and the mass removed to be reheated in a separate hearth for further processing. Perhaps this is why there have been few,if any, iron smelting furnaces excavated.

There have been attempts at classifying prehistoric and medieval iron smelting furnaces, notably by Pleiner (12) Martens (13), Serning (14), Cleere (15) and others (16), these classifications refer mainly to post-Roman periods. There has yet to be excavated a pre-Roman iron smelting furnace from the Eastern Mediterranean. Nevertheless, most scholars agree that the type A, i.e.,the sunken pit and bowl-shaped arrangements were most likely the earliest configurations used for iron smelting.

Without a shaft a natural draft of air could not supply sufficient air to attain the needed smelting temperatures. The bellows had been known for some time by the advent of the Iron Age and examples of pot bellows in use during the MBA and the LBA are shown in App. G) taken from the study of Davey (17). Where the tuyeres are positioned is of great importance as has been shown by Tylecote (18). For example, only at about 15 cm from the wall at the tuyere level does the temperature reach 1200 degrees. At 10 cm above this area the temperature drops below 1200. Hence, in a furnace about 2/3rds of a meter in diameter, the volume for the smelting is about 26 cm in diameter and only 10 cm high. Assuming a cylinder 13 cm in diameter and 10 cm high in which most of the smelting occurred a weight of pure iron of only 40 kg could be produced. This amount would be further reduced to about 25 kg since the volume contained a mixture of iron and slag. This low production could have been overcome by having a number of furnaces operating at the same time.

Smelting results from the CO gas which is produced when the charcoal first reacts with the air at the tuyere as it enters the furnace to form CO_2 which in turn reacts with additional carbon to form the CO. It is the ratio of the CO/CO_2 that is of importance. In iron smelting this ratio must be greater than about 3.

The subject of iron mineral reduction is more readily comprehended with the application of physicochemical considerations. Time, however, permits only a brief discussion of the concepts as they refer to the reduction process alone. The subject of the atomistics of gas diffusion and the sintering of particles, also necessary in an understanding of ironmaking, can be found in any undergraduate level metallurgy textbook.

To determine if the reduction of a mineral will occur a thermodynamic property known as the free-energy change for the reaction at various temperatures (and pressures) should be considered. In a general form:

$$\frac{2x}{y} M + O_2 = \frac{2}{y} M_x O_y$$

where M and M_xO_y are metal and metal oxide. For pure metal and metal oxide a constant K is defined as related inversely to the equilibrium pressure in the system as:

$$K = \frac{1}{p_{O_2}}$$

Here p_{O_2} is the standard pressure of oxygen at the temperature we wish to consider. The standard free-energy change for oxidation (the same for reduction) is given by the relation:

$$\Delta F^o = -RT \ln K = RT \ln p_{O_2} = 2.303 \; RT \log p_{O_2}$$

where ΔF^o = the standard free-energy change

T = temperature (deg. K)
R = the gas constant

Free-energy data, first compiled by Ellingham (19) and modified by Richardson and Jeffes (20), are shown in App. H) for various oxides. In this figure the standard free-energies of the oxides are plotted against temperature. The tendency of an oxide to decompose, or to form at a given temperature and pressure, is easily determined from the relative positions of the free-energy lines. Thus, carbon as a reducing agent is easily revealed as being able to reduce many oxides. The oxides for which the free-energy lines are above CO, such as Fe, S, Ni, Cu, are reduced by CO while those below, such as Cr, Mn, Si and others, (1200 deg) are not.

The case of Cu is of interest for us. Above 700 the free-energy line for Cu_2O is below that for Fe_2O_3 and at temperatures above 700 Cu reduces Fe_2O_3 to Fe_3O_4.

The diagram can be used together with one constructed in the same way for the CO/CO_2 ratio from which it can be determined at what ratio there will be oxidation or reduction. These ratios have been determined for blast furnaces; nevertheless, the same principles apply to the technology of ancient ironmaking.

The mechanism to show how solid iron oxides are reduced has been studied by a number of scientists (see, for example McKewan (21), Quets et al,(22) Rao, (23)). In a series of scanning electron microscope photographs Rao has documented the morphology of particle reduction and formation to the sponge shown in App. I). Small particles of reduced iron conglomerate and, on coming into contact with other particles, sinter together but are prevented from growing to large size by a coating of liquid slag that in the end fills the voids of the sponge. This spongy mass of coalesced iron particles (relatively pure ferrite grains), containing pockets of slag throughout has to be hammered at high temperature to expel the slag thereby compacting the mass into a bloom forgeable into usable objects. We call this today a direct reduction process. It remained the only process in the Old World until the development of the blast furnace that produced a high carbon product requiring a decarburising step to render a low carbon forgeable product. This process hence became known as an indirect process.

In Africa the direct process is still in use today; van der Merwe and Avery (24) suggest that the process may have been introduced into sub-Saharan Africa from the North African coast or Egypt/Nubia by ca 800 BC by Phoenician maritime traders. In Nigeria iron smelting occurred at Taruga as early as 400 BC using pits cut into soft rock containing shafts and bellows i.e., little different from those in the Eastern Mediterranean. There are other pathways by which iron may have been introduced into Africa and these are discussed by van der Merwe and Avery (24).

Schmidt and Avery (25) describe a method in use today that may have originated quite early (how early is not known). By positioning the tuyeres well into the furnace thus preheating the air the temperature in the reducing part of the furnace can reach as high as 1800 degrees C, i.e., well above the melting point of iron. The mechanism for the growth of iron crystals are sufficiently different above the melting point to result in a "pure" iron without slag since the slag at these high temperatures is fluid and permits the separation of the iron. Another innovation in the African method was the erection of a shaft high enough to produce a draft strong enough so that a bellows was not required. Here, again, how early this development was in use is not known.

Iron appears in Europe more than sporadically during the 8th century BC towards the end of the Hallstatt period when iron was used for tools as well as weapons (Late Hallstatt-7th/6th century BC) (26). Although the volume of iron increased dramatically during the La Tène period there does not appear to have been a major development in the technology of iron production. Rather there seems to have been an extensive experimental phase concerned with the production of a variety of artifacts. One change did take place towards the end of the first millennium in that the early ironmakers introduced a slag-pit furnace which rapidly spread to various parts of Europe and into the southern Scandinavian regions. It was during these times that the first "shaft-type" furnaces began to take shape (26). A model of such a furnace is shown in App. J) taken from a recent publication by Pleiner (26). Such a structure would permit higher temperatures above the tuyere level, some high enough to permit separation of more of the solid iron from the now more fluid slag.

In China the production of iron proceeded along different lines. The first iron appears ca 7th century BC in the form of a completely corroded bar not yet, as far as I know, tested. A bloomery iron bar, ca 500 BC, has been studied by the group at the Beijing University for Iron and Steel Technology under the direction of T. Ko who considers the object to have been produced by the decarburization of cast iron. Cast iron has its first appearance in the 6th century in the form of some items with cast iron legs. After this the development of iron takes two paths; one proceeds with the use of bloomery iron while the other is the development of a technology based upon the use of cast iron. There has been excavated a casting (470 BC) consisting of an outside cast iron casing with a steel inside shell considered to have been produced by the decarburization of the inside cast iron layer (27).

Malleable iron shows up at the beginning of the fifth century BC (early Warring States period) and by the beginning of the fourth there are abundant iron farming tools. In attempting to determine the technological reasons why iron developed along these lines in China we must first examine the technology of copper smelting during the beginning of the first millennium. In the excavation of the ancient copper mine at Tonglushan in Hubei there were unearthed parts of several copper smelting furnaces.
The reconstruction of one of these furnaces, App K, shows a shaft; the base diameter is 1.2 to 1.5 m and the estimated height is 1.5 m above the floor of the furnace. There were blast apertures and an opening for tapping slags as well as for the molten copper. Such an arrangement when used for iron production with a good air supply and charcoal as a fuel would easily have reached temperatures as high as 1350-1400 degrees C. At these temperatures the diffusion of carbon in iron is sufficiently rapid to increase the carbon content thereby reducing the melting point quickly to the eutectic temperature at 1152 degrees C (see App. L) Cast iron is a term given to iron with a carbon composition of more than about three per cent. Liquid metal at these temperatures can readily be cast.

The term "cast iron" refers to an iron containing on the order of 3 to as much as 5 per cent carbon. This much carbon reduces the freezing point of the iron from 1537 to 1152 degrees C (at 4.27 per cent). Iron castings today are grouped into chilled-iron, gray-iron, malleable and nodular iron depending upon how they are made and cooled. Their hardness varies from 100 to 500 (Brinell Hardness Number). At fast cooling rates such as in chilled-iron the resulting metallurgical structure is referred to as white iron, i.e., the carbon is combined in the iron in the form of iron carbide. This variety of iron is hard but brittle and not suitable for the bells which appear to be the earliest uses for the castings, i.e., white cast iron has poor impact properties.

Malleable cast irons are not really malleable but they are softer and can withstand a small amount of ductility such as slight bending without breaking. There are two types characterized by the resulting properties and the process used in producing the iron; white heart (European) and black heart (American). In the white heart iron the carbon is reduced by heat treatment to values as low as 2 to 2.5 per cent whereas in the black heart iron the form of the carbon is changed to an uncombined graphite with a nodular shape. Hua Jueming, from the Foshan Institute for Nodular Graphite Cast Iron in the PRC (28), considers that the development of this process occurred perhaps as early as the Spring and Autumn Period (Eastern Chou-770-475 BC) and certainly by the Warring States Period (475-221 BC). Other scholars favor the development of malleable iron sometime during the Warring States Period. Cauldrons and balls from Changsha dating from the 6th century and plows, spades, sickles, axes, adzes, chisels, arrows and clothes hooks have been excavated. Iron moulds for casting instruments and weapons have also been uncovered from Xinlung. Metallurgical studies (28) of excavated objects (an iron pick from Tieshenggou and the Mianchi Han Wei iron plough share) show the presence of spherical graphite in the microstructure but not however, in sufficient amounts to have effected seriously the properties of the iron.

In present day technology various chemical elements are added to control the structure and hence the properties. For example, silicon promotes graphitization while the addition of cerium or magnesium promotes a spherical form of the graphite. Incidentally, this process was introduced in AD 1948! In ancient China the malleable iron is considered to have been made in a process in which the iron was annealed in a kiln or furnace at high temperatures for a time sufficient to allow the iron carbide to decompose into the ferrite and graphite flakes that formed into spherical shape. The research of the group at the Foshan Institute makes it clear that inoculants were not responsible for the nodular arrangement of the graphite as they are today.

Uncarburized iron followed by steel was made early in the Chinese Iron Age (some say as early as the late 9th or early 8th Century BC for forgeable iron) by the decementation of cast iron (29). One of the six scissors excavated from the DongshiMa village, Zhengzhou in 1974 examined metallographically is reported to have a homogeneous structure with a carbon content of 1 %. The thicker section contained some graphite globules different from that produced by graphitization of steel. Two other of these Eastern Han Period scissors had carbon contents of 0.55 % and 0.4 % with non-uniform pearlite distribution in the one case and a uniform spheroidized carbide distribution in the other. No evidence for quenching was detected presumably because of severe corrosion. Other objects, an iron knife with a forged ring from a Western Han tomb at Da Bao Tai in Beijing, a Western Han forged steel knife from Nanyang, another Han steel knife from Yinquashan, Shandong as well as objects from the Guxing excavation (see below), Eastern Han chisels and more than 300 arrowheads from the Yiu Sheng tomb in Mancheng (113 BC) show steel with different carbon contents all made by the decarburization of cast iron. These studies leave little doubt that a decementation process was in constant use at the end of the first millennium BC (30).

A good variety of steel was produced early in a process known as the Bailian Steel (steel of a hundred refinings), a term "thousand beatings and hundred refinings" still in use in China today. The term itself does not appear in the literature until the end of the 2nd century BC. In 1974 a knife was excavated in Shandong containing an inscription in gold "A knife made of steel of 30 refinings, made in the fifth day, fifth month of the sixth year of the reign of Yongchu for propitious omens" with a further inscription buried beneath the thin veneer of rust reading "for the good fortune of the descendants" (31). This corresponds to AD 112.

Han Rubin and Ko Jun at the Beijing University for Iron and Steel Technology have examined this knife (31) and report the presence of the constituents of steel (pearlite and some martensite). By studying the inclusions in a knife from the tomb of Xu Meiran (AD 299), a Han knife (AD 1-25) and an octagonal steel rod from an Eastern Han tomb at Dongfu Dajie, along with a steel rod from a tomb near Nanjing dated to ca 500 BC considered to have been made by the direct reduction of the carbon, cemented steel swords from the burial ground of the Yen State (ca 3rd Century BC), steel swords from the tomb of Liu Sheng (113 BC) as well as the steel chisels left by grave robbers in the coffin of the eldest son of Han Wu Di (Liu Dan-80 BC) they conclude (from other evidence as well) that the Yongchu and Xu Meiran knives were made by puddling high carbon iron (pig iron) to reduce the carbon to an equivalent carbon content of a high carbon steel and then forging, folding and forging again repeatedly for as many as 30 times. The term "hundred refinings" is now considered to mean the quality of the steel where 100 refinings is the highest quality as compared with 30 and 50 refinings.

The smelting of the iron seems to have changed dramatically by the Han Period (206 BC to AD 220). Ten years ago scholars from the museum of Zhengzhou excavated an iron smelting arrangement about 20 km from Zhengzhou (from the ancient city of Xingyang, an important city in the Qin and Han Periods) considered to have been from the Han Period (see map App. M). The remains included hearths from two large shaft furnaces along with several salamanders, some weighing more than 20 tons each. Inscriptions from castings and moulds indicate the remains to have been from "The first Iron and Steel Works of Henan Prefecture" of the Han Dynasty. In the operation of an iron blast furnace continuously the refractory of both the wall and the sides of the furnace are eaten away and are replaced by iron of approximately the same composition as that of the iron being produced. This replaced wall material is called a salamander. Such a salamander "in situ" is shown in App. N).

The total area was 400 by 300 m of which 1700 sq. m have been excavated. There were two foundations of blast furnaces, one being elliptical in cross section with the major axis 4 m and the minor axis 2.7 m for a total area of 8.5 m. The walls were on the order of one m thick supported by rammed earth some parts of which were 6 m thick. It now appears that the earliest of the furnaces (known as the Guxing Blast Furnaces) may have dated from the Western Han (206 BC to AD 24) and the other from the Eastern Han (AD 22 to 250). The refractory linings have been studied by Lin Yulian of the Luoyang Institute of Refractory Research and Yu Xiaoxing from the Zhengzhou museum of Henan province. Their first report (32) describes the furnace as having been built by ramming different material into the various parts of the furnace, i.e., the stack had been built with rammed clay and the bosh, hearth and bottom from a carbon containing refractory. The bottom of the furnace was situated about 3 m below ground level on a foundation consisting of 12 layers of a rammed mixture of clay, iron ore and charcoal dust containing pebbles about 1 to 3 cm in size. There were buried in front of the furnaces 9 salamanders three being more than 20 tons each. One of them is described as elliptical with measurements similar to one of the excavated furnace, i.e., 3.24 m long, 1.72-2.13 m wide and 0.42-1.1 m thick, with some refractory still attached. One of the salamanders contained 4-4.5 % C, 0.2-0.3 % Si, 0.2-0.3 % Mn, 0.24-0.38 % P, and 0.06-0.11 % S; this is a typical gray cast iron composition. The bosh angle (62 deg) and its height (80 cm) and shaft angle (90 deg, i.e., perpendicular to the ground) were measured.

They calculate the height to have been 6 m with an effective volume of 50 cubic m or certainly the largest furnace excavated to that time since earlier furnaces normally had hearths of 1 to 2 m. These salamanders would have been too heavy to have been lifted out of the furnace or to have been broken up; they were most likely pulled out during the reconstruction of the furnace and buried underground according to the excavators.

The archaeologists discovered a large quantity of pottery pipes with internal diameters of 26 cm and wall thickness 1 cm each pipe having a tapered end, presumably to be able to connect one to the other. The outside of the pipes were covered with a mixture of straw and clay showing signs of melting. The tuyeres had to have been placed perpendicular to the long axis of the hearth for the blast to be located at the center. They consider that there had to have been four tuyeres, two on each side. No blowing apparatus was excavated. They think, however, based upon relief drawings in literature of a Han forge, that the bellows were made of hide. No sign of mule or hydraulic power was found.

There was found close to the furnaces a pile of crushed and screened hematite (about 300 tons), lumps of about 2-5 cm with some lumps as large as 20 cm. The ore contained about 48.4 % Fe and was low in both S (0.054 %) and P (0.068 %). Iron and stone hammers were excavated.

The slag in the area, fully melted and glassy, had a melting temperature of 1030-1090 deg C. The basicity of the slag suggests that limestone had been used as a flux. A second variety of slag, of lesser amounts, was black and contained iron particles. They are thought to have come from 'irregular' operations.

In addition to finding briquets of charcoal made from oak there were briquets of coal believed to have been used for heating or for use in kilns. The excavators are not aware of any evidence to suggest that coal was used as part of the blast furnace burden.

There is disagreement among scholars on the question of supplying sufficient air to a hearth with such a large volume, i.e., 50 cubic m. There are those (33) who think that even with four double-action bellows, such as the one shown in App. O), air pressure to such a large volume could not have been supplied. The suggestion has been made that the smelting technology at Guxing was not a blast furnace but rather a kiln. In the smelting of iron minerals below the melting point of the iron (1537 deg C) temperatures on the order of 1300 to 1400 are needed for the carbon from the CO, the CO_2 and the charcoal to diffuse into the iron at a sufficiently fast rate to reduce the melting point of the carbon-iron (along the liquidus line of the gamma + liquid) to the eutectic composition and temperature (see the iron/iron carbide phase diagram, App. L). In a large kiln, considered to have been in use early in China, the heat from the combustion could build up by reverberating against the roof and walls raising the temperature to the 1300-1400 range. Such an operation would have required refractories for the kiln able to withstand these temperatures.

Dr. Li Jia-zhi, Director of the Institute of Refractories in Shanghai, however, has determined that by the Han Period refractories were able to withstand temperatures no higher than 1150 (34). Franklin (35), on the other hand, has recently suggested that the air from the tuyeres could have been pre-heated thereby raising the sensible heat so that the high temperatures could be achieved. Since the temperature increases to its maximum a distance away from the wall the refractories used in the hearth wall need not have withstood the high temperatures in the smelting zone provided each smelting was not too long. The evidence for this idea may be found in the excavated tuyeres many of which showed evidence of having been heated from the outside. The excavated coal briquets may have been used for this purpose.

The reason the hearth was elliptical, say the excavators, was to permit the blast to reach the 'center' of the hearth by positioning the tuyeres perpendicular to the long axis axis of the elliptical cross-section. This geometry will not satisfy the pressure requirement for the volume. The operation of four bellows of the type shown in App. O), considered to have been in use by the late Han Period (36), even operating hydraulically, would not have been able to supply the air pressure (33). How the air was supplied, hence, remains an unsettled matter at the present time.

Many clay patterns for permanent iron moulds were found in the vicinity. Some had inscriptions such as "He-1" to be part of the iron mould. There were as many as 13 ancillary furnaces close by considered to have been used for annealing and heating.

Among the more than 300 iron artifacts found, mostly farm implements, there were tools, ratchet wheels, carriage axles many of which have now been examined metallographically. Iron plates, cast and then decarburized to a steel with 0.1-0.2 % carbon, served as the starting material for forging into other objects.

So far, some 17 to 18 sites of ancient ironworks have been discovered, some of which were used for foundries, some for making iron and some for making steel artifacts.

Stack casting is thought to have been in use in China by the 6th century BC (37). Hua Jue-ming has studied remains of stack casting foundries from Henan, Shandong, Shaanxi and Jiangsu provinces and reports a major stack casting industry. In one case a kiln with several hundred intact sets of moulds were excavated. Stack casting is a process in which a series of moulds are stacked one on top of the other and fed with molten metal from a common duct greatly reducing the cost of casting copies of the same object (see App. P). There is a good discussion of this technique by Hua Jue-ming in the January 1983 issue of Scientific American (37).

The iron-mould founding technology was apparently well developed by the Qin and Han Dynasties (221 BC-AD 220). Bronze founding techniques had been developing during the Shang and Chou Periods (1500-221 BC), particularly the horizontal stack moulding of copper boxes, and no doubt were influential in the development of the iron-moulding process. Li Jinghua of the Henan Institute of Cultural Relics in Zhengzhou (38) has studied this process from the remains of ancient loam moulds excavated in the Nanyang and Guxing districts. There were two stages in manufacturing the iron mould. The different sets of moulding equipment were put together and filled with loam moulding material. The two piece loam moulds were closed and strengthened and insulated with a mixture of straw and loam paste on the outside. These closed moulds were baked after which the metal was poured into the hot moulds. With one set of a six piece loam mould there was produced one set of a three piece iron mould that then was used to cast farming implements, among other objects. Examples of farm implements excavated from Guxing are shown in App. Q). There were developed sophisticated methods for knocking off the risers without damaging the castings, for inclined pouring rather than vertical and the use of gray iron moulds rather than the white cast iron types common during the Qin and Han Periods.

The technology of ironmaking, as advanced as it was in China, lagged considerably behind in the Old World. Up to at least Medieval times ironmaking continued to be essentially a bloomery process with furnaces having little capacity. The several anchors excavated from the AD 11th century Serçe Liman shipwreck were constructed from as many as seven sections welded together to make each anchor (see App. R) (39). This method of manufacture is consistent with the calculation of the mass of iron able to have been produced from one direct process furnace (see above). Although a smelting technology to produce cast iron followed soon after, it wasn't until the middle of the 16th century AD when English ironmakers built twin furnaces were they able to smelt a sufficient volume to cast one entire cannon (40). The introduction of the indirect process as differentiated from the direct or bloomery process in the 15th century in the Old World soon enabled those ironmakers not only to catch up but surpass the Far East ironmakers in ironmaking development.

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The review and comments by Professor James D. Muhly of an early draft of the manuscript were useful and much appreciated. The financial support of Jernkontoret to attend the symposium in Klackbergsgarden, Sweden is gratefully acknowledged.

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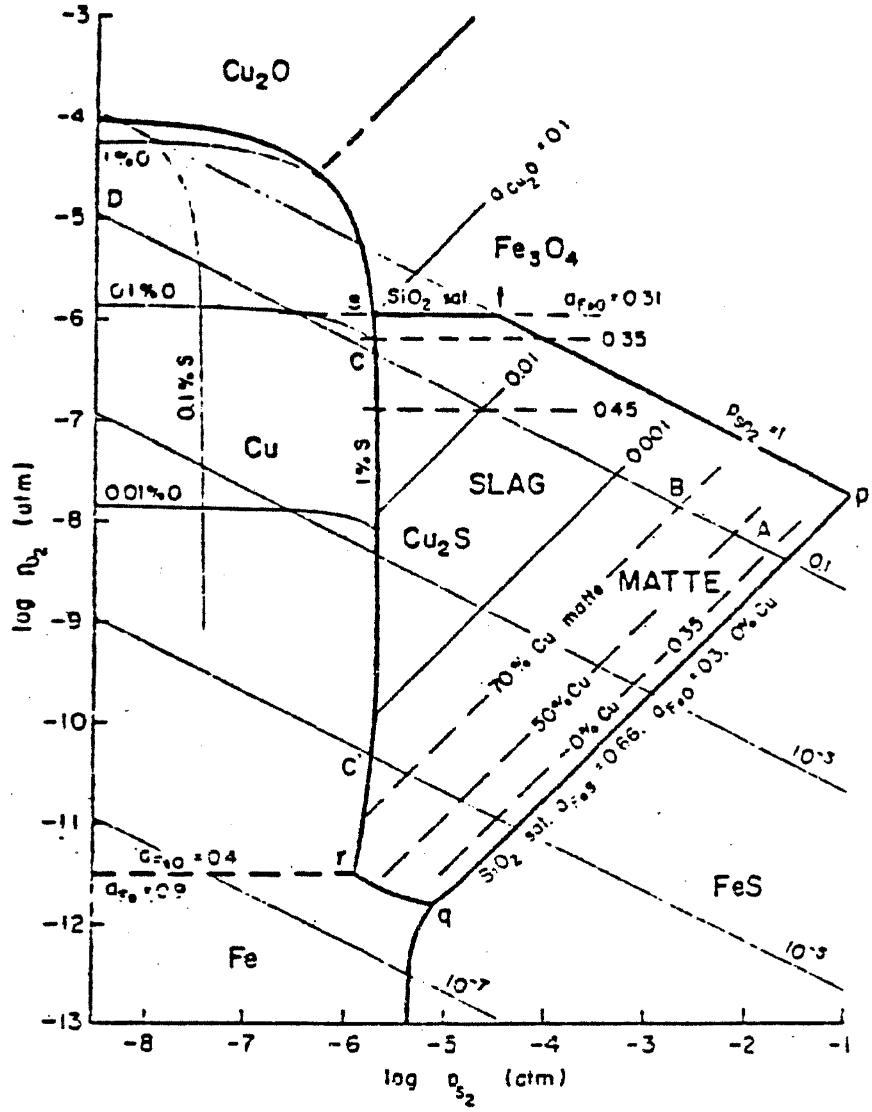
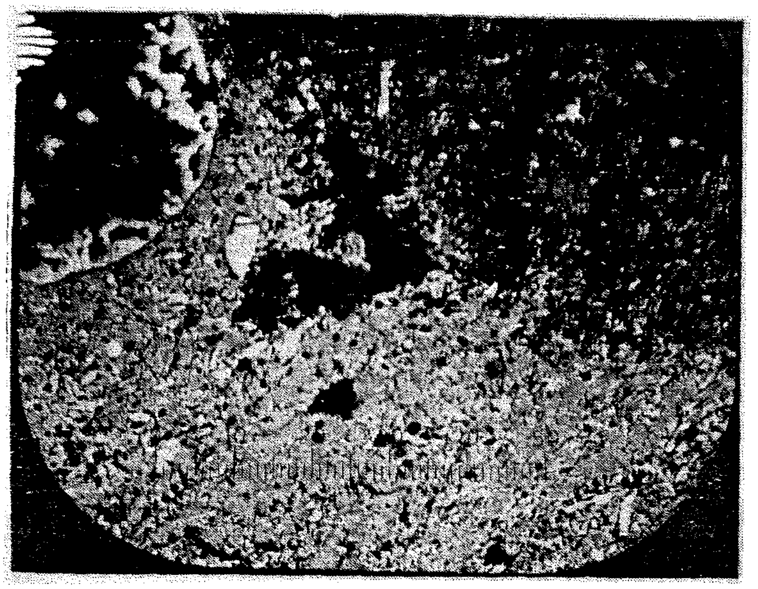
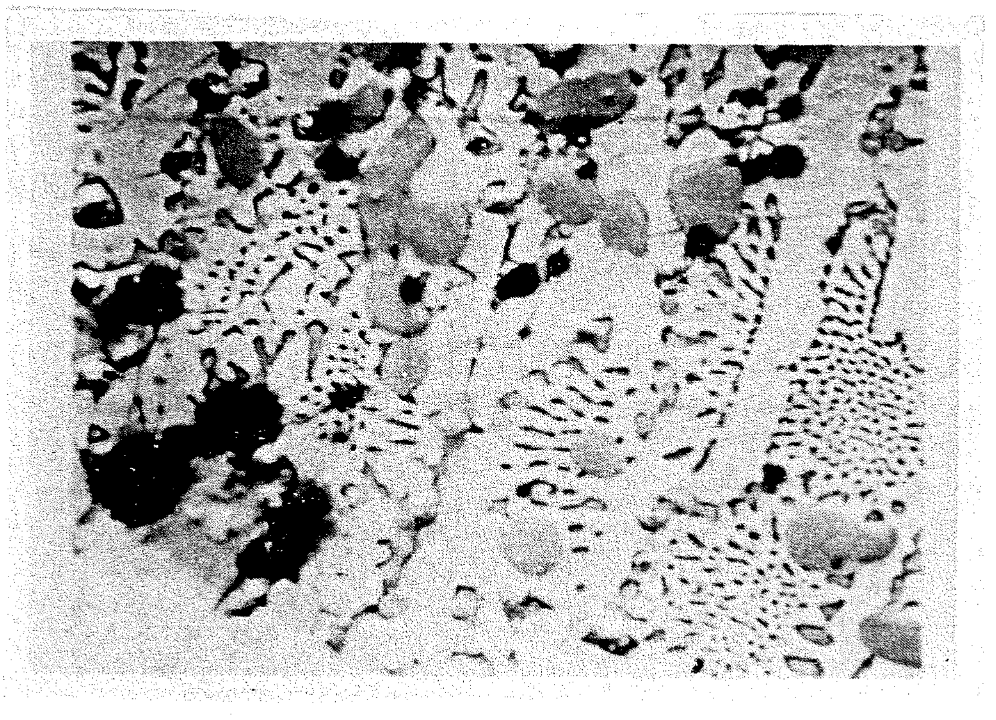


App. A) Sulfur-oxygen potential diagram for the system Cu-Fe-S-O-SiO_2 at 1300 deg. C (after Yazawa)

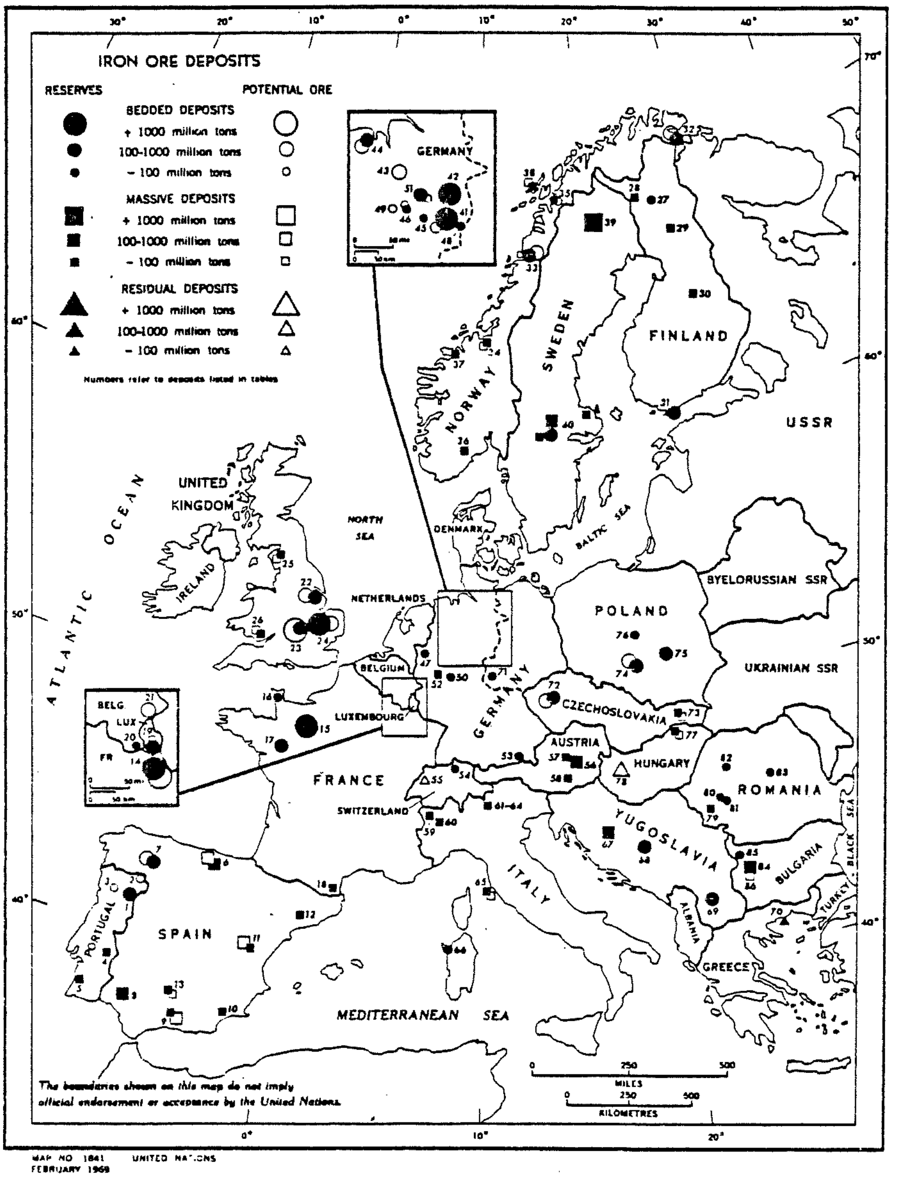


App. B) Metallurgical microstructure of a fragment discovered from Sa Serra 'e Sos Carros in the district of Oliena, Province of Nuoro, Sardinia. The structure is unetched; the large particle in the upper left is a copper prill. Additional smaller copper prills are dispersed within the iron matrix. The fragment is strongly magnetic (x50). (The kind permission of Dr. Fulvia LoSchiavo to refer to these results is gratefully acknowledged).



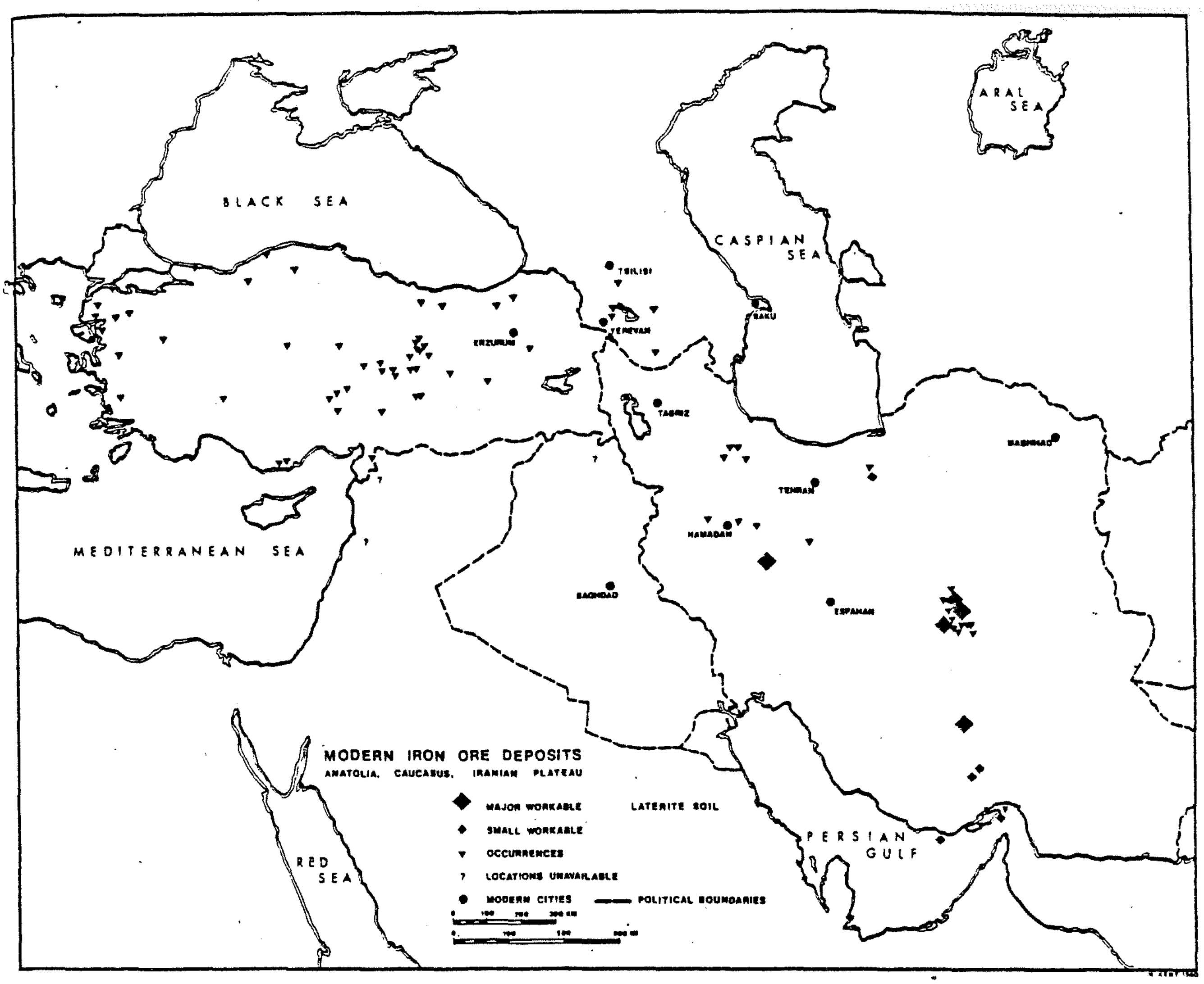
App. C) Scanning electron microscope photomicrograph of the structure of an object of Hittite origin excavated at Boğazköy. The structure consists of a series of iron arsenic phases produced in the smelting of an iron mineral containing arsenic or an iron-arsenic mineral. In these cases smelting gives four layers, iron, matte, iron-arsenic (speiss) and slag. The iron, the speiss and the matte are too brittle to forge into a useful object.

D(a)

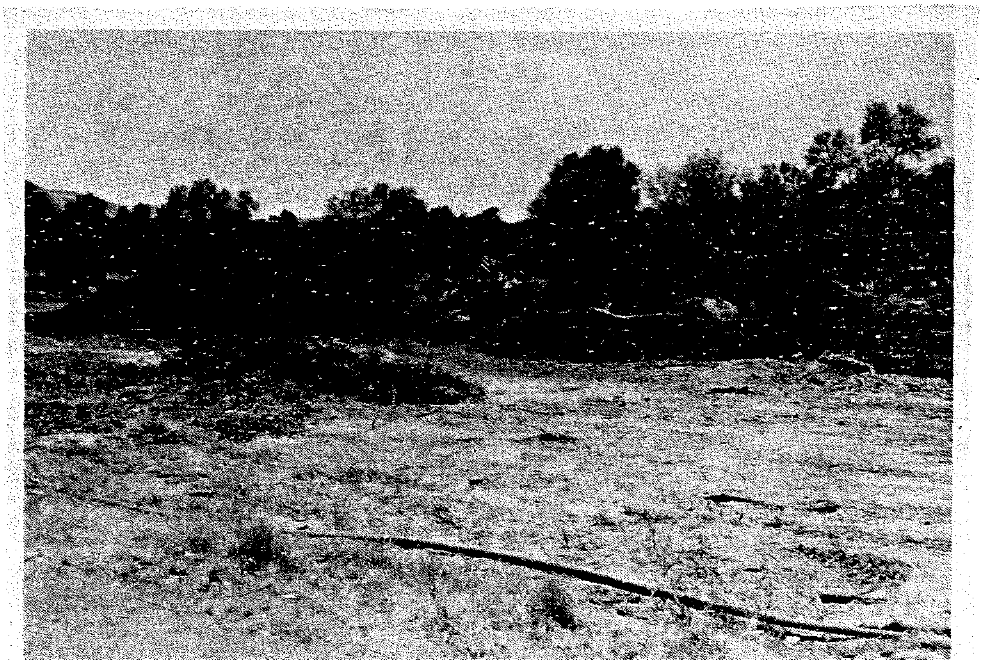


Map showing iron ore deposits of Europe

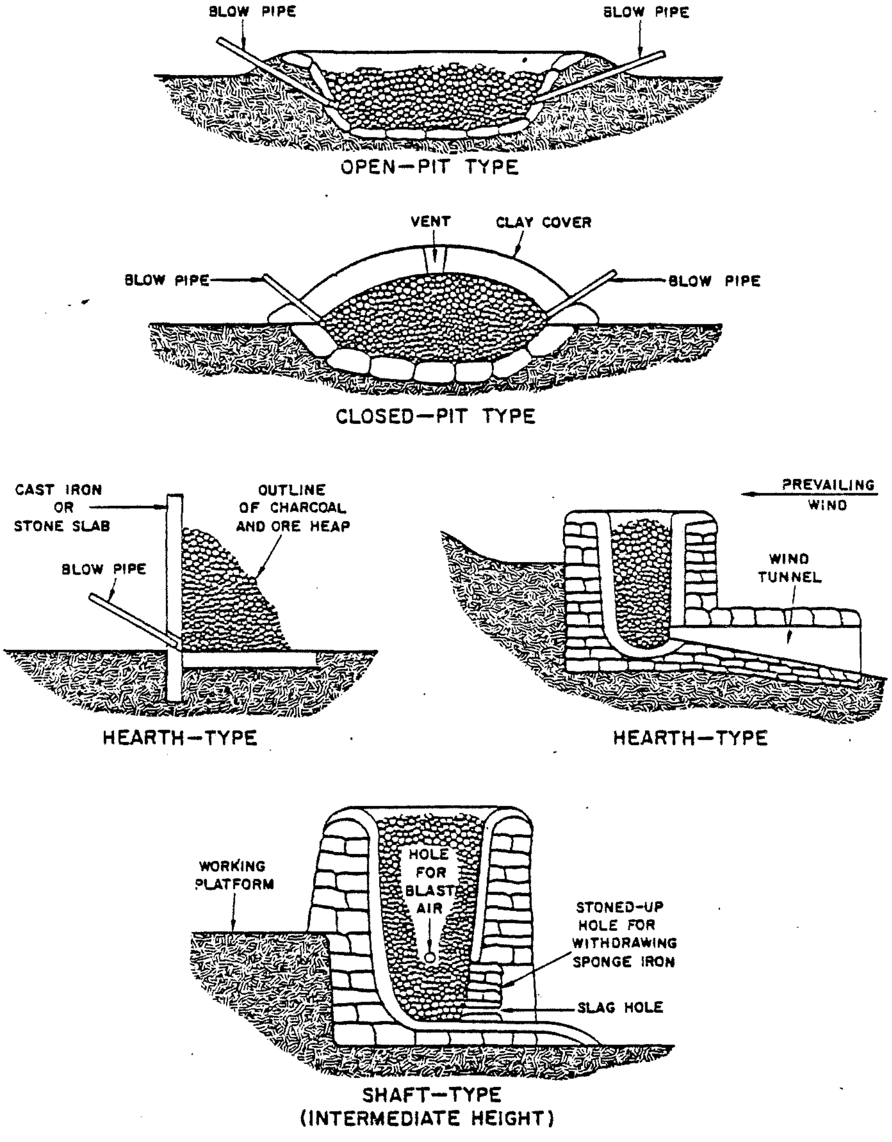
App. D) Modern iron ore deposits in Europe (a)



App. D) Modern iron ore deposits in Turkey (b)

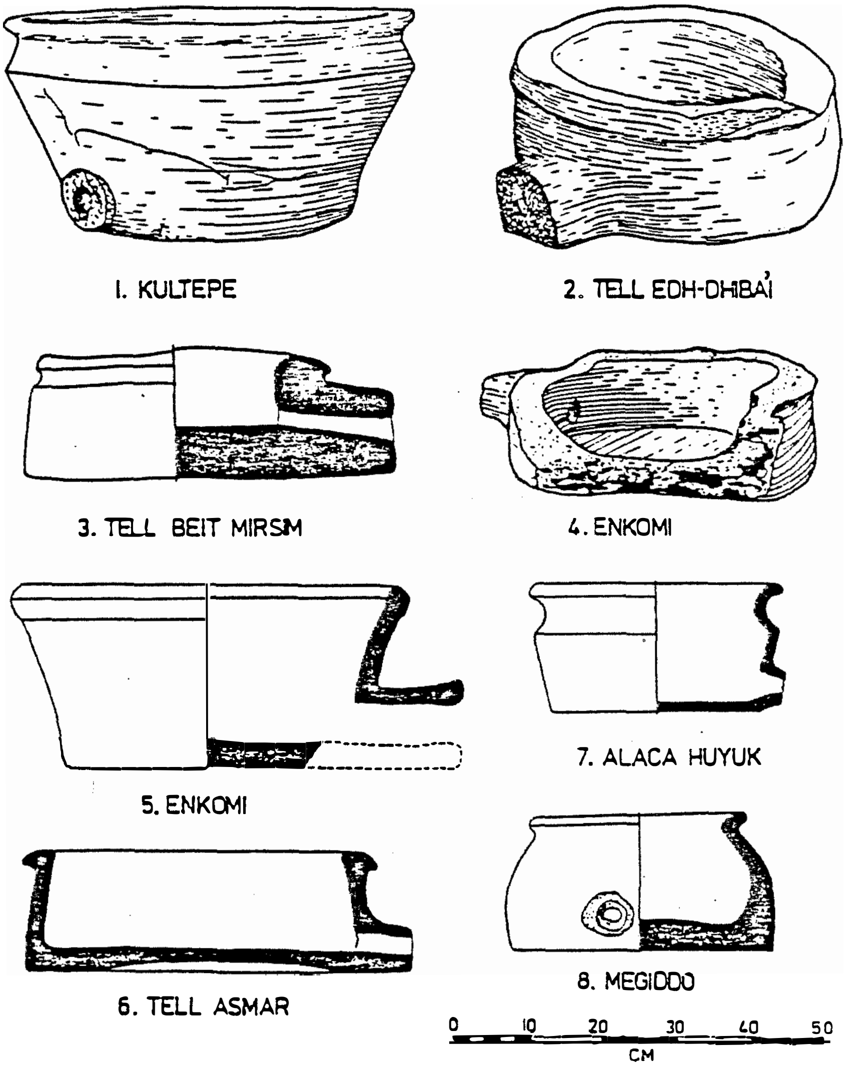


App. E) Making charcoal in modern Crete.

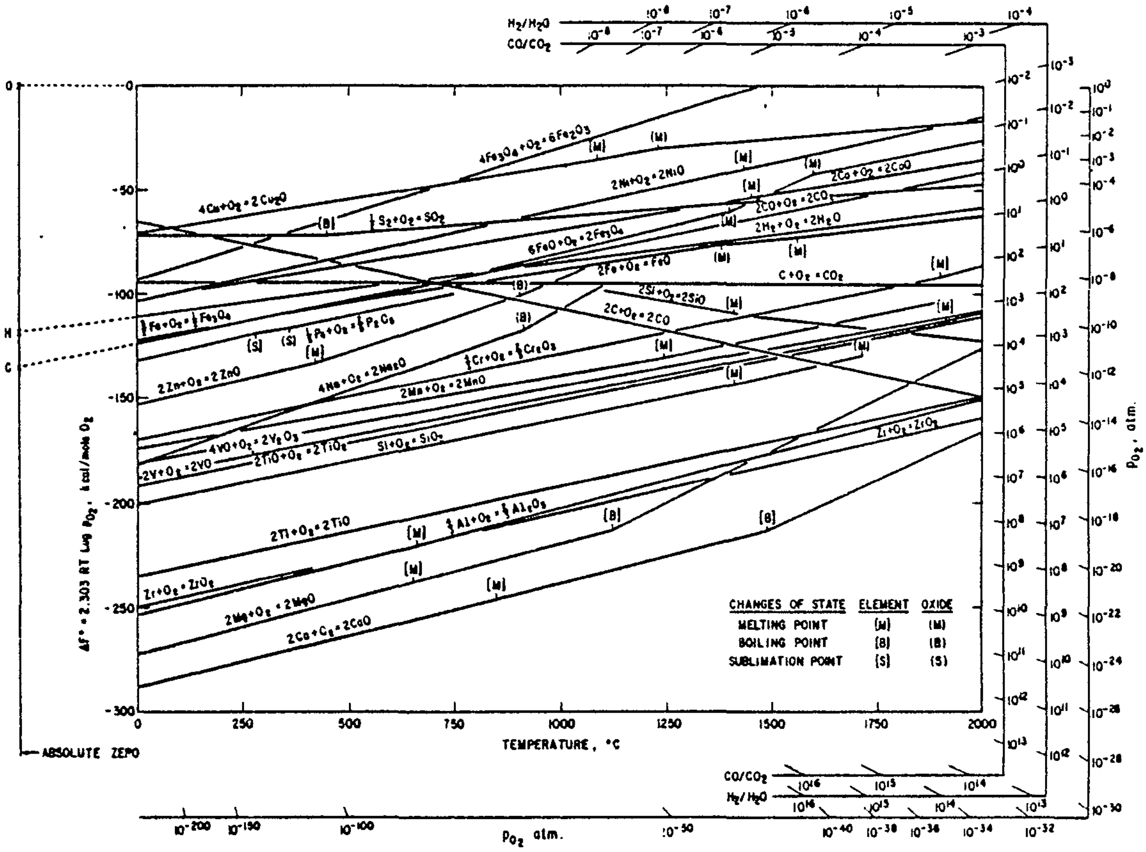


Schematic cross-sections (not to same scale) of some early types of furnaces for reducing iron ore, using charcoal as fuel.

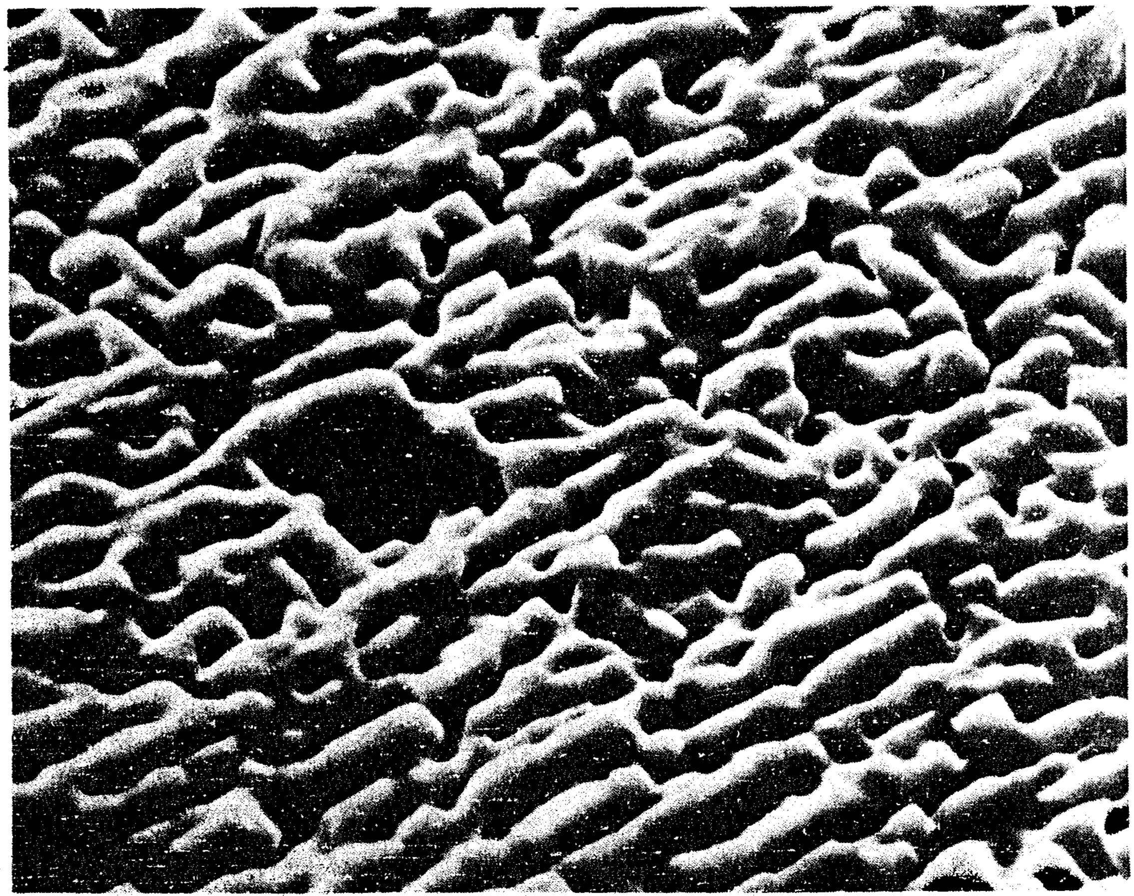
App. F) Schematic cross-sections (not to scale) of some early types of ironmaking furnaces (from The Making, Shaping and Treating of Steel, The U.S.Steel Co. (1971) ninth edition 4



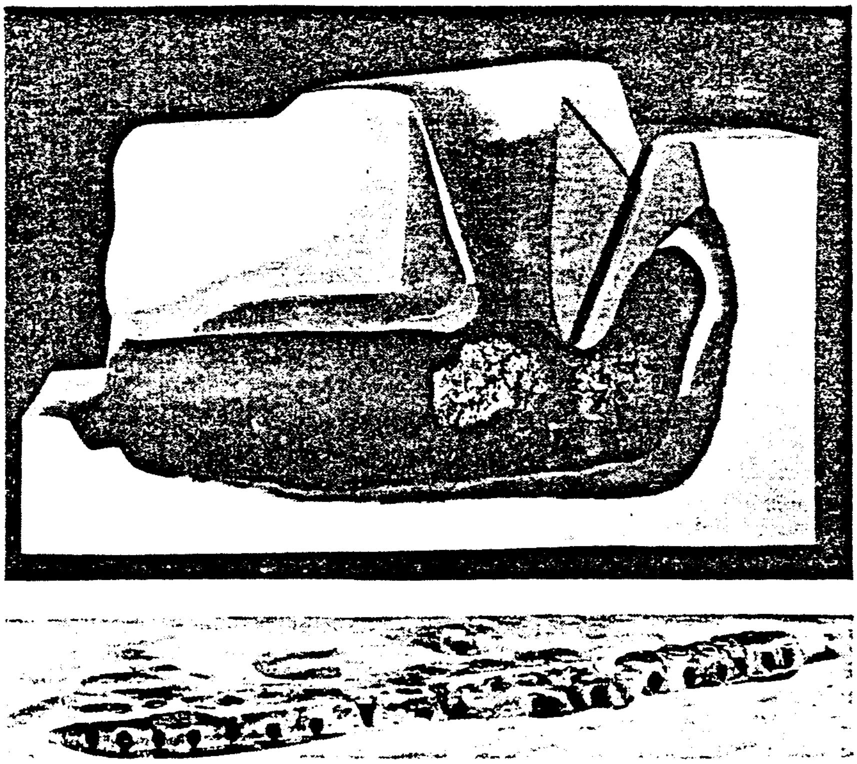
App. G) Examples of pot bellows considered to have been in use in the Middle and Late Bronze Age (from Davey-17).



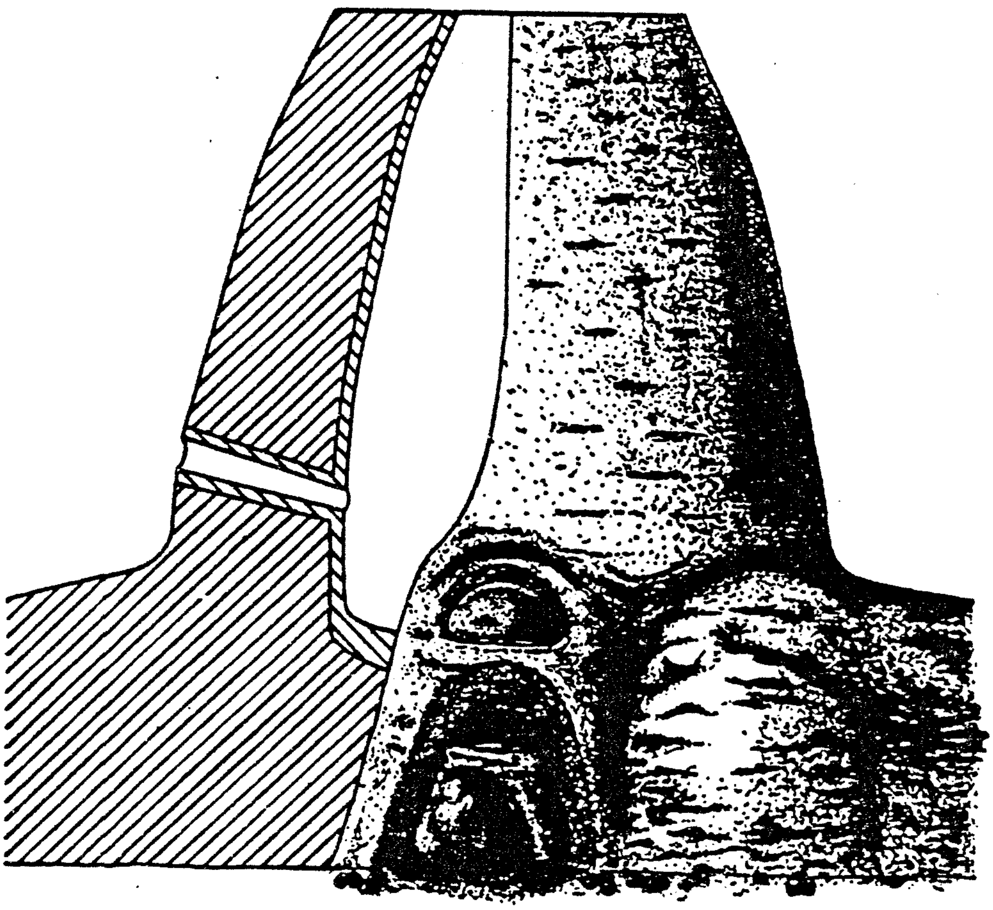
App. H) Free energies of formation of oxides for the standard states: pure elements, pure oxides and gases at one atmosphere.



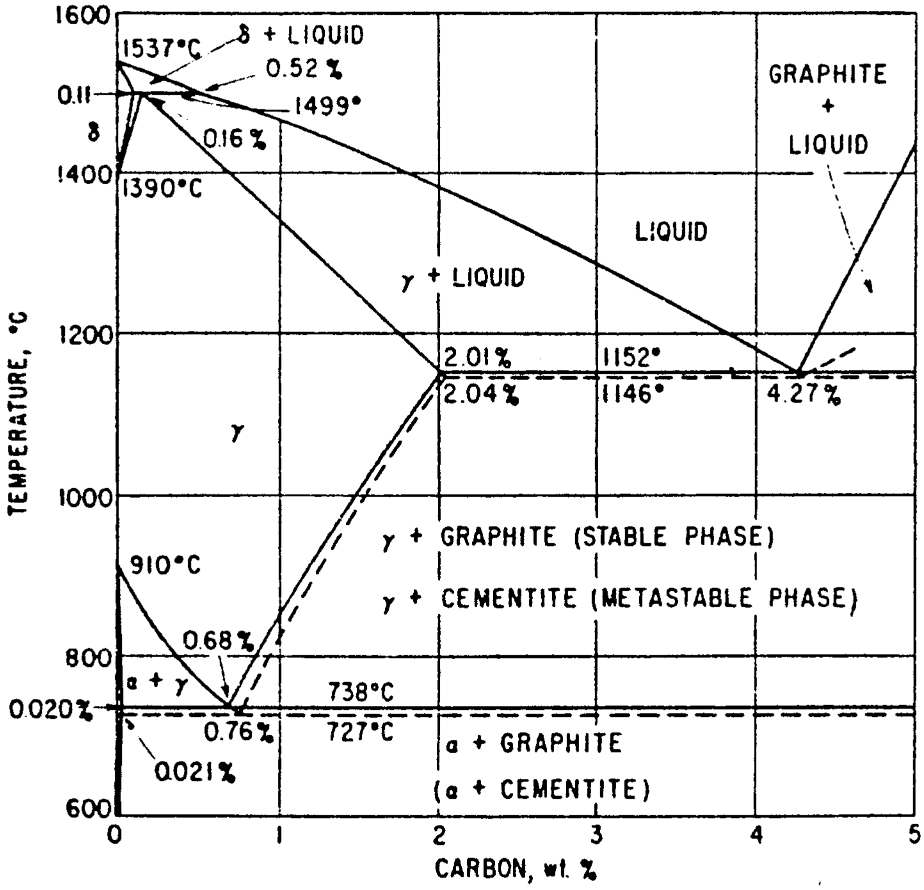
App. I) The structure of iron reduced in the solid state from FeO (wustite) at ca 1200 deg. C. SEM x2400. (Courtesy of Y.K.Rao, University of Washington).



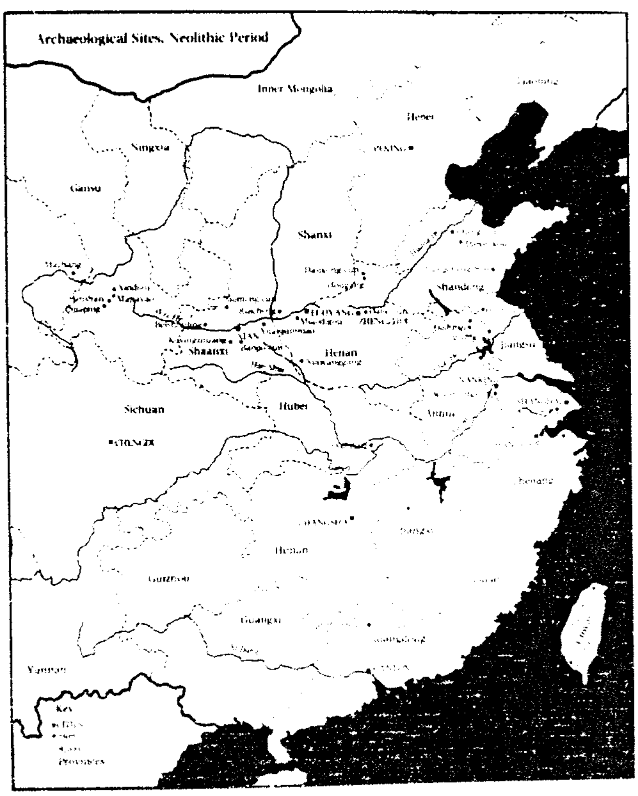
App. J) Model of a slag pit furnace from Podbořany, Bohemia- La Tene period (from Pleiner: The beginnings of metallurgy on the territory of Czechoslovakia,



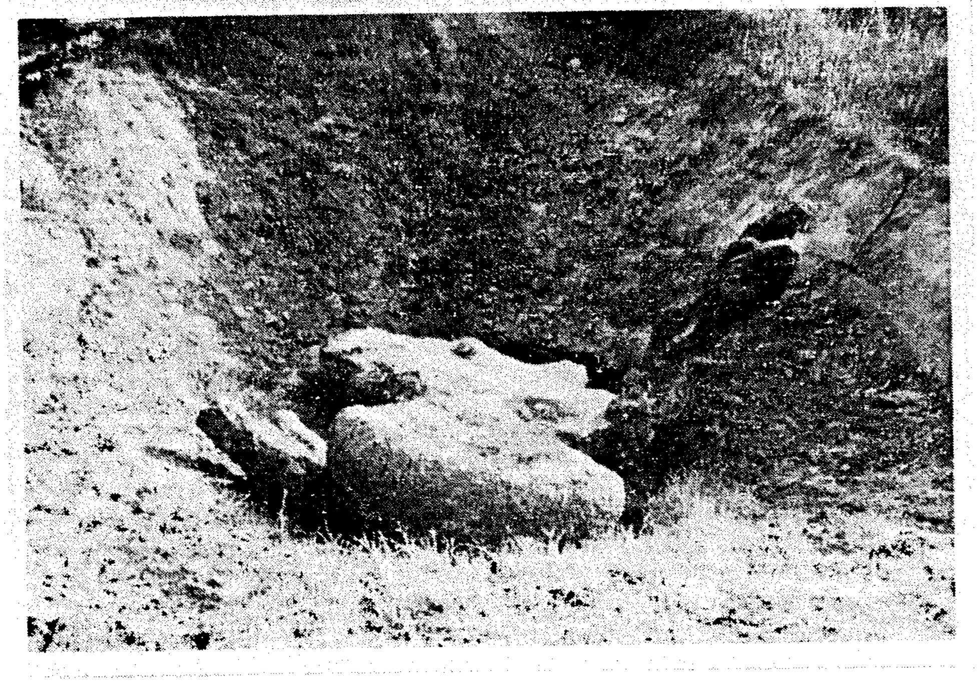
App. K) Reconstruction of a copper smelting furnace from the excavated remains (from <u>Tonglushan-Mt. Verdigris Daye-A Pearl among Ancient Mines</u> Cultural Relics Publishing House, Beijing) <u>Bulletin of the Metals Museum</u>, (1982) (7) 16



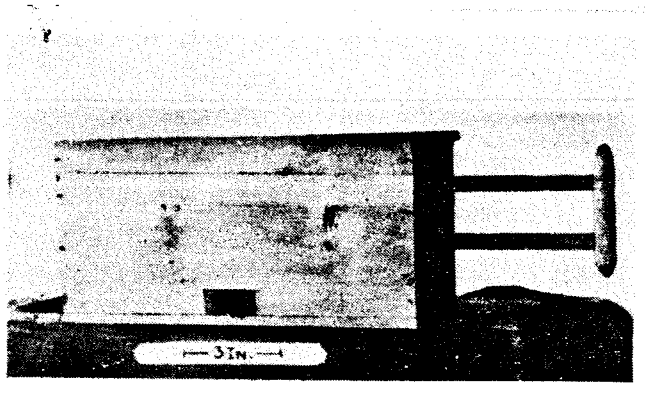
App. L) Iron/Iron-carbide phase diagram showing the phase relationships among the various phases of iron, carbon, iron-carbide and carbon in the form of graphite as a function of temperature and composition.



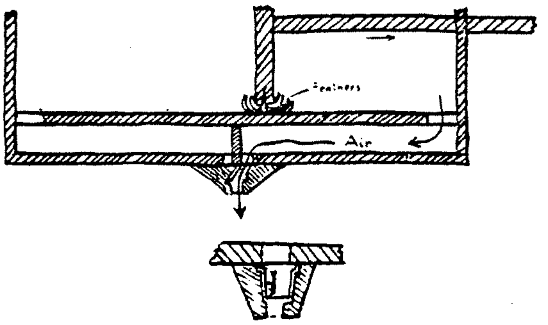
App. M) Some Chinese archaeological sites of metallurgical significance.



App. N) Salamander "in situ" at the site of the Han (He-1) iron blast furnace, Guxing, Henan



(a) Chinese double-acting piston bellows

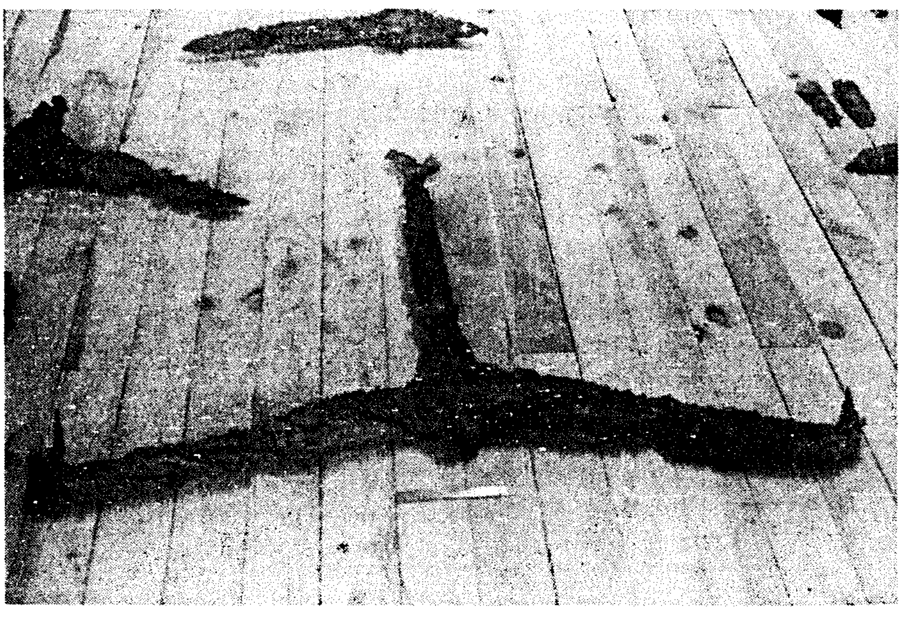


(b) Construction of piston bellows

App. O) Chinese double-action bellows and construction of piston bellows (after J.Needham: The Development of Iron and Steel Technology, W.Heffer & Sons, (1964) Figure 30 (Plate 18)

App. Q) Three views of moulds for plow shares excavated at Guxing.

App. P) A stack-cast mould excavated at Guxing along with experimental castings made in the mould.



App. R) Iron anchor excavated from the shipwreck at Serçe Liman by F. van Doorninck. The anchor is constructed from at least seven pieces of bloomery iron welded together.

THE EARLY HISTORY OF THE IRON BLAST FURNACE IN EUROPE; A CASE OF EAST-WEST CONTACT?

by R. F. TYLECOTE, The Historical Metallurgy Society Limited, Oxford, England

SUMMARY: Recent work in Sweden has shown the existence of two blast furnaces which are dated to the 13th century or earlier, thus making them the earliest iron producing blast furnaces in Europe. This paper demonstrates the possibilities of East-West contact with the aid of metallurgical and engineering evidence. The alternative possibility of indigenous development from copper smelting furnaces is also considered.

While there are examples of the accidental production of cast iron in Roman Europe (Table 1), and 11 % of the ferrous finds from Magdalensberg in Austria had contents exceeding 1.8 % carbon[2], it appears that the first people to use such material intentionally were the Chinese who produced it first during the Warring States period (475-221 BC) and very extensively in the Han Dynasty (206 BC-AD 220) which was more or less contemporary with Roman Europe.

Although we are well-endowed with the odd bits of cast iron which seem to have been made by accident in the pre-Roman and Roman periods of the European Iron Age, we are surprised, not unnaturally, when an intentional artifact of cast iron turns up in a controlled excavation. We have at least three examples of pieces of cauldrons having been found under such circumstances. In the Ukraine at Nikolaievka, 3 fragments of a cauldron were found in a level dated to the 4th-3rd century BC (Hellenistic)[3]. These were mottled cast iron with a carbon content of 4.3 % C and a phosphorus of 0.14 - 0.19 %. It was presumed that these had been imported - presumably from the Far East.

In the Roman Fort at Caerhun in North Wales[4], in a level dated to AD 80-110 was found a single fragment from a vessel 24 cm diameter. It was assumed that this was intrusive and no further work was done on it. At Corby Glen, Lincs, 3 fragments of a cast iron cauldron were found with a rim length of 18 cm and a depth of 12 cm[5]. The thickness varied from 0.29 to 0.40 cm with a thickened rim of 0.65 cm. This would appear to belong to a small vessel, similar to the one from Wales. It was of a grey iron with graphite, pearlite and ferrite with some phosphide. The hardness is 196 HV. It was found on a slag heap with a considerable amount of bloomery slag and pottery of Romano-British date.

The most likely explanation is that these were imports from the Far East. If so, it shows the extensive trade from Hellenistic into Roman times. This is not impossible as the presently accepted date for the introduction of cast iron to China is the Warring States period of 475-221 BC[6].

It is beginning to look, from C-14 dated material from excavations, that the Swedes were the first people to make cast iron in Europe. Two excavations have given early dates, Vinarhyttan (AD 1250-1275)[7] and Lapphyttan (AD 1370 ± 60)[8].

It also appears that Swedish people were some of the first Europeans to establish close contact with the Orient. The Swedes, as Varangians, were trading with the Orient using the Baltic, Black Sea and Caspian river systems by the 7th century[9]. The Varangians established their first capital in Russia at Novgorod in AD 862 and as this control was gradually extended south and eastwards, they came into contact with the Volga Bulgars, whom the Varangians under Sviatislav brought briefly under their rule. In 1223 the Mongols attacking from the east were defeated by the Volga Bulgars. Further attacks were made from 1236 onwards on what is now European Russia. We know that by this time the Mongols were using cast iron for cart hubs and many other iron artifacts[10] and it is quite probable that the descendents of the Varangians transmitted this piece of information to the west, together with other technical innovations, in the normal course of trade. Considering the coin hoards found on Swedish territory there is little doubt that this trade was both extensive and lucrative.

An iron furnace 50 cm in diameter in use at the time of the Volga Bulgars dated to AD 1000 was found at Novy-Usad III (in the middle Volga). But it is uncertain whether this was connected with cast iron or wrought iron[11].

While we are aware that the Chinese were the first to use cast iron (5th century BC) which they did in an extensive way for agricultural implements, it is difficult to demonstrate its diffusion to the west. Needham[12] thinks that technology can diffuse more easily than scientific knowledge and gives examples of such diffusion as being gunpowder (AD 1240) transmitted via the Mongols, textile technology (China to Italy before Marco Polo), and the vertically-shafted water wheel and windmill. We know that the latter was used for metallurgical blowing in China by AD 1313[13] (Fig. 1). Its coming to the west was probably due to Muslim contact (there was an Arab colony in Peking in AD 758).

Judging by the early appearance of such wheels for corn-milling in Anglo-Saxon England (Tamworth, AD 850)[14], it seems that if China was the origin of such wheels, its diffusion took place very rapidly. It is also interesting that the two places in Europe where these can be best seen today are in ex Norse (Shetland)[15] and ex Muslim (Crete) lands. (Fig. 2-5).

Chinese goldsmiths settled in Abbasid Kufan after AD 751 and a Paris goldsmith - William Boucher - served in Karakorum (now in the Mongolian Peoples Republic) between AD 1246 and 1259[12]. Excavations in the latter city have shown that cast iron cart hubs were being used there in the 13th century. These had high sulphur contents and were clearly smelted using coal as a fuel[10].

The carts could, of course, have travelled from other parts of China. But the Volga-Bulgar town of Bolgar has provided cast iron cauldrons dated to the 14th century which are of much better iron, which had been smelted with charcoal (Table 2). These cauldrons could have been made locally (bog iron ores?) and, of course, Bolgar is much nearer to Sweden.

Soon after the Mongols had defeated the Russian confederation in 1221, Swedish trade routes turned southwards towards the Black Sea.

The sudden increase in copper output in the Falun area of Sweden from 800 BC was deduced from the copper content of lake sediments[16].

Smelting on this level needed quite sophisticated bellows-blown furnaces, details of which have become available from the 14th century onwards[17]. During this time most of the iron was being produced by the bloomery process. But the smelting of oxidised copper ores requires a ferruginous flux. If the ore is a sulphide, the necessary iron will already be present. In either case, the production of ductile iron is likely in a "furnace bottom" below the main product of matte or copper. Several scientists have noticed this whilst investigating 19th-20th century copper smelters in the Near-East[18, 19]. It is suggested that the putting together of these two pieces of knowledge - iron in copper smelting furnaces - and the use of cast iron for castings - first happened in Sweden where the necessary technology was present.

Unfortunately the Vinarhyttan iron blast furnace had been robbed, probably after a fire. It had been a timber clad furnace with clay bound walls made of carefully cut pieces of micaceous leptite. The hearth and stack had minimum diameters of 0.5 and 1.5 m respectively, which suggests a small furnace, no bigger than the bloomeries and the copper smelting furnaces.

There had been a rosting hearth nearby, and a second furnace. Power was provided by a dam and what is presumed to be an overshot wheel. The ore and slag analysis are given in Table 3. The ore was self-fluxing as it contained some lime and alumina. Additional alumina had been introduced, probably from the furnace lining. The metal was high in carbon and low in silicon, typical of a cold blast charcoal furnace and very similar to the Chinese iron (Table 4). More of the furnace remained at Lapphyttan.

We have to look at the evidence from Lapphyttan and Vinarhyttan where we find that a low phosphorus ore with 14 % SiO_2 was smelted without fluxing to give the slag shown in Table 3. This low lime slag resulted in quite a high iron content (6.08 % iron oxides) and certainly did not compare with Chinese practice in Han times where the slags contained 24 % CaO and 2.44 % FeO[20].

Swedish iron ores were, of course, not high in sulphur and such high lime slags did not need to be used. Comparison between ore and slag at Vinargruvan would suggest self fluxing conditions.

The cast iron produced (Table 3) has the expected low silicon of cold blast charcoal iron but, of course, much of the iron made in Europe before the use of coal/coke would have this composition.

As shown by Magnusson[8], Lapphyttan could have had a vertically-shafted wheel in the brook. Lindroth[17] suggests that smelting of copper may have started by 1250 or earlier from Swedish Sumpf-erz which is what we call cupriferous peat. We find this in Wales and it is known from New Brunswick in Canada[21]. Peat can be easily burnt to ashes which yield as much as 10 % Cu in Wales[22]. This material was smelted as late as the 17th-18th century.

The foregoing is somewhat of a digression but it shows evidence of a link between copper and iron smelting, as what we might call bog ores were used in both cases in the 13th century. Lindroth[17] believes that Swedish copper smelting in no way relied on German (Harz) experience at this early date. This perhaps leaves the way open for the Swedish contact with the East.

The introduction of water-power to Europe

At the time of the Domesday survey it is estimated that Britain had over 5000 water mills for the milling of grain[23], and it is likely that these were of the "Norse" type with a vertical shaft and a horizontal wheel like that at Tamworth (Fig. 4, 5) which can still be seen at Millbridge in Orkney[24], and in Shetland which are more suited for small flows. Furthermore these are simpler to make as they do not require gearing like the Vitruvian vertical-wheeled mill. Wulff[25] states that in the Near East this type used a wooden jet with a bore of 11.4 cm and 7.6 m head, running at 164 rpm to give about 7.5 kw. Clearly this amount of water is not always available and the jet may be reduced to 7.5 cm and the rate to 151 rpm to give 3 kw. The bottom bearing is like that shown for the Tamworth mill and could be adjusted to raise the stone by means of a lever. A pair of millstones (1.52 m dia.) requires 3 kw and most 19th century mills had at least two pairs and required 8 hp which was normally obtained from a Vitruvian type water wheel.

While the Norse-type mill is difficult to apply to the working of a hammer it can be adopted to working bellows, as the Chinese have shown (Fig. 1). We do not know whether any of the Norse-type mills were adapted in this way, but since the bellows would be the most used part of an early iron mill of the Domesday period it is quite possible that the Domesday iron mills were using this type of bellows' drive and that the hammer was manual. It is estimated that a mill like the Tamworth mill could produce 1 to 2 kw.

The Chinese drawing reproduced in Fig. 1 dates from 1313 (just before the Ming Dynasty), but we know from a book quoted in Taiping Yulan (see Ye Jun, trans. Wagner)[26] that in the period AD 424-453 a pond was used in conjunction with water-powered bellows near the copper-iron mine site of Tonglüshan. Ye Jun suggests that this use of water-power was the key to the achievement of conditions suitable for making cast iron in Western Europe in the 14th century. Certainly continuity of water flow was a pre-requisite for the successful operation of blast furnaces, but the actual power required was not all that great, and small mills of the Shetland/Chinese type would have been quite adequate.

The vertically shafted water wheel was not the only type used in Europe; there is no doubt that the Vitruvian horizontally shafted wheel, known in Rome, spread along the Mediterranean and into north-west Europe with the monastic orders.

We have no recorded details of early water-powered furnaces, whether for iron or copper smelting before the 16th century. Apart from Taccola's hearth of 1438[27] and that described in Das Mittelalterliche Hausbuch of 1480 we do not get firm evidence of copper smelting furnaces in Sweden until the 18th century. But Lindroth[28] feels that by the 13th century there was little, if any, influence from continental Europe on Swedish copper smelting. This is interesting, as the Massa Marittima records[29] from Tuscany suggest that German miners from the Harz were having considerable influence in Tuscany around 1325 AD.

The early development of the blast furnace in Europe.

The situation in the rest of Europe has not changed much since the furnaces described by Filarete (1464)[30], the poem by Bourbon (1517)[31], and the painting by Blès (1511-1550) described by Schubert[27] and others[32,33].

Blès[34] shows the Vitruvian overshot wheel with horizontal bellows. Burbon describes two large bellows of bulls-hide which sound in all respects like the traditional picture of a horizontal shaft with cams. And Olaus Magnus[35] seems to show the same in 1565 (Fig. 6).

Clearly, by the early 16th century the traditional European blast furnace had become the type we know so well. But Spencer[33] and others[36] have drawn attention to one peculiarity in Filarete's description of a furnace at Ferriere. These are the bellows which were quite unique. Filarete emphasises that these were installed vertically rather than horizontally as was the practice elsewhere in Italian smithies. He gives the drawing shown in Fig. 7. They were water-driven and double acting and bear a strong resemblance to the Chinese piston-bellows shown in Fig. 8. The pipes from the two sections were brought together in a single cone-shaped tuyere. The bellows however, measure 3.35 x 2.2 m and air was taken in through a flap-valve in the vertical faces (Fig. 6). But they were made of cow-hide like other European bellows and must have had a concertina look. They must have been operated by a push-pull mechanism from a vertical or horizontal water wheel as shown by Needham in Fig. 9.
The one departure from Chinese bellows is that they were not box (piston or fan) bellows but were made of cow-hide - like concertinas.

A possible reconstruction of all the main parts is shown in Fig. 9, where we have used Barnard's reconstruction[37] of the Chinese water wheel of 1313 and connected it to the concertina bellows with a crank to give the push-pull action.

Bert Hall[38] has recently discussed the use of cast iron in guns and shot at about this time and has come to the conclusion that the parts made from cast iron were small and more likely to be shot rather than guns. Of the latter he suggests that only 60 guns were attested in western Europe between the years 1400 and 1450. Clearly then, most of the iron from these early western blast furnaces went into the manufacture of wrought iron via the finery.

Thus, one is not surprised to hear from Filarete that the furnace at Ferriere granulated the product into water and sent it down to a forge where it was fined into wrought iron. No doubt some granulated iron was mixed with iron to make steel the Brescian way. But the combination of the blast furnace and the finery was a typical Chinese assemblage, as Wagner[39] has recently shown.

As Dr. Needham has demonstrated we could go on producing possible examples of east-west contact leading to technological developments in the west. Whether or not we owe all such developments to such contact or stimulus is largely a matter of individual conviction. But the case for the arrival of the manufacture of cast iron in the west via Sweden has now become a strong one.

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Table 1

Examples of early cast iron in Europe

(after Tylecote[1])

Object	Provenance	Date	C	Si	Composition % Mn	P	S	others
Bloom	Hengistbury Head	ca. C1 AD	3.49	0.38	tr.	0.18	0.035	-
Bloom	Siegen	Roman	2.78	0.05	nil	0.29	nil	Cu 0.21
Lump	Wilderspool Lancs.	ca. C2 AD	3.28	1.05	0.403	0.76	0.49	-
Lump	Tiddington Warw.	Rom.-Br.	3.52	1.92	0.63	0.77	0.77	-

Table 2

Composition of early cast iron in Eastern Europe and Asia

(after Terekhova[10])

Object	Composition %				
	C	Si	Mn	S	P
Cart hubs. Karakorum 13th cent.	2.52 1.88	0.60 0.51	0.105 0.08	0.89 1.00	0.55 0.44
Cauldrons. Bolgar 14th cent.	3.99 3.31	0.09 0.18	0.08 0.31	0.035 0.047	0.026 0.48

Table 3

Composition of material from Vinargruvan (%)

	Ore	Slag 17 (normalised)
SiO_2	13.7	69.27
$T\ O_2$	0.08	0.27
Al_2O_3	1.2	10.10
Fe_2O_3	49.9	1.34
FeO	26.9	4.74
MnO	0.67	1.44
V_2O_5	0.03	-
MgO	1.5	4.12
CaO	5.3	4.23
Na_2O	0.12	2.63
K_2O	0.12	1.86
P_2O	0	-
S	0.013	-
LoI	0.5	-

Cast iron

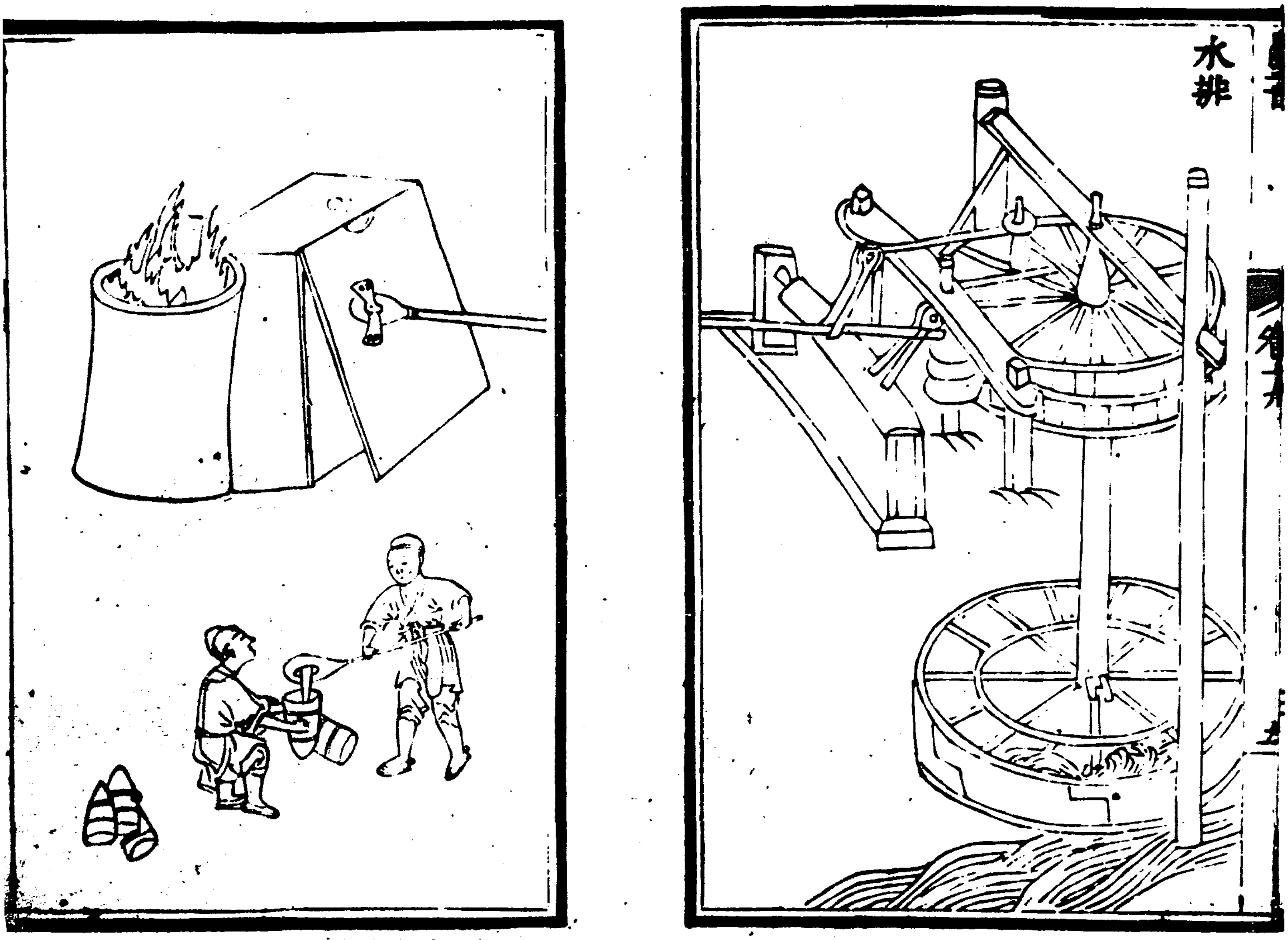
%	No 51	No 11
C	4.3	4.1
Si	0.36	0.34
Mn	0.04	0.01
P	0.045	0.021
S	0.038	0.012
Cr	< 0.01	0.01
Cu	< 0.01	0.01
V	0.02	0.02

Table 4

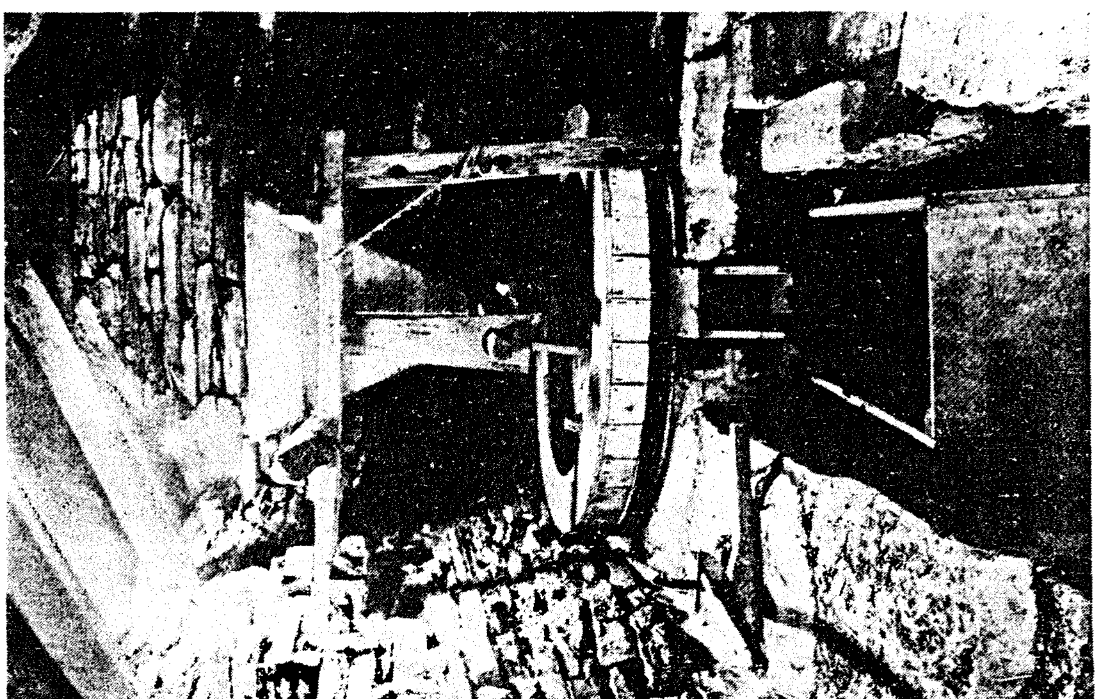
Analysis of iron artifacts found at Tieshengou and Daye and made at ironworks HE-3 at Tieshengou (%)

	C	Si	Mn	P	S
Plate	4.12	0.27	0.125	0.15	0.043
Brazier	2.57	0.13	0.16	0.49	0.024
Shovel	3.82	0.09	0.12	0.40	0.022
Plate	3.80	0.22	0.09	0.48	0.040
Fragment	4.00	0.42	0.21	0.41	0.07
Agric. tool (?)	1.98	0.16	0.04	0.29	0.048
Fork	3.30	0.09	0.10	0.14	0.03

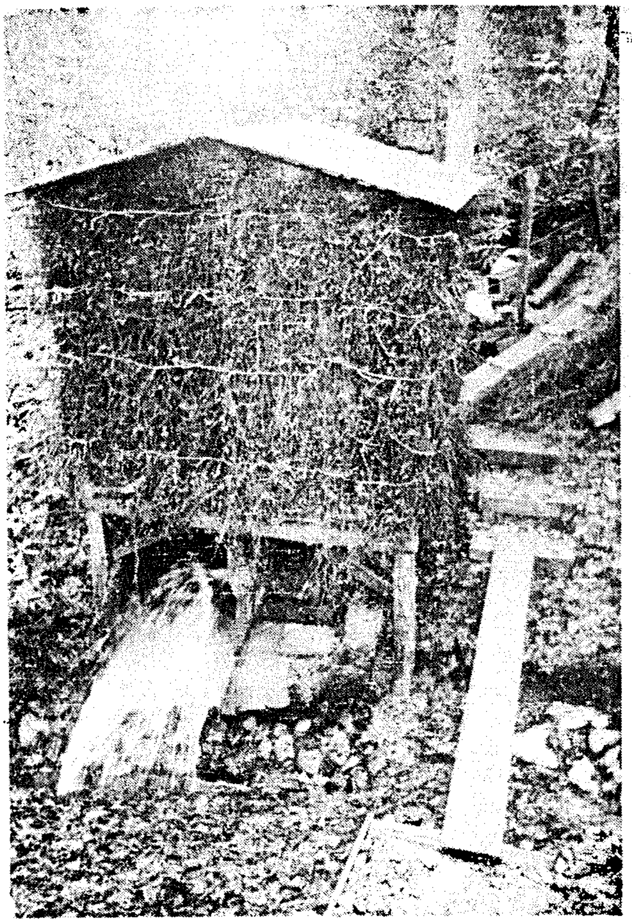
(After Zhao Qingyun, Li Jinghua, Qiu Lianghue, Han Rubin, T.Ko.)

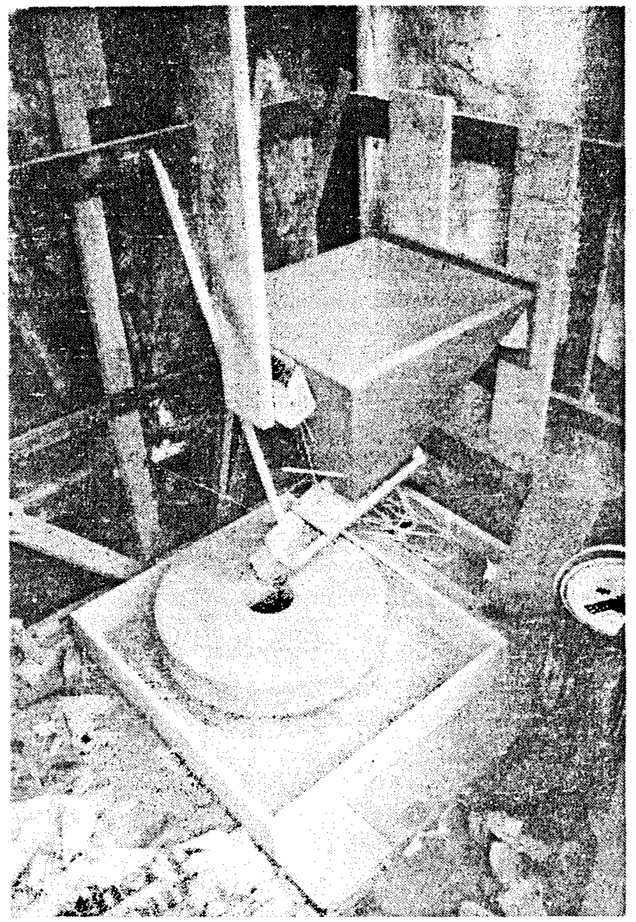


1. The Earliest illustration of a hydraulic blowing engine (AD 1313) (After Needham, Newcomen Soc.[13])

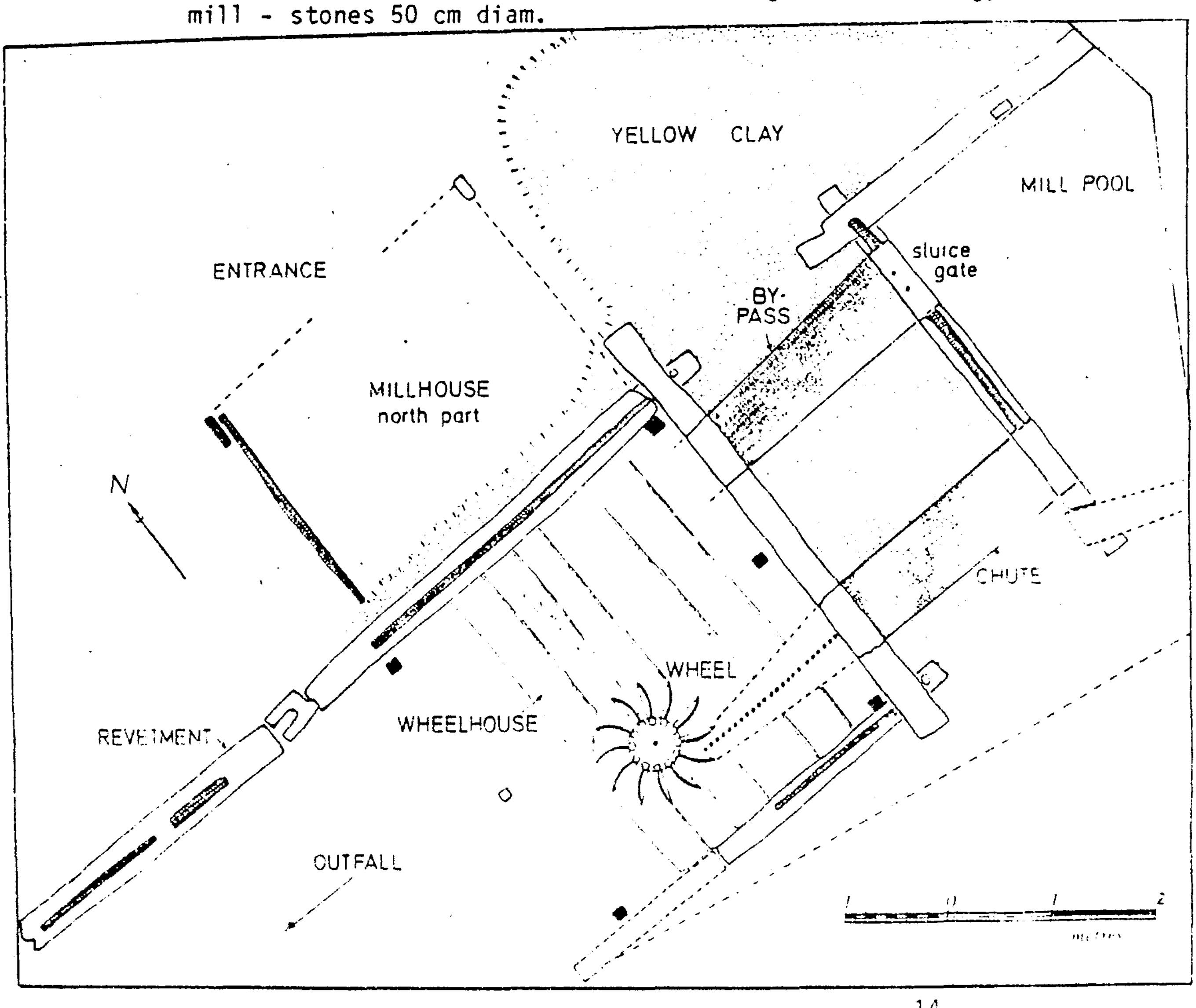


2. Inside of old water mill at Millbridge, Orkney (After RCAMS[24])

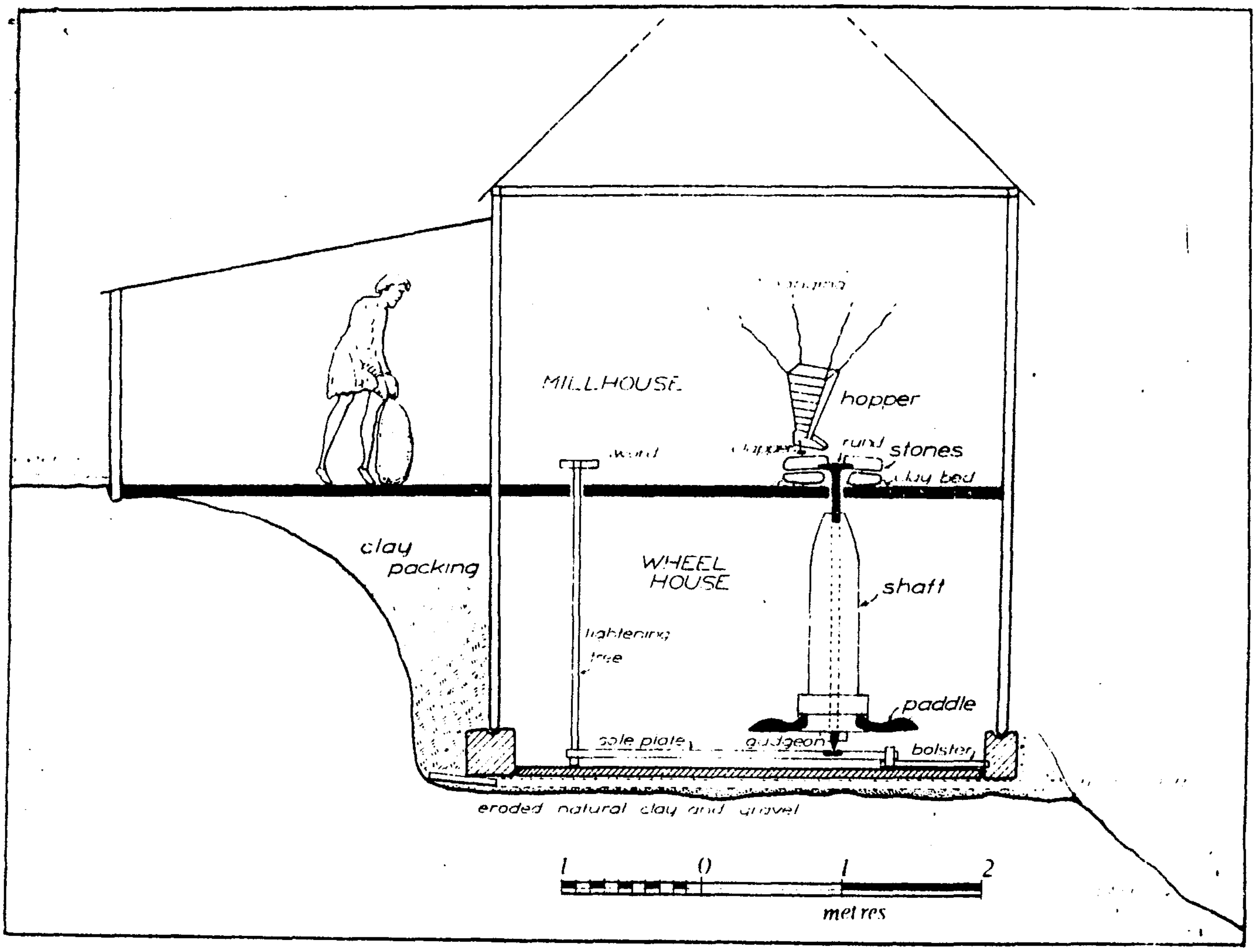




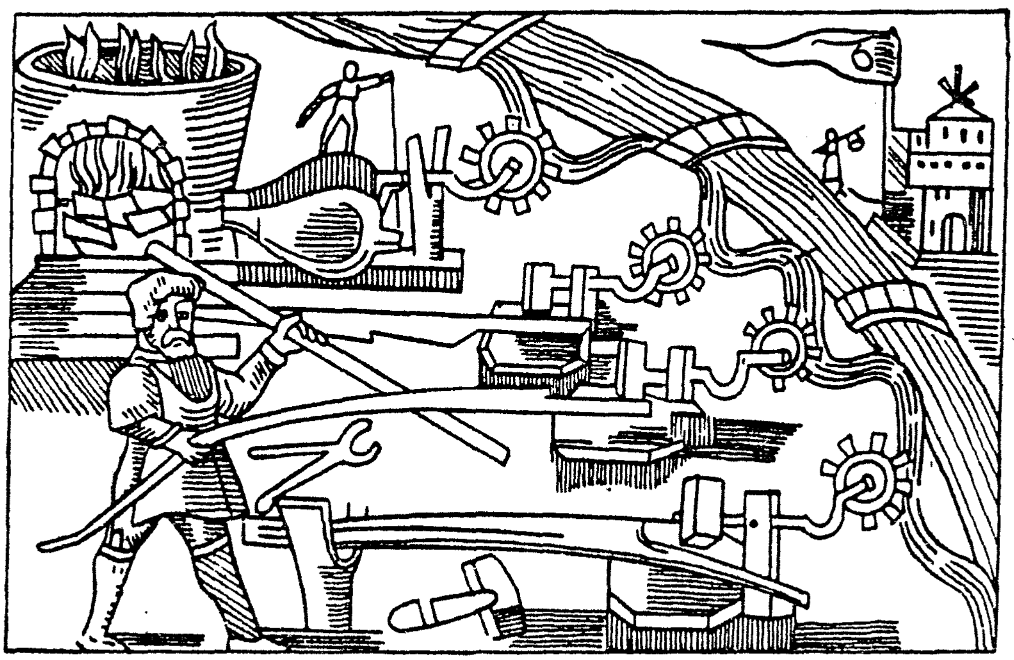
3. Half-scale model of vertically shafted water mill built by Roger Adams in Sussex. (a) rear of mill showing water exiting; (b) inside mill - stones 50 cm diam.



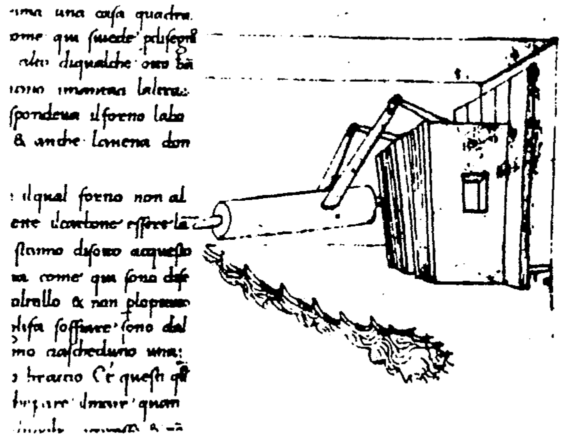
4. Plan of Saxon mill from Tamworth (After Rahtz[14])



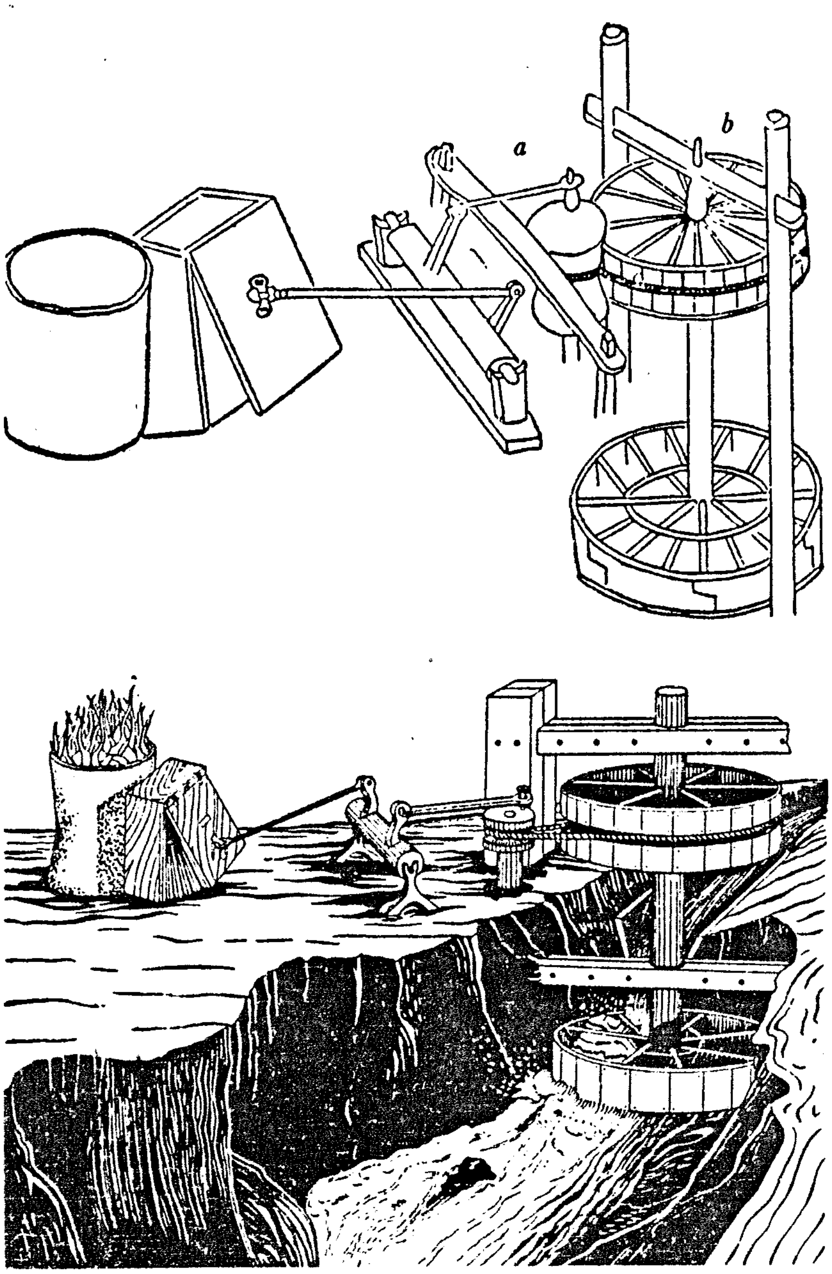
5. Section of Saxon mill at Tamworth (reconstruction, after Rahtz[14]) (Note steel bearing block in sole plate)



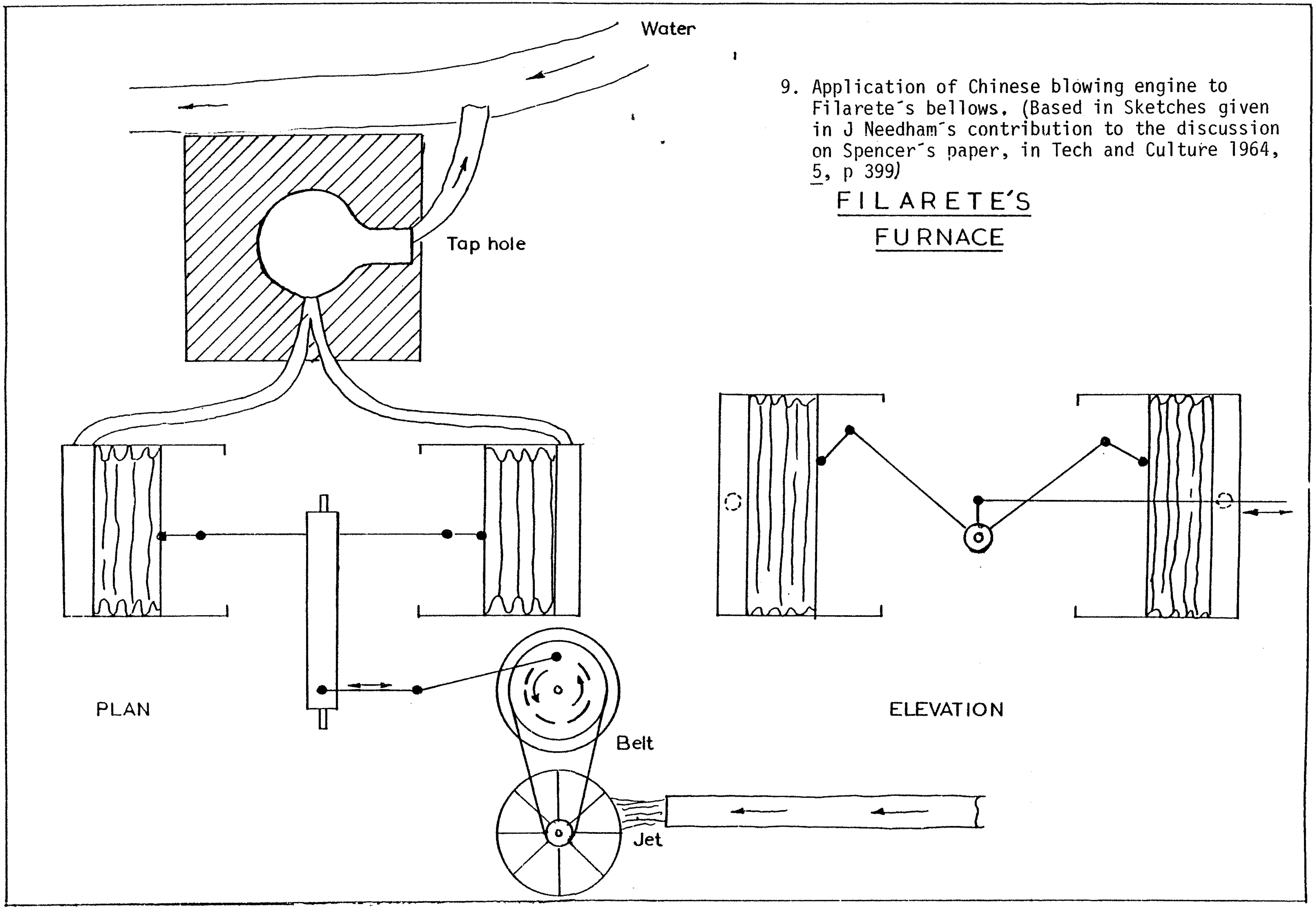
6. Furnace, bellows and forge hammers (from Olaus Magnus 1565 AD). (From J. Needham, Science and Civilisation in China, Vol. IV, Pt. 2, p. 395)



7. Filarete's bellows from Drawing in Biblioteca Nationale, Florence. (From Spencer[33])



8. Barnard's reconstruction of Chinese blowing engine shown in Fig. 1 showing application to piston/fan bellows. (Ref. 35).



9. Application of Chinese blowing engine to Filarete´s bellows. (Based in Sketches given in J Needham´s contribution to the discussion on Spencer´s paper, in Tech and Culture 1964, 5, p 399)

FILARETE´S FURNACE

DIE TECHNOLOGIE DER DIREKTEN EISENHERSTELLUNG IM ALPENRAUM (DER STUCKOFENPROZESS)

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ZUSAMMENFASSUNG:

Bezüglich der Vorgänge im Renn- und Stuckofen zur Herstellung des Schweißeisens herrschen noch immer unterschiedliche Vorstellungen. Ein wesentlicher Schritt in der Metallurgie wurde durch die Einführung der Wasserkraft im Eisenhüttenwesen erreicht, die im Alpenraum im 13.Jahrhundert nachweisbar ist. Die vorher gebräuchlichen "Rennöfen" wurden zu "Stucköfen", die im Komplex des sogenannten "Radwerkes" als wirtschaftlicher Einheit vom Erzabbau bis zum Eisenverkauf integriert waren.

Offensichtlich aus dem Süden kommend, begann im Alpenraum 1541 der Floßofen mit der Erzeugung flüssigen Roh- und Gußeisens seinen Siegeszug, den er mit der Einstellung des letzten Stuckofens 1775 beendete. Für diese Umstellungsperiode, die in der Zeit 1750 bis 1762 ihren Höhepunkt hatte, sind uns Dokumente erhalten, die die Fachdiskussion der Hüttenleute über Vor- und Nachteile des Stuck- und Floßofens schildern.

SUMMARY

As far as the reactions in the bloomery furnace are concerned, there exist different theories. The most important step in the historical development was the introduction of the waterpower during the thirteenth century. The earlier used "Rennöfen" were converted into "Stucköfen", which are integrated into the "Radwerk", which is the commercial unit of the ore mine, the related transport system and the metallurgical plant, including the furnace (Stuckofen), the charcoalstore (Kohlbarren), the roasting kilns (Gramatln) and the housing of the ironmaster (Radmeister) and his crew (Blahaus-Arbeiter).

Coming from Italy the intentional production of pig-iron started in 1541 at Kremsbrücke, Carinthia. The development continued until 1775, when the last "Stuckofen" ceased to work. During the period of change of technology we have some documents that show the discussion of advantages and disadvantages of the processes using the fining process in finery hearths.

GRUNDSÄTZE DER TECHNOLOGIE DER DIREKTEN EISENERZEUGUNG

Die zusammenfassende Darstellung der Schmelzversuche zur frühen Eisenherstellung(1) hat bereits gezeigt, daß man bisher noch keine einheitliche Linie zur Beurteilung der Vorgänge im Rennfeuer* gefunden hat. Im Wesentlichen gehen die Diskussionen darum, ob die Entstehung einer soliden "Luppe" aus Schweißeisen direkt durch Dekantieren* aus der Schlacke(2) oder indirekt durch eine Aufkohlung bis zur eutektischen Zusammensetzung und anschließende Entkohlung vor den Düsen anzunehmen ist(3). Die vorherrschende Meinung ist allerdings, daß die Eisenerzeugung im aufsteigenden Ast der Kohlung erfolgte und daß, bedingt durch das ungleichmäßige Temperaturfeld im Ofen auch die Kohlungsbedingungen ungleichmäßig sind. Auch findet sich ein direkter Zusammenhang zwischen dem Anteil an hochgekohltem flüssigen Eisen (Roheisen*)und der Eisenausbeute aus dem Erz, die beim Stuckofen von anfänglich 15 bis 25% bis auf über 60% am Ende der Stuckofen*-Ära getrieben werden konnte. Von Beginn an war ein gewisser Anteil an flüssigem Roheisen durchaus nachweisbar, wie bereits römerzeitliche Funde im Alpenraum beweisen. Am Ende der Stuckofen-Ära wird ein Anteil von Roheisen*(Graglach*) von 15 bis 30% als typisch für guten Ofengang angesehen.

Die Aufkohlungsbedingungen im Renn- und Stuckofen sind deshalb von ganz besonderer Bedeutung für den Prozeß. Diese hängen von der Ofenatmosphäre und damit über das Boudouard-Gleichgewicht(4) mit der Temperatur, andererseits aber auch von der Körnigkeit und Gasdurchlässigkeit des Erzes, ab. Die Temperaturverteilung selbst wird vom Ofendurchmesser und der Windeintrittsgeschwindigkeit sowie dem Erz-Kohle-Verhältnis bestimmt (2,5).

VOM RENNOFEN ZUM STUCKOFEN

Eine wesentliche Änderung in den Herstellungsbedingungen erfolgte, als man von den handgetriebenen Blasbälgen zu dem Wasserradantrieb der Blasbälge übergehen konnte. Alte Urkunden aus dem Erzberggebiet zeigen uns eindeutig(6), daß im 13.Jahrhundert eine sprunghafte Steigerung der Produktionsmenge je Ofen erfolgte, die nur durch eine technologische Neuerung wie die Einführung der Wasserkraft erreicht werden konnte. Mit diesem wichtigen Schritt war man nicht von der Leistungsfähigkeit der Menschen, sondern von der Leistungsfähigkeit des zulaufenden Bachwassers abhängig geworden. Damit ergab sich natürlich auch, daß die Eisenhütten künftig am Bach liegen mußten und daß die Winterzeit mit niedrigen Wasserständen und gefrierendem Wasser im Alpenraum ungünstig für die Eisenerzeugung war. Für die Archäologie des Eisens im Alpenraum ist es bezüglich der Datierung daher auch wichtig, ob der Rennofen im Gelände und erznah gelegen, (wie die Feistawiese (7)) oder in der Nähe des Baches(8), energienah errichtet wurde; somit ist eine grobe Datierung: vor oder nach dem 13. Jahrhundert, möglich.

Die Einführung der Wasserkraft und die damit verbundene Vergrößerung der Eisenluppen, die anfänglich kaum mehr als 30 kg wogen, hatte aber noch andere Konsequenzen. Auch die Hämmer mußten jetzt stärker werden, wurden allerdings auch hier jetzt mit Wasserkraft betrieben. Und was lag näher, als diese Hammerwerke mit dem Stuckofen für die erste Bearbeitung der Luppe aus der ersten Hitze zu vereinigen. Diese sogenannten "Deutschhämmer"* erwiesen sich aber bald als nicht sehr zweckmäßig, da man bestrebt war, die Wasserkraft nur für die Eisenreduktion, die Herstellung der Luppe, zu benutzen und da es ohneweiteres möglich war, die Luppe in einem weiteren Feuer aufzuheizen und weiterzuverarbeiten, somit die beiden Produktionsschritte zu trennen. Nachweisbar seit dem 16.Jahrhundert aber bis in die späte Zeit der direkten Eisenerzeugung im 18.Jahrhundert, ist daher der "Deutschhammer" im Alpenraum mit der Verarbeitung des Abfalleisens, des "Graglachs"(6), also des hochgekohlten Eisens, im Zerrenn*-Prozeß verbunden. Damit erfassen wir die ersten Spuren der indirekten Eisenerzeugung im Alpenraum etwa seit dem 15.Jahrhundert. Die Luppen* (Stuck*) ihrerseits wurden nachweislich im 16.Jahrhundert im sogenannten "Welschhammer"* verarbeitet und zu Rohlingen für die Weiterverarbeitung (Zaine*, Schienen, d.dgl.) verformt(9).

DER BETRIEB IM STUCKOFEN BIS ZUM AUSLAUFEN DER PERIODE 1775

Es gibt mehrere Darstellungen von Stucköfen aus dem Alpenraum, die uns vor allem die Konstruktion der Öfen und der Windzuführung durch Wasserräder zeigen. Auch die Arbeit im Feuer selbst ist insbesondere durch die berühmten Darstellungen Agricolas gut belegt. Eine Stuckhütte umfaßte (Bild 1) im 17.Jahrhundert ein Gebäude, in dem sich der Ofenstock und die Rösteinrichtung (Gramatln*) befand. Dieser Stuckofen, in dieser Zeit auch bereits in eine mit "Radwerk"* bezeichnete wirtschaftliche Einheit integriert, erforderte naturgemäß relativ hohe Investitioskosten, nicht nur für den Ofen und seine technische Einrichtung selbst, sondern für die zugehörigen Gebäude, die diese Produktion umgaben. Nicht nur das Hüttengebäude, sondern auch der Kohlbarren und die Wohngebäude für den Radmeister, das Personal und die Ställe für die zahlreichen Pferde für den Erz- und Eisentransport gehörten zur Einheit des Radwerkes (6). Damit kam die Notwendigkeit auf, die Stucköfen zu finanzieren und da dies meist nicht aus Eigenem von vornherein möglich war, mußten die Radmeister sich an die Weiterverkäufer, im Falle südlich des Erzberges an die Rauheisen*-Verleger* in Leoben wenden. Ähnlich war es auch auf dem Gebiete der Innerberger Hauptgewerkschaft, die von Eisenerz nach Norden die Produktion, Verarbeitung und den Verkauf des Eisens besorgte. Damit kam die Rolle des Kapitals in dieser frühindustriellen Phase bereits deutlich zur Geltung und schließlich wurde, wie im Falle der Gründung der Innerberger Hauptgewerkschaft, der Anteil überhaupt nur mehr bezüglich der Einlagen, bzw. Schulden beurteilt. Es ist daher nicht verwunderlich, daß bald viele Eisenverlegerfamilien Leobens im Besitz von Radwerken in Vordernberg waren. Das Auf und Ab der Eisenindustrie, im Erzberggebiet mit "Würde" und "Unwürde" des Erzberges bezeichnet, erforderte eben seine Opfer auf der wirtschaftlichen Seite.

ZEUGNISSE TECHNOLOGISCHER STELLUNGNAHMEN FÜR DEN ÜBERGANG VOM DIREKTEN ZUM INDIREKTEN EISENERZEUGUNGSVERFAHREN

Die "Zerrennfeuer"* stellen frühe Betriebseinheiten zur Herstellung von Stahl und vor allem weichen Eisen aus den "Provianten"*(Roheisen, Graglach, Wascheisen) dar. Die Technik des Roheisenfrischens entwickelte sich offensichtlich im Ausland früher als im Alpenraum, wo man den ersten Floßofen 1541 in Kremsbrücke errichtete(10). Damit war es notwendig, daß das Zerrennfeuer größere Produktionskapazitäten umfassen mußte, somit wurden die einfachen Schmiedegruben allmählich durch mit Gußeisenplatten (Zacken) ausgekleidete Feuerstellen ersetzt. Obwohl die Technologie des Stuckofens um 1750 schon so weit gediehen war, daß man 60% des Eisens aus dem Erz gewinnen konnte(11), war durch das indirekte Verfahren praktisch das gesamte Eisen des Erzes als Roheisen gewinnbar, wenn man auch in den nachfolgenden Schritten im Frischfeuer wieder einige 10% an Verlusten hinnehmen mußte. Bezüglich des Holzkohlenverbrauches ergaben sich ebenfalls Vorteile, die aber hauptsächlich beim Floßofen, der Vorstufe des Hochofens, lagen und damals etwa 30% Brennstoffeinsparung zeigten.

Das anschließende Frischen* erforderte allerdings wieder große Mengen an Holzkohle und erst die Einführung des Puddel*Prozesses ermöglichte die Loslösung von der Holzkohle, die mittlerweile wegen der gestiegenen Eisenerzeugung recht selten und daher auch teuer geworden war. Im Gebiete von Eisenerz und Vordernberg erfolgte der Übergang relativ spät, aber umso intensiver(6,11). Eisenerz hatte schon früh begonnen, die Produktion im Floßofen zu erproben, war aber im 17.Jahrhundert damit wenig erfolgreich. Im 18.Jahrhundert war der Druck seitens der Holzkohlenerzeuger und damit auch über die Kaiserin Maria Theresia durch ihre Waldordnung(12) so groß, daß man konzentrierte Maßnahmen ergreifen mußte, um umzustellen. Besonders gut belegt ist die Umstellung in Vordernberg, die 1760 bis 62 erfolgte. Die Radmeister-Communität(13) kaufte das Radwerk VI in Vordernberg und einige der Protokolle dieser Versuche zur Herstellung von 100% Roheisen sind uns zumindest in ihrem Ergebnis erhalten(11). Interessanterweise behielt man aber in der Abrechnung die Produktionscharakteristik bei, sodaß in den Büchern die reglementierte Menge an Luppen (Maß) daneben errechnete Mengen an Graglach und Wascheisen aufschienen. Dieses hatte sicherlich steuerliche Vorteile, die erst durch die Reformen Kaiser Josef II. in den 80-er Jahren des 18.Jahrhunderts aufgehoben wurden. Während Eisenerz manche Schwierigkeiten mit der Umstellung hatte und erst 1806 einen wirklichen Hochofen errichten konnte (Bild 2), war in Vordernberg der Prozeß vollständig geglückt. Um den Kärntner Erzberg hingegen war der letzte Stuckofen bis 1775 in Betrieb(9).

ERGEBNIS

Die Herstellung des Schweißeisens (wrought-iron) ist offensichtlich von Anfang an wegen der ungleichmäßigen Temperaturverteilung und damit der wechselnden Gaszusammensetzung mit einem gewissen Anteil an hochgekohltem Eisen verbunden. Freilich ist die Zusammensetzung des Erzes, die Körnigkeit und die Erzvorbereitung von besonderer Bedeutung für diesen Anteil. Im Stuckofen mit Wasserradantrieb der Blasbälge hatte man ein Gerät zur Hand, das eine gleichmäßige Produktion ermöglichte und damit wurde der Eisenerzeugungsprozeß beherrschbar, wie die Produktionszahlen der Jahrhunderte zwischen 1500 und 1775 zeigen(14). Die Umstellung des Stuckofenbetriebes selbst war am Ende der Ära so ausgefeilt, daß man bei der Einführung des Floßofens größte Bedenken bezüglich der Qualität und Preiswürdigkeit des Produktes hatte(15). Dies wurde im Alpenraum erst durch einen 25-jährigen Ablöseprozeß bereinigt.

BEZEICHNUNG DER FACHAUSDRÜCKE *(16)

* Dekantieren - Trennung von festen Kristallen (des Eisens) aus einer Flüssigkeit (Schlacke) und anschließendem Abschöpfen (Abstich)

* Deutschhammer - ursprünglich die Kombination von Stuckofen und Hammerwerk, später Bezeichnung für ein Zerrennfeuer mit Hammerwerk

* Frischprozeß - Weiterentwicklung des Zerrennfeuers mit einer Feuerstelle, die mit Gußeisenplatten (Zacken) ausgekleidet ist

* Floßofen - Frühform des Hochofens zur Erzeugung von flüssigem Roheisen

* Graglach - flüssiges (hochgekohltes) Eisen, Nebenprodukt des Stuckofens, das als "Proviantsorte" an die Zerrennhämmer verkauft wurde

* Gramatl - Röststätte, gemauert und in das Hüttengebäude einbezogen, wohl von slaw. grmada, Scheiterhaufen

* Luppe - Produkt des Renn-, bzw. Stuckofenprozesses, auch als Maß oder Stuck bezeichnet, bestehend aus verschieden gekohltem schmiedbarem Eisen

* Proviantsorten - Graglach, Waschwerk = Roheisensorten, die als unbeabsichtigtes Nebenprodukt am Stuckofen anfielen; als Gegenfracht gegen Proviant befördert

* Puddelprozeß - jüngste Stufe des Frischverfahrens mit indirekter Beheizung in einer Art Flammofen meist unter Benützung mineralischer Kohle

* Radwerk - mit der Einführung des Wasserrades aufkommende Bezeichnung für eine mittelalterliche Eisenhütte, bestehend aus Erzberganteil, Transporteinrichtungen, Kohlbarren, Wohnungen für den Radmeister und seine Arbeiter, sowie dem Stuck-, bzw. Floßofen

* Rauheisen - Bezeichnung für das Material der Maß (= schmiedbares Eisen)

* Rennofen - Schachtofen zur direkten Erzeugung von Schmiedeeisen mit handbetriebenen Blasbälgen

* Roheisen - moderner Begriff der mehrere hochgekohlte Eisensorten umfaßt, meist Ausgangsmaterial für das Stahlwerk

* Stuckofen - seit dem 15.Jahrhundert nachweisbare Bezeichnung für den mit Wasserrad betriebenen Rennofen

* Verleger - Eisenhändler; aufgrund der Privilegien seit dem Mittelalter, auch Geldgeber für die Radmeister

* Welschhammer - Hammerwerk zur Verarbeitung der Halbmaße (Luppen) zu verschiedenem Rohmaterial für die Schmieden

* Zain - Ausgangsmaterial für die Drahtherstellung, hergestellt in sogenannten Zainhämmern

* - Zerrennprozeß - Frischverfahren im Schmiedeherd zur Herstellung von Schmiedeeisen aus Roheisensorten (Graglach, Waschwerk, usf.).

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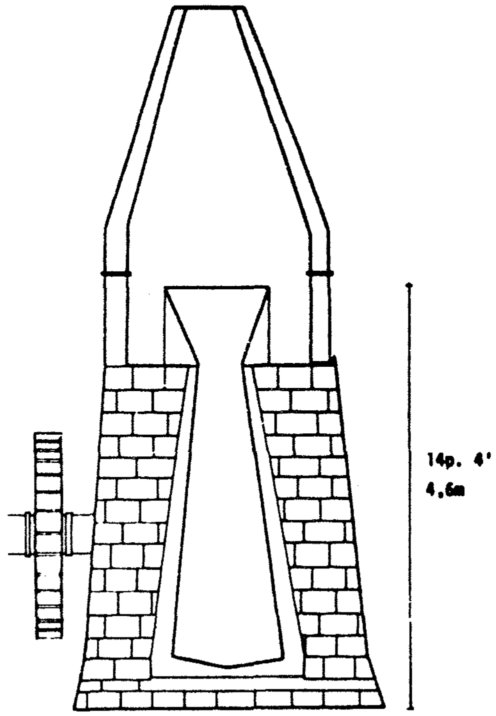
Der Ofen A. Die Stufen B. Erz C. Kohlen D.

Stuckofen nach Agricola (1556) - das Wasserrad treibt den Blasbalg, der den Schachtofen (A) die Verbrennungsluft zuführt. Die Ofenbrust ist mit Lehm verschmiert und muß für das Ziehen der Luppe aufgebrochen werden. Ein Arbeiter mit Gesichtsschutz gegen die giftigen Gichtgase gibt von einem kleinen Podest (B) Erz (C) und Holzkohle (D) in die Gicht des Ofens. Daneben ein am Reitel erkennbarer Aufwerfhammer.

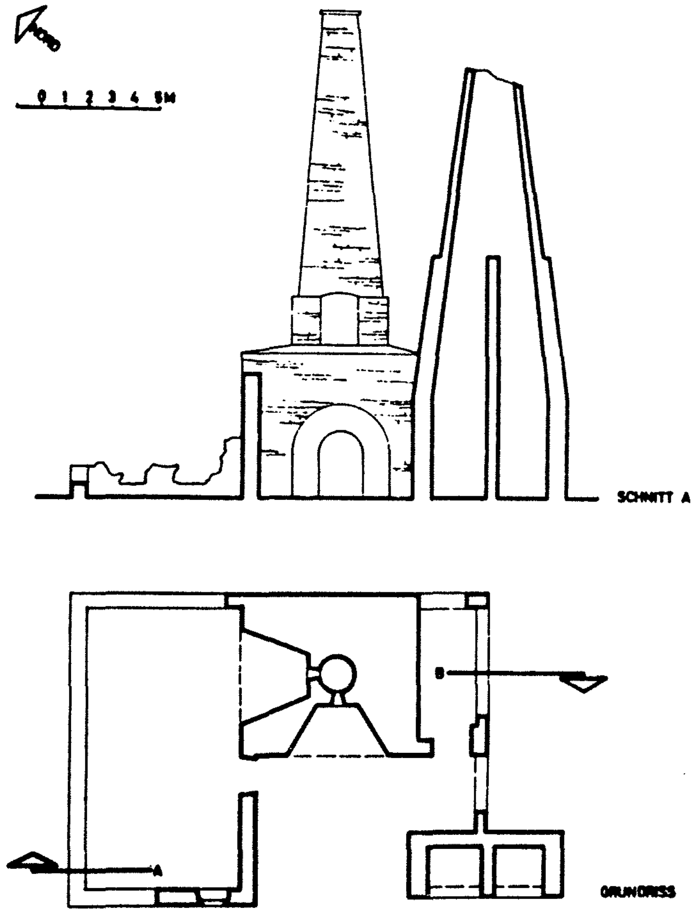
App. B

A.



Vordernberger Stuckhütte nach Hüttenmeister Anthes. Schnitt durch den Ofenstock (1719)(17). Das aus behauenen Steinen errichtete Rauhgemäuer weist im Ofenschacht eine Lehmauskleidung auf. Ein Paar Spitzblasbälge führt die Verbrennungsluft zu. Der Wasserradantrieb dient auch zur Förderung der Möllersätze auf den Gichtboden und zum Ziehen der Luppe mit Hilfe einer Zange, die an einer Kette befestigt ist.

App. C



Hüttenanlage Kendlbruck. Ein Hochofen zur Erzeugung von flüssigem Roheisen, in traditioneller Manier konstruiert, beliefert die Frischfeuer zur Herstellung von schmiedbarem Eisen, die im Hüttengebäude integriert sind(18).

METALLURGY AND TECHNOLOGY AT LAPPHYTTAN

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SUMMARY

For several centuries BC iron was made in Sweden in low-shaft direct reduction bloomery furnaces. This iron production was entirely based on limonite ores. During the period 600-1050 AD - usually denoted Vendel and Viking Age in Sweden - this iron production reached a considerable magnitude in the region north of the eastern part of the bedrock ore districts of Central Sweden. The iron was carried along natural transport routes across the bedrock ore district to the settlements around Lake Mälaren and to the trade centres there, Helgö and Birka.

The iron production in low-shaft furnaces in the old iron districts ceased by the end of the 11th century, and was superseded by an iron production based on bedrock ore using the old transport routes. From the 14th century and later, conditions of ownership and of taxation of mines and ironworks - "hyttor" - are elucidated by a number of medieval documents. Mostly on technical evidence the hypothesis has been proposed that "hytta" is equivalent to blast furnace. This has not been generally accepted until a medieval furnace ruin was archeologically excavated.

The fairly well preserved furnace ruin at Lapphyttan is shown to have been a blast furnace dating from the mid-14th century. The extensive activities in the area, the eight fining hearts for working pig iron into wrought iron and the large amounts of slag confirm other datings indicating that activities there have lasted for several centuries.

The blast furnace at Lapphyttan was of the same general construction as later ones. The ores, pig iron and slag produced have been investigated and the production and productivity have been assessed. The people working the eight fining hearths have refined pig iron from the blast furnace and made blooms of wrought iron, which they have cut up into smaller pieces of the same kind as pieces of osmund. The use of manganiferous ores facilitated the production of both low-carbon iron and of steel. Production at the site has been considerably larger than local iron consumption warrants.

The ironworks at Lapphyttan is not unique. Besides Vinarhyttan, other medieval furnace sites in the Norberg region of the same kind as that at Lapphyttan have been preliminarily investigated. Documents from the 1360s show that at least some 20 furnaces have been in operation in the Norberg district only at this time.

It is against this background that we must consider the Swedish export of osmund iron and steel, well known from 13th century British documentary sources. An industrial production of high quality iron, introducing new technology into Sweden in the 13th century at the very latest, grew to such a scale and became so well organized that the products could be sold on the European market through the agency of the Hanseatic League.

1. History

During the Germanic Iron Age and the Viking Age, from about 400 to 1050 AD, the settlements of Central Sweden were concentrated to the eastern part of the country, the counties around Lake Mälaren. There was a considerable production of iron going on in the adjoining fringe regions to the north and northwest of this central district. The iron production was based on bog ore and deposits of iron ochre in lakes and in sand and clay strata, (Hyenstrand 1972 and 1974, pp. 146 ss.).

Ever since 1938, The Central Board of National Antiquities has been investigating and listing ancient monuments and sites all over Sweden. Until now about 500,000 sites have been listed, of which about 5,000 are bloomery sites and about 700 are remnants of iron production sites from later periods, situated near brooks and streams. An increasing number of sites have been excavated in these regions, the counties of Västmanland, Dalarna and Gästrikland. The oldest known well preserved iron production site is situated in Västmanland and dates from the 5th and 4th centuries BC, (Serning 1948). Finds of furnaces from this period and until the 7th and 8th centuries AD - a period called Vendel Age in Sweden - are few and far between in this region as in Sweden generally. Most of the excavated iron production sites can generally be dated to the period 600 to 1050 AD, (Hyenstrand 1974, p. 147). Iron coming from these districts played an important part in society during the Vendel Age as well as during the expansive Viking Age, fig. 1. In summer the iron was brought to Lake Mälaren on age-old routes along streams and lakes or on tracks along the ridges running north and south. Frozen lakes and rivers offered quicker and easier transport in winter.

At the crossings of these land and water lanes there are several burial grounds, giving rich archeological finds and indicating former centres of transhipment. The centres were dominated by wealthy land owners or local chieftains controlling the routes to Lake Mälaren. There were two important trade centres situated on islands in Lake Mälaren. The one, Helgö, flourished from about 300 AD to 1000 AD, the other one, Björkö, played the leading part during the latter half of the first millennium AD, to be replaced by Sigtuna situated on the mainland, and later - in the 13th century - by Stockholm.

After the 11th century there are generally no remnants of low-shaft furnaces to be seen among the archeological finds from these iron producing districts. But this kind of furnace was still used by peasants for example in the northern part of Dalarna outside the old iron producing districts.

The ferriferous bedrock of Central Sweden is mainly situated between these old iron producing districts to the north and the agrarian settlements north of Lake Mälaren in the south. All along this new iron producing district benefited from existing transport routes, a functioning trade organization, and - supposedly - financiers for investments in new technology among those businessmen and merchants who of old were in the trade.

The oldest existing document mentioning an iron mountain dates from 1303 and actually concerns Norberg. It is a letter from Lord High Constable Tyrgils Knutsson about the selling to king Birger of his share in the Norberg mine. There is a 17th century notation telling about the discarding of a number of old, torn and illegible charters, among them one said to be issued by king Magnus Ladulås, king of Sweden between 1276 and 1290, (Kumlien 1958, p. 193). Other circumstances, too, indicate that mining of rock ore in Sweden began in the 13th century at the latest. Neither is there any evidence that rock ore ever was used in low-shaft furnaces, in which only the easily crushed and reducible limonite ore could be smelted.

Peder Månsson - writing in the period 1512 to 1524 - is the first author in Sweden telling about blast furnaces, pig iron production and refining in a separate hearth. The furnace shaft is round and 8 ells or 4.8 m deep. There are three apertures as in a copper furnace: one for letting in the blast, one for tapping of slag and one for iron. The pig iron - called "skärsten", the Swedish expression for matte in the copper smelting process - is cast in sand into thin cakes, which are broken up later to be refined into wrought iron in a separate hearth with hand-driven bellows. The bloom is then cut up into pieces of osmund. Steel running off the bloom in the refining process remains in the hearth.

King Gustavus I introduced a centralized administration into Sweden, and from the 1540s there are accurate accounts of all the blast furnaces and the taxes they paid in iron. From now on the amounts used at the Crown's iron works of ore, charcoal, costs of labour and other items, pig iron production per day and per year are all accounted for in detail. There are similar accounts of the refining of pig iron into osmund iron, bars, sheets and so forth.

The oldest evidence of the word "osmund" is found in a British text from 1280, (Rogers, Vol. 2 p 457.) The customs accounts of the Hansa League in Bergen in Norway from 1304-5 tells us that osmund is a produce of Sweden destined for the British market, (Falck-Muus, p. 153). The iron is packed in barrels, each barrel containing 480 pieces of osmund, the same number of pieces per barrel as in the 16th century. The oldest evidence of the word "hytta" - still in every day use in Swedish and meaning the building around a blast furnace - is from 1328. Despite the fact that much information from the 14th to the 15th centuries can be taken as evidence for the existence of blast furnaces during this period (Sundholm 1928, Björkenstam 1971, 1972) the lack of tangible proofs has prevented the hypothesis from being generally accepted.

2. Necessary conditions for the blast furnace process

An unconditional necessity for an intentional, efficient and economic production of pig iron is a continuous smelting process working in a strongly reducing atmosphere, (Björkenstam 1983). This demands mechanically operated bellows for the blast: the existence of water wheels at the time of introducing the process.

A common and popular belief explaining the transition from low-shaft furnaces producing blooms to blast furnaces producing pig iron is that when the furnaces were made bigger to increase production and the blast therefore had to be increased, this astonishingly resulted in a non-malleable product, pig iron. After a while the smiths somehow learnt how to make it malleable and usable. It cannot have been like this, at least not in Sweden. Limonite ores are usually very rich in phosphorus. In the making of blooms, the discontinuous running of the furnace results in a very high oxide-content of the slag. Most of the phosphorus goes into the slag and the bloom attains a reasonably low P-content. When a blast furnace is run continuously and charged with limonite, the slag in these strongly reducing conditions attains an extremely low FeO-content and the phosphorus goes mostly into the pig iron. The product is an excellent iron for casting, but as it is well-nigh impossible to reduce the P-content, the result after refining will be a cold-short and generally quite useless wrought iron. No smelting of cast iron from limonite ore is known in Sweden before the 18th century.

Generally the bedrock iron ores of Central Sweden are very low in phosphorus and in bygone times only such ores were ever used. The use of the blast furnace process is entirely tied to bedrock ores. In the Inventory of ancient monuments of the Central Board of National Antiquities there are no finds of blast furnace slag noted from the old iron producing districts, where limonite ores were smelted. All blast furnaces listed in the 1540 Inventory of lands are situated by streams and near iron mines, but the Inventory of monuments of the Central Board of National Antiquities also lists finds of blast furnace slag from sites, which are not listed in the 1540 inventory nor mentioned later, and where production must have ceased before that date.

Lapphyttan is one of these sites and a preliminary C14-analysis of slag from that site gave the 13th century as a probable date.

3. Lapphyttan, a general description

Lapphyttan is situated in a district of primary granite about 6 km east of the ferriferous bedrock of Norberg mining district. The furnace was built close to a small stream that dried up fairly recently. All substantial sources of quartz-laminated iron ores and low-manganese skarn ores of Norberg mining district are found in that ore field which is situated closest to Lapphyttan, (Geijer-Magnusson, p. 418). On the opposite side of Lake Noren is another ore field containing manganese-rich calciferous ore, fig. 2.

The mines of Norberg are mentioned not only in the previously mentioned letter of 1303, but also in a Hanseatic document from 1313, (Carlberg, p. 217). The first ore mining seems to have occurred in the Risberg field, that is the field nearest to Lapphyttan. The field is mentioned in 1440 in a letter from Karl Knutsson, who later became king of Sweden, when he wrote to the miners of Norberg criticizing them for mining the Risberg field without paying the bishop of Västerås, as they should (Carlberg, p. 220). Neither is Norberg the only iron producing district in the middle of the 14th century. Three more districts in Västmanland and three districts in Dalarna are mentioned in tax accounts from 1365-67, (Styffe, p. 115). At that time the iron tax paid by the people of Norberg was about 7 metric tons altogether. Supposing this amount to be about 1/10 of the production, this would indicate a total production of pig iron of about 85 tons. Reckoning with ironworks the size of Lapphyttan, this would mean that at least about 20 such blast furnaces would be operating at that time in Norberg only. The Crown, the nobility, the church, and the Hanseatic League all had great interest in the production of iron as early as the 14th century at the latest, which is a strong support for the idea that already then there was an industrialized iron production going on supplying international trade in iron.

The works

Investigating Lapphyttan situated in unspoiled countryside, the archaeologists not only excavated the visible overgrown mound of the ruined smelting furnace by the stream, but also during several years of work investigated all activities going on at the site by excavating about 7,000 m^2 of ground around the furnace. This work was crucial for the interpretation of the technology.

Fig. 3. The iron works is situated in non-arable land about 2 km from Olsbenning, the nearest village. In Olsbenning, too, is a stream which actually is bigger than that of Lapphyttan, and where blast furnaces are known from written sources to have been in operation in the 16th century.

However, there are two factors to be taken into account when discussing the setting up of a blast furnace situated at Lapphyttan: firstly, there was much more water power available at that time, before the stream was drained, and secondly, people were used since the time of the low-shaft furnaces to build their furnaces at some distance from the agrarian settlements.

Ore

The ore was transported from the mines to the southern slope at Lapphyttan, where some 20 storage places were found. The ore was crushed and sorted into lumps as big as a fist. The lumps are smaller at the storage places closer to the furnace, there being as big as a thumb, which supposedly was the size attained after roasting and a second crushing. The ore lumps found at the storage places were lumps pressed down into the soil and left when the stores were emptied either at the end of the ultimate campaign, or when the remaining ore was transferred to some other blast furnace site when Lapphyttan was abandoned. In some places the ore lies in two layers, as for instance at site A 35. Here the strata are separated by about 30 cm of sand, which might indicate two entirely different periods of running the furnace. The same kind of ore, however, is found in both strata. The ore lumps may have been pressed down to different depths because of varying firmness of the topsoil. The sand might have been intentionally deposited to raise the ground to its original level. The various kinds of ore will be discussed in the section treating the metallurgical process.

Roasting pit (fig. 4)

As is well known from old blast furnace sites the roasting pit lies near the furnace. It is dug into a slope, open in front like a stall and walled with stone at back and sides, and with a horizontal sole. Roasting is done by laying ore in several layers between layers of thick logs. The ore is mixed with charcoal and slits between the logs are filled up with charcoal dust. The purpose of roasting the ore is generally to reduce sulphur by oxidation. The sulphur content of ore from mines in Central Sweden is usually very low, and only such ores were formerly used. By roasting magnetite is transformed into hematite, the ore becomes more porous and easily reduced. Heating also leads to insipient crack formation which makes both magnetite and hematite easy to crush. At Lapphyttan they used ores with gangue containing carbonaceous skarn. Roasting makes such ores porous and easily reducible. There were lumps of ore left in the roasting pit. Considering the amount of work done, we may suppose that the ore lumps from each batch were carefully collected. The remaining lumps therefore seem to come from the last campaign. It must be remembered that different kinds of ore need various times for roasting and that the various kinds of ore therefore were roasted separately. The mixing of ores to obtain the best composition of slag was made only when charging the furnace. Of course it is possible that the remaining lumps of ore come from several roasting batches during the last campaign. They are nevertheless ore of the same kind, so it seems reasonable to ask, whether this was the only kind of ore that was roasted at that time.

Charcoal

In the same area where the stores of ore were found and at about the same level as the furnace, was a 5 cm thick layer of charcoal and soot beneath a layer of 5 x 4 x 0.2 m of blast furnace slag. This seems to indicate that the charcoal was stored under a roof, as until very recently in our country both dwellings and other houses were covered by several layers of birch bark which were held in place by turf, stones or lumps of slag as at Lapphyttan.

Blast furnace

In Sweden there were two patterns for building blast furnaces of the kind that we can study in fig. 5, either the old model called Old Swedish blast furnace or the younger one, called German blast furnace. According to Otto Dress writing in 1687, the first blast furnace in Värmland to be built to the German pattern was erected in 1610. When Dress writes his account of iron and steelmaking in Sweden, there is a growing number of German blast furnaces in use, but there are still old Swedish blast furnaces in operation. The figure shows a German blast furnace such as they were built at the end of the 18th century, somewhat bigger and sturdier than before. There is a considerable number of them still standing in many places, preserved as industrial monuments. According to Dress as well as to Garney, the German furnace differed from the Swedish only in being bigger and roomier, in being more carefully built, and in having the taphole fitted with a damming stone. The taphole of a Swedish blast furnace was stopped with "a lot of sand" only. Slag and iron were here tapped by making a hole in the sand dam with a tapping bar. Garney gives a description of these Swedish blast furnaces. The furnace was low and small, 6 - 9 ells or 3.6 - 5.4 m high, and it had a stone foot 8 ells or 4.8 m square. It was so deeply built into the dug out slope of the river bed that only little of it was visible above the slope. The front with taphole faced the stream. The tapping and tuyere arches were narrow, spanned with long stones rather than vaults. The top walls of the furnace were timbered.

This description corresponds very well with the furnace at Lapphyttan, fig. 6. Here the stone base is about 4.6 m square instead of 4.8 m. An estimate of furnace height based on the volume of rubble gives a height of 3.2 m, as compared with Garney's minimum value of 3.6 m. Some rubble may have been washed away in the course of time, so the furnace height might have been slightly greater. The lower back side of the stack was supported by the surrounding earth. The curvature of this section corresponds to a stack diameter at the end of the campaign of about 1.1 m. The inside wall was built of refractory stone, in this case a sandstone mainly consisting of SiO_2 (about 80 %) and Al_2O_3 (about 12 %). A determination of melting temperature of the stone gave 1 285°C. Before the days of machine-made dimensionally accurate refractory bricks, it was impossible to build the stacks exactly circular, so they were made polygonal. According to Garney, the old blast furnace stacks were built square or eight-sided. The stack of Lapphyttan seems to have been square but with cut-away corners, fig. 7. The stones of the lining were about 1 foot long, the mortar consists of clay having a melting temperature of 1 260°C, somewhat lower than that of the stones. About 5 cm of the lining seems to have melted away and the surface is very slaggy. A test sample of the lining taken about 1 m above the sole gave a melting temperature of 1 100°C. Further down near the tuyere level more of the lining had melted. Around the tuyere the lining has been repaired with several vertical layers of flat sandstones, indicating that the furnace has been used several times. It is now impossible to determine the profile of the newly built stack. There is nothing here contradicting Garney's statement in his book that in the old Swedish furnaces the constriction of the shaft towards the hearth began at a lower level than in the German furnace.

As is usual in all excavated furnace ruins, nothing is left of the hearth. The hearth had to be rebuilt for every campaign, as it usually was badly burnt. When blowing down a furnace at the end of a campaign, there remains in the hearth a bear consisting of low-carbon iron and slag. When the bear is removed, the hearth walls are badly damaged, which does not matter, as the hearth anyhow must be rebuilt for the next campaign. At Lapphyttan the construction of the foundation beneath the sole indicates that the hearth was rectangular and scarcely bigger than 0.3 x 0.5 m. The position of the tuyere is known. Its lower rim was about 0.25 m above the sole and the sole must have been at a level of a few cm above the tapping floor. The lining of the stack was supported by a wall built of the same kind of sandstone. Outside this wall was a filling of clay mixed with old sandstone rubble from previous rebuildings of the furnace. The outer wall above the stone foundation was timbered. This is evidenced by the find of a log at the back of the furnace.

An important constructional detail of the German furnace is the pillar between the tapping arch and the tuyere arch. This pillar must be carefully built with great exactness. There were no vaults at Lapphyttan. The walls above the arches were supported instead by long flat stones spanning the openings. The tuyere arch was made as small as possible. The bellows stood on a shelf cut into the slope somewhat above the level of the tapping floor, thereby giving firmer support to the foot of the pillar between the arches, fig. 6. It is not known what the inner part of the arches looked like, neither the arrangements for tapping slag and iron nor the form of the tuyere. The situation by a stream and the finding of a waterwheel bearing stone in a place where the wheel should be, shows that the bellows were driven by water power.

Water power

About 300 m north of the site is a dam, surrounding a flat area and turning it into a water reservoir. At point A 52 (fig. 3) is a stone foundation and the remains of a dam provided with gates for regulating the water to the wheel. The direction of the dam makes it less probable that water was conducted directly to the wheel in a leat. The wheel was probably undershot, driven by the running water in the nearly horizontal stream in front of the furnace.

Refining and forging (Point A 14, 15, 21-25, 30)

Seven out of the eight fining hearths have been excavated. They are all similar in principle, consisting of three or four stone walls forming a rectangle or square. They are all surrounded by typical refining slag. The hearths are very simply built and badly preserved, having been for centuries exposed to rain, snow and ice. In interpreting the finds, we consulted Peter Saxholm's description from 1725 of a refinery for making osmund from pig iron. The author grew up in an old iron making district, Saxhyttan, where they in the 18th century still made osmund iron from pig iron scrap and iron droplets collected by crushing blast furnace slag. The hearth in Saxholm's description is better built and the bellows are water driven. However, the dimensions are the interesting feature. The bottom or sole consists of a 2" thick stone slab. The firebox is 3/4 ell or 45 cm square and about 10" or 25 cm deep. The two side walls are extended towards the work opening, so that the tuyere wall is 1 1/2 ells or 90 cm long, and the opposite wind wall 1 ell or 60 cm. There is a horizontal stone slab on top of these extended side walls level with the top or the firebox. Surplus slag can be tapped through an opening beneath the slab. The tuyere is set some 6 - 7" above the sole somewhat closer to the back wall. Comparing this with the hearth dimensions found at Lapphyttan, you will find that all the hearths were 40 to 50 cm wide. Four hearths seem to be 50 - 60 cm long and two 85 - 90 cm long. One hearth was too demolished to be measured. The lengths of the four first mentioned ones correspond with the wind wall length of Saxhyttan and the second hearth corresponds with the length 1 1/2 ells of the tuyere wall. It seems less probable that the hearths of Lapphyttan were larger than this 18th century hearth of Saxholm. Therefore the original dimensions of the fireboxes seem to have been 3/4 of an ell square.

At Lapphyttan it may well be so that the wall towards the work opening is lost and that in four hearths the retained longer walls correspond to a wind wall of 1 ell or 60 cm, and that in two hearths the retained side wall corresponds to an original tuyere wall of 1 1/2 ell or 90 cm.

The bellows were hand operated, and all hearths have been used. The great number cannot be clearly explained. Certainly there were stipulations in the 14th century regulating the number of owners of a blast furnace: no single owner was allowed to have a share of less than 1/8. On the one hand there might have been eight owners running the forges at Lapphyttan, or on the other hand, there existed a special category of workers - osmund smiths - and their wages were regulated by the Crown. Refining slag was found by all the hearths, but the overwhelming majority of it was found at points A 14 and A 15, lying close to each other. Either has most of the refining be done here or else has slag been carried here and the place used for slag storage.

In 1983 Tomas Jacobson built a fining hearth of 45 x 45 cm. He has shown that about 2 1/2 kg of pig iron is a suitable batch for refining, giving a low-carbon bloom of 1.7 - 1.9 kg after puddling for 70 - 100 minutes. It was found possible using a hatchet and a hammer to divide the hot bloom into pieces of about 300 gr, the size of an osmund. Both as to size and macro-structure they are identical with those pieces of iron in the museums' stores, which are generally known as "klimpjärn", iron lumps. As Jacobson states himself, it is not hereby demonstrated that all lumps in our museums' stores are made by refining pig iron, but the experiments do show that it is quite feasible in hearths of the kind found at Laphyttan to refine pig iron into blooms of low-carbon iron, and that the bloom easily can be divided into small pieces like lumps of "osmund" iron. Blooms as well as such lumps from the cutting have been found at Lapphyttan.

4. Metallurgy

Ores

In Sweden, the magnetite ores are generally compact and difficult to reduce. The phosphorus content is universally low, but sulphur content may in some cases be high. Sulphur as well as arsenic in the ore are mostly removed in the roasting. The ores most sought after in olden days were the quartzose hematite ores of low sulphur content, but often containing somewhat more phosphorus than the magnetite. Formlerly these quartz-rich ores were usually not mixed with limestone, but with basic ores which were called "mixing stones".

The ore specimens collected at Lapphyttan have been investigated by a committee chaired by Boris Serning within the Historical Metallurgy Group of the Jernkontoret. The specimens have all been checked against Geijer-Magnusson´s work on the ore geology of Central Sweden. When considering the analyses we must always remember that the amount of ore from each storage site is very small, between 1 and 10 kg. Large random variations can therefore occur, despite the fact that the specimen samples come from the same ore deposit. In the following, the ores are arranged according to their metallurgical suitability.

Table 1. Low-manganese ores

Sample No 51 is considered to be quartz-laminated hematite from the Risberg field. The characteristic of slags with a low content of MnO is that the CaO-content is several times higher than the MgO-content, in contradistinction to slags with high MnO-content. The low-manganese slags have a markedly higher SiO_2-content and lower Al_2O_3-content. The only kind of ore giving pig iron of low manganese content is that which is represented by sample No 51. The specimen was found in 1980 embedded in the topsoil.

Table 2. Low-manganese ores with high Al_2O_3-content

With considerable certainty samples No 116 and 119 can be taken as skarn ores of that kind which is found in "Åsgruvan" mine and "Smörbergsgruvan" mine close to the Risberg field. The cerium content has been determined in both samples and was found to be 0.0221 and 0.0231 % Ce respectively which is typical of these mines. Ores with composition according to the analysis of table 2 cannot have been extensively used because of the high Al_2O_3-content, if that determination really is reliable. This is doubtful in itself judging by modern analyses of ore from these mines. They have most probably been used for smelting pig iron of low Mn-content. Sample No 55 was found in 1980 embedded in the topsoil, No 116 comes from point A 36, and No 119 from point A 39.

Tables 3 and 4. Manganese rich ores with low Al_2O_3-content

Ore samples having a composition in accordance with table 3 and samples from the roasting pit seem to be of the same general kind, even if the analyses vary somewhat. We believe this manganese-rich ore was mined at

Klackberg. The samples No 53, 54 and 56 were found in 1980 embedded in the topsoil.

Table 5. Manganese-rich ores with high Al_2O_3- and P_2O_5-content

These samples, too, are thought to have come from the Klackberg field. The content of arsenic is also rather high, which sometimes is the case with Klackberg ore. The high Al_2O_3-content together with the SiO_2 makes this more acid in character than the above mentioned Klackberg ore. The rather high phosphorus content in some pig iron and the iron lumps shows that this ore was used. Sample No 111 comes from point A 41, No 112 from A 40.

Table 6. Iron-manganese-silicate ores

The high manganese content comes from the mineral braunite (3 Mn_2O_3·$MnSiO_3$). The "Assesorskan" mine in the ore deposit between the Risberg field and Lake Noren is one deposit of this kind of ore which is near to Lapphyttan. The low iron content means that this ore can only have been used as an addition because of the high manganese content. Samples No 110 and 114 come from point A 35, as well as No 123, but No 123 was found beneath the 30 cm layer of sand. No 118 comes from point A 37 close to the furnace.

Charcoal

Called-in Germans and Walloons introduced into Sweden the method of making charcoal in stacks with the wood arranged vertically. Until the end of the 16th century the method of horizontal stacking had been universally used in Sweden, and it was still used in many places at the end of the 19th century.

In 1872, G. Svedelius published a description of the difference between the two methods. Horizontal stacks must be built with the straight trunks of conifers. Vertical stacking allows the use of hardwood and bent branches of softwood or conifers. The ash from burning deciduous trees as well as branches and tops of conifers contains more phosphorus than does the ash from burning trunks of conifers, therefore the ash of former days contained little phosphorus.

In 1911, A. Leffler published a comprehensive study of charcoal, based on several hundred samples. Dry charcoal made in stacks weighed 14.5 kg per hl. A standard sample of charcoal based on 99 samples gave 3.04 % of ash of the following composition:

SiO_2	38.02 %	Fe_2O_3	22.69 %	SO_3	0.93 %
K_2O + Na_2O	6.10 %	Al_2O_3	3.88 %	CO_2	1.35 %
CaO	19.52 %	Mn_3O_4	1.89 %	Sum	100.98 %
MgO	5.59 %	P_2O_5	1.01 %		

The analysed samples also contained ash of charcoal made of sapwood in ovens. Therefore, the charcoal used at Lapphyttan made entirely from coniferous logs, obviously contained far less phosphorus than the quoted analysis above would indicate.

The ash considerably increases the volume of slag in the blast furnace. Still in the beginning of the 19th century, simple old peasant ironmakers' blast furnaces sometimes consumed more than 300 hl of charcoal per ton of pig iron. We may suppose a consumption of no less than 500 hl per ton of pig iron in the small furnace at Lapphyttan. This would indicate an ash amount of about 200 kg per ton of pig iron.

Furnace lining

The hearth is usually burnt out in one campaign. Disregarding the burning out around the tuyere, the refractory shaft lining generally served for 30-50 years without rebuilding and relining the stack, say in the period 1600-1800. In the beginning of the 17th century there were usually two campaigns of about two weeks each in a year, in spring and autumn.

In the beginning of the 19th century furnaces bigger than that at Lapphyttan were run with 1 to 1 1/2 furnace loads a day. The volume of the Lapphyttan furnace was about 3 m^3. One and a half loads equal 45 hl and, reckoning with 500 hl of charcoal per ton of pig iron, this should give 90 kg of pig iron per day or about 2.5 tons a year. Running such a low-shaft furnace harder will result in very short reaction times in the shaft. Two and a half loads per day seem to be a maximum, resulting in a cold, low-carbon pig iron, yielding 150 kg per day or about 4 tons of pig iron in two campaigns per year, which probably not always was the case. Based on this estimate, not less than 50 kg of lining material per ton of pig iron must have melted away in the process. This influences the process, besides increasing the amount of slag. The sandstone used is rich in alkali; three analyses of stones from the stack gave the following mean composition:

SiO_2	76.6 %	Fe_2O_3	2.7 %	Na_2O	2.8 %
TiO_2	0.27 %	CaO	1.8 %	K_2O	2.5 %
Al_2O_3	12.5 %	MgO	0.6 %	MnO	0.02 %

Large amounts of alkali evaporate and partly sublimate higher up in the stack. The slaggy furnace wall about 1 m above the bottom contained a good 11 % of alkali. Alkali functions as a catalyst in the reduction of ore into iron: it facilitates reduction without itself taking part, especially so in the last step of the process, the reduction of wüstite (FeO) to iron (Fe) (Fornander, 1983). You may ask if this lucky, but unknown condition has facilitated an early birth of the blast furnace process in Sweden, especially so as charcoal also contains alkali.

Blast furnace slags

A very high yield and therefore very low FeO-content of the slag is a characteristic of the blast furnace process. The FeO-content of the slag from the last charcoal blast furnaces was below 1 %, and at the end of the 19th century hot-blast furnaces produced slag holding 1-3 % of FeO. Because of the quartz-rich ores and acid furnace linings, the slag from Swedish blast furnaces contained about 50 % of SiO_2. Using cold blast and running the furnace cold, you get pig iron holding 3.5 % of carbon and a glassy black green slag containing about 10 % of FeO. A FeO-content of the slag below 10 % can be taken as a characteristic of Swedish blast furnaces giving a silicate-rich slag. Out of 37 slag samples in tables 7 and 8, 33 contain between 1.7 % and 10.9 % of FeO. Two of the samples are obviously misses or come from the blowing-in or the blowing-down of the furnace, they contain 21.5 % and 27 % of FeO, and two samples show 13.5 % and 14.1 %. Even today you hit trouble in the process, and in former days trouble was very frequent, as you can see in any old textbook on metallurgy. They did not analyse the ore, which was measured by the shovelful. The charcoal was measured, too, and the weight varied with content of water and size of the lumps. Adding to this, blowing in and blowing-down always yield FeO-rich slag. Tapping four times a day for 10 days results in at least 2 slags out of 40 with a higher than normal FeO-content.

Considerable work has been devoted to the study of the slags. A systematic investigation has been made on the initiative of Mr Hans Hagfeldt. About 5 tons of slag have been collected from the slag heaps A 3 and A 4, which have been cut by 9 vertical sections. All slag has been inspected and classed in three groups: 1) glassy green or blue slag, 2) mixtures of glassy and grey slag, and 3) grey - dark brown slag. Analyses of samples from these three groups gave the following mean results:

	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O
1)	3.5 %	11.8 %	12.1 %	10.0 %	6.2 %	53.9 %	0.91 %	0.90 %
2)	3.2 %	10.1 %	17.8 %	9.7 %	4.8 %	52.9 %	0.63 %	0.82 %
3)	7.2 %	11.7 %	14.0 %	10.2 %	6.0 %	48.7 %	0.85 %	1.11 %

As we can see the slags are of the same general kind. The difference in appearance depends upon slags of group 3) having higher FeO and lower SiO_2-content being darker, and SiO_2-rich slags of group 1) with a lower FeO-content getting a glassy structure by rapid cooling. Slags of group 2) in between is somewhat more basic than those of group 1). Neither is there any significant difference between the analyses when they are sorted according to the various strata of the heaps. In addition to this set, a number or random samples have been taken from heaps A 3 and A 4, besides samples from the hearths and samples of the slag used as filling material in the storage place for ore. The analyses are all shown in tables 7 and 8.

The previously mentioned striking difference of composition between MnO-rich and slags low in MnO is clearly seen. The blast furnace slag collected near the hearths A 21, 24 and 25 are all MnO-rich as is the slag used as filling material on the storage place for ore. The spread of MnO-rich and slags low in MnO is as follows:

		Low-MnO	High-MnO
A 1	Filling at the blast furnace	4	2
A 2	West of the brook near the furnace	3	0
A 3	- " - fineries A 14 & 15	1	10
A 4	East of the brook	1	4
A 9	West of the brook, fireplace of dwelling	1	1

Out of 10 low-MnO slag samples, 9 were found west of the brook, 4 of these had been used as filling material beneath the furnace, and 3 were found in the smallest slag heap A 2 close to the blast furnace. The material is limited, but it might indicate that iron production began using ores low in manganese. The explanation of heap A 3 west of the brook which mainly contains MnO-rich slag might be that they always used this place when extracting pieces of iron worth collecting from the slag.

Computing the composition of the charge

The primary condition for achieving an evenly and smoothly running smelting process and an acceptable iron yield is a melting temperature of the slag as low as possible using available ores. During the last hundred years of the charcoal blast furnace, the starting point when computing the proportions of mixing ore, lime or sand to be added to the available main ore was the desired basicity - $(CaO + MgO)/SiO_2$ - of the slag. The proportions were adjusted in running which anyhow had to be done every day because of variations in density of the charcoal, accidental variations of ore composition and so forth.

Here in the Lapphyttan case, the slag composition is known. It is therefore possible by simple estimates based on known basicity of the slag and ores roughly to compute which ores and mixtures of ores can be responsible for these specific kinds of slag. After such a preliminary calculation, we must compute in detail the distribution of elements in iron and slag.

The one kind of slag is characterized by a MnO-content of 1.7 - 6.4 %, a ratio of CaO/MgO of 3.5, and a mean SiO_2-content of more than 50 %. The other kind of slag contains 8.1 - 17.7 % of MnO, a CaO/MgO ratio equal to 1 and a SiO_2-content slightly below 50 %. The following applies for the two charge compositions which might have been used:

1. Only two ores may be used: a main ore and a mixing ore. The relative proportion must be given as a single ratio.

2. The FeO-content is calculated to be the same as the mean content in tables 7 and 8.

3. Charcoal ash of the above mentioned composition is taken to give 200 kg of ash per ton of pig iron.

4. Lining stone is taken to add 50 kg to the slag per ton of pig iron.

5. Only half of the alkali in ash and lining stone is taken as going into the slag.

6. The amount of manganese going into the slag depends upon the basi-

city and the temperature of the slag, and these conditions vary from campaign to campaign. In the 1930s in hot-blast furnaces giving little slag of higher basicity than slags at Lapphyttan, some 70 % of the manganese went into the slag. About 1900, the usual estimate was that roughly half of the MnO went into the slag, when using MnO-rich ores, and all MnO went into the slag when using ores containing less than 1 % of MnO. Because of the large amount here of acid, low-temperature slags, 2/3 of the manganese in the ore is supposed to go into the MnO-rich slags and 3/4 of it into slags low in MnO.

Example 1. Slags low in MnO.

The computation was made using a charge consisting of 3/4 of the ore in table 1 and 1/4 of an ore having the mean analysis of tables 2 and 3.

The only kind of ore that can have been used primarily is the quartz-rich ore of table 1 containing much CaO and little MgO. It must be mixed with a basic ore to give a slag according to table 7. The ore of table 3 is the commonest basic ore containing little Al_2O_3, and it has been added to the ore from the roasting heaps, which belong to the same general kind.

Result:	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	TiO_2
Example	7.3%	3.8%	20.9%	5.9%	4.5%	55.7%	1.8%	0.1%
Table 7	7.3%	3.7%	20.3%	5.7%	4.7%	56.7%	1.5%	0.1%

You can see that the result almost coincides with the given analysis. The amount of slag is about 550 kg of slag per ton of pig iron, containing 0.35 % of manganese.

Example 2. MnO-rich slags

We have here assumed that ore from Klackberg with a composition according to the analyses of tables 2 and 3 has been used primarily, and that iron-manganese-silicate ore has been added to obtain a suitable slag composition and to raise the manganese content of the pig iron. The computation was made using 9/10 of ore of the mean analysis of tables 2 and 3 and 1/10 of ore of the mean analysis of table 6.

Result:	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2	Alkali	TiO_2
Example:	5.6%	12.4%	15.1%	11.5%	6.8%	46.7%	1.8 %	0.1 %
Table 8	5.6%	12.7%	13.1%	11.0%	6.3%	49.3%	2.0 %	0.16%

It is possible to obtain a slag composition of this general kind by mixing these ores in this proportion and under conditions stated above. The slag amounts to a good 700 kg per ton of pig iron because of the low FeO-content of the silicon ore. The manganese content of the pig iron amounts to 2.5 %.

It was formerly assumed that at Lapphyttan perhaps only the Klackberg ore was roasted. It is possible that the iron-manganese-silicate ore did not become more easily crushed by roasting. Another not so obvious reason why there is no such ore at the roasting pit is that so very little of it was needed in comparison to the demands of today's iron production. Let us suppose that the production at Lapphyttan was 120 kg of pig iron per day, then the consumption of iron-manganese-silicate ore was about 1 kg per hour. During a fortnight in blast only about 3 buckets of ore of about 10 litres each was used. Roasting a couple of batches sufficed for several years of production.

The Saxhyttan project

To get an idea about what pig iron smelting at Lapphyttan might have been like, a blast furnace of the Lapphyttan size was built at Saxhyttan in 1982, using modern refractory bricks, fig 8. The height of the stack is 3 m and the diameter 1 m, the hearth is rectangular and provided with one tuyere. There is a stone dam in the taphole which also is plugged with sand. Stefan Agorelius, Boris Serning, and the two authors of this paper have made three tests with the furnace. The nowadays very high price of charcoal has limited the running time of the experiments. At the first experiment, a cold pig iron was obtained which ran out and mixed with the slag in tapping the furnace. At the second experiment the furnace initially was charged with sinter from Oxelösund ironworks and later with Dannemora ore, which is of the same general kind as Klackberg ore. After a lengthy heating up of the furnace with very careful charging of ore, the experiment continued for 2 1/2 days including the day of blowing-in, yielding 70 kg of pig iron out of 170 kg of ore used. The furnace had not reached full capacity when the experiment was stopped.

The general analysis of the pig iron obtained is: C 3.5 %, Si 0.26 %, MnO 0.19 %.

The carbon content varied between 3.2 and 4.1 %; the silicon 0.03 to 0.82 %, and manganese 0.05 to 0.44 %.

The mean analysis of the slag is:

	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2
Saxhyttan	8.0 %	2.4 %	21.3 %	6.9 %	4.1 %	53.4 %
Table 7	7.3 %	3.7 %	20.3 %	5.7 %	4.7 %	56.7 %

The surprisingly good agreement here seems to indicate that the furnace at Lapphyttan did not allow a thorough reduction of the iron content of the slag. The pig iron must have been cold and much of it went with the slag.

In the prevailing circumstances including time of blowing in, a not fully charged furnace and having trouble because of our limited experience in running the process in such a small furnace, the charcoal consumption was preposterous: 2 000 hl per ton of pig iron, as reckoned on the total yield of 70 kg. Therefore in the third experiment, the heating up was very carefully done and the furnace charged with Klackberg ore only, intending to obtain a better estimate of the charcoal consumption. Unfortunately the tuyere clogged up, and it took some time to set this right. The temperature dropped so much that the experiment was stopped as a miss in testing charcoal consumption.

Two important observation were nevertheless made. The charcoal consumption increases considerably when air is let in through the taphole which must be kept tightly plugged with clay and sand between tappings, a fact which Garney stresses in his textbook.

Cracks in the stack wall from heating, and the holes in the walls for measuring furnace temperature caused considerable loss of charcoal. It was further noticed that the wall temperature dropped for every increase of the burden. Here lies seemingly the reason for the extremely thick walls of old timbered blast furnaces. The filling of clay and sand is there both as a tightening material and as a heat accumulator.

A comparison was made between this slag and that from Lapphyttan. The coincidence mainly depends upon the fact that slags from Swedish charcoal blast furnaces using quartz-rich ores have this general composition:

	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2	
Högfors 1878	1.2 %	4.4 %	32.5%	3.0 %	2.4 %	55.9 %	(Odelstierna p. 353)
Västanfors 1882	0.2 %	6.4 %	25.0%	11.8 %	7.0 %	42.0 %	(Nisser p.62)

The slag analysis from Högfors concerns pig iron with about 1 % of MnO. Västanfors produced Bessemer pig iron containing about 4.5 % of manganese. They differ from the Lapphyttan slag primarily because Högfors and Västanfors used hot-blast furnaces with two tuyeres, resulting in more efficient reduction of iron and manganese.

Pig iron

In the taphole at Lapphyttan two, about 10 cm long, flat and oblong pieces of pig iron were found, sample No 180, fig. 9. They have been metallographically analysed by Mrs Helfrid and Mr Sten Modin, together with five other pieces of pig iron:

Sample No	180	White, somewhat sub-eutectoidic pig iron	4.1 % C
"	1231	" , sub-eutectoidic pig iron, less than	4 % C
"	1682	" , super-eutectoidic pig iron, more than	4 % C
"	2141	Grey, with traces of white pig iron, " "	4 % C
"	2722	White, sub-eutectoidic pig iron, less than	4 % C
"	3052	" " " " " "	4 % C

A very surprising find was the existence of thousands of iron droplets found in the area in front of the furnace and mostly in and around the fining hearths. Droplets here means small pieces of iron of irregular or nearly spherical form, from about 0.5 to 40 mm across.

In the soil by the brook beside the furnace droplets were found in a layer of iron hydroxide, also containing charcoal and slag particles. In the mid-15th century the Italian architect Filarete wrote about a water filled pit by the tapping arch of a blast furnace and the idea has been suggested that this pit was used for granulation of pig iron (C.S. Smith 1964). It was therefore considered necessary to check whether the droplets from Lapphyttan were intentionally made by granulating in water. The droplets were compared with granules made at Hagfors ironworks. The droplets from Lapphyttan showed no similar structure. It has later been shown that Italian blast furnaces formerly always had a water pit, in which the hot pig iron was cooled, partly to remove slag and partly to make it brittle and easily crushed. (Ferragni-Malliet 1982, Ferragni-Malliet-Torraca 1984.) No granulation occurred at Lapphyttan, most probably not at the blast furnace of Filarete either. In a 6 m high pilot blast furnace at Hagfors, Ivar Bohm (1982) made pig iron from an iron ore hard to reduce, which resulted in a cold pig iron containing 3.1 % of C and a very viscous slag containing 5 % of FeO and 8 % of pig iron droplets. We can find that the viscous and FeO-rich slag of Lapphyttan certainly contained considerable amounts of pig iron, which was collected and used.

Seventytwo droplets have been metallographically investigated and a large number chemically. Most droplets were totally corroded, only 33 had a metallic core.

All droplets found on the tapping soil were corroded. Out of six found in the tuyere arch, two were corroded, one consisted of half white pig iron, one of drops of slag in a metallic matrix, two consisted of low-carbon iron. One of those two was analysed and contained: C 0.77 %, Si 4.26 %, Mn 4.48 %, P 0.028 %, S 0.023 %. All of these droplets may have come out through the tuyere opening.

Six droplets have been investigated at the laboratory of the Swedish Association of Foundries in Jönköping by professor Bertil Thyberg. Three droplets come from fluid pig iron. Different composition and solidifying at different rates has resulted in entirely white pig iron, sample 28; mottled pig iron, sample 35, fig. 10; and quite grey pig iron, sample 4. The other ones were samples of low carbon content collected at the fining hearths.

There was a considerable number of these droplets in and around the fining hearths, both low-carbon ones and those of pig iron composition. The analyses are reproduced in tables 9 and 11. All pig iron analyses are in table 9.

Fining hearths

Near the fining hearth were found both blast furnace slag, refining slag, pig iron droplets and droplets of low-carbon iron, as well as pieces of iron of 100-400 gr weight cut from the blooms.

The slag composition depends upon that of the pig iron and it varies in the course of the process. No carbon can be oxidized until all silicon and manganese in the pig iron has been oxidized. The slag is partly tapped during the refining, and it becomes more FeO-rich the longer the refining process lasts. When refining pig iron in a hearth, refining slag from previous runs is always added. Some SiO_2 is also added with the sand coming with the charcoal. As the hearth is built of the same kind of sandstone that is used in the blast furnace lining, this, too, goes into the slag to some extent which is clearly seen in the analyses. Slags No 18 - 22 are examples of this very conspicious mixing of the refractory lining. Table 10.

The silicon and the manganese contents of the pig iron affect both puddling time and process in fining hearths of this kind. During the introductory phase much of the phosphorus goes into the slag, although it later will be almost entirely taken up by the iron. Sample 196 may be an example of this. Manganese in the pig iron makes the slag more fluid and delays the reduction of carbon; or contrariwise it can be said to assist in producing more blooms of a steely composition. In the Middle Ages manganese-rich ores were called steel ores, therefore it is very probable that at Lapphyttan they changed low-manganese pig iron to manganese-rich as steel was better paid on the market. Most of the pig iron analyses show a high content of manganese, and the carbon content of the refined iron is usually high, see table 11. Reducing low-manganese pig iron usually results in wrought iron with less than 0.1 % carbon.

I must here put in a warning with respect to the iron droplets of table 11. They did contain some slag which it might have been difficult to remove before the analysis was made. However, in any case they are not made up of fully refined iron. Either they are splashing droplets from the puddling process, or droplets not absorbed in the bloom and therefore not fully refined.

All analysed, fully refined end-products are puddled until the silicon and manganese contents are very low. Mr and Mrs Modin have analysed them all metallographically.

Sample 834. There is rather little slag in the iron. The structure is that usually found in puddled iron with local variations in carbon contents. A very interesting observation is that there are clear traces of hardening of this lump (fig. 11 and 12). It seems reasonable to assume that one lump of iron was hardened for a test when the hot bloom was cut up, so that they immediately were able to sort the product into wrought iron or steel.

Sample 1410. This lump of iron shows clear marks of the cutting up process, fig. 13, and the structure is mostly ferritic which corresponds with the analysis.

Sample 2734. Porous, with varying carbon content.

Sample 3734. Heavily corroded. Porous, unevenly puddled and containing much slag.

At point A 15 is a pit lined with stones which has been interpreted as the foundation of an anvil, an anvil support. Here, too, a number of forged implements were found, e.g. forged rods and scrap from forging. A metallographic analysis by Mr and Mrs Modin of a piece of scrap - sample 1738 - showed that it is low carbon iron, containing oxide rich forging slag. A rod was found to be low-carbon iron, containing the long threads of slag characteristic of forged iron.

The production in the forge does not seem to have been very high. Probably the forge has been used only for local needs of different items. The end product to be delivered from Lapphyttan was cut pieces of wrought iron of the same type as osmund, iron as well as steel. Two deposits are found with 33 osmund pieces and 37 smaller pieces - scrap from the cutting operation.

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Table 1. Low-manganese ores

No	Fe tot	FeO	Fe_2O_3	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5	TiO_2	V_2O_5
51	53.7	–	–	0.16	6.48	0.18	0.15	15.4	0.12	–	0.016	0.01	0.02

Table 2. Low-manganese ores with high Al_2O_3-content

No	Fe tot	FeO	Fe_2O_3	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5	TiO_2	V_2O_5
55	55.5	–	–	0.11	3.15	1.89	2.70	12.0	0.06	–	0.007	0.04	0.02
116	59.6	26.3	55.8	0.17	2.38	2.77	3.69	9.8	0.21	0.04	<0.039	0.04	<0.01
119	57.7	24.0	55.8	0.18	2.45	3.28	2.76	11.0	0.11	0.02	<0.035	0.02	<0.01
Average	57.6	25.2	55.8	0.15	2.66	2.65	3.05	10.9	0.13	–	–	0.03	–

Table 3. Manganese-rich ores with low Al_2O_3-content

No	Fe tot	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5	TiO_2	V_2O_5
53	55.6	6.54	2.24	4.04	0.23	1.00	-	0.02	0.008	0.01	0.02
54	59.2	4.60	1.23	2.50	0.28	6.72	-	0.05	0.007	0.01	0.02
56	58.4	5.06	2.11	3.02	0.80	5.30	-	0.14	0.007	0.03	0.02
Average	57.7	5.40	1.86	3.19	0.44	4.34	-	0.07	0.007	0.02	0.02

Table 4. Manganese-rich ores with low Al_2O_3-content

No	Fe tot	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5
63	60.3	4.2	1.3	2.4	1.6	12.6	-	1.65	0.027
64	57.4	7.1	0.9	1.8	0.4	2.3	-	0.12	0.016
65	45.5	6.4	10.2	6.3	1.2	5.4	-	0.31	0.020
66	57.0	4.2	1.8	3.4	0.7	7.4	-	0.02	0.010
67	56.1	4.7	0.8	2.6	0.8	11.7	-	0.13	0.018
68	55.7	5.9	0.7	3.8	0.4	13.2	-	0.05	0.008
Average	55.3	5.4	2.6	3.4	0.9	8.8	-	0.4	0.017

Table 5. Manganese-rich ores with high Al_2O_3- and P_2O_5-content

No	Fe tot	FeO	Fe_2O_3	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5	As	Ba
111	65.09	21.60	69.02	5.11	1.37	1.46	2.21	2.00	0.01	0.01	0.126	0.04	<0.01
112	57.88	17.30	63.53	6.57	0.54	2.70	3.05	8.60	0.03	0.02	0.093	0.03	<0.01
117	64.44	14.10	76.48	6.66	0.32	1.27	2.08	1.90	0.01	<0.01	0.123	0.03	<0.01
120	63.76	13.99	71.17	4.81	0.69	1.68	3.28	6.00	0.05	<0.01	0.093	0.03	0.01
121	59.18	16.90	65.95	5.36	0.93	1.67	2.70	9.50	0.30	0.22	0.100	0.05	0.01
Average	60.4	16.3	67.3	5.6	0.8	1.7	2.6	5.5	0.08	0.05	0.11	0.04	<0.01

Table 6. Iron-manganese-silicate ores

No	Fe tot	FeO	Fe_2O_3	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5	As	Ba
110	13.44	-	19.22	22.55	2.07	2.90	6.13	41.8	2.16	1.68	0.035	0.05	0.06
114	16.77	-	23.98	20.60	3.62	3.07	4.66	38.2	2.89	0.47	0.096	0.58	0.24
118	13.46	-	19.25	18.65	4.03	3.28	6.15	42.8	2.43	1.60	0.003	0.11	0.08
123	10.19	-	14.57	8.21	8.92	2.93	9.95	47.9	3.20	4.74	0.156	1.59	0.23
Average	13.58	-	19.39	17.67	4.64	3.06	6.72	42.82	2.68	2.11	0.073	0.58	0.15

Table 7. Composition of slags from the reduction furnace. A1 - Low MnO

No	Fe tot	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	TiO_2	V_2O_5	P_2O_5	S	Finding - place
194	7.7	9.9	3.9	19.4	7.3	3.8	54.3	0.58	0.73	0.10	0.03	<0.01	0.038	Deposite A 4 - layer 5
14	6.0	7.7	3.4	20.9	5.5	4.0	57.5	n.d.	0.85	0.10	0.02	n.d.	0.020	" A 2 - surface
15	3.2	4.1	3.8	21.3	6.2	6.3	57.0	"	1.10	0.17	0.02	"	0.017	Filling material - A 1
16	10.9	14.1	2.3	15.9	4.7	5.4	56.8	"	0.62	0.16	0.03	"	0.011	- " -
17	2.7	3.5	5.6	28.2	7.5	4.2	50.2	"	0.53	0.20	0.03	"	0.018	- " -
18			(1.0)											Deposit A 2. (Total 110.8!
22	21.0	27.0	0.9	12.6	2.6	4.3	49.6	"	1.00	0.16	0.03	"	0.018	Deposit A 2
24	3.8	4.9	2.6	23.1	5.4	3.4	60.0	"	0.47	0.06	0.02	"	0.010	Filling material. A 1
27	5.2	6.7	6.4	16.0	6.2	6.2	56.3	"	1.96	0.17	0.03	"	0.010	Deposit A 3 - surface
31	6.0	7.7	1.7	18.0	3.8	4.3	63.2	"	1.09	0.11	0.02	"	0.017	Filling material - House A
Average	5.7	7.3	3.7	20.3	5.7	4.7	56.7	0.6	0.9	0.1	-	-	0.02	

(No 18 and 22 not included in the average)

Table 8. Composition of slags from the reduction furnace A 1 - High MnO

No	Fe tot	FeO	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	TiO_2	V_2O_5	P_2O_5	S	Finding - place
23	4.9	6.2	8.1	13.4	11.0	5.4	55.0	n.d.	0.75	0.12	0.02	n.d.	0.018	Deposit A 3 - surface
28	5.7	7.3	13.3	9.3	10.7	7.0	50.6	"	1.56	0.16	0.03	"	0.024	- " -
29	2.6	3.3	13.1	15.9	11.2	7.2	48.0	"	1.04	0.20	0.03	"	0.076	Filling material, A 1
30	2.8	3.6	12.2	9.3	10.3	6.3	56.5	"	1.66	0.18	0.02	"	0.010	- " - , "
34	4.2	5.4	15.2	14.8	13.6	7.2	42.5	"	0.99	0.16	0.03	"	0.070	- " - , A 9 (House)
4 B	10.5	13.5	12.6	11.4	10.6	5.6	44.5	0.66	0.83	0.1	0.1	0.06	0.01	Deposit A 4, Layer 2
4 D	16.9	21.5	13.3	11.9	12.7	5.1	33.9	0.72	0.79	0.1	0.1	0.06	0.01	- " -
5 B	3.6	4.7	13.7	10.4	11.6	6.4	51.0	0.84	1.01	0.2	0.1	0.03	0.02	- " -
6 A	4.1	5.2	10.8	11.6	9.3	5.8	55.1	0.86	1.11	0.1	0.1	0.05	0.01	- " -
7 A	6.3	8.1	15.3	9.6	11.5	7.3	45.0	1.33	1.54	0.1	0.1	0.06	0.03	- " -
181	4.0	5.1	13.3	8.9	10.1	5.4	55.1	0.87	0.95	0.17	0.03	<0.01	0.008	Deposit A 3, Layer 1
182	2.9	3.7	9.2	17.2	7.6	4.1	56.7	0.79	0.54	0.17	0.03	<0.01	0.007	- " - , " 5
184	3.1	4.0	11.2	19.4	11.5	6.5	45.1	1.04	1.12	0.16	0.03	<0.01	0.071	- " -
185	4.9	6.3	13.6	13.6	12.5	6.1	46.0	0.80	0.86	0.16	0.03	<0.01	0.066	- " -
186	5.5	7.0	10.8	9.0	8.9	7.8	54.1	1.03	1.21	0.17	0.02	<0.01	0.024	- " -
187	1.3	1.7	13.1	10.3	12.4	9.2	50.6	1.33	0.97	0.28	0.03	<0.01	0.017	- " -
188	3.3	4.2	10.7	18.1	11.6	5.9	47.6	0.77	0.87	0.17	0.03	<0.01	0.053	- " -
189	5.6	7.2	13.7	12.0	10.6	6.0	48.3	0.97	0.89	0.18	0.03	<0.01	0.050	- " - , Layer II
190	7.6	9.8	17.3	10.2	10.5	6.4	44.0	0.75	0.88	0.15	0.03	<0.01	0.034	Deposit II, " 5
193	1.6	2.1	9.4	17.6	7.7	3.7	58.2	0.48	0.76	0.10	0.02	<0.01	0.008	- " - , - " -
A 21	5.0	6.4	13.0	16.1	13.4	7.8	40.7	1.3	1.1	0.19	1)	0.022	0.022	Outside the hearth
A 24	8.4	10.9	12.1	9.7	10.8	7.6	45.9	1.4	1.3	0.22	"	0.014	0.032	- " -
A 25	2.4	3.7	17.7	12.8	14.1	6.2	43.4	0.9	0.9	0.20	"	0.008	0.076	- " -
A 35	3.9	5.0	10.2	17.7	10.7	6.4	49.0	n.d.	0.72	0.15	0.02	n.d.	0.016	Filling material. Ore deposit 114
A 36	3.3	4.2	8.8	14.6	9.5	4.8	57.3	"	0.69	0.11	0.02	"	0.015	- " - . - " - 116,
A 37	2.7	3.5	17.5	12.6	12.7	6.1	46.4	"	0.98	0.14	0.02	"	0.019	- " - . - " - 118
A 39	2.6	3.4	14.8	16.3	12.6	6.2	45.5	"	1.1	0.13	0.02	"	0.019	- " - . - " - 119
Average	4.3	5.6	12.7	13.1	11.0	6.3	49.3	1.0	1.0	(0.16)	-	-	-	

(4 D not included in the average)

Table 9. Composition of pig iron %

No	C	Si	Mn	P	S	Cu	Ni	V	Ti	Co	
180	4.10	1.10	1.35	0.028	0.028	n.d	0.04	<0.01	<0.01	<0.01	Furnace. Tap hole
4295	4.46	0.21	1.80	0.026	0.039	"	n.d.	n.d.	n.d.	n.d.	Hearth, A 22 droplets
5004	2.79	1.40	0.44	0.025	0.024	"	"	"	"	"	- " - " " - " -
4367	4.57	0.17	2.52	0.038	0.012	"	"	"	"	"	- " - A 23 - " -
2884	3.06	0.79	0.32	0.018	0.050	"	"	"	"	"	- " - A 15 - " -
127	4.0	1.02	1.05	0.030	0.030	<0.01	<0.01	<0.01	<0.01	0.038	- " - A 25 - " -
132	4.34	0.84	1.95	0.021	0.021	0.05	-	-	-	0.046	- " - A 21 - " -
163	4.14	1.18	1.40	0.040	0.011	-	-	-	-	0.019	- " - A 24 - " -

Table 10. Composition of finary slags %

No	Fe tot	Fe met	FeO	Fe_2O_3	MnO	CaO	MgO	Al_2O_3	SiO_2	Na_2O	K_2O	TiO_2	P_2O_5	S		
18	16.5	–	–	–	1.03	11.6	2.3	26.7	47.5	n.d	0.27	0.05	n.d	0.017	Deposit A 17.	Surface
20	24.7	–	–	–	6.6	5.1	4.0	7.2	38.0	"	5.0	0.19	"	0.027	– " –	– " –
21	31.6	–	–	–	5.0	6.8	5.6	3.1	29.8	"	2.7	0.09	"	0.056	– " –	– " –
* 22																
196	49.0	(0.5)	55.9	8.5	5.4	1.7	0.9	3.4	22.0	0.6	0.8	0.2	0.57	0.033	– " –	Layer 1
197	58.7	(18.1)	32.9	47.3	4.8	3.2	1.6	1.2	8.1	0.4	0.3	0.1	<0.01	0.052	– " –	Layer 4
198	46.2	(1.2)	51.0	8.8	11.5	2.4	1.3	3.3	20.2	0.6	0.7	0.2	0.11	0.013	– " –	– " –

(196, 197 and 198 are normalised)

*) This slag was placed both on deposit A 17 and deposit A 2 by mistake.
A later control shows that it belongs only to A 2 and is mentioned in table 7.

Table 11. Composition of iron items %

No	C	Si	Mn	P	S	
834	0.58	0.04	0.03	0.024	0.005	Osmund-piece
1410	0.16	0.07	0.03	0.017	0.005	- " -
2734	0.51	0.10	0.06	0.011	0.019	Wrought iron
3734	0.34	0.10	0.08	0.012	0.024	- " -
2421	0.97	0.03	<0.01	0.009	0.007	Knife
4291	1.06	1.51	1.39	0.005	0.028	Droplets. Refinery A 22
5008	0.83	1.66	0.18	0.031	0.020	- " - - " - A 21
3191	0.40	5.20	5.68	0.020	0.021	- " - - " - A 14
2886	1.60	0.50	0.44	0.006	0.073	- " - - " - A 15

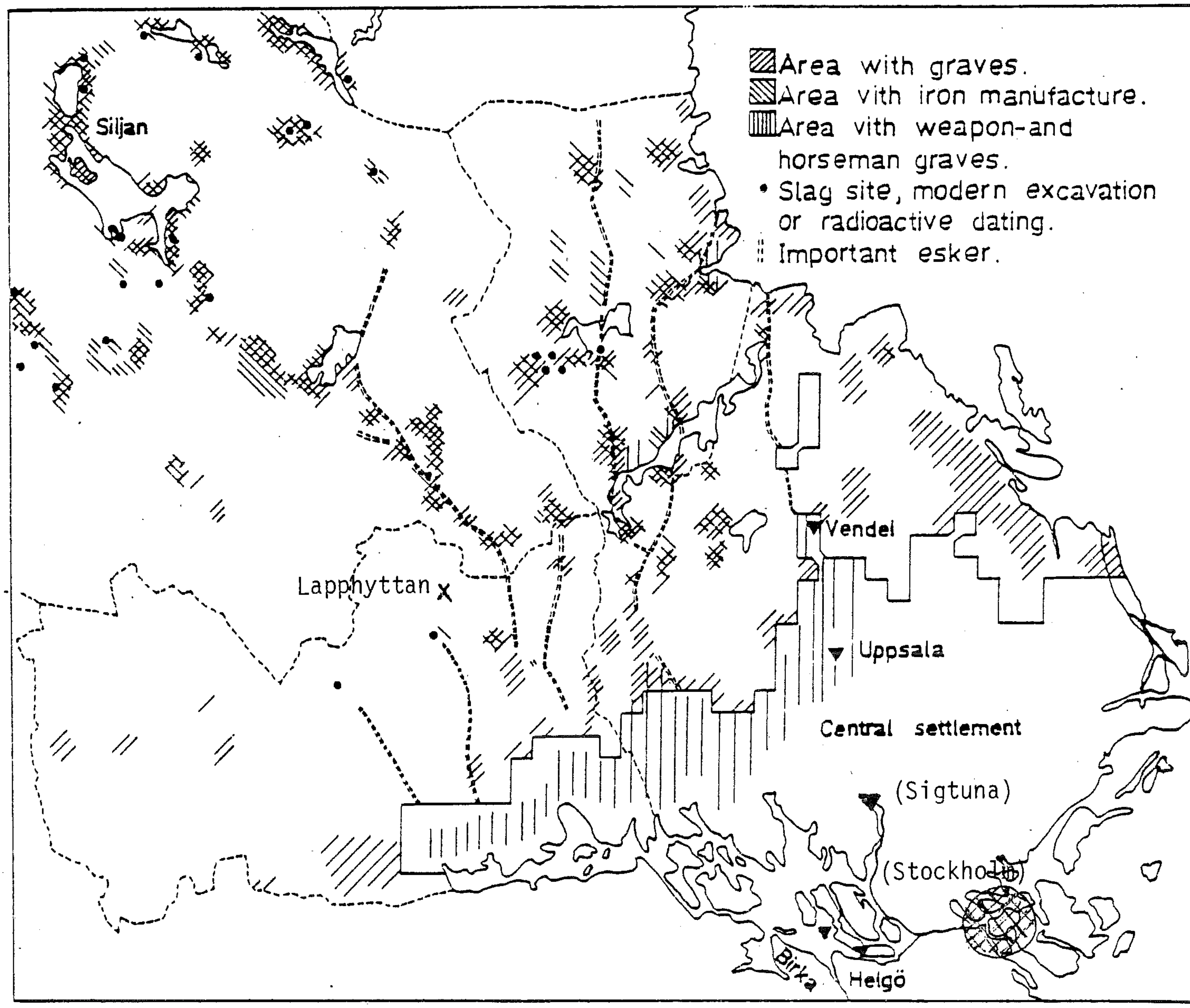

Fig. 1. Map of the districts north of Lake Mälaren during the Germanic Iron Age. The Central Board of National Antiquities.

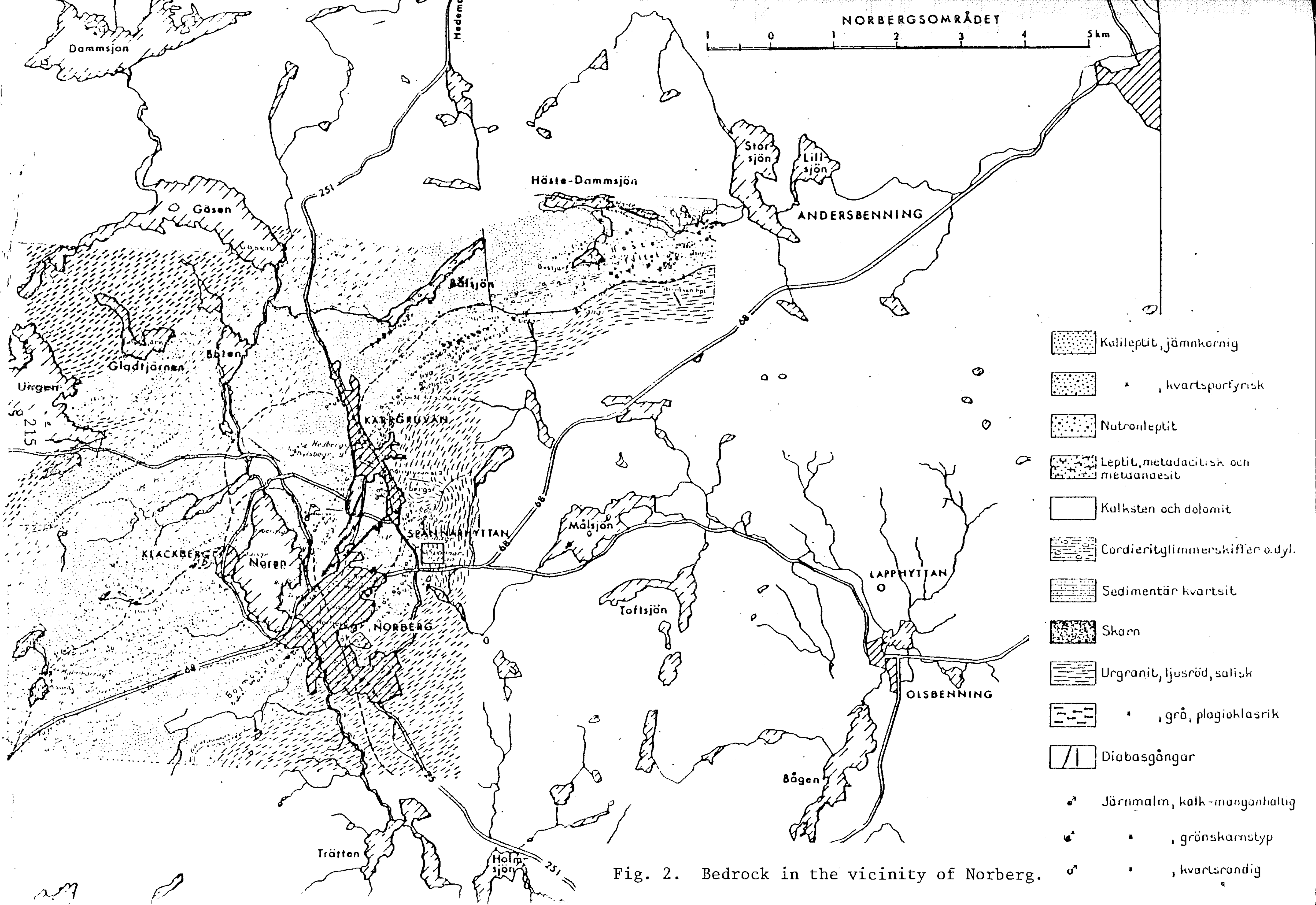

Fig. 2. Bedrock in the vicinity of Norberg.

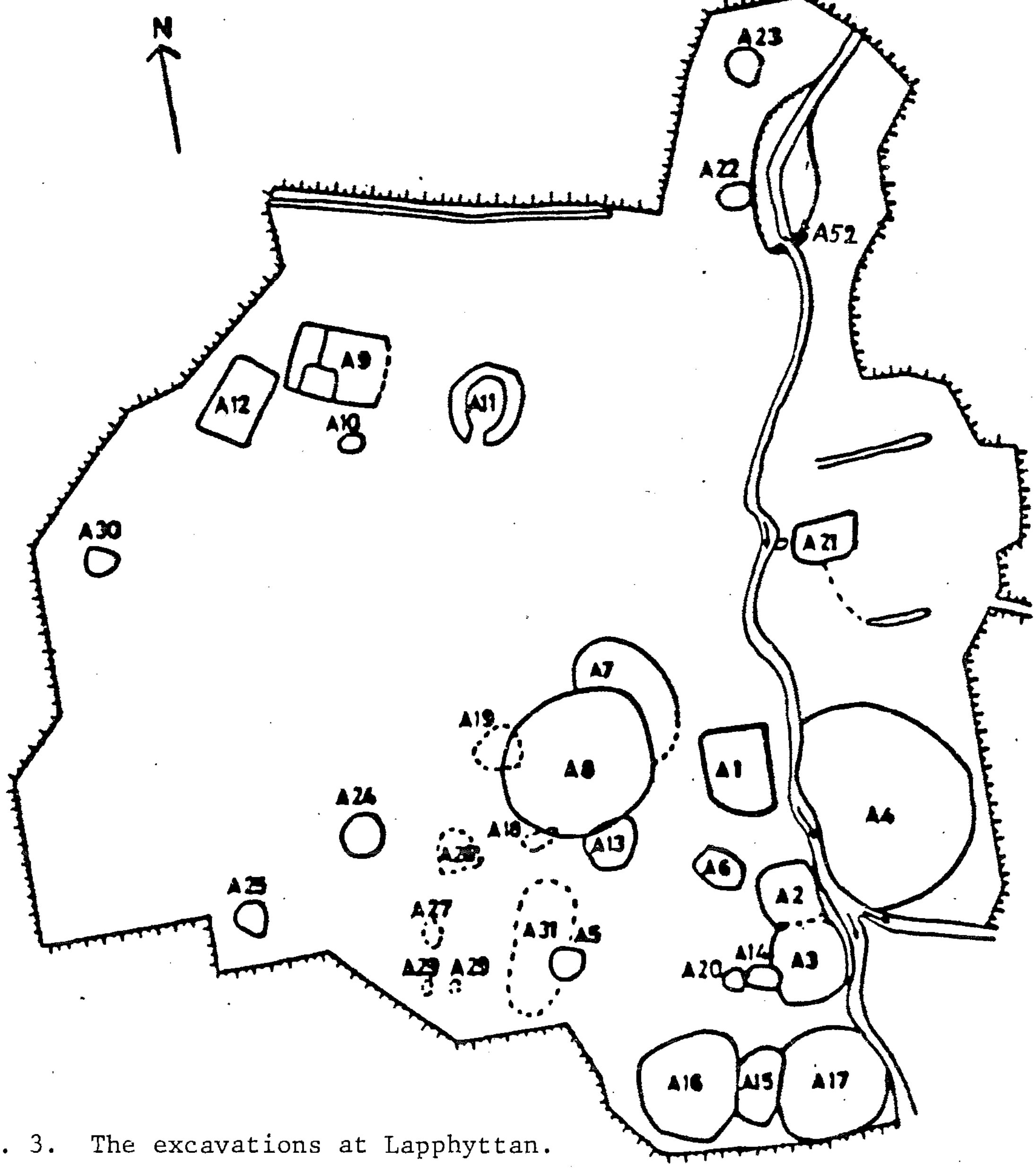

Fig. 3. The excavations at Lapphyttan.

A I = Blast furnace ruin	AI5 = Finery
A 2 = Slag heap	AI6 = Slag heap
A 3 = Slag heap	AI7 = Slag heap
A 4 = Slag heap	AI8 = Heap of ore
A 5 = Slag pieces	AI9 = Heap of ore
A 6 = Roasting pit	A20 = Slag heap
A 7 = Charcoal stack	A2I = Finery
A 8 = Charcoal stack	A22 = Finery
A 9 = Dwelling house	A23 = Finery
AI0 = Hearth	A24 = Finery
AII = Iron shed	A25 = Finery
AI2 = Stable	A26-A29 = Heaps of ore
AI3 = Charcoal shed	A30 = Finery
AI4 = Finery	A3I-A5I = Heaps of ore
A52 = Pond and timbered stone caisson	

Fig. 4. The roasting pit.

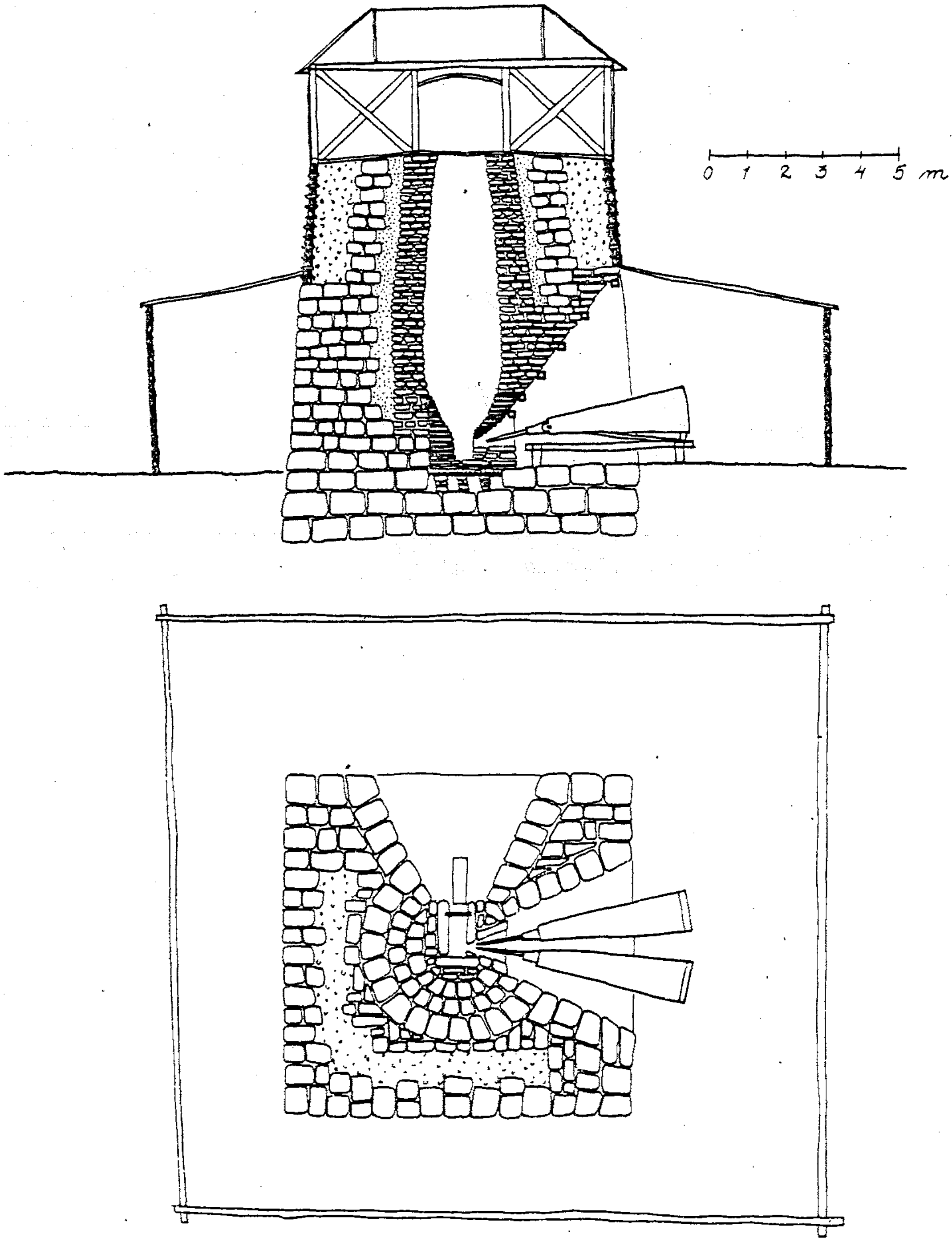

Fig. 5 According to Garney: Handledning uti Svenska Masmästeriet (Guide to the design and operation of Swedish blast furnaces); plan and section of a timber-clad blast furnace. In use until the middle of the 19th century.

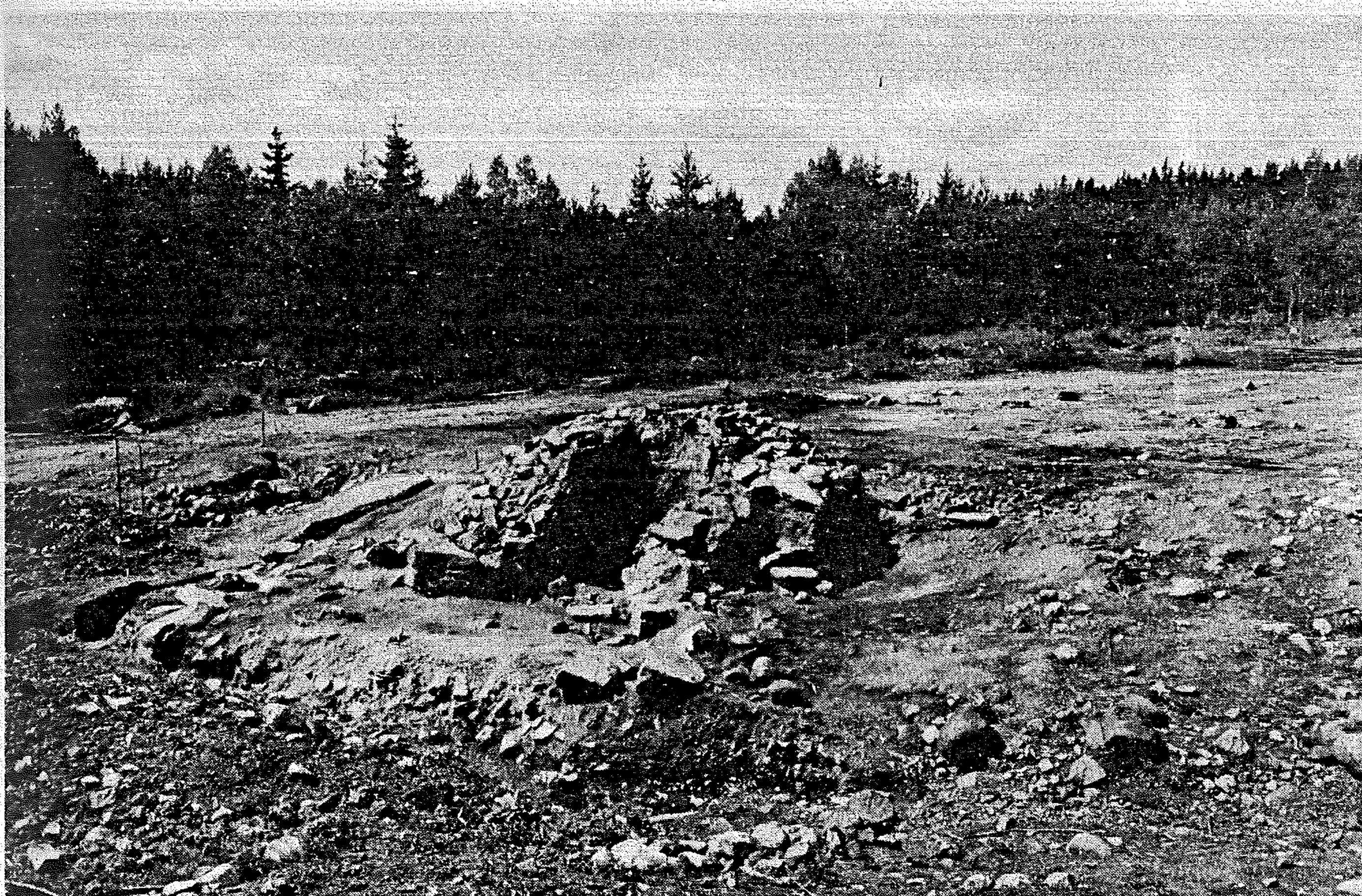

Fig. 6. The remains of the blast furnace as seen from the tapping side.

Fig. 7. The blast furnace as seen from above.

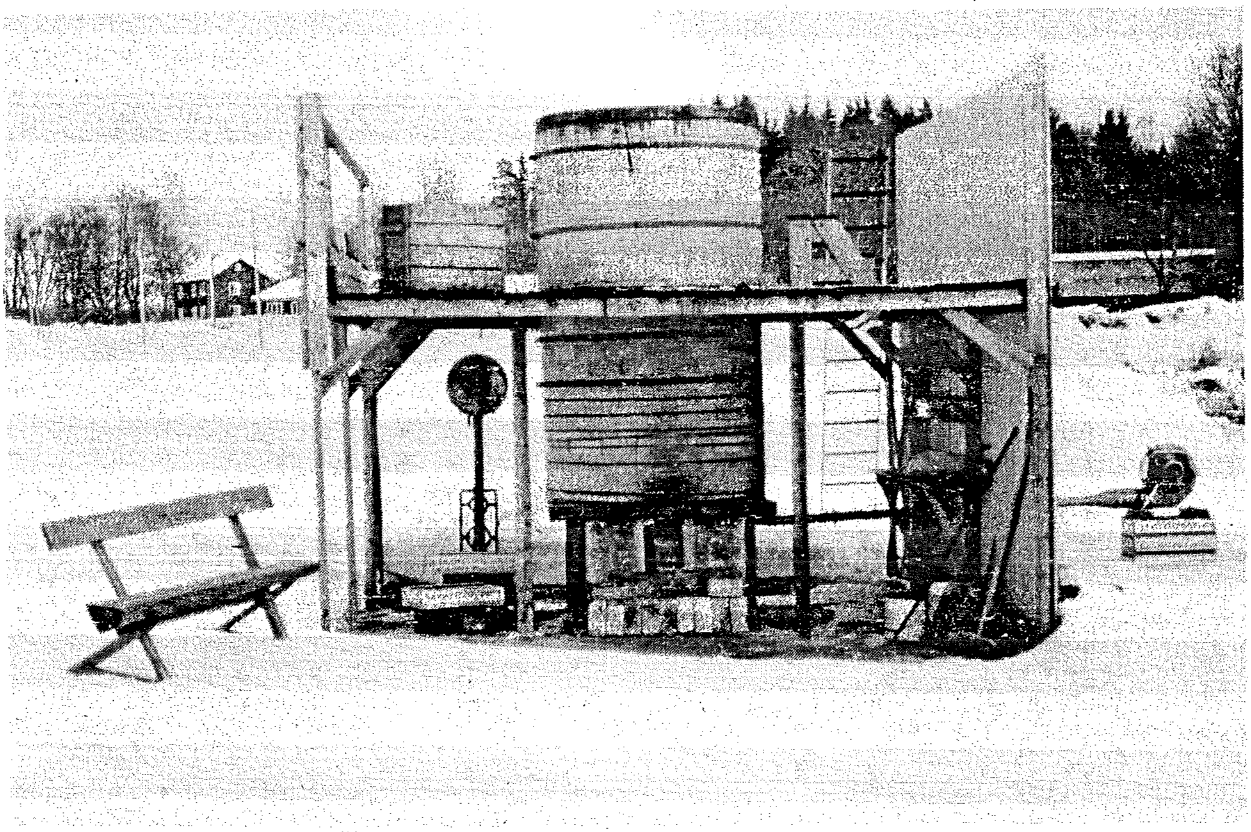

Fig. 8. The experimental blast furnace at Saxhyttan.

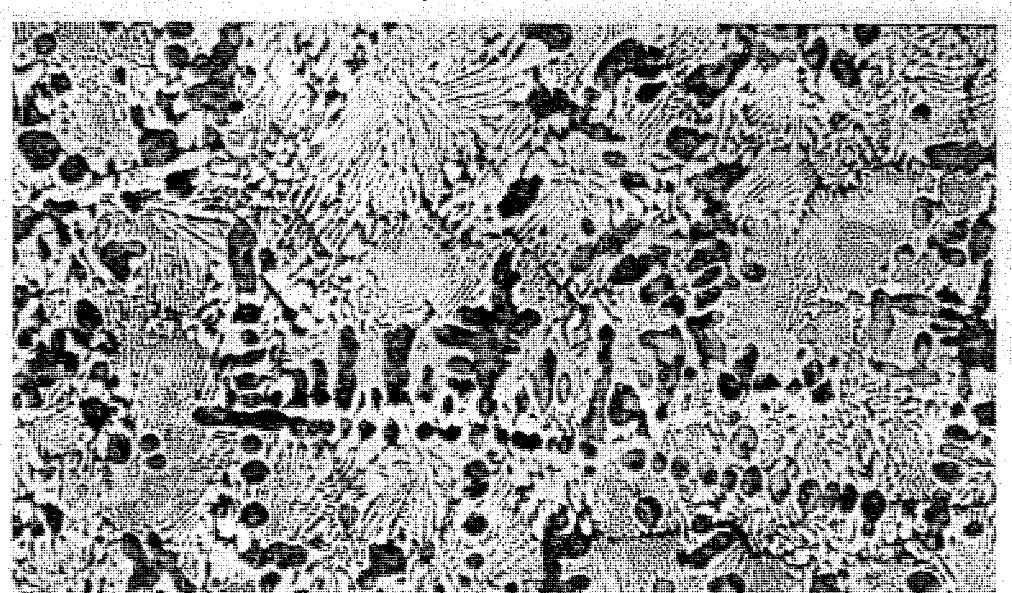

Fig. 9. White pig iron found in the taphole of the blast furnace. Primary austenite dendrites and ledeburite. The austenite later transformed into perlite x 60. Modin.

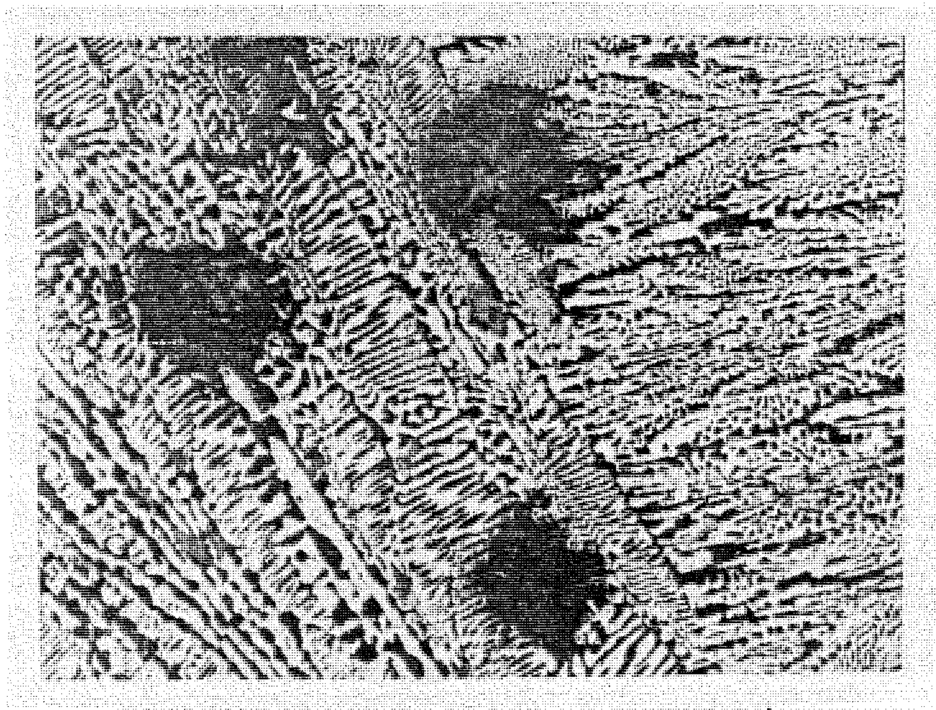

Fig. 10. Mottled pig iron droplet from the hearth A 15. x 200. Thyberg.

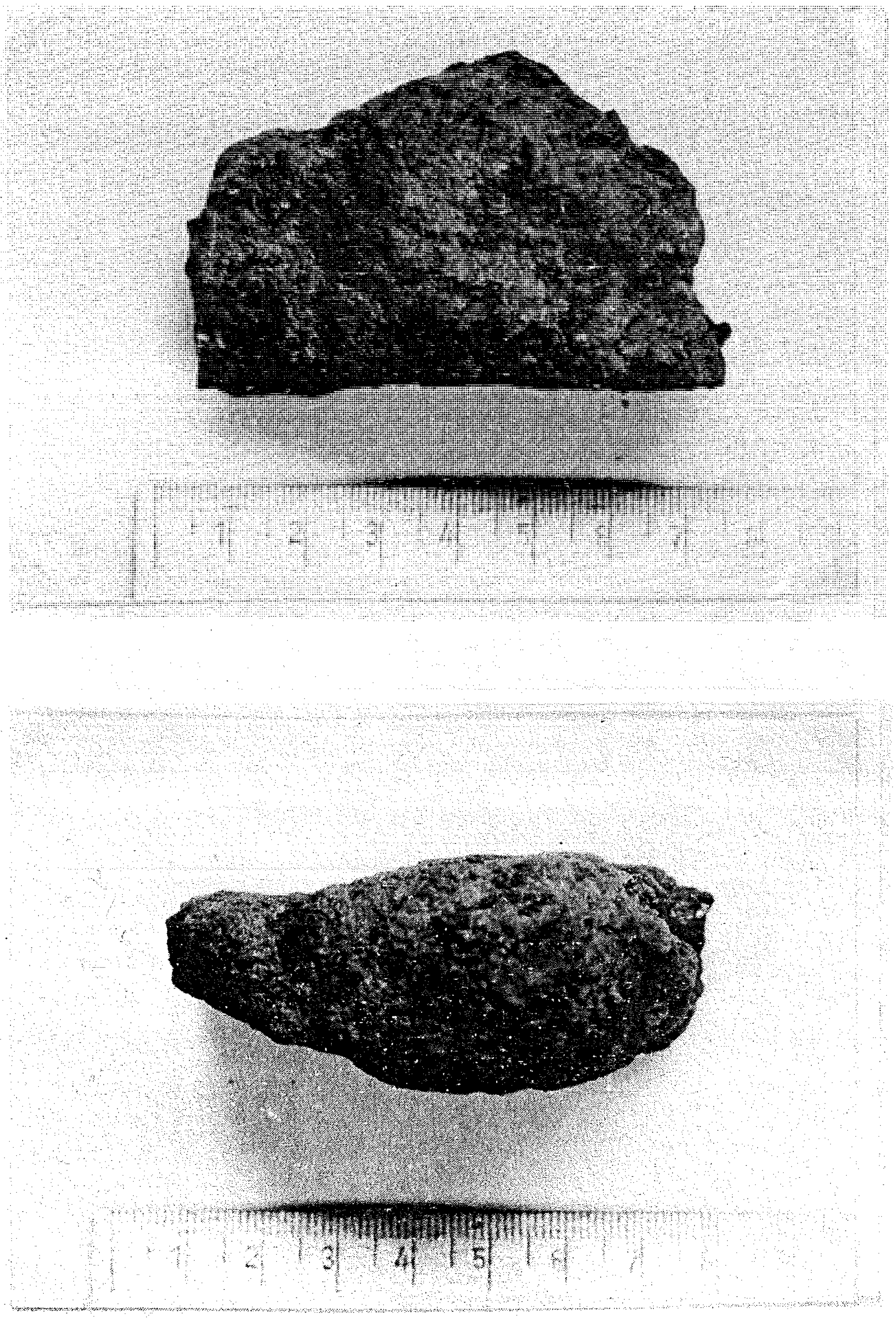

Fig. 11. Unprepared lump. (834) Modin.

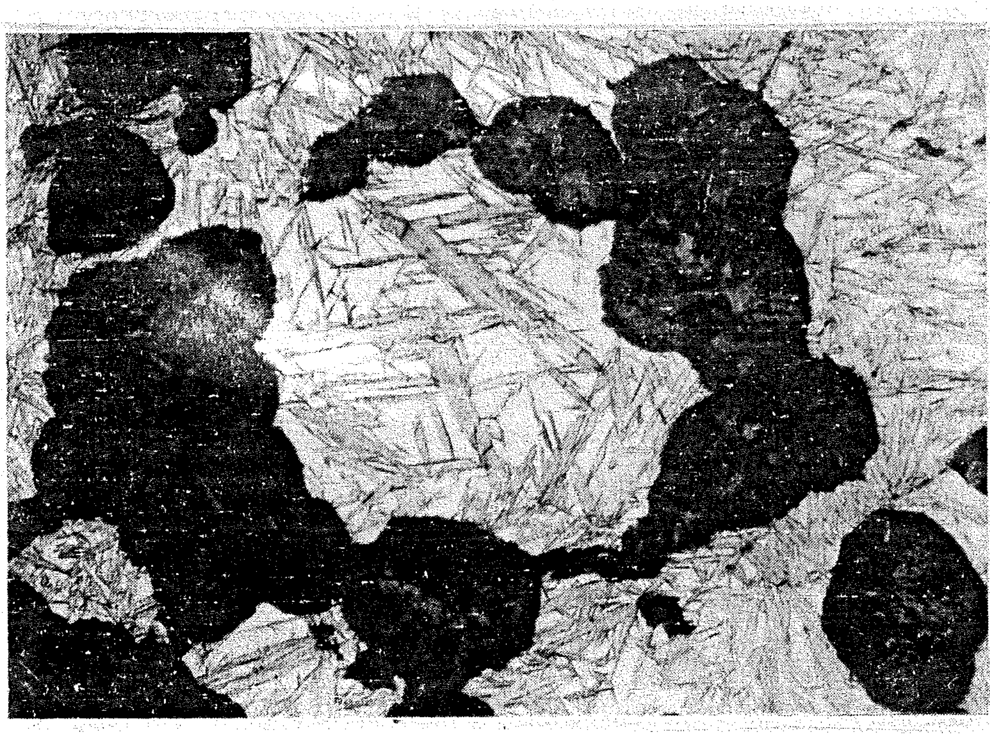

Fig. 12. Lump 834. Perlite (dark), Martensite needles (grey) and rest-austenite (light). x 700. Modin.

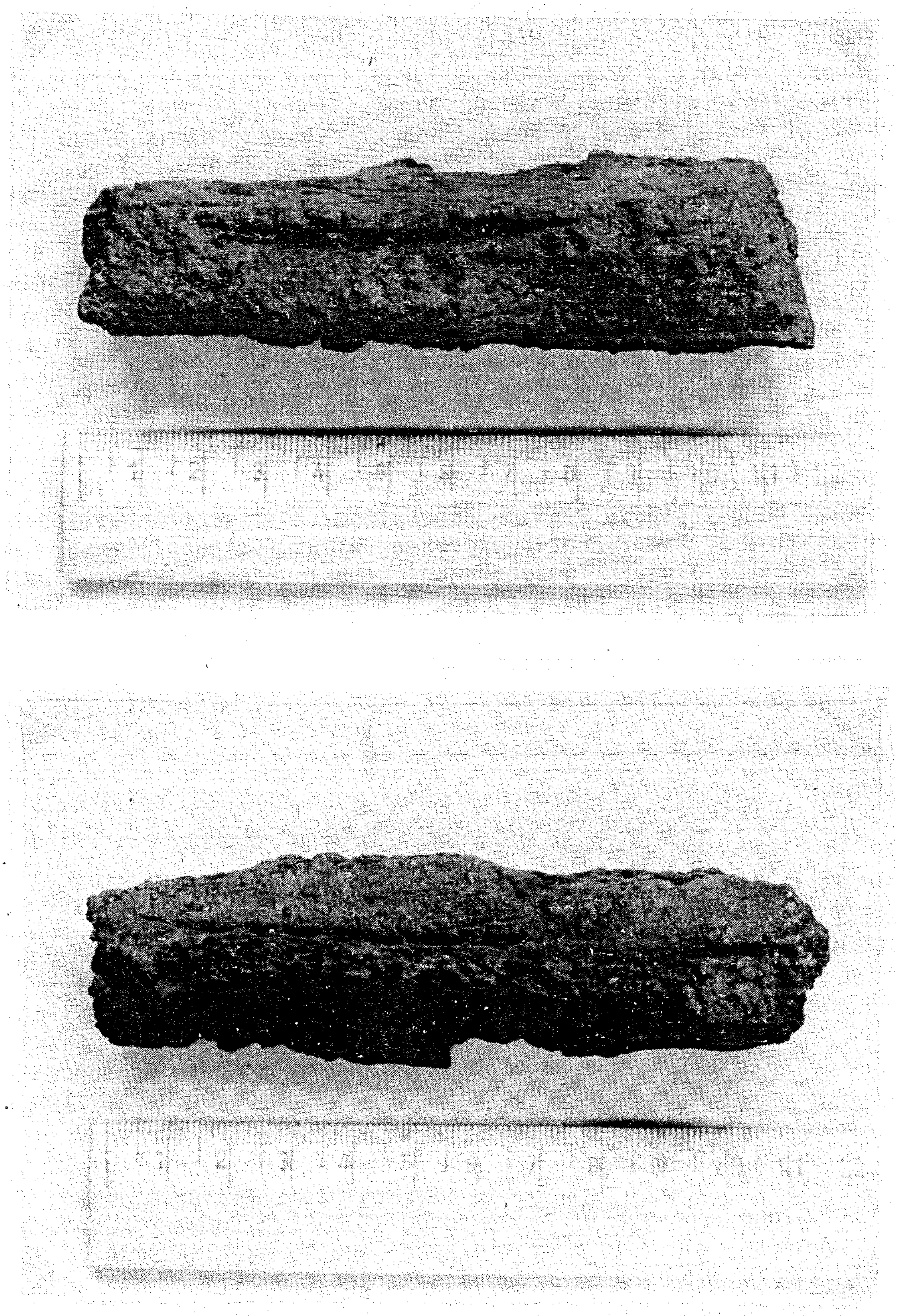

Fig. 13. Lump 1410. Unprepared. Cutting marks made by an axe. Modin.

VINARHYTTAN AND JUTEBODA - TWO MEDIEVAL BLAST FURNACES IN MIDDLE SWEDEN

INGA SERNING
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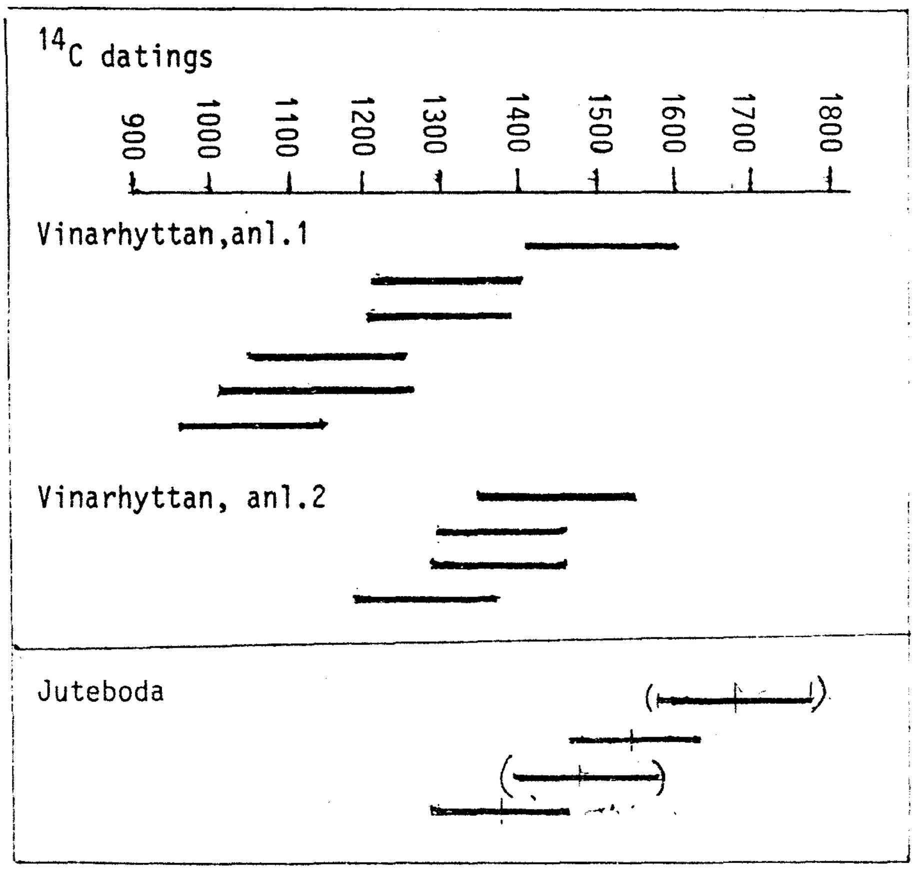
SUMMARY
In the Vinar-area in southern Dalarna and in Juteboda in northern Västmanland, remains of medieval blast furnaces have been excavated. Carbon 14 has dated Vinarhyttan within the period 950-1590. The earliest date for Juteboda is the 14th century AD. The furnace in Juteboda was much better preserved than the Vinarn-furnace of which fragments of the walls were lying in a heap. Near the sites were quarries for building material for the furnaces and near Vinarhyttan were two small open cast mines. Pig iron prills were found at both furnaces in abundance, showing the type of iron produced.

As a complement to the papers read on Lapphyttan short mention will be made of the remains of two recently excavated blast furnaces, Vinarhyttan in southern Dalarna and Juteboda in northern Närke. Since Vinarhyttan was published in 1982 and the report from the excavations in Juteboda is available at this symposium, I will here confine myself to some comments.

The ^{14}C-datings for the sites are given in the diagram below.



As can be seen Vinarhyttan is contemporary with Lapphyttan.

The excavations in Vinarhyttan had to be restricted to the furnace remains since the site was situated on built up land. On the site were two heaps separated by a narrow brook which was dammed about 500 m from the furnace. One of the heaps contained pieces of furnace walls of micacous leptite which was quarried nearby. In the bottom of the heap one could descern the place for the hearth as a pit with stones,clay and some big slag pieces. The heap contained a lot of charred wood, remains of the timber which had held the furnace together. The upper layers of the heap had a lot of slag. It is conceivable that the furnace had burnt and that the heap had later been used as a slag dump when the surrounding fields were cleared.

To deem by the pieces of furnace walls and by big blocks of slag the hearth and the stack had had a minimum diameter of 0.5 and 1.5 m respectively.

A roasting hearth about 10 m northeast of the furnace was partly excavated.

Two small open cast mines lie 350 and 500 m respectively from the site, Vinargruvan and Svartviksgruvan. The ore is quartsbanded iron ore with some skarn minerals. Svartviksgruvan has also some minor deposits of sulphide ore. Based on chemical analyses of ores and slags either one or both of the mines could have been used in Vinarhyttan. The ores are self-fluxing.

The slags are mostly grey to brown. Greenish blue, vitrous slag occur but sparsely. The same is the case in Lapphyttan where that type of slag amounts to only 5 % in the big slag heap.
The slag starts melting at between 1012^{0}C and 1245^{0}C according to DTA.

One sample of vitreous slag contained metallic iron and tiny droplets of silver. It seems to be a bi-product from treatment of argentiferous iron ore.

Strongly magnetic slag samples were choosen for investigation since it was desireable to obtain information on the type of iron produced. 9 out of 11 samples had inclusions of pig iron. One of the two deviating samples was ferritic with nitride needles and may originate from a spot near the tuyere. The other sample had ferrite and pearlite. Perhaps it formed when the furnace was blown out.
An abundance of pig iron prills found at the furnace in Vinarhyttan as well as in Juteboda are of the same type as in Lapphyttan. They show that pig iron was produced on the sites.

Before the excavation an iron blank was found about 5 m from the furnace. Its composition deviates from all other iron samples studied by a high phosphorus content, 0.32 % as opposed to the average content of about 0.05 %. Another type of ore, possibly lake ore, has obviously been used in this case - if the blank is a product made on the site at all.

Conclusions drawn from the excavations are that in Vinarhyttan a timber-clad blast furnace with water-powered bellows had been in working in the period

Juteboda is situated at the Juteboda brook, about 1 km east of Löa hytta. The latter was working during the period about 1500 to 1900 AD and has lately been restored. The datings of Juteboda hytta suggest that it was a predecessor to Löa hytta. As far as known, Juteboda is not mentioned in written sources. The most reliable samples for ^{14}C-dating were taken in front of the tapping side of the furnace. They are dated to 1365 AD and 1540 AD respectively. One sample from the bottom layer of the slag heap is dated to 1475 AD and a fourth sample from the upper layer of the heap to 1670 AD. The last mentioned, late date may be explained by the fact that the upper layers are disturbed. The landowner has dumped slag there from other sites and he has also removed slag for i.a. road building purposes. For a more reliable dating of the site more samples are needed.

On the eastern side of the brook is arable land which lies about 2 m higher than the brook. On the slope is a 1 m thick layer of slag, covering an area of 35 x 12 m and formed as a bank in its northern part.

Where the slope was highest were tons of rubbish. After the clearing of this area the remains of the furnace were revealed,partly buried in the slope. The front part of the furnace was ruined. The stack was circular and built of carefully cut stones of micaceous leptite quarried nearby. From the bottom slab of the hearth the stack was preserved to a height af about 2 m, where the diameter was 1.8 m. Nothing remained of the tuyere opening and only the bottom part of the tapping arch on the western side of the furnace. Between the tuyere opening and the tapping arch the lower part of the intermediate pillar was preserved.

The bottom of the hearth consisted of one single, 70 mm thick slab with a diameter of 0.7 m. The slab did not seem to be affected by heat except where some small iron droplets had stuck. It is plausible that it had been protected from heat by sand;a thin layer of which was still preserved. The layer was now strongly mixed with small pieces of slag , iron and stone-splints. Beneath the slab was an empty space with a height of 0.1 m, probably for cooling arrangements. No walls remained in the much damaged hearth.

The slag was fluidal, dark or light grey, very seldom green or blue and vitrous.

As i.a. in Lapphyttan and Vinarhyttan a lot of iron prills of pig iron were found, witnessing the type of iron produced.

The ore found on the site was magnetite, some of which was roasted.

Technical investigations of ore, slag and iron have as yet not been made.

The archaeologist in charge of the excavation was Viking Wedberg, Archaeometallurgical institute, Håksberg.

SPREAD OF BLAST FURNACES IN POST-MEDIEVAL HUNGARY

/ Production, trade and use of iron/

JÁNOS GÖMÖRI

Liszt Ferenc Múzeum, Sopron, Hungary/

SUMMARY

1. Iron ore deposits and production sites in the Carpathian Basin in the Medieval age.

2. Árpád - age Hungary's / 10-12 th centuries/ iron production came to an end in the 13 th century.

3. Founding of Cistercian abbeys in Hungary from the last quarter of the 12th century.Forge house/fabrica/ using water power discovered in the Cistercian monastery Pilis.

4. First documentary evidence of a water hammer erected in 1344 in Csetnek,today Stitnik in Slovakia/county Gömör,Upper Hungary/:"fabrilis domibus qui vulgo hamur vocant".

5. Changes of sites of iron smelting in consequence of immigration of groups of guest workers / hospites/ and of donation of royal privileges and town franchises.

6. The high level of precious metal mining in Medieval times did not stimulate the development of iron smelting. As an equivalent for exported non-ferrous,high-quality iron products could be imported from the leading iron metallurgy centres in Western Europe.

7. Iron was transported from iron producing centres in Upper Hungary to the lowland areas of the country, moreover between 138o and 1424 to Poland and further on from the port Danzig to England.Transylvanian iron was exported to the Romanian principalities.

8. The first Hungarian cast iron plate is known from Selmecbánya/Banska Stiavnica,Schemnitz/ being a sepulchral monument from 1598.

9. The first blast furnace/Flossofen,Massa,hoher Ofen/ was built in 1690 in Libetbánya/Lubiatova by K.Pf. Kropf from Silesia,and his workers came also from Jägerndorf in Silesia.

10. Connection between social,economical and political sitution and metallurgy in Hungary.

DIE VERBREITUNG DES FLOSSOFENS IM 17-18.JAHRHUNDERT AUF DEM GEBIETE UNGARNS

/ Produktion-,Handel- und Gebrauch des Eisens/

Vom 1o-11. Jahrhundert an bis 192o fand man auf dem Gebiete Ungarns berühmte Eisenvorräte /1/

Während der La Tene-Zeit befanden sich viele Eisenverhüttungsanlagen in den Becken vor den Ausläufern der östlichen Alpen,also auch in der Umgebung von Sopron /2/ Im Frühmittelalter wurden diese nahe der Oberfläche liegenden,öfters sedimente Lagerstätten wieder abgebaut. Im 1o-12.Jahrhundert hatte das ungarische Eisenhüttenwesen zwei bedeutsame Zentren.Im Westen in den Komitaten Vas und Sopron, im Norden im Komitate Borsod /1. Karte,A./ Der organisatorische Mittelpunkt der beiden Gebiete war immer je eine Eisenburg"Vasvár"/Zentraleisendepot/3/.Die Schmelzöfen konnte man den Ausgrabungen nach in drei Typen teilen:

1. Freistehende Schachtöfen mit Schlackenabstich / Typ Nemeskér/ Mediterraner Ursprung.
2. Eingebaute Öfen/ Typ Imola/. Östlicher Ursprung.
3. Schachtöfen mit seitlicher Windeinblasung, Vasvárer Typ/.Der letztere Typ ist westlichen Ursprungs/

Den geographischen Namen /Kovácsi,Csatár,Rudnok,Tömörd,Vasas etc/ und den vielen Ofenausgrabungen nach entwickelt sich uns langsam die Organisation des frühen ungarischen Eisenhüttenwesens.Diese Königliche Eisengewinnungsorganisation breitet sich über das ganze Land aus. Dies beweisen auch die gleichen Ofenfunde in Siebenbürgen/Transylvanien/, im Csiker Becken / 1.Karte, IV/.

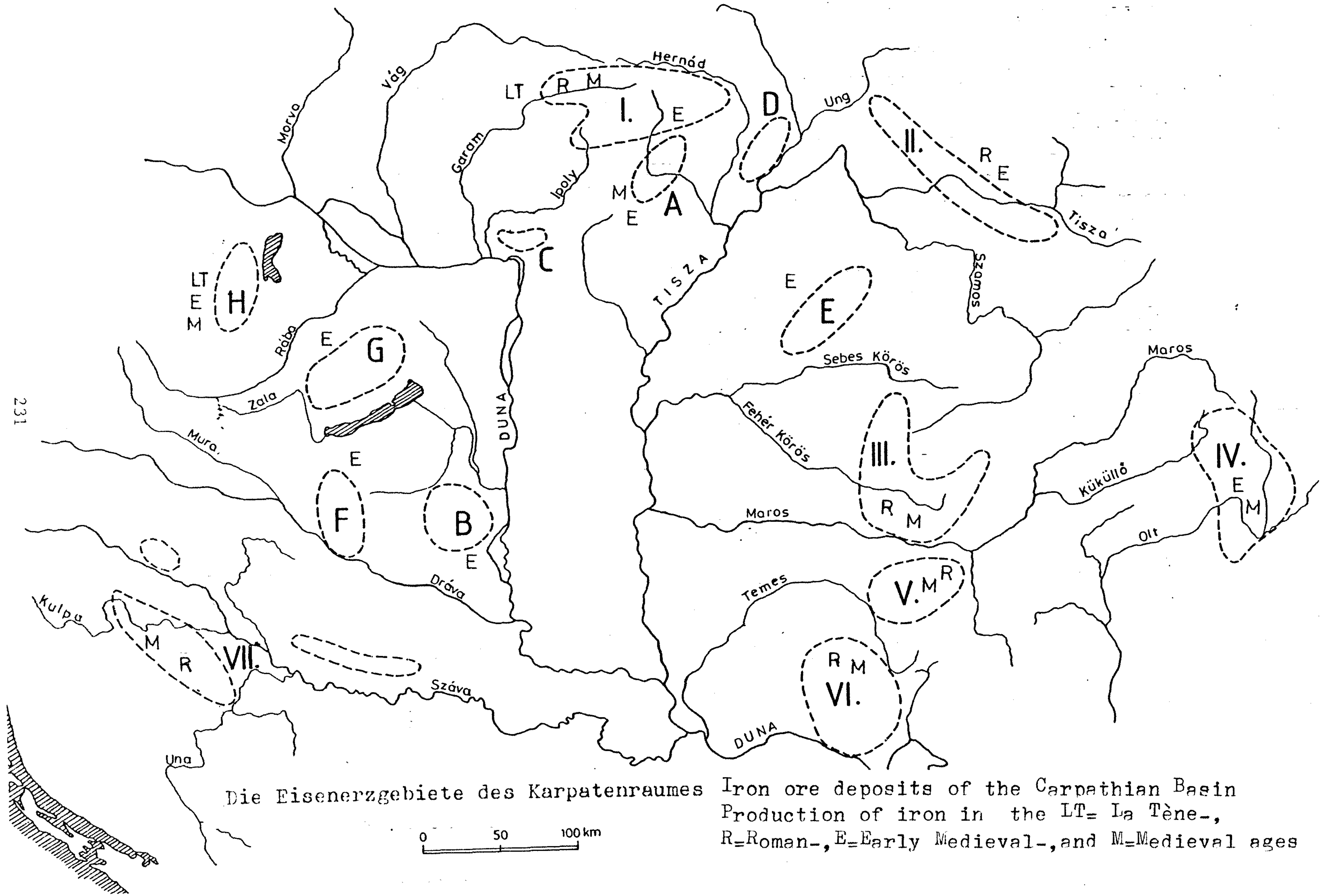
Ab des 13. Jahrhunderts an,besonders von der Regierungszeit Andreas II./ 12o5-1235/ verschenkte der König ganze königliche Domäne, ganze Komitate.

So begann sich die frühere wirtschaftliche Ordnung z.B. die Eisengewinnungsorganisation aufzulösen.Andreas II. baute eine ganz andere Wirtschaftspolitik auf.Die königliche Salzwirtschaft ging in die Hände der Pächter über.

Andreas II.ging langsam daran den Staatshaushalt auf Geldeinnahmen umzustellen.Er ersetzte somit das System, welches auf die Einnahmen von naturalischen Gütern aufgebaut war mit diesem.Dies brachte den grossen Aufschwung des Buntmetall-Erzbaues mit sich und zog so auch den Eisenbergbau mit sich.

Die Hauptstützen der königlichen Politik waren vor allem die mit seiner Frau Gertrudis aus dem Deutschen Reich nach Ungarn gekommenen Meraner,Deutschen.

Die drei Brüder von Gertrudis kamen auch nach Ungarn und bekleideten hier hohe Ämter;von ihnen erhielt Ekbert Bischof von Babenberg, in der Zips,inder Umgebung von



Die Eisenerzgebiete des Karpatenraumes

Iron ore deposits of the Carpathian Basin
Production of iron in the LT= La Tène-, R=Roman-, E=Early Medieval-, and M=Medieval ages

Poprád grosse Grundschenkungen / 1.Karte I. in der Nähe von Eisenerz-Lagerstätten/.Hier,in das bisher unbewohnte Gebiet wurden deutsche Siedler angesiedelt.Besitze in dem Nachbarkomitat Gömör kamen 1216-1217 samt ihren Eisenvorkommen in die Hände ungarischer Adelsherren.

Im Donauknie,zwischen Esztergom und Buda /zwischen den königlichen Zentren/ in den Piliser Bewaldungen wurde 1184 das Piliser Zisterzienser Kloster gegründet.Bei den archäologischen Grabungen schloss László Gerewich die frühesten ungarischen Werkstätten auf,wo man das Eisen und die anderen Metalle mit Hilfe der Wasserkraft verarbeitete."Das Wasser des künstlichen Teiches kam über einen in Steinen gehöhlten Behälter mit senkrechter Sperre zu einem steinernen Rohr von 25 cm Durchmesser.Das so geleitete Wasser strömte von 2,5-3 m Höhe aus auf das Rad der Mühle.Das Rad selber war von 3 m Radius und es drehte sich in einem ca. 6 m tiefen Schacht,dessen Länge 6,4o m und Breite 1,5 - 2 m betrug"/4/.

Das Hammerwerk wurde im XIII.Jahrhundert gemeinsam mit dem Wasserrad erbaut.Nach öfteren Reparaturen brannte die Werkstatt 1526 bei einem türkischen Angriff ab.Nachher wurden nur noch einige Metallschmelzöfen errichtet.Das Wasserrad wurde nicht mehr erneuert.

Die Klöster des Zisterzienser-Ordens verbreiteten sich ab 1179/auch am Anfang des XIII.Jahrhunderts/ sehr schnell in ganz Ungarn.Sie wurden öfters auch in der Nähe von Eisenlagerstätten gegründet.Es ist interessant,dass die im Jahre 1960 noch bestehende Sensenschmiede von Szentgotthárd auch an der Stelle einer früheren zisterzienser Wassermühle erbaut wurde.

Von der Wende des XII-XIII.Jahrhunderts ab,waren alle Bedingungen zur technischen Erneuerung des ungarischen Eisenhüttenwesens gegeben.Den anfänglichen Aufschwung brach aber der Tatarensturm von 1241-42 ab.Die Tataren nahmen einen Teil der Berg-und Hüttenmänner,die sie in Ungarn angetroffen haben-so die sächsischen Bergläute aus Radna /Siebenbürgen/- als Sklaven mit sich.

Um die geschrunfte Einwohnerzahl wieder zu ersetzen wurden in grossen Mengen Hospites/Gastvölker/ ins Land gerufen,die auch noch verschiedene Privilegien genossen. In Ober-und Unterungarn entstanden nacheinander Bergmannsstädte.Die Bürger von Gölnicbánya/heute Hlines in der Slowakei/ mit ihrer altbayerischen Mundart bekamen um 1255 ihr Stadtprivileg/5/. Im Flusstal der Gölnic beschäftigten sich die Einwanderer mit dem Bergbau von Gold-, Kupfer und Eisenerzen.

Der Aufschwung des Eisenhüttenwesens vom Gömörer Komitat begann in den Jahren um 132o herum,als Detre's Sohn Benedek aus dem Geschlecht Ákos Ansiedler in das Murány-tal rief und dort ansässig machte.Nach den Forschungen von Gustav Heckenast wurde zwischen 1334 und 1348 die Bergstadt Dobsina gegründet,über deren Gold-,Silber-, Kupfer-und Eisenerzgruben man in den Urkunden des 15.Jahr-

Die Handelswege des ungarischen Eisens - - - - ->
und die Wege des Importeisens im Mittelalter-·-·-·->

hunderts lesen kann. Die angesiedelten Bergleute waren Bayern,Tiroler und Österreicher /5/.

Im Jahre 1344 erfahren wir durch eine Verschuldung von Polyán's Sohn Miklós, Bürger von Jolsva über ein Hammerwerk in Csetnek."Fabrilis domibus quod vlgo hamur vocant".Das ist die erste Erwähnung eines Hammerwerkes in Ungarn /5/.Aufgrund des Piliser Beispiels kann man aber annehmen,dass die Nutzung der Wasserkraft in Ungarn,in der Eisenhüttenindustrie schon im XIII.Jahrhundert begonnen hat. G.Heckenast/5/ hat noch ab der Mitte des XIV. Jahrhunderts das Weiterbestehen der alten Technik neben der Neuen nachgewiesen.

Auf dem Gut der Familie Máriássy im Komitat Szepes erscheint neben der "Minera"/Bergwerk/, die "vychnye" und auch "hamor"/Hammerwerk/.Demnach wurde hier im Jahr 1352 die Wasserkraft nur bei der Verarbeitung und nicht aber beim Eisenschmelzen verwendet.

Von der zweiten Hälfte des XIV.Jahrhunderts an produzierte die Eisenindustrie im Komitat Szepes-Gömör auch schon für den Export.

Im Jahre 1368 schliessen der ungarische König LajosI. und der Polenkönig Kasimir III./ der Grosse/ einen Handelsvertrag ab. Dieser Vertrag und die spätere ungarisch - polnische Personalunion erleichterten den Export des Eisens aus dem Szepes-Gömörer Erzgebirge nach dem Norden auf die Märkte von Novy Sacz und Krakkau und von dort auf der Weichsel bis Danzig.Vom baltischen Meer kamen die Waren sodann in den Jahren um 1380 auch in die verschiedenen englischen Häfen./6/ /7/.In den Depots von Danzig, Torun und Königsberg des Deutschen Ritterordens lagerten somit viele Tonnen ungarischen Eisens/8/.Ausser den guten Handelsbeziehungen kann man dies auch der Einführung der neuen Technik,der Wasserkraft zuschreiben.

In der Mitte des XIII. Jahrhunderts stellte Ungarn mehr als 80 % des Goldes und annähernd 25 % des Silbers der europäischen Produktion her. Im XIII.Jahrhundert bekam auch das ungarische Kupfer internationale Bedeutung. So lieferten die oberungarischen und siebenbürgerischen Eisenerzgruben mehr das Eisen für die Sicherung der Produktion der Buntmetallerzgruben.Ausserdem versorgten sie auch die im gleichen Teil des Landes gelegenen Märkte von Kassa,Debrecen,Kolozsvár und Szeben mit Eisen.

Für die Edelmetalle und das Kupfer wurden im Tausch während des ganzen Mittelalters hindurch Eisenwaren guter Qualität-auch Fertigprodukte- eingeführt.Diese kamen hauptsächlich für den westlichen Teil Ungarns auf der Donau aus deutschen Gebieten,auf der Mur und der Drau aber aus der Steiermark /bzw Kärnten/.

Von 1526 an verhinderten die türkischen Kriege die Witerentwicklung des Eisenhüttenwesens in Ungarn,die alte Eisenhüttentechnologie wurde für cca 200 Jahre konserviert.Während des 16-17.Jahrhunderts tauchen immerwieder neuere, von aussen unterstützte Neuerungen auf. Zur Einführung dieser aber investierten die Grundbesitzer kein,oder nur wenig Kapital. Der sich in die Mitte des Landes eingekeilte Türke bedrohte nämlich ständig die eisenerzeugenden Gebiete.

Gustav Heckenast versuchte aufgrund der Benennungen der Schmelzöfen die Technik des Eisenhüttenwesens zu rekonstruieren.

Am Ende des XVIII. Jahrhunderts nennt man die Schmelzöfen in Siebenbürgen als vasválasztó-kemence/Eisenscheidender Ofen/,vaskőolvasztó kemence/Ofen zum Schmelzen von Eisensteinen/,vasfuttató kemence/Eisenlaufender Ofen/, kőolvasztó kemence/Steinschmelzofen/.In Oberungarn erscheinen sie während des XVI-XVII.Jahrhunderts unter dem Namen Plähütten,Pläöfen,Bloswerk und Blauofen.Im "Bloswerk" /1570,Vashegy im Komitat Gömör/ wurde laut den Beschreibungen "rudis Massa" also Roheisen/Rauchmass/ erzeugt und Eisen floss aus dem Ofen aus/liquefit/. Nach Heckenast bedeutet das einen Schlackenausfluss und so ist dies noch kein,nach dem indirekten Verfahren arbeitender Ofen.

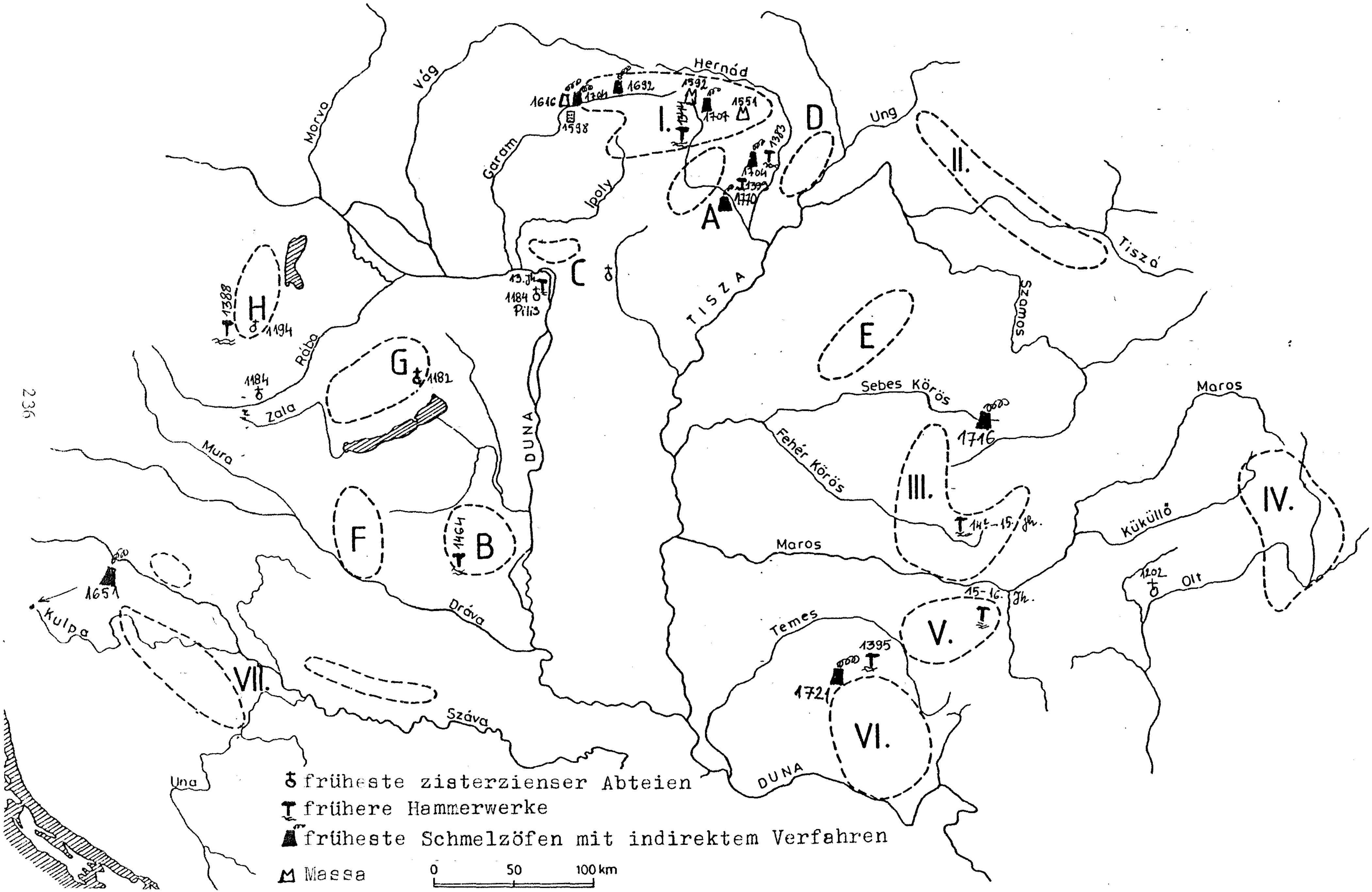
1562 wird ein "deutsches Hammerwerk"und ein"slowakisches Hammerwerk"/Murány/ erwähnt.Das " deutsche Hammerwerk" muss auf höherm Niveau gestanden haben,den sein Census war grösser/9/,in ihm kann nebeneinander ein Stuckofen und ein Ausheizfeuer gewesen sein,wie in Kärnten/10/.

1551,als sich aus den verschiedenen Teilen Deutschlands"viros metallicorum rerum peritos" niederlassen, erscheint in Gölnic auch die Massa/ Masshütte/,neben einem Hammerwerk, einer Mühle,sowie einer Säge.Hier bedeutet die Massa / aus dem lateinischen "massa"dem deutschen "Mass",dem slowakischen "mas" eigentlich aus dem Namen /"Eisenluppe"/einen alleinstehenden Schmelzofen. Seine Produkte wurden im Hammerwerk verarbeitet.

1598 scheint dann in Selmecbánya die erste,in Ungarn bekannte Gusseisentafel auf:Polixenia Kielmann's Grabtafel /11/

1616 erwähnt man in Besztercebánya einen steirischen Plähofen,den man öfters auch als"hoher Ofen" bezeichnet. /9/.Ab 1651 begann man an der Grenze Krain-Kroatien die Csabarer Hüttenanlage der Familie Zrinyi zu bauen.Diese belieferte den italienischen Markt über den Hafen Buccari mit Roheisen, Masseln,brescia-Eisen,Eisenstäben, feinem Werkzeugeisen, Kanonenkugeln,Granatenhülsen,Waffen, Hufeisen und Nägeln.Csabar arbeitete mit einem"fornax mineralis maior pro fiendo ferro Grogloch nuncupata" indirekten Verfahren."Fornax mineralis minor pro fiendis Wolff dictis" war noch ein Stuckofen/12//9/ alten Types.

Nach den vorhergehenden erwähnen die Quellen im Jahre 1692 zuerst einen "hohen Ofen" in dem in Niederungarn liegenden Libetbánya.Der aus Schlesien stammende Karl Philip Kropf liess einen verlassenen Ofen zu einem 7 Fuss hohen Hochofen umbauen.Hier gossen die aus Schlesien gekommenen Arbeiter mit dem direkt aus dem Hochofen he-



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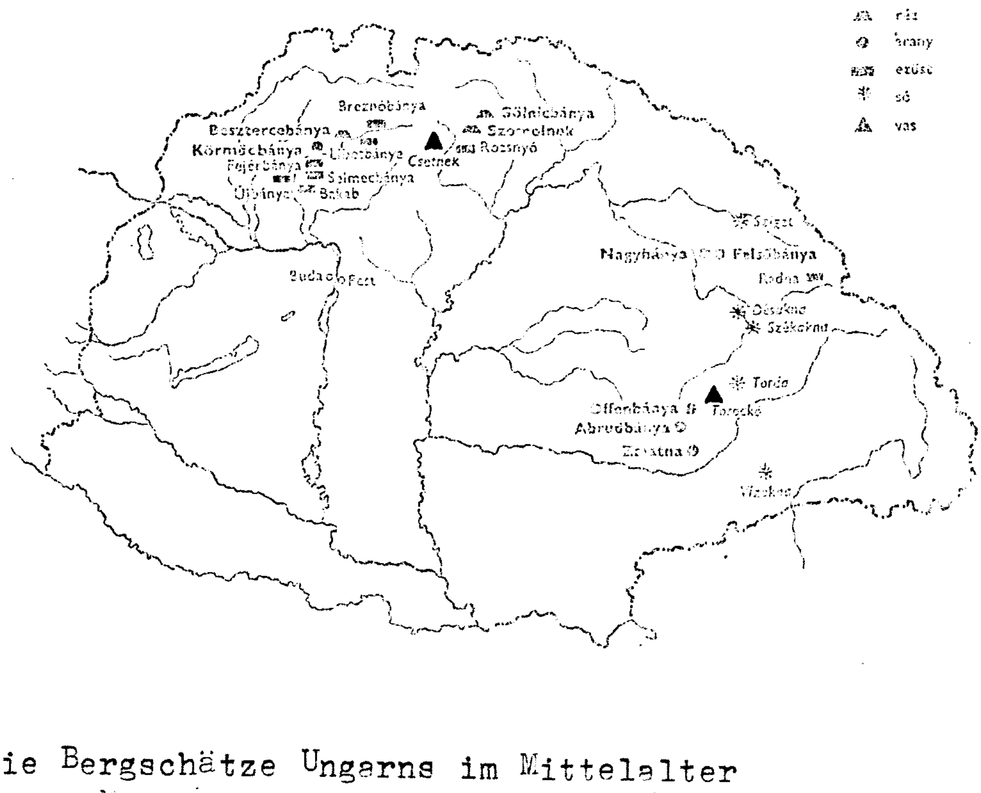
1202
1395
1721
1651
früheste zisterzienser Abteien
frühere Hammerwerke
früheste Schmelzöfen mit indirektem Verfahren
Massa
0
50
100 km

rausfliesenden Eisen Kanonenkugeln,Küchengeschirr,Ofenplatten usw.Sie bekamen ausserdem auch noch"Gänse,"Eisenluppen vom Hochofen.Nach einigen Jahren der Produktion hielt dieses Eisen,welches von schlechterer Qualität als das Zipser Eisen war, der Konkurrenz nicht mehr stand /9/.

1703 hat die Kriegsindustrie der Kurutzen zwecks Unterstützung des Freiheitskampfes von Rákóczi die"liquefactorien" /Giessöfen,Eisengiesshütten/ in Besztercebánya, Dobsina,Libetbánya,Tiszolc weiterentwickelt.

Das indirekte Verfahren verbreitete sich im XVIII. Jahrhundert nach Beispielen aus Schlesien, aus der Steiermark,der Krain, in den Eisengebieten des ganzen Landes, so in Sebeshely /1716-1784/,Bogsán/1721/,Dobsina /ab 1722/, Pojnik /1726/,Pila und in Rhónic / ab 1740/ /9/.

Einer unserer technischen Denkmäler,der Hochofen aus Ujmassa dokumentiert auf dem Gebiet des heutigen Ungarns allein diese Periode der Geschichte des Hüttenwesens.Die wirtschaftlichen,politischen,gesellschaftlichen Verhältnisse des XVIII.Jahrhunderts förderten die Entwicklung des heimischen Hüttenwesens nicht.



Die Bergschätze Ungarns im Mittelalter /nach Magyarország története 1984/

▲ Kupfer, ● Gold, ▬ Silver, ✱ Salz, ▲ Eisen

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Ich möchte mich auch an dieser Stelle bei Dr.Gusztáv Heckenast bedanken,dass er es mir ermöglichte sein im Druck befindliches Manuskript zu lesen und zu benützen.

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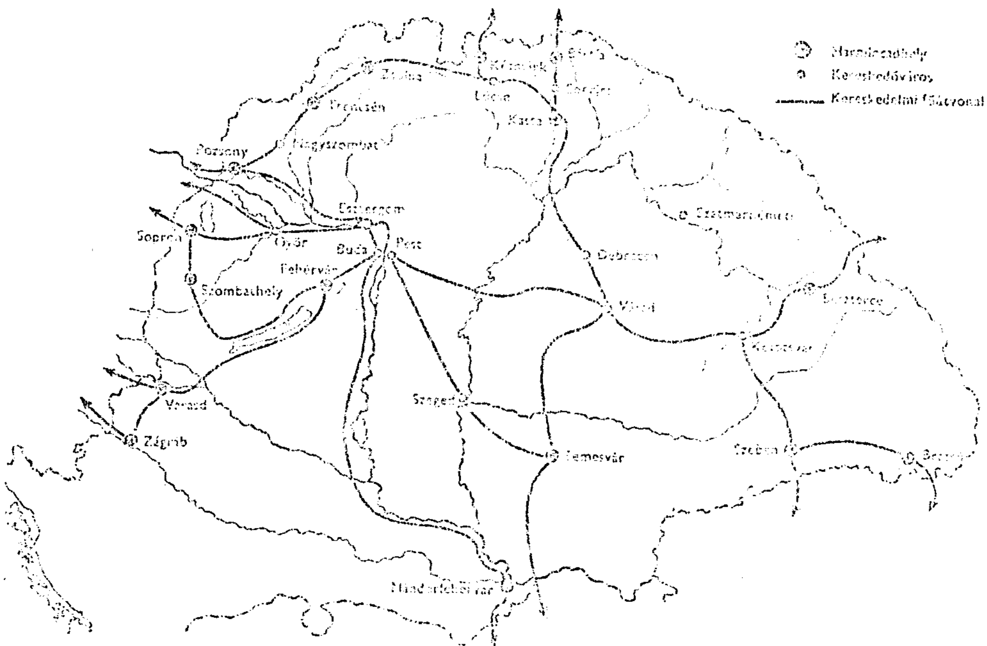

Handelswege im mittelalterlichen Ungarn /nach Magyarország története,1984/

⊛ Dreissigste-Teil Zollstelle
∘ Handelsstädte
—— Wichtigste Handelswege

Iron smelting in medieval bloomery furnaces on Castle Hill at Muszyna, distr. Nowy Sącz, Poland

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SUMMARY

In the southern part of Poland, the Carpathian mountain range shelters the famous health resort of Krynica, Muszyna and Żegiestów, which boast abundant mineral and ferruginous water sources and springs.

The action of these water accounts for surface deposits of among others, goethite -rich ores in the area. This kind of ore contained up 62% of iron, small amounts of SiO_2 and very low ortrace concentration of P_2O_5 and sulphur, and was very easy to reduce.

The other kind of ore was mainly deposited in the mountain crevices. Apart from the usual components, it contained significant amounts of NiO and CuO.

By the nineteenth century, these ores had been completely exploited.

The Castle Hill sites revealed 25 various pieces of slag in the shape of a bowl / from the bottom of the furnaces/, with the diameter ranging from 13 -19 cm, and dating back XIV -XV centuries. This indicates that 2 or 3 different size bloomery furnaces must have been operating in the area. Their diameter was 16 to 22 cm and they used the artficial draught. The material used for their construction was made up from clay, small stone and chaft.

Either goethite or a mixture of the two ores were used for smelting. The smelting site was found just outside the castle walls. The castle was inhabited untill 18th century.

From a small, 13th centrury settlement a top the mountain, archaeological findings of 17 iron objects from 13th-14th centuries were taken for analyses. It was stated, that they consisted of low-carbon iron, smelted from local ores, and had very low contents of P and S as well as Ni and Cu. Impliments and tools as well as part of weapons were intentionally carburised and quenched.

The metallurgical production from these bloomery furnaces covered the economic and defense purposes.

1.Historical Introduction

The iron smelting centre was located in the middle part of the Carpathian mountains range,which is situated in the southern part of Poland. It was part of large estate complex,extending south-east of Nowy Sącz city and bordering on the former Hungarian Kingdom /App.A/. This property frequently changed hands in 12th-13th century.From 1391 to 1783 it became the demesne /property/ of the Cracow-Bishopric. Between the 14th and 18th centuriesthere were two towns with the castles: at Muszyna and Tylicz and over 30 villages in that area. Its economy and managment were conditioned by the requirements of self sufficiency and defence of the frontier zone.

As far as has been established,the first traces of iron smelting appeared on Castle Hill at Muszyna,where it seems, iron was already smelted in 12th-13th century.

The Castle Hill with an average altitude of 525meter /App.B/ above sea-level /circa 1.800feet/ is a narrow branch of the main Koziejówka massif. The face of the mountain verges on the Poprad river.On the top of the Hill,about 300metres from its face a small castle was built in 12th century. In the first half of the fifteenth century a large castle was erected on the mountain face. On the surface of Castle Hill between the small and large castle traces of iron were found /App.C/.

The first archeological exavations on Castle Hill were carried out in 1963 and repeated throught 1973-1974. Apart from several iron objects unearthed in the area, two pieces of iron slag and pieces of goethite were uncovered. All these objects were colected from the north-western part of the castle wall.

In 1976 while streightening a part connecting the castle

with its moat,an importand find was made. Namely,a concentration of iron smelting remains was detected over a restricted area, some 12 metres distant from the main entrance gate to the castle compound one metre square, 30cms under the level of the ground. The find included 25 pieces of slag bowls,smaller slag fragments with the furnace wall /App. D/ charcoal and cramics dating back to first half of fifteenth century. These remains indicated that a nearly iron smelting site have existed.

The localisation of the smelting site is similar to those in the thirteenth-fourteenth centuries, which had been found in the Polish defence castles near the frontier in Silesia in the region of Częstochowa /Olsztyn,Bobolice,Koziegłowy/. And similary the iron-smelting sites were found there, near the main gates, just outside or inside the defence walls. Possibly the discovered find of slag pieces and one piece of goethite ore from the Muszyna Castle may date back to the period proceding the construction of the small castle.

The 15th century iron smelting sites on Castle Hill would, then belong to the last phase of iron smelting conducted in Muszyna area in small furnaces with hand operated belows. Probably in the second half of the fifteenth century, a water wheel was introduced. This would testify to rapid economicgrowth of Muszyna city, lying at the cross -roads of international trade routes. That was why, the city reached the pin nacleof its development in the 15th century.

On the other hand, the castle needed the water forge not only to supply its own soldiers with arms, but to provide similar services to regular army troops patrolling the frontier area. This coupling of economic-defensive interests between the cas tle and ironworks was much in evidence in the above mentioned Silesia, another border area, where the cas-tle developed their own ironworks in the 14th -15th century.

A historical document refers to an annual levy paid by Muszyna in 1529, amounting to one ton of iron and 200 kilos of steel. This seems to confirm to existence of an active ironworks rather than a small furnace iron smelting.

The fact that throughout the 16 century, the threat of Turkish invasion was kept alive would justify the necessity of having a larger iron production at the time and even later.

In 1584 a water ironworks capableof producing steel was built at Tylicz, a small town in the same area. Its production was kept until the first quartier of the seventeenth century.

In the years 1610 -1622, the first blast furnace was built in Poland at Bobrza, near Kielce. Its architects were two Italians, the Caccia brothers who moved there from Bergamo. This iron plant produced on an industrial scale among others things good quality steel from pig iron. It seems that the activity of blast furnace at Bobrza brought about closing down of steel and iron production at Muszyna and Tylicz in the first half of the seventeenth century.
On the other hand, it was indispensable to preserve the forest in the Muszyna-Tylicz frontier region for defensive reasons.

There is no mention of iron and steel production in that are in Walenty Rozdzienski swork entitled " Officina ferraria published in 1612.
Obviously, for some reasons , it was deemed uncessary to publicise the existence of this production, which was not destined for open domestic markets.

The first half of the eighteenth century saw but one mention of the fact in the form of an expertise on Muszyna ore entitled " Invention about Muszyna Ore", and one preserved written order for its exploitation. This in turn would indi cate that metallurgical production was intended.

On the other hand, the subjects of expertise would include the matter of good quality raw materials which surely would point to exellent goethite ore abundant in the area at the time.

2. The 14th century iron production on the Castle Hill.
As it was mentioned above several pieces of slag were found in the area between the ruins of the large and small castle /App.D/. Among them 25 bowl-shaped slag were discovered. Three kinds of the bowl-shaped slags can be distinquished: 12cms in diameter /2 bowls/, 14-16 /9 bowls/ and 17-19cms /9 bowls/. Five bowls were incomplete. The thickness of the bowls varied from 8 to 11cms. The bowls were rather light porous and greyish in colour.
The other pieces of slag were hard and more heavy.
The analyses of slags are given in Table I.

Table I

Analyses of slag samples

%	1	2	3	4	5	6	7	8
SiO_2	10.0	29.44	30.13	67.80	80.44	75.97	76.87	41.50
Al_2O_3	12.01	2.57	1.14	6.39	0.18	0.17	0.18	18.77
Fe_{met}	1.45	0.00	0.00	0.00	0.02	0.00	0.14	0.06
Fe_2O_3	59.28	56.74	50.92	10.51	7.80	6.52	11.13	10.60
MnO	0.10	0.64	0.01	0.26	0.10	0.32	0.00	0.20
MgO	2.01	0.01	3.61	tr	0.09	0.42	0.18	2.07
CaO	10.10	3.10	4.72	4.56	1.59	4.53	1.83	4.15
Na_2O	0.37	0.52	0.20	0.75	nd	nd	0.15	0.60
K_2O	0.74	0.90	0.71	1.60	nd	nd	0.80	1.70
P_2O_5	0.82	0.30	tr	tr	0.40	0.00	0.51	1.80
S	0.03	tr	tr	tr	tr	tr	tr	0.03
loss	0.10	0.50						
NiO	nd	0.05	0.02	0.01	0.00	0.00	0.00	0.00
CuO	nd	0.15	0.05	0.05	0.02	0.01	0.00	0.00

Nos 2,3 pieces of slag

Nos 4,5,6,7 samples of bowl

No 1-gromp / slag part
No 8 sample of bowl with small fragment of wall

As the analyses in Table I seem to indicate the samples of slags could be divided into two groups: one with high amount of silica / Nos 4,5,6,7/, small amount of iron, varying amount of calcium and aluminia ; the another group / samples 2,3/ with higher amount of iron, varying amount of silica, aluminium and calcium.
The analysis of tha slags part of gromp is also included /sample No 1/

The large amount of aluminia found in sample8 seems to be due to presence of wall fragments.
All the slag are characterised by small amount of phosphorous / trace to 0.82 % P_2O_5/

Sampling the charcoal found in the same place were established that a mixed charcoal obtained from hard wood like beech and from coniferous tree e.fir was used.This was predominantly wooded area with fir forest.

Above the slags and pieces of charcoal the fragments of furnaces wall were also discovered.The remains of tuyeries proved that the artificial draught were used for smelting proces.

The bloomery furnaces were made from clay and small stones glued together.Some of the discovered fragments of furnace lining had some small stones in them.

The shape of the shaft was circular.A layer of clay and chaff lined its interior.A layer of slag covered the fragments of the lining.

We have be unable to establish the hight of the furnace. The various in the diameter slag bowls would indicate that were two or 3 various size bloomery furnaces on Castle Hill. This may have been conditioned by using the different charcoal and two kinds of ore separately or mixed together, with rich high quality goethite ore.

The above -mentioned castles of Częstochowa region,used one kind of bloomery furnace only with the diameter of 12 cms.

As regards to ore used for smelting process,sampling of the ore found on the Castle Hill and the vicinity of the Castle Hill has established that two type of the ore were used. The ore analyses are given in the TableII. The analyses of ferrugineous rock and deposits are also listed.

Samples 1 and2 represent the rich iron ores. The concentration of iron varied between 53.8 and 52.3%Fe. They are characterized by small amount of silica and phosphorous and varying amount of calcium.

The second group represented by the sample 5 and 6 contain smaller amount of iron,varying amount of silica and aluminium and calcium. The phosphorous content is higher then in the sample belong to group 1. The nickel content varied between 0.06 -0.85%Ni,while copper concentration ranged from 0.40 to 1.90% Cu.

The ore -mining region under reviews was centered in the Poprad river basin and the Carpathian mountains range with its rich mineral water deposits. It was these ferruginous mineral waters with their bicarbonate - calcium -magnesium composition which gave rise to such renowned spas and health resorts as Krynica,Muszyna,Złockie.
Disruptions of geological composition resulted in the formation of two zones with a particular abundance of natural

Table II

Analyses of ore samples. ferruginous ock and sediments

%	1	2	3	4	5	6	7
SiO_2	0.72	5.40	75.80	69.90	23.94	24.98	5.03
Al_2O_3	0.40	0.91	10.48	1.45	11.07	4.17	0.61
$Fe_{tot.}$	52.33	37.65	7.52	19.76	28.67	30.75	3.50
Fe_2O_3	74.83	53.84			40.94	43.97	
MnO	0.20	0.17	0.40	1.25	0.30	0.36	1.26
MgO	0.59	0.71	0.05	0.04	0.02	0.13	0.81
CaO	2.05	14.80	0.05	0.07	3.62	2.32	45.18
Na_2O	0.40	0.91					0.28
K_2O	0.91	1.45					0.16
P_2O_5	0.20	tr	1.25	0.40	1.14	1.31	0.05
S	tr	tr	0.15	0.17	0.12	0.11	0.07
NiO	nd	nd	0.65	0.08	0.06	0.86	nd
CuO	nd	nd	0.50	0.05	0.40	0.80	nd
loss	17.6	19.2			17.20	19.9	40.75

No 1 -sample of goethite -Castle Hill

2 sample of goethite - Złockie

3,4 - ferruginous rock

5,6 sample of epigene ore

7- sample of deposits -Jastrzębik

water sources and mineral water exudation namely in the region Krynica - Tylicz and in the vicinity of Muszyna and Złockie.

Mineral waters outflow in the distant past has produced surface deposits on the slopes of the mountains and its valleys, composed from calcium and iron oxides.

Different contents of these elements resulted in multi-coloured look of sediments. The colours varied from white ,cream yellow to red,cherry,old gold and brownish. The last two colours appeared in solid concrecions of iron oxides which in fact,were ores of the goethite type.

They contain,in raw state about 75% of Fe_2O_3 with CaO content ranging from 1 to 2%.Other sedimentation fragments showed decreasing amount of Fe_2O_3, sometimes minimal,while CaO content rose markedly.

Since the mineral waters in the region are devoided of phosphorus and sulphur comositions ,the ore which resulted from

from the process of sedimentation was completely without phosphorous and sulphur in its pure form. Insignificant amount of H_2SiO_3 in the mineral water produced SiO_2 content upto 1% in the ore.
Rich iron ore contained very few slag -forming components and these, as a rule were predominantly alkaline.
Increased amounts of SiO_2, Al_2O_3, P_2O_5 and S, frequently found in that goethite ore resulted from outside contaminations due to silting up sand and clay brought in by the action of the wind and organic mixtures.

The goethite structure in its pure state is porous and show an abundance of small ducts and holes. The porosity of the ore was significantly increasing by roasting. (App. D)

It would be difficult to provide an exact estimate of the original iron resources in the fourteenth century. Since that time up to the 19th century the ore deposits had been completely exhausted.

The ore was also transported to distant smelting works.

But the another kind of ore is found more frequently through out the Krynica -Muszyna -Tylicz region. It is more dispers ed and the ore is found both on the surface and deep inside the rock -face. The ore owes largely its origin, as was the case before, to the action of mineral waters.
The geological structure of the region is composed of thin layers of limestone, interspersed with slate.
The waters, along with the dissolved CO_2, proved to be agressi ve agent leaching out from the rocks their mineral deposits. All the elements brought together from the environment as result of the water action are deposed in the form of iron ores.
The ore has an average chemical composition : 25-35% Fe, 20-35% SiO_2, varying contents of P_2O_5 and rather low sulphur con-tent. An important feature of the ore is frequenty high con-tents of NiO and CuO.
From a geological point of view the ore which is a mixture limonite, siderite, hemaetite can be described as epigene.
Insignificant and scattered resources of this ore no longer find important production use today.

3. Iron findings

Within the walls surrounding the castle and the medieval city, 17 iron objects were found. /App. E/
The discovered objects were, for the most part, military accessories but included 4 household and farming articles as well. All these finds dated back to 13th -15 th century.

Chemical analyses /Table III/ revealed that all these objects were made of low phosphorous 'iron'. The concentration of phos phorous ranged from 0.04 to 0.09% P. Moreover both nickel and copper were detected in the metal / 0,02 -0.09% Ni and 0.01 -0.46 % Cu/.

A piece of gromp proved exception to the rule, it contained in its metallic part 0.35% P. The iron had ferrite structure.

Table III

Analyses of the 17 iron findings

%	C	Mn	Si	P	S	Ni	Cu
gromp	0.11	0.04	o.21	0.35	0.01	0.12	0.01
fragm.	0.45	0.06	0.02	0.06	0.02	0.09	0.22
fragm.	0.36	0.06	0.08	0.01	0.01	0.06	0.23
knife	0.19	0.03	0.05	0.009	0.005	0.02	0.04
sickle	0.20	0.04	0.013	0.02	0.01	0.02	0.08
arrow	0.43	0.04	0.08	0.004	0.002	0.02	0.08
sword		0.05	0.12	0.004	0.002	0.03	0.20
sabre		0.04	0.09	0.027		0.03	0.02
sword		0.02	0.09	0.02		0.02	0.03
knife		0.02	0.10	0.04		0.07	0.13
arrow		0.03	0.07	0.03		0.04	0.03
key		0.06	0.16	0.096		0.03	0.01
helmet		0.03	0.07	0.032		0.04	0.20
horse shoe		0.03	0.14	0.073		0.03	0.07
nail		0.05	0.05	0.036		0.04	0.25
horse bit		0.03	0.08	0.046		0.04	0.46
fragment		0.03	0.08	0.050		0.04	0.40

The horse-shoe was forged from soft ferritic iron with a large amount of non-metallic inclusions /App. F/.
The helmet, too was made from soft metal with insignificant carbon content.
Insignificant carbonisacion was observed in a metals fragments, arrow heads, key and horse-bit /App. F/.
One of two swords was forged from iron with carbon content amounting to 0.4%C. The whole cross-section of the sample reveals, ferrite-perlite microstructure according to Widmannstätten s structure /App. G/.
The second sword showed carbonisation along the cutting edges of the blade up to 0.6%C /App. G/. After carbonisation, the sword was quenched. Large-grained microstructure of the carbonised layer and large-needled martensite testify to quenching iron from high temperatures.
The sabre underwent the process of quenching as well. In its blade, a martensite microstructure, with an average hardness H_v-400-450 kG/mm^2 was stated. The other side of sabre had ferrite-perlite microstructure with 0,2%C near the edge

and 0.4 %C in its core. This untypical /App.H/ ferrite-perlite microstructures indicate that the final operation of forging was performed in the range of α,γ, that is to say susfficiently temperature to reach austenite range in place with high carbon content, while forging in this range of temperatures in less carburised fragments is suggested by the characteristic cementite shape.

The other objects i.e. 2 knives and a tinder box were made by welding together the carburized blade with the soft ferrite core /App.I/.

A few of the carburised objects revealed a layer of corrosion products with a visible nin corroded cementite.

All the objects had small amounts fo non metallic inclusions elongated in the direction of plastic working. On the app.H the complex non-metalic inclusion is shown.

Very low phosphorus content in metal which facilitated its carburisation and which is evident in all objects seems to justify the assumption that goethite ores, which are characterized by minimal phosphorus content, had been used for the purpose of these smelting.

The concentration of Cu and Ni in the objects, suggests that insignificant additions of epigene ore may have been used un the smelting.

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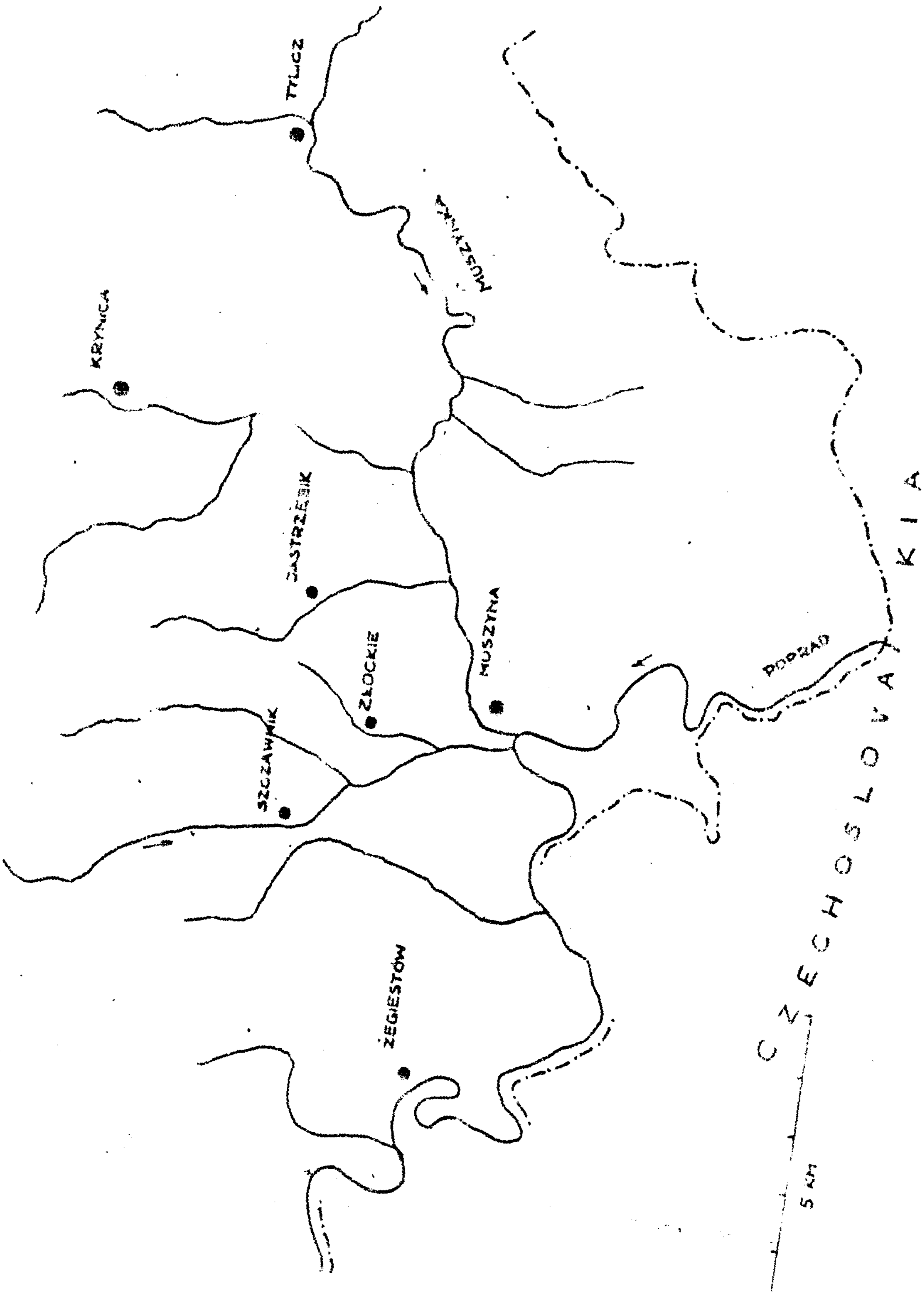
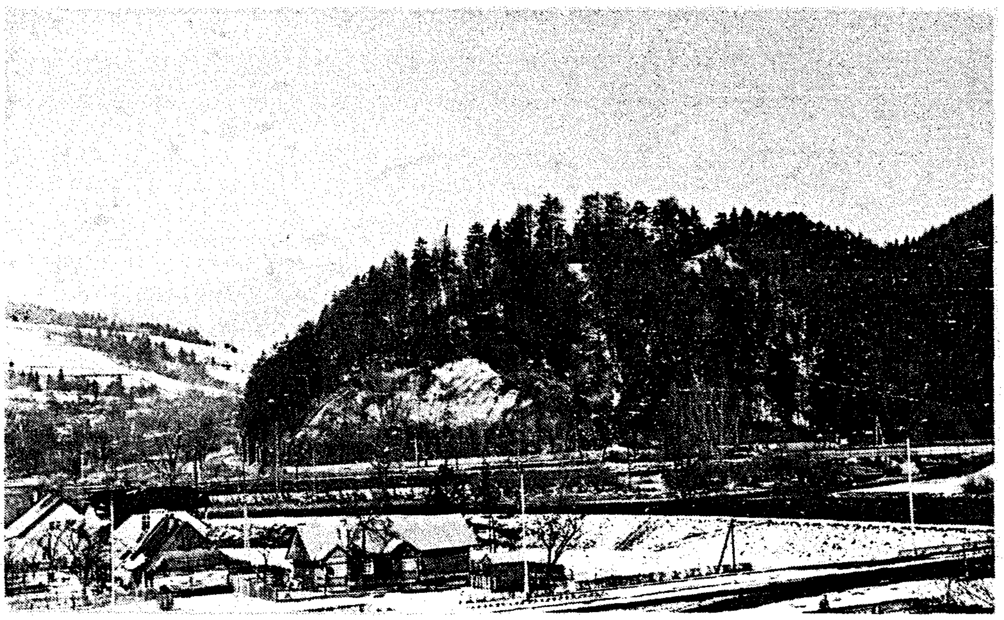
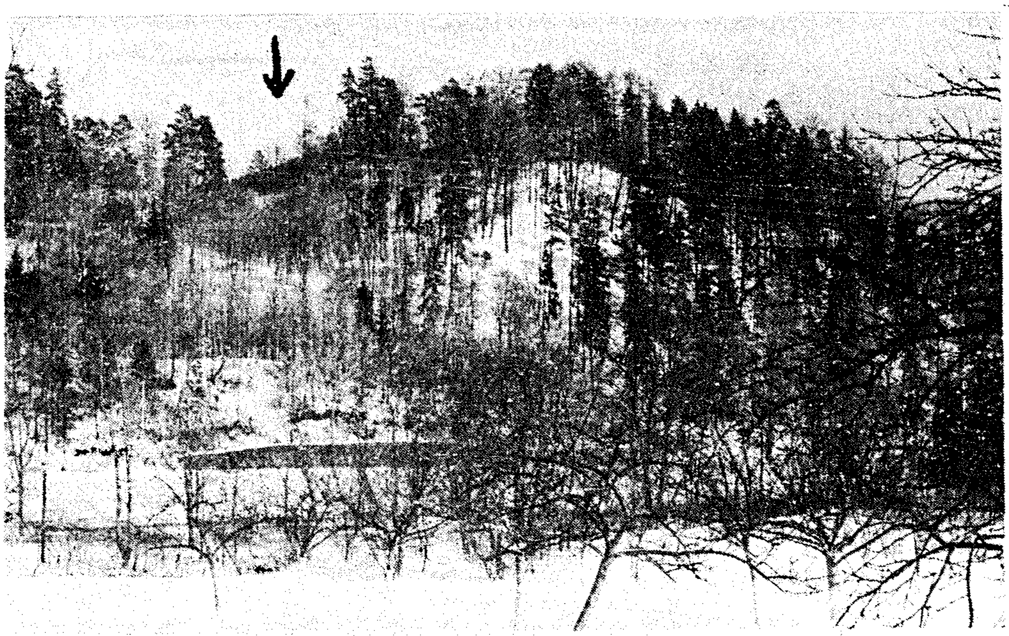
Appendix I
General plan of Muszyna area.



Appendix B



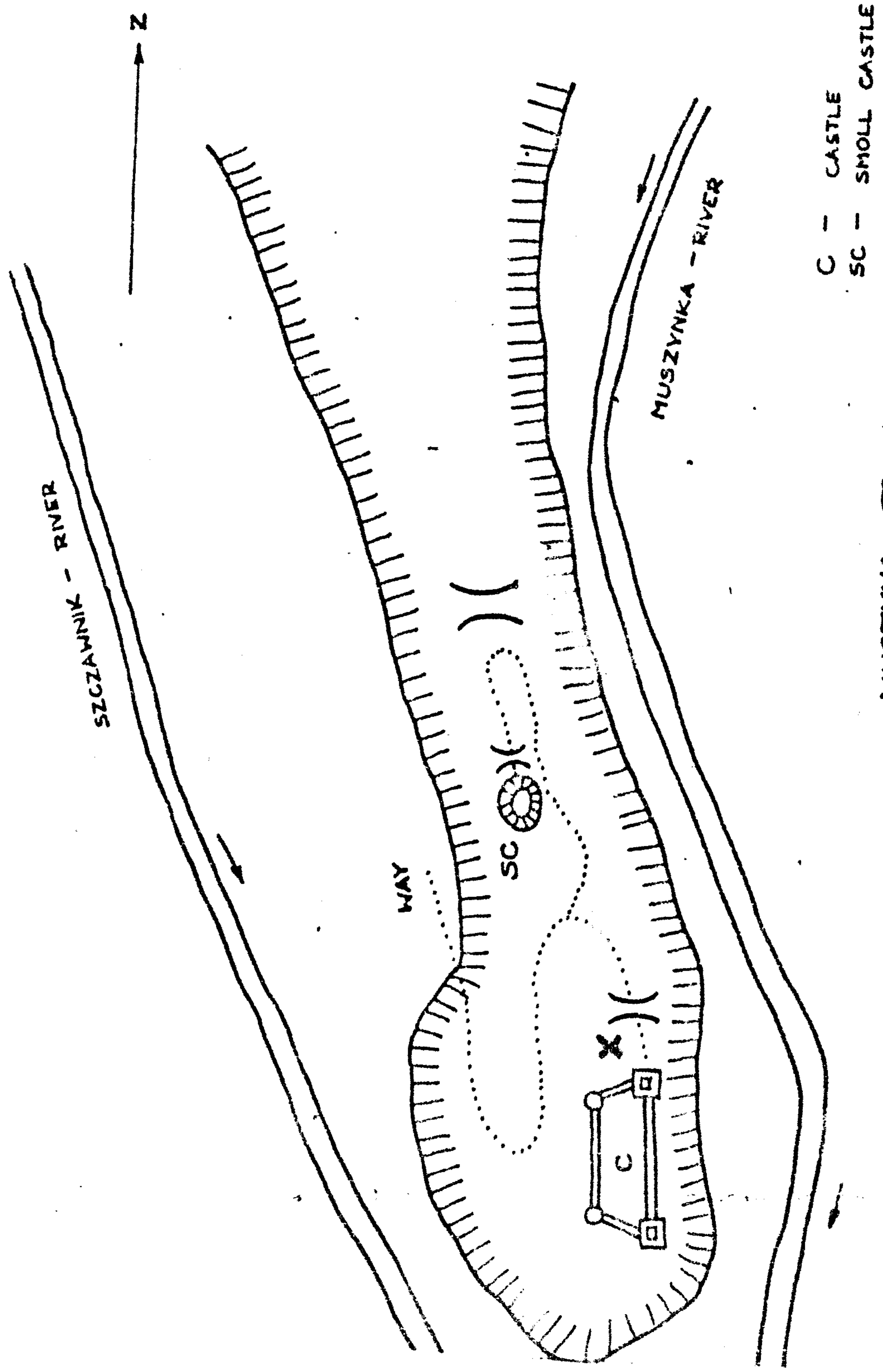
Castle Hill. View from the Poprad river.



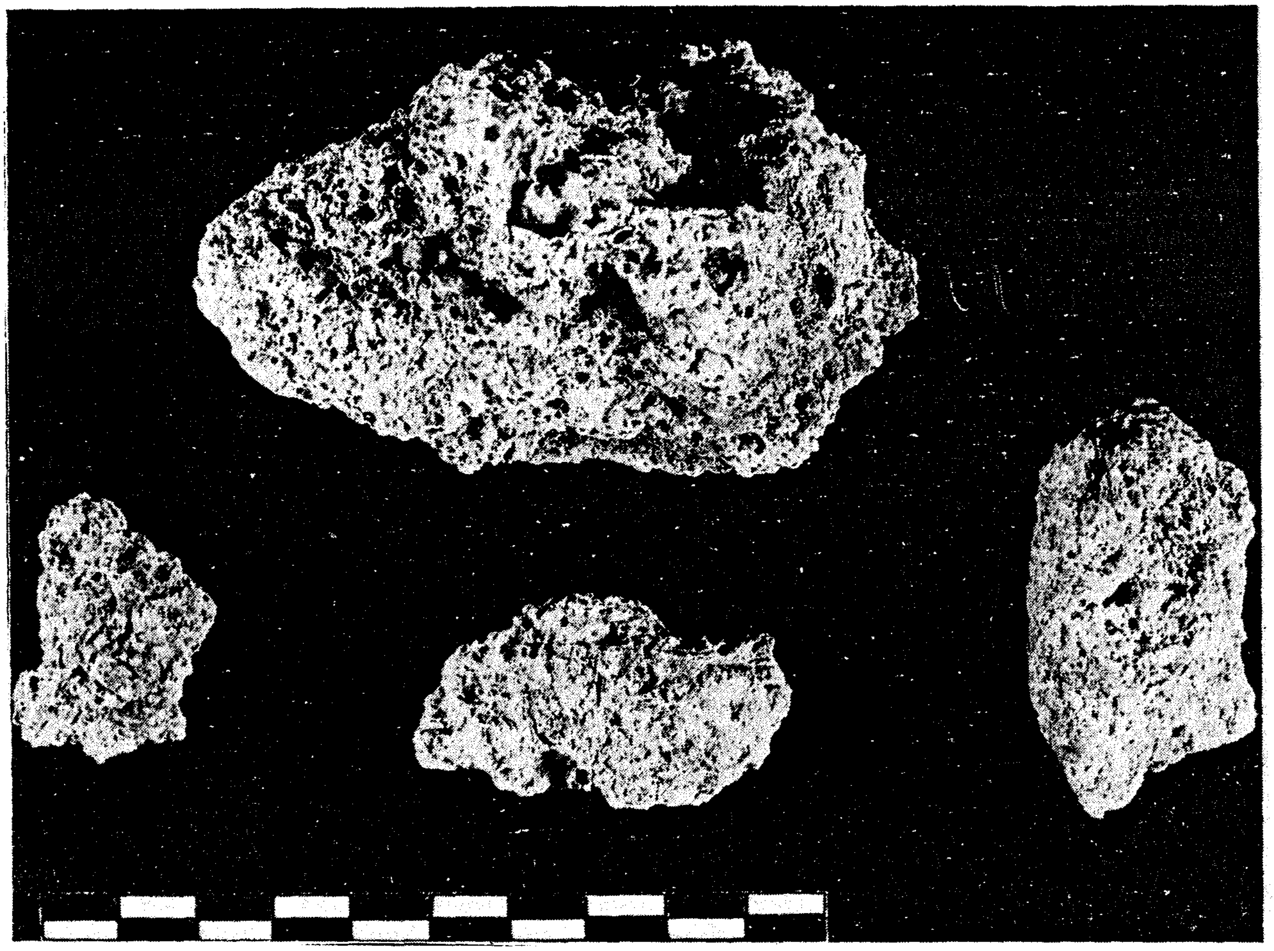
Castle Hill. View from the Szczawnik river. Place where the slags were found.

Appendix C

General plan of the Castle Hill area. 1-small castle, 2-place of find, 3-large castle.

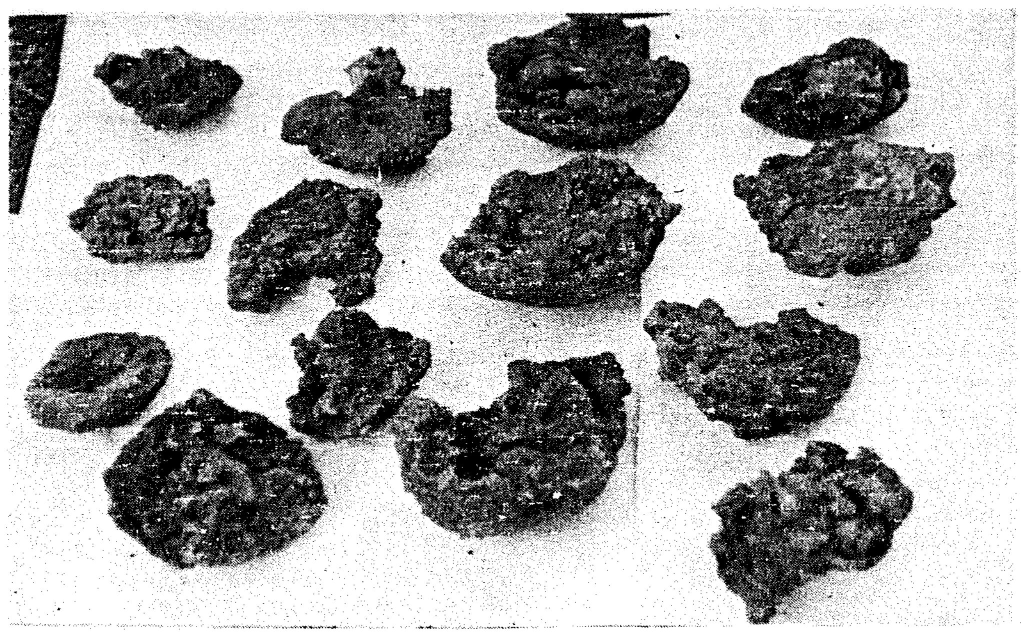


Appendix D



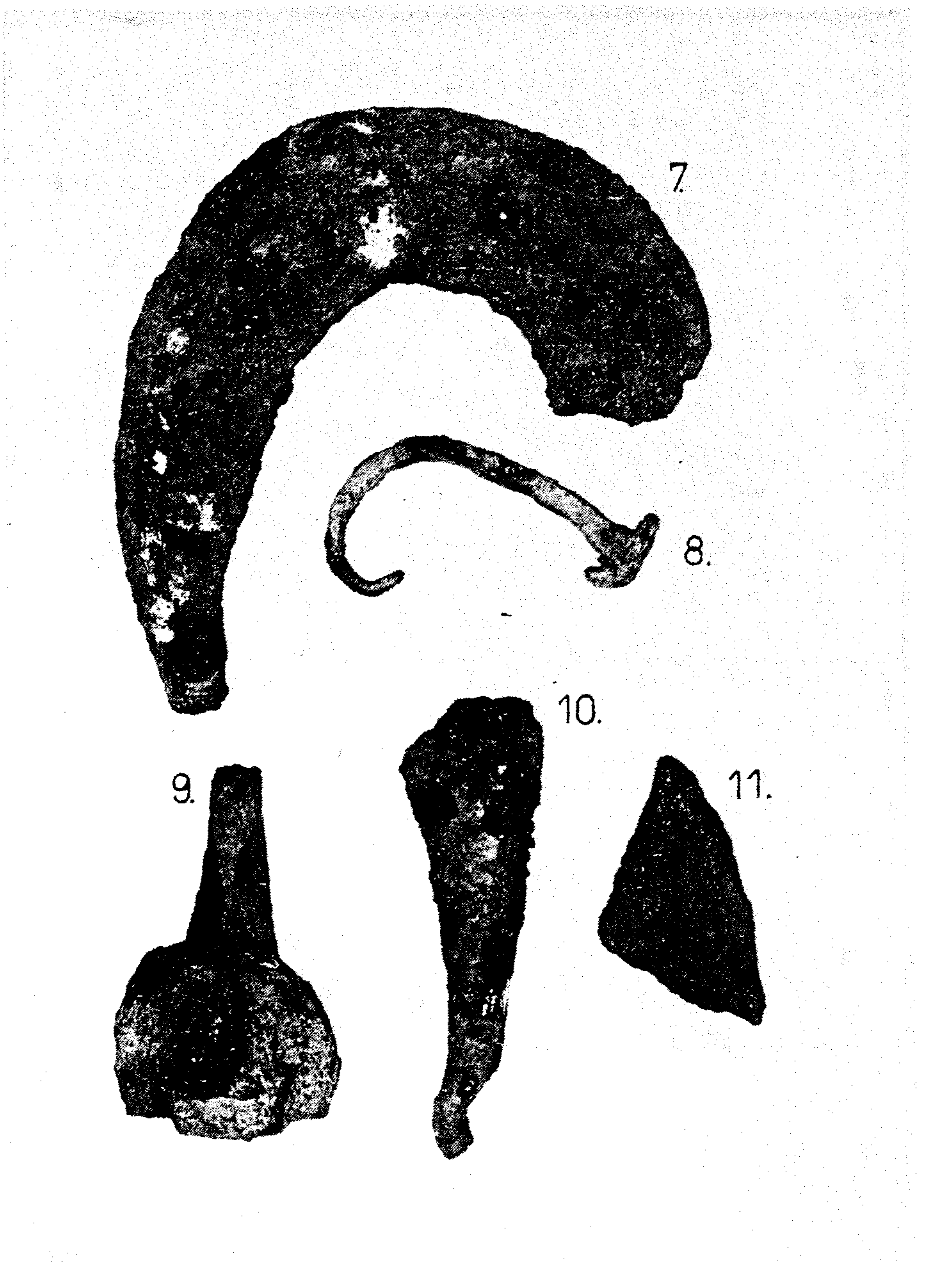
Sample of the porous goethite.

Appendix D



The slag bowls.

APPENDIX E



The iron findings discovered, on the Castle Hill nearby the small castle.

APPENDIX F

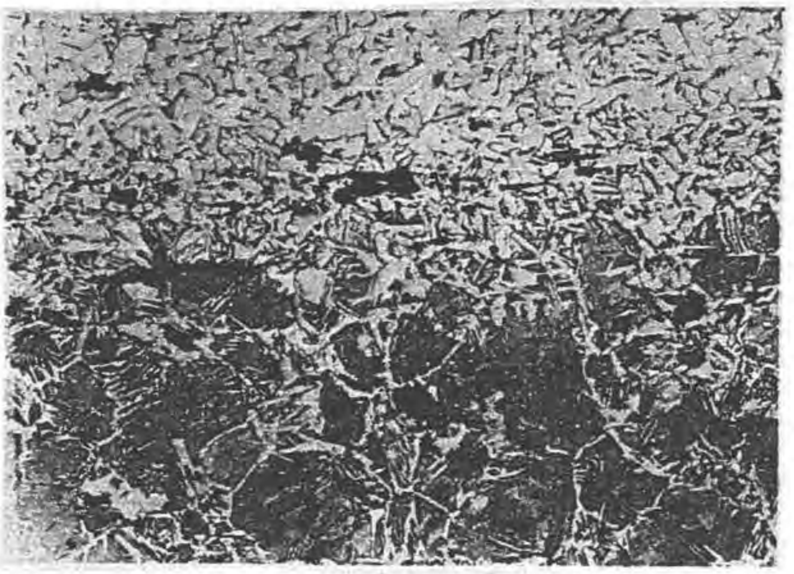
The horse shoe. Microstructure ferritic. 630x. Etched nital.

APPENDIX G

The sword. Microstructure of blade. Large needle of martensite and ferrite - perlite in the core. 500x. Etch. nital.

The sabre. Martensite in the blade. Untypical ferrite-perlite structure in the middle part. 500x. Etch. nital.

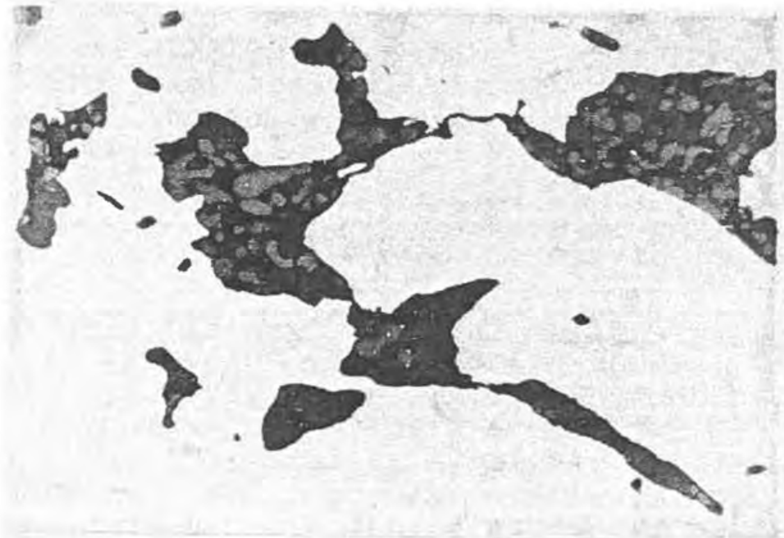
APPENDIX H



The knife. Pearlite-ferrite microstructure in Widmannstätten a rrangement. 100x. Etch. nital.

The sword. Elongated non-metallic inclusions. 500x

APPENDIX I



The horse -bit. The complex non-metallic inclusions. Magn. 630x

IRON AND STEEL TECHNOLOGY ON THE TERRITORIES OF POLAND IN THE 11th - 14th CENTURY A.D.

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SUMMARY

The investigations into the iron and steel technology on the territories of Poland during the early mediaeval period (6th - 14th cent. A.D.) are quite advanced. Until the present day 858 implements from 76 archaeological sites have been examined. A considerable number of these implements originates from the 11th - 14th cent. During that period the metallurgists processed almost the bog iron ores containing large amounts of phosphorus. Hence 83.5% of the examined iron implements contain above 0.1% P (59.9% of the implements contain above 0.2% P). Together with the iron the metallurgists also smelted steel.

For the manufacture of tools the process of carburizing (cementation) was applied, together with welding of iron and steel. Those processes were used as early as in the 6th cent. but after the 11th cent. they were used much more often. From among the 122 examined knives from the 11th - 14th cent. - 12.8% were made of iron, 5.3% - of steel, 10.5% were forged in iron and cemented, while 71.4% were welded in iron and steel. Almost all of the tools were subjected to a correctly perfomed heat treatment.

The examined implements also included pattern welded knives as well as a sword and a misericord from the 14th - 15th cent. (from Gdańsk) forged in iron and the finery steel (with a pommel made of cast iron).

INTRODUCTION

The research carried out by the Russian historians of material culture (1) inspired metallurgical examinations of the ancient and early mediaeval iron objects in Poland. Of particular interest were the examinations carried out by B.A. Kolčin (2), who in 1953 published his work on the technology of manufacturing iron objects on the territories of Ruthenia in the 10th - 13th cent., basing on the examinations of 286 implements from 32 archaeological sites (3). The research done by B.A. Kolčin aroused a vivid interest among the Polish metallurgists and archaeologists.

The results of the first metallurgical examinations of early iron implements were published in Poland as early as in 1953 (4), (5), but examinations of this type have been developing since 1955, when the author together with several other investigators started these works under the auspices of the Institute of the History of Science and Technology of the Polish Academy of Sciences (6).

The examinations included iron implements encountered on the territories of Poland since the 8th cent. B.C. until the 14th - 15th cent. A.D. Within the scope of these works the iron implements from the early mediaeval period, i.e. since the 6th until the 14th - 15th cent. A.D. were examined, namely 853 implements from 75 archaeological sites.

A quantitative chemical analysis was also carried out on the samples of iron ore and slag, from the numerous archaeological sites. In some samples of the slag its softening and melting point was determined.

The initial results of the investigations into the iron technology on the territories of Poland during the early mediaeval period were disclosed by the author in some of his ealier publications (7), (8), (9), (10), (11), (12), (13). The examinations made during the past ten years have confirmed the former observations.

Methods of investigations and criteria of an identification of the technological processes

The author carried out examinations on 760 early mediaeval iron implements from 66 archaeological sites, applying a "standardized" methods of examinations (14). The examinations covered:

a) a quantitative and qualitative spectrographic, chemical analysis determination of the content of P by means of a photometric or volumetric method, determination of the content of Ni and Cu by means of a photometric method or atomic absorption, determination of the carbon content basing on the structure,

b) metallographic observations and examinations of the structure of the specimens etched with a 4% nitric acid and Oberhoffer's reagent at an enlargement of up to 500x (for some specimens - up to 1000x), including a determination of the grain size of the structural constituents,

c) measurements of the microhardness of the structural constituents using a Hanemann's hardness tester (loading for iron and steel - 50 gms, for the heat treated steel - 100 gms, time 15 sec.),

d) measurements of the metal hardness by means of Vicker's method (loading for iron and steel - 10 kg, for heat treated steel - 30 kg, time - 15 sec.).

Moreover, some special examinations were carried out using a Quantimet 720 image analyser or an X-ray microanalyser (15).

An application of the identical methods of examinations in an analysis of the very large number of iron objects as well as slag enabled the author to use several methods of the mathematical statistics and the calculus of probability even in his earliest works (16). Later on, the statistical methods were used by the author to process all the results of his analyses.

For an identification of the technology of the examined iron implements, some objective criteria were used. The main objective criteria for a determination of the welding process are as follows:

a) the presence of a chain of the small, usually rounded or slightly elongated slag inclusions, possibly also - though not always - a characteristic seam visible after Nital etching; an area of the carbon diffusion from the metal of a higher carburization (steel) to iron can also be noted,

b) a sharp change in the direction of the slag inclusions,

c) a very sharp change in the content of carbon, phosphorus or other elements.

The criteria for a determination of secondary carburization (cementation) are as follows:

a) the gradient of carbon content in metal perpendicular to the carburized surface,

b) content of carbon in metal assuming values according to the law of diffusion.

The presence of steel or carburized parts (surfaces) has to be proved from the technological point of view.

To verify if the determination of a technology is correct, the criterion of reproducibility can be used. If two or more parallel test pieces are cut out from an object, then - in the case of welding or cementation - the structural pattern will be identical or slightly shifted in a given direction. If, on the other hand, the object has been forged in the iron of an uneven primary carburization, then the distribution of carbon will show some differences on the separate test pieces, sometimes even quite notable.

A more detailed presentation of the above described criteria together with the discussion of errors was published in the author's former papers (17), (18).

Numerous investigators determine the technology of the examined objects basing on their own subjective suggestions. Usually the "band structure", which is formed in the iron implements as a result of the segregations of phosphorus or arsenic, is regarded by them as an effect of welding the rods with a varied carbon content, f. ex. "packeting" (19), (20), while the non-uniform primary carburization is regarded as cementation secondary carburization (21).

Such subjective criteria of the evaluation of a given technology neither give us a possibility to know the real development of the iron technology, nor do they enable a comparison of the results of examinations of several investigators.

Smelting of iron and steel

Basing on a statistical evaluation of the chemical composition of bloomery slags from the different metallurgical centres on the territories of Poland, a classification of these slags and of the iron ore was proposed. The following variations are distinguished here (22):

a) the slag (ore) with a low content of phosphorus (below 0.75% P_2O_5) and with a higher content of this admixture,

b) the slag (ore) with a low content of clay (below 6.0% Al_2O_3) and with a higher content of this admixture,

c) the slag (ore) with a low content of manganese (below 3.5% MnO) and with a higher content of this admixture.

In the Middle Ages the Slavic metallurgists processed almost the bog iron ores with a high phopshorus content, which occurred on the surface of the earth.

The low phosphorus siderites occur very rarely on the territories of Poland; haematite is encountered only in the Holy-Cross Mountains, but no data are available as regards processing of the latter type of iron ores in the Middle Ages.

Therefore the early mediaeval slags encountered on the territories of Poland almost always contain above 0.75% P_2O_5 (App. A. Fig. 1).

Table 1 gives some examples of the analyses of the slag from several early mediaeval metallurgical centres on the territories of Poland.

The research carried out so far are still not sufficient to enable a determination of the type of furnaces used by the Slavic metallurgists for smelting of iron. Presumedly, the process was carried out in bloomeries in the huts like those encountered in Ruthenia (3); this is confirmed by some archaeological findings.

Most probably, in the Early Middle Ages smelting was carried out in the bloomeries. The following hypothesis can be formulated here. A semicircular recess with a diameter reaching about 30 - 40 cm was made in the earth, and it was filled with ash. Then the whole was encircled with a "wall" made of the pieces of a raw iron ore, which formed something like a shaft of the low furnace. To the inside of the shaft the air was supplied by means of a clay-made tuyère. At the beginning, the "shaft" was filled with charcoal and the fire was lighted; next roasted ore was placed there alternately with the charcoal.

After a few hours of operation the "wall" was broken, and the strongly contaminated iron bloom was taken out from the "shaft".

After checking the content of metal, the second smelting was started in a similar way. Then, they put into the furnace those pieces of iron ore which formed the furnace "wall" during the first smelting. When the pile of ore and charcoal was glowing, the blooms were placed on its top, and they were heated for a time so long until the slag melted away. The remainders of slag were removed from the blooms on forging.

The early Polish literature from the 17th cent. states that with a correct control of the smelting process, the smelters were able to achieve the carburization in some parts of the bloom, and the metallurgists were able to identify it. Probably they heated the bloom to a temperature above 900°C, and quickly immersed it in water. Due to this procedure the carburized parts got quenched, and they could be separated with a hammer from the non-carburized part (iron).

If the carburized fragments "grompies" were small, they were welded together to form larger pieces (23).

The investigations carried out by the author have proved that the lower was the content of phosphorus in the ore, the easier and the higher was the carburization of the smelted metal, which is consistent with the theoretical considerations (24). Probably, when the iron ore with a very high content of phosphorus was smelted (f.ex. above 3% P_2O_5), it was very difficult, and perhaps even impossible, to get the metal carburized, i.e. to obtain steel.

It is assumed that in the 14th cent. the low bloomery furnaces, similar to those described by G. Agricola (25), were operating on the territories of Poland (25). The bellows and hammers of those furnaces were already equipped with a water driving system. Smelting of iron was referred to in the subsequent descriptions (27), (28), (29), (30).

Characteristics of the smelted iron and steel

In the Early Middle Ages, on the territories of Poland the slavic metallurgists were consciously using bloomery furnaces for smelting of iron and steel. This is testified by the polygon of distribution of carbon content in the examined objects (App. A. Fig. 2) as well as by the technique of welding iron and steel in the process of manufacturing tools (31).

And yet, the iron and steel obtained in this process contained a relatively high, and sometimes even very high, content of phosphorus (App. B. Fig. 3). In steel the content of phosphorus was slightly lower, which is consistent with the theoretical considerations (24). As many as 83.5% of the examined objects contained above 0.1% P (59.9% of the objects contained above 0.2% P). It is a well-known fact that phosphorus is an unfavourable element in iron and steel, as it results in the cold-shortness of metal. Therefore the metal smelted on the territories of Poland both iron and steel was usually of a rather poor quality.

The Slavic metallurgists classified iron according to the level of phosphorus it contained. For example, to manufacture the knives, they welded three rods: one made of steel, one made of the high-phosphorus iron and another one made of the low-phosphorus iron (the knife No 10 from Tum near Łęczyca).

Apart from this, the high-phosphorus iron (containing 0.4--1.0% P) was used for the manufacture of coulters. Phosphorus increased the hardness and microhardness of ferrite, and probably also the abrasion resistance. The regression equations were calculated for a relationship between the hardness (HV) or microhardness (μHm) of ferrite and the content of phosphorus (P) in bloomery iron.

$$HV - 171.8 = 99.5\ (P - 0.47)$$
$$P - 0.47 = 0.00334\ (HV - 171.8)$$

and

$$\mu Hm - 207.1 = 73.5\ (P - 0.44)$$
$$P - 0.44 = 0.00344\ (\mu Hm - 207.1)$$

Phosphorus caused the growth of ferrite grains. The bloomery iron containing 0.1 - 0.3% P was characterized by the grains from the class 6 to 4 (App. B. Fig. 4a), while the iron with a higher content of phosphorus above 0.4% P revealed a coarse-grained structure with the grains included into the class 3 to 1 (App. B. Fig. 4b).

Phosphorus was characterized by a non-uniform distribution in iron (App. B. Fig. 4c), which caused the formation of a "band structure" (German - Zeilengefüge, French - structure en bandes), well- known to the metallurgists.

The steel smelted by the Slavic metallurgists on the territories of Poland usually contained from 0.3 to 0.8% C and a relatively high content of phosphorus - up to about 0.4% P (App. B. Fig. 4d). Segregations of phosphorus and carbon were also noted to occur. Hence the quality of this type of steel was lower than that of a low-phosphorus steel, and it was not called "steel" but "dul" (23).

In the 14th - 15th cent. the first products of an indirect process of smelting the iron appear in Poland, that is, the objects made of pig iron or of the finery iron.

Most probably the finery steel was used for forging a misericord from Gdańsk (32). It was subjected to a heat treatment, probably quenching and tempering, as indicated by its structure (App. C. Fig. 5a).

Moreover, the sword as well as its guard from Gdańsk was forged in the soft finery iron (App. C. Fig. 5b). The pommel of the sword was cast in pig iron: its structure includes the flake graphite in a pearlitic-ferritic matrix (App. C. Fig. 5c).

As examples, the chemical composition and structural charactetistic of the ferrous alloys used on the territories of Poland in the Early Middle Ages are given in Tables 2 and 3.

The tensile strength and elongation was also determined for a few rods made of the bloomery iron and found at Piekary near Cracow (13th cent. A.D.). Table 4 gives the examined mechanical properties and chemical composition of the rods (33).

Most probably the misericord and the sword were not made on the territories of Poland but in a leading metallurgical centre - perhaps in western Europe - supplying ornaments to the Teutonic Knights. Undoubtedly this was a large-scale production. The quality of metal used for the sword (soft iron) was poor, compared with the bloomery steel possibly welded with iron used formerly. And yet the possibility of a large-scale manufacture of armaments, which was ensured by the indirect process, compensated even the inferior quality of the swords.

Main technologies of processing iron and steel

In the Early Middle Ages, on the territories of Poland the iron and steel objects were made by means of hot forging. The process of heating and forging was carried out properly which is testified by the size of the ferrite and pearlite grains in the manufactured objects.

The tools and some other objects forged in iron were hardened by means of secondary carburization (cementation).

A very regular and deeply penetrating carburization observed in a knife from Gdańsk from the 14th cent. (App. C. Fig. 6) points out to the fact that a highly specialized technique of cementation was applied, most probably using a special carburizing mixture.

In the process of manufacturing the tools, forge welding was quite often applied. The working part of a tool (f. ex. the edge of a knife, of a reaping hook, etc.) was made of steel, and the remaining part - of iron. The combination of iron with steel aimed at an increase in the impact strength of a tool.

The iron and steel rods combined with each other were welded in a forge and forged together on an anvil. In order to remove the iron oxides, the surfaces of the rods joined together were covered with sand. The method was described by V. Biringuccio in 1540 (34). An X-ray microanalysis of the slag inclusions present in the weld of a knife from Piekary (13th cent. A.D.) revealed the content of SiO_2 almost twice as high as in the slag inclusions from the process of smelting the metal.

During the process of making knives and spearheads, the Slavic metallurgists (f.ex. at Tum near Łęczyca, 12th-13th cent.) were using iron inserts with a high content of phosphorus (35). The main reasons were decorative purposes: after etching with a diluted acid the steel had a dark colour, the low-phosphorus iron remained grey, while the high-phosphorus iron assumed a light, silvery colour.

To facilitate a simultaneous carried out at the same temperature welding of steel and both grades of iron, in the process of manufacturing multi-layer knives the surface of welding a high-phosphorus iron rod, which was to be joined with low-phosphorus iron, was subjected to cementation (App. C. Fig. 5d).

To increase the hardness of tools made of steel or iron and cemented the Slavic metallurgists applied a heat treatment, mainly quenching or toughening.

The heat treatment was not used in the case of spearheads and horseshoes, as they would be too brittle after this type of treatment.

The methods of making different iron objects

Knives. The technology of making knives was a most diversified one, and some special techniques were applied in the process of manufacturing these tools. Basing on the examinations carried out, 10 main types of the technologies of manufacturing the knives and other cutting tools, like scissors, scythes, reaging hooks, etc. were proposed. They are shown in App. D. Fig. 7.

The knives welded in iron and steel, Type IVa and Va, occur at the earliest Slavic sites on the territories of Poland (6th - 8th cent.); more often, however, the knives were made of iron or steel.
Among the 53 examined knives from 17 archeological sites from the 6th - 10th cent, the portion falling to the knives welded in iron and steel amounted to 34.0%.

About the 11th - 12th cent. the technique of manufacturing knives became very obviously differentiated; a scarse number of the multi-layer knives appeared (Types VI-IX) along with the pattern-welded knives (Type X) - App. E.Fig. 8 (36). The latter type was encountered in large cities (Cracow, Wrocław, Gdańsk).

In the 11-th - 14th cent. the portion falling to the knives welded in iron and steel increased up to 71.2% apart from this, 12.9% of the knives were forged in iron, 10.6% of the iron knives were subjected to dementation, and 5.3% of the knives were made of steel. These numbers were observed during the examinations of 132 knives from 18 archaeological sites. During that period, however, the development of technique and at the same time a "standardization" of the methods of manufacturing the knives took place.

Since the 12th cent. welding together one iron and one steel rod became a most popular method of making the knives (Type IVa).

Parts of armaments and the horse-riding equipment. Swords are rarely encountered at the mediaeval archaeological sites on the territories of Poland. Therefore only 6 swords were examined. The typical techniques of their manufacture are presented in App. F. Fig. 9.

Spearheads were most often made of iron and steel. A very complicated technique of welding numerous layers of iron and steel (this also including pattern welding) were revealed by the spearheads from the cemeteries at Lutomiersk and Buczek near Łask (37) from the middle of the 11th cent. (App. F. Fig. 10) it is not known, however, whether they were made on the territories of Poland.

Arrow-heads were forged in iron, rarely in steel. Some of the iron arrow-heads (from Tum near Łęczyca, 12th - - 13th cent.) had cemented points. One of the examined arrow-heads was welded in iron and steel.

Stirrups and spurs were made of iron, rarely of steel. Horseshoes and bits were forged in iron; one of the examined horseshoes had a cemented surface.

Cutting tools. The technology of manufacturing such cutting tools as scissors, scythes, reaping hooks as well as axes and chisels was not as diversified as that of making the reaping hooks. The typology proposed for the knives and be accepted here App. D, Fig. 7 . The number of the examined cutting tools of this type is not sufficiently great to enable a statistical determination of the portion falling to particular techniques of their manufacture.

Scissors were made either entirely of steel (Type II), or they were welded in iron and steel (Types IVa, IVd). Scythes were made either of iron (Type I), or by means of welding iron with steel (Type IVa). Reaping hooks were quite often forged in iron without the application of hardening processes (Type I). It is, however, possible to find some reaping hooks made of iron and cemented (Type III) as well as the reaping hooks forged in steel (Type II) or welded in iron and steel (Types IVa, IVb, IVe).

Chisels were quite often welded in iron and steel (Types Va, Vb). Axes were made of steel Type II , or they were welded in iron and steel Types IVa, Vb, VIId .

Almost all the knives and other cutting tools from the 11th - 14 cent. were subjected to a correctly performed heat treatment (quenching or toughening).

Other iron tools. Flints were made of iron, and they had a welded layer of steel; they were also quenched, probably in water. Welding was used by the Slavic smiths in the process of manufacturing awls; awls were also forged in iron sometimes they were also case-hardened or in steel.

Needles were made of iron; fish-hooks were made of steel.

Coulters were made of iron (usually the high-phosphorus one). Iron was also used for keys; sometimes the working surface was cemented. Moreover, iron was used for buckles, rivets, nails and different ferrules.

General evaluation of the early mediaeval technology of iron and steel on the territories of Poland

The technology of iron and steel on the territories of Poland in the 11th - 14th cent. represents a very high level of development, although the smelted metal was usually of a rather poor quality.

During that time a similar technology was used on the territories of Ruthenia nad the Baltic countries (Lithuania, Latvia), although some technological differences were noted to occur. It was not possible to make a more exact comparison due to some limitations imposed onto this paper.

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Table 1

Statistical characteristics of the element composition of the iron slag from some mediaeval metallurgical centres on the territory of Poland

Locality date	Statistical characteristics	Constituents, %								
		$Fe^{x)}$	FeO	Fe_2O_3	SiO_2	CaO	MgO	P_2O_5	MnO	Al_2O_3
1	2	3	4	5	6	7	8	9	10	11
Szeligi by Płock (V-VIII cent.)	X_{min}	35.55	11.80	11.70	3.40	1.75	0.44	0.40	0.05	2.20
	X_{max}	54.00	46.90	64.10	40.20	5.37	1.20	6.21	1.20	14.26
	X_{mean}	44.27	32.99	26.73	25.40	4.03	0.87	3.33	0.64	6.25
	R_X	18.45	35.10	52.40	36.80	3.62	0.76	5.81	1.15	12.16
	S_X	6.85	11.1	10.95	8.45	1.18	0.27	1.81	0.48	4.85
	$S_{\bar{X}}$	2.61	4.20	4.15	3.45	0.45	0.11	0.53	0.22	1.84
Tum near Łęczyca (XII-XIII cent.)	X_{min}	39.33	7.50	2.05	6.86	1.51	0.11	0.17	0.25	0.24
	X_{max}	57.70	61.88	71.00	25.46	8.44	1.55	7.15	3.61	12.11
	X_{mean}	49.62	34.17	32.82	13.12	3.46	0.40	2.58	1.13	4.87
	R_X	18.47	54.38	68.95	18.60	6.93	1.44	6.98	3.36	12.87
	S_X	5.09	18.17	19.65	5.66	1.79	0.37	2.19	0.64	3.83
	$S_{\bar{X}}$	1.20	4.29	4.63	1.34	0.42	0.09	0.53	1.16	0.90

Table 1 cntd.

1	2 xx)	3	4	5	6	7	8	9	10	11
Gdańsk XII-XIV cent.	X_{min}	46.01			12.82	0.59	0.09	0.69	0.10	1.24
	X_{max}	79.72			50.52	4.56	0.74	2.11	2.09	1.86
	X_{mean}	60.53			24.94	1.64	0.22	1.24	0.46	3.18
	R_X	33.71			37.70	3.97	0.65	1.42	1.99	3.62
	S_X	12.6			12.3	1.17	0.16	0.45	0.51	1.04
	$S_{\bar{X}}$	3.37			3.29	0.31	0.04	0.12	0.14	0.28

x) calculated on the basis of FeO and Fe_2O_3 content

xx) total Fe content analysed

Table 2

The results of chemical analyses of some mediaeval iron implements found in Poland (the examples)

Implement locality	Weight of implement g	Part of implement	Content, %			Qualitative analysis x)					
			P	Si	Mn	Bi	Cr	Pb	Sn	Ti	V
1	2	3	4	5	6	7	8	9	10	11	12
Knife No 10	17,8	edge	0.17			?		x	x	x	
		intermediate insert	0.31			?		x	x	x	
		back	0.24	0.17	0.00	?		x	x	x	
Arrowhead No 1 Tum (XII-XIII cent.)	14.8	leaf	0.63				?	x		x	
Knife No 5 Piekary (XIII cent.)	21.8	edge	0.14				?	x	x		
		back	0.30	0.00	0.00		?	x	x		
Knife No 11 Gdańsk (XIII cent.)	38.4	edge	0.07	0.00	0.00					x	
		pattern-welded insert	0.33	0.06	0.00						
		back	0.15	0.00	0.01						

Table 2 cntd.

1	2	3	4	5	6	7	8	9	10	11	12
Misericord Gdańsk (XIII cent.)		blade	0.08	0.06	1.83						x?
Sword Gdańsk (XIV-XV cent.)	1642	blade	0.13	tr.	0.52		x			x	x
		guard	0.10	0.36	0.71		x			x	x
		pommel	1.13	2.09	0.45 xx)		x			x	x

x) Also Fe, Si, Mn, P, S and Al, As, Ba, Ca, Cu, Mg Ni and Zn (?) which are always present in bloomery iron

xx) 3.15% C, 0.136% S

Table 3

The results of metallographic examinations, microhardness and hardness measurements of some mediaeval iron implements found in Poland (the examples)

Implement locality	Part of implement	Structure constituents	Grain size	Micro-hardness kg/mm^2	Vickers hardness HV
1	2	3	4	5	6
Knife No 10 (Tum)	edge	sorbite		396	270
	intermediate insert	ferrite	3	218	181
	back	ferrite	5	223	168
Arrowhead (Tum)	leaf	ferrite ferrite	8 3	225 265	197
Knife No 5 (Piekary)	edge	martensite troostite		617 480	474
	back	pearlite ferrite	3 1	317 241	163
Knife No 11 (Gdańsk)	edge	martensite		753	643
	iron insert 1	ferrite	6	271	
	steel insert 1	troostite		514	
	iron insert 5	ferrite	5	274	
	steel insert 5	sorbite	8	353	
	back	ferrite	4	162	184.4

Table 3 cntd

1	2	3	4	5	6
Misericord Gdańsk	blade	troostite		374	463
Sword Gdańsk	blade	ferrite ferrite	7 3	175 152	113,4
	guard	ferrite	7	194	140,5
	pommel	graphite pearlite ferrite	5 8	347 162	161.5

Table 4

Mechanical properties of bloomery iron bars from Piekary (XIII cent. A.D.)

	Phosporus content %	Grain size of ferrite	Micro-hardness of ferrite kg/mm^2	Vickers hardness HV	Results of tensile tests			
					Cross section mm	Rupture stress kg/mm^2	Allongation % on 10 mm	Allongation % on 20 mm
Fragment No 1	0.48	1	232	190	7.4x2.4	31.6	5	2.5
Fragment No 4	0.04	8 x)	147	141	3.0x1.8	51.9	15	6.5
Fragment No 6	0.40	3	223	148	6.1x2.2 4.5x2.2 4.4x2.2 3.3x2.2	57.8 62.5 66.0 63.0	25	15
Fragment No 8	0.24	5	237	145	6.7x2.2 5.4x1.8	39.4 42.2	20 15	10.5 5
Fragment No 9	0.30	7	196	125	6.2x2.4 5.0x1.8	40.2 51.1	16	10

x) traces of pearlite

APPENDIX A

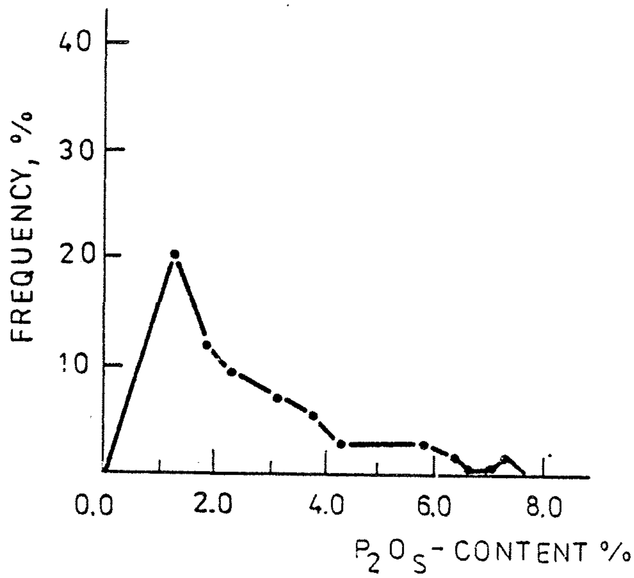


Fig. 1. Polygon of distribution of P_2O_5 content in bloomery slags from the early mediaeval period encountered on the territories of Poland (72 analyses)

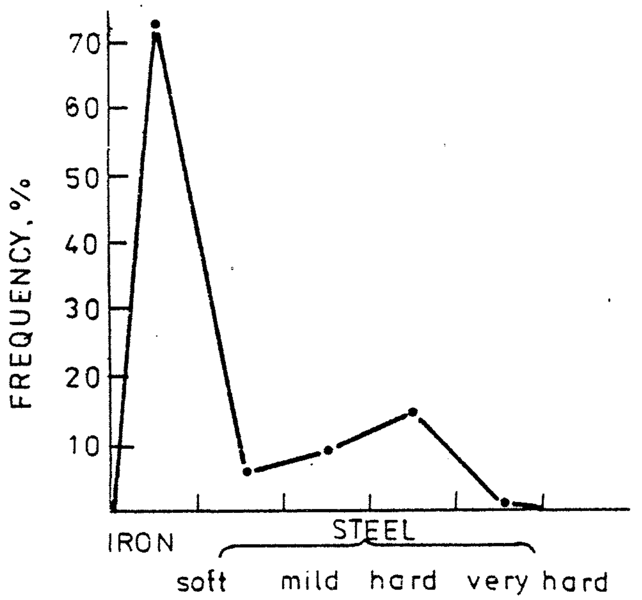


Fig. 2. Polygon of distribution of carbon content in the early mediaeval iron objects encountered on the territories of Poland (541 analyses)

APPENDIX B

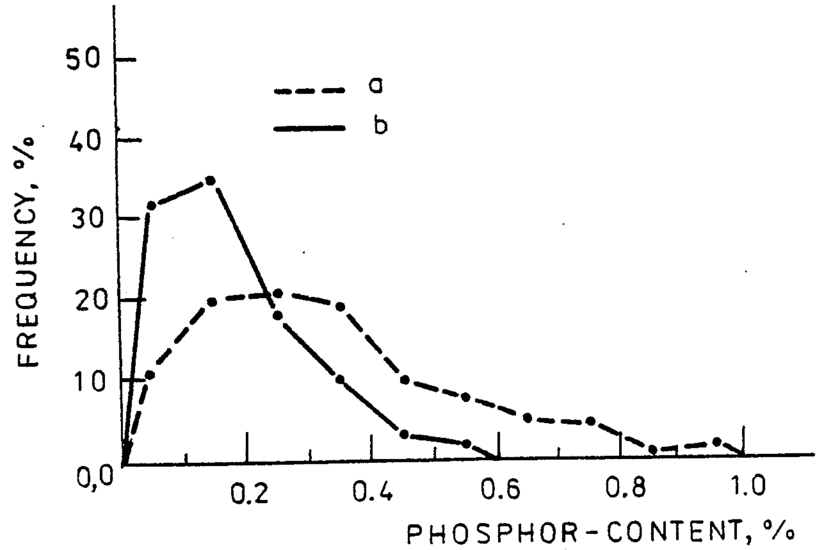


Fig. 3. Polygon of distribution of phosphorus content in a) iron (339 analyses), b) steel (120 analyses)

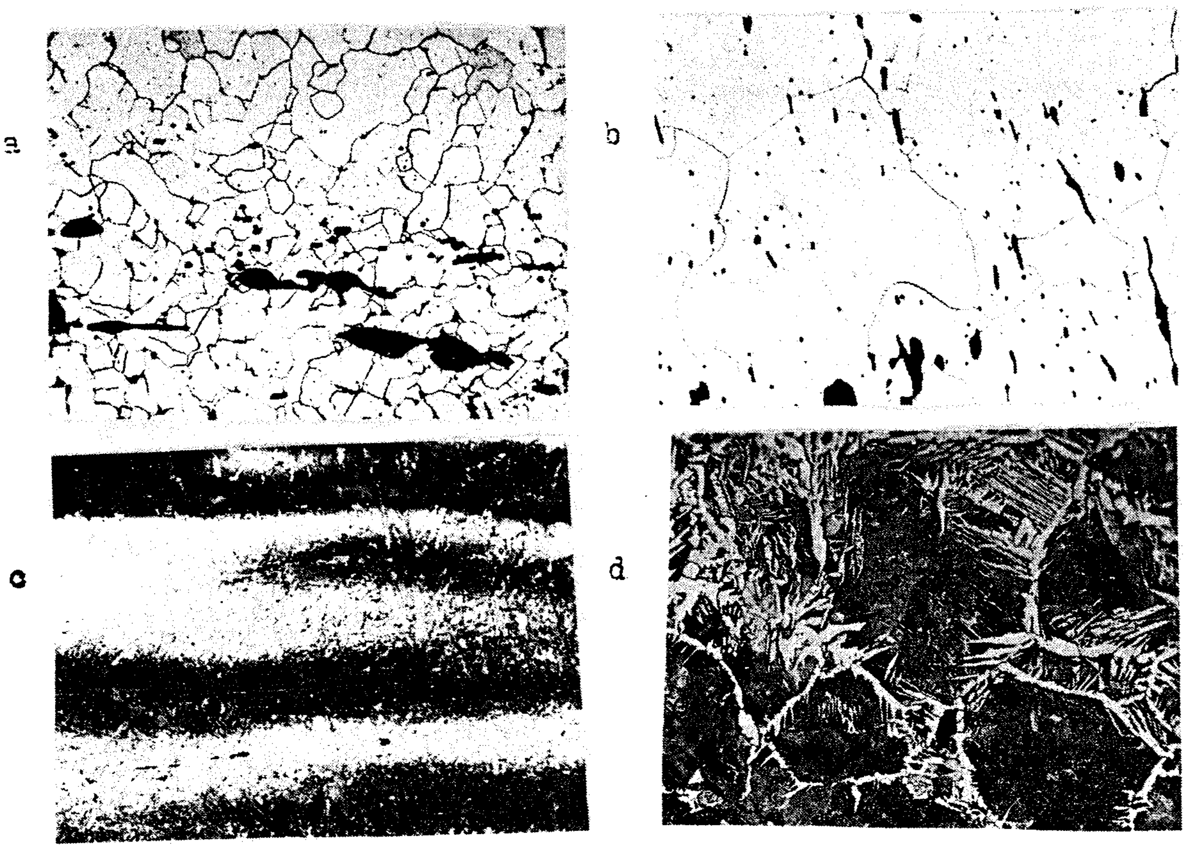
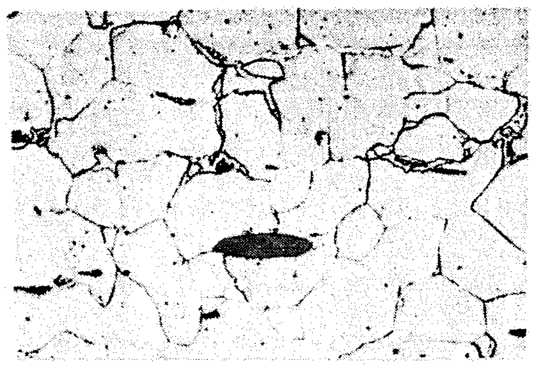


Fig. 4. A typical structure of the: a - bloomery iron, b - high-phosphorus bloomery iron, c - phosphorus segregations in bloomery iron, d - bloomery steel 100x (a,b,d - Nital etching, c - etching with Oberhoffer's reagent)

APPENDIX C

a

b



c

d

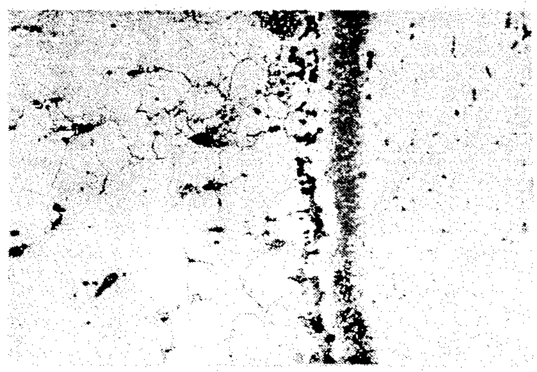


Fig. 5. A typical structure of: a - finery steel (heat treated), b - finery iron, c - pig iron, d - cementation in high-phosphorus iron in the manufacturing of multi-layer knife. 100x (a,b,c,d - Nital etching)

Fig. 6. Macrostructure on the cross-section of a cemented knife. Nital etching, 100x

APPENDIX D

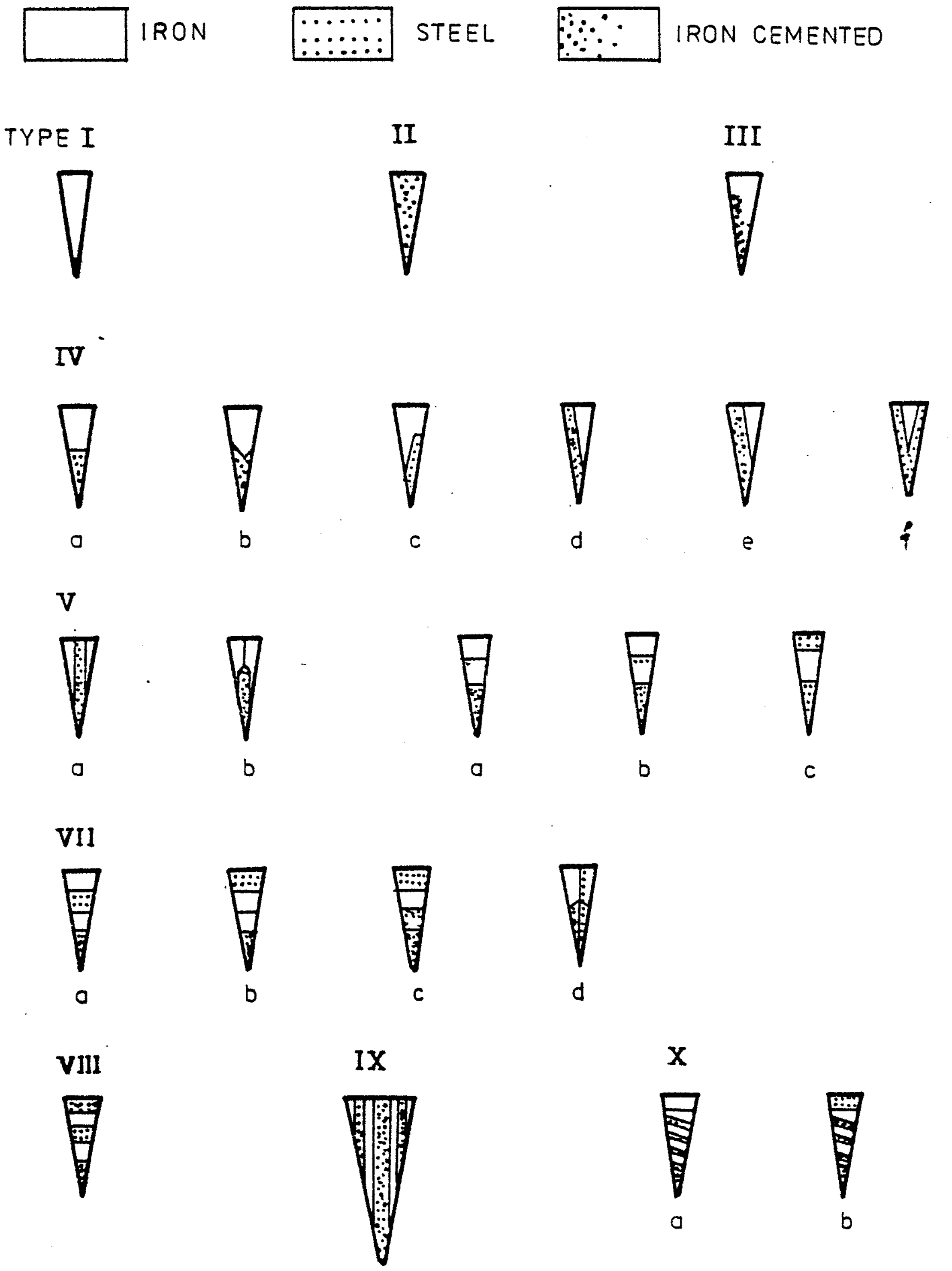


Fig. 7. Main techniques of making early mediaeval knives on the territories of Poland

APPENDIX E

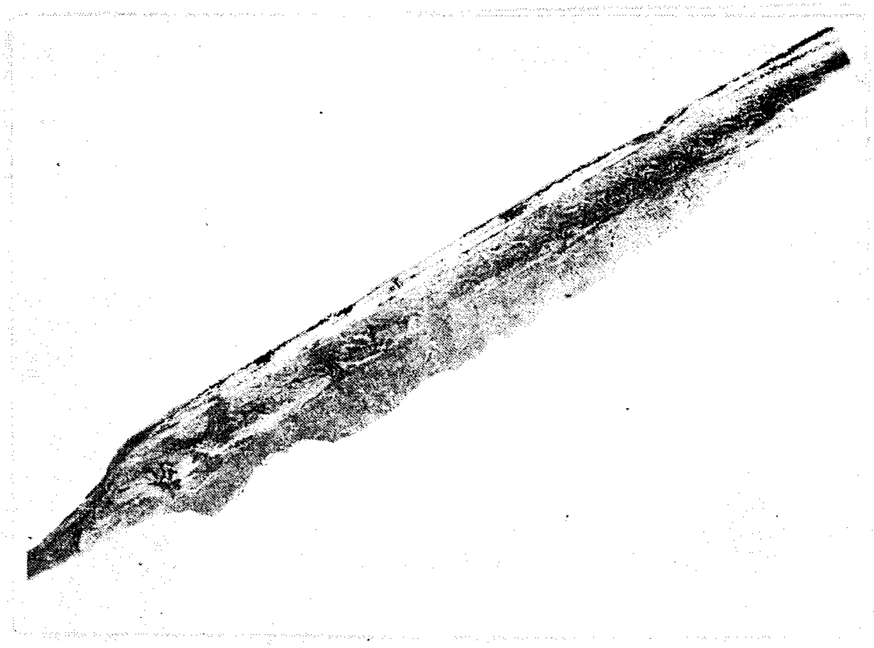


Fig. 8. Pattern-welded knife No 11 from Gdańsk (12th - 14th cent.)

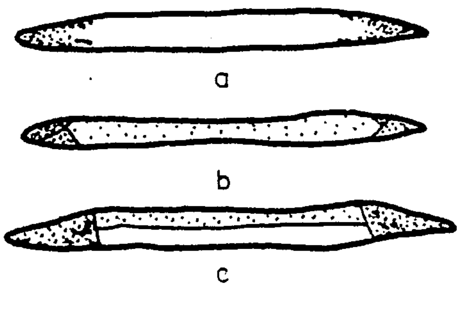


Fig. 9. Some techniques of making the early mediaeval sword encountered on the territories of Poland

APPENDIX F

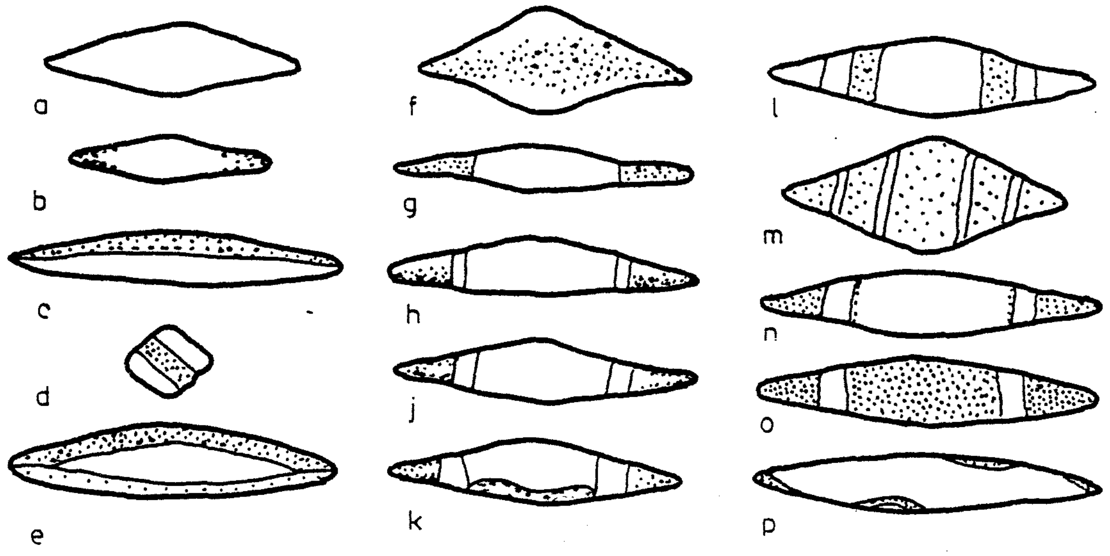


Fig. 10. Some techniques of making the early mediaeval spearheads encountered on the territories of Poland

THE BLAST-FURNACE IN IRELAND: A FAILED INDUSTRY

B.G. SCOTT

Ulster Museum, Belfast, N. Ireland

There is verie riche and great plentie of iron stone....and wood sufficient to mayntayne divers Iron workes (with good husbandrie) for ever.

Richard Payne *Description of Irelande* 1589

I think that God hath ordained my ironworks to be an endless trouble to me

Richard Boyle, first Earl of Cork

Oh the ironworks, the ironworks in Kerry, invented in hell (which they resemble) have nipped me cruelly, and the misery is I must go on.

Sir William Petty 1672

SUMMARY

The 17th century in Ireland opened in continution of the warfare between Tudor England and the Irish, saw bloody uprising in 1641 and bloody repression between 1649 and 1653 under Cromwell. The country was visited by plague in 1650 and famine in 1652, and the century was drawing to a close when William III and James II used the country as a battleground in the war of 1689 to 1691. Nearly one third of the native population perished between 1641 and 1653, while the Tudor policy of settling 'loyal' immigrants on lands from which the Irish had been dispossessed was continued throughout the century. But these disturbances were compressed into a comparatively few years, and during the rest of the century, there was an expansion in land use and an increase in agricultural output, an upturn in trade and a widening of trading contacts. This in no small measure was due to a number of English entrepreneurs exploiting the opportunities presented to them in the form of lands expropriated from the native population. Some were attracted by the prospect of the profits to be made by founding an industry new to Ireland, and based on blast-furnace smelting of iron.

(1) *Resources*

During the earlier part of the 16th century, English production of cast iron from blast-furnaces burning charcoal rose dramatically. By the middle of the century, English cast iron ordnance had gained a high reputation (e.g. Lewis 1961).

In fact, the consumption of charcoal by the expanding industry was causing more than a little concern, as may be seen from the acts passed under Henry VIII in 1541 and 1544 to restrict the felling of timber, and by the complaints of the Commission under Sir Thomas Carden that the price of wood in Sussex had risen from 4 pence to 12 pence in the space of fifteen years (Straker 1931, 114*ff*). For the rest of the century, the price of charcoal was progressively inflated by the consumption of wood by blast furnaces, and as a consequence, the price of the iron rose accordingly. The primary objective of those who invested capital in Tudor England was to make money (an objective sometimes not evident in modern state subsidised industries). And in a time when profits were diminishing, what better source of new revenue than from the development of new, well-wooded lands in Ireland.

In 1589, Thomas Payne extolled the potential for development here. In 1631, Thomas Wentworth, Earl of Strafford, later Lord Deputy of Ireland, received the results of a survey which suggested that Ireland was so well wooded as to provide charcoal for several centuries to come. Ireland had already become a major producer of wood for barrel-staves, and the total cost of cutting, coaling and delivery to the works (including labour) was stated to be about one tenth of comparable costs in England (Ireland £1 0s 10d compared with England £10 1s 8d per ton of bar iron: Schubert 1957, 188 and references). A remarkable feature of what we shall see to have been a gross overestimation, was that it was made some forty years after the first charcoal-burning ironworks was erected, and more than twenty years after the start of large-scale production by Richard Boyle, first Earl of Cork. At the turn of the century, it is likely that more than 12% of Ireland was woodland and forest (Mitchell 1976, 192*ff*), and although by 1631 Boyle had manufactured thousands of tons of iron in his works, the full effects of his and others' production was not yet fully evident, at least to some. By 1652, however, the traveller and natural historian Gerard Boate wrote (*Boate* 67 - 68)

> Through the aforesaid causes [*use of timber for barrel staves and in ironworking*] Ireland hath been made so bare of woods in many parts, that the inhabitants do not only want wood for firing....but even timber for building....Yet notwithstanding the great destruction of the woods in Ireland, there are still sundry great woods remaining....

We shall return to Boate on several occasions since, despite a comparative wealth of documentary record about the general doings of those associated with the iron trade, he is one of the few writers actually to describe an iron works in action in Ireland.

Ireland is not ungenerously endowed with deposits of iron ore, albeit of quality varying from poor (*ca* 35% iron) to excellent (*ca* 75% iron). Boate (*Boate* 70 - 71) described three main forms of iron ore found in Ireland thus:

> Of the iron mines there are three sorts in Ireland .... the first sort is called bog-mine....found in low and boggie places, out of the which it is raised with very little charge .... This oar is very rich of metal and that very good and tough, nevertheless in the melting it must be mingled with some of the oar of some of the other sorts: for else it is too harsh, and keeping the furnace too hot, it melteth too suddenly and stoppeth the mouth of the furnace.... [*bog iron ore*]
> The second sort is rock-mine....This mine or oar is not altogether so rich as the bog-mine, and yieldeth very brittle iron, hardly fit for anything else but to make plow-shares from it....and therefore it is seldom melted alone, but mixed with the first or the third sort.... there hath but two mines.... [*clay ironstone*]
> The third with several names, white mine, pin mine and shell mine is digged out of the mountains in several parts of the kingdom....The stuff is digged out of the ground in lumps of the bigness of a man's head....The iron coming from this oar is not brittle, as that of the rock-mine, but tough and in many places as good as Spanish iron [*siderite*]

There is some degree of confusion over the attractiveness of the Irish ores to English ironworkers. The quality and yield of some ores was described as being the equal of any others in Europe (e.g. Kane 1845, 125f). But poor quality was one of the reasons why the attempts by Sir William Petty to set up production to rival that of Richard Boyle proved an expensive failure (Barnard 1982, 15). In fact, Boyle's original intention in 1607 was to establish his blast-furnaces to burn Irish charcoal but to smelt imported English ores, such was the perceived profit. It was difficulty in obtaining a steady supply of English ores that forced him instead to exploit native resources, a path followed by the owners of many other ironworks. Boyle and the others did sell their product. Indeed, the petition to Charles I by Henry Wright and Richard Blacknell of 1626 (*Cal. SPI* Addenda 1625 - 1660, 74 - 75) refers to the suitability of ore from a mine in Co. Cork for casting ordnance. This mine, possibly opened in 1624, had a shaft claimed to be 60 feet deep, like the earlier-opened Balliregan mine which was drained by a rag-pump (Schubert 1957, Appendix XI, 407). Such investment may, in part, have been due to difficulties in importing English ores, but also indicates that the return of marketable iron which could indeed be smelted from Irish ores made it worthwhile.

Schubert (1957, 188) suggested that in addition to cheap fuel, a major attraction for English ironmasters was the abundance of equally cheap labour. Since there was no basis of expertise here in the new production technology, it was obviously necessary to import specialists from England and the Continent. In one instance, Walloons from Liège were engaged for ironworks in Co. Clare (Schubert 1957, 190). But as a rule, Irish basic labour was infrequently used, the preference being for immigrant Englishmen. Thus, for example, the Wright and Blacknell proposal of 1626 stipulated that the work would employ some 800 Englishmen 'in the various departments of the business....and to have arms to serve the King where necessary.'. In fairness, it may be noted that the natives frequently showed themselves less than friendly, but such was the attitude towards them that Sir Charles Coote, whose works were reputed to have employed upwards of 2500 persons, supposedly employed only English and Dutch workers to prevent the Irish from learning the secret of casting ordnance (Meehan 1906, 128). Furthermore, when in 1654, Coote's son was forced, of necessity, to employ local labour at his works at Mountrath, Co. Laoise (McCracken 1957, 131), it was only permitted by the authorities on the conditions first that they would be replaced as soon as possible, and second that all lived within musket-shot of the works (McCracken 1957, 131)!

* * * * * * * * * *

(2) *A Description of Blast-Furnace Operation*

Set beside the archaeological evidence for blast-furnace ironworking, written records, not to mention the sparse evidence for earlier bloomery smelting, speak volumes. Although some 154 furnaces in all are known from records, not one has been either surveyed or excavated: indeed the whole subject is virtually ignored in the two industrial 'archaeologies' of Northern Ireland (Green 1963: McCutcheon 1980). While the locations of many are known from their recording on Ordnance Survey maps, few traces are readily recognisable on the ground. For these reasons, I make no apology for returning once again to Boate, since he offers us a description of the layout and working of an ironworks in 1652, since it is as complete and detailed as many of those of his English and Continental contemporaries, and provides the best evidence for the construction and working of a blast furnace ironworks in Ireland. He wrote (*Boate* 72 - 77):

> The fashion of the iron-works....is such as followeth. At the end of a great barn standeth a huge furnace, being of the height of a pike and a half or more [*probably about 4 - 5 m*], and four-square in figure, but after the manner of a malt-kiln, that is narrow below, and by degrees growing wider towards the top [*sic*]....This mouth is not covered, but open all over, so that the flame when the furnace is kindled, rising through the same....may be seen a great way off in the night....
>
> These ovens are kindled not with wood or with sea-coal, but merely with charcoal , whereof they consume a huge quantity: for the furnace being once kindled, is never suffered to go out, but is continually kept a burning from the one end of the year to the other....it is continually blown day and night without ceasing by two vast pair of

timber, and with their pipes placed into one of the sides of the furnace, are perpetually kept in motion by the means of a great wheel which being driven about by a little brook or water course....

The manner of melting the iron, usual in Ireland is thus. The furnace is not filled to the top....and to put new stuff into it they do not stay until the former be quite consumed, but only until it be somewhat descended, and then they cast in some charges or basketfuls of coals, and at the top of them, the same quantity of mine....in most furnaces they add some quantity of iron cinders, and in others of limestone, wherebye the melting of the iron is greatly furthered, and the furnace made to work more mildly.

....at the bottom of the furnace stand constantly two men, one on each side, the which with long iron hooks....draw out the unburnt coals, ashes and cinders....

And here is to be observed that even in furnaces of the same bigness, yea in the self same furnaces, the same quantity of iron is not always cast in the sme space of time, but that varieth both according to the nature of the oar and the seasons of the year....and in the summer time, when the coals come in dry and fresh than in the winter.

The iron itself descendeth to the lowest part of the furnace, called the hearth; the which being filled .... they unstop the hearth and open up the mouth thereof (or the timpas as the arts-men call it) taking away a little door like unto that of a baker's oven....The floor of the barn hath a mold of sand upon it, wherein, before the furnace is opened, they make a furrow .... from the bottom of the furnace to the barn's door: into which furrow....the molten iron runneth very suddenly and forcibly....turning into a hard and stiff mass, which masses are called sowes by the workmen.

The sowes are with teams of oxen drawn to the hammer works where, being put into the fire again, they melt them into the finery, the finer turning the melted stuff to and fro, till it come to a solid body, then he carrieth it under the hammer, where it is hammered out into such flat narrow and thin bars....the hammers being huge big ones....kept at work by means of certain wheels, turned about by water courses....

By means of this....sow-iron becometh to be useful ....being therefore called merchant iron; one tun whereof is usually to be had out of a tun and a half of sow iron....

Apart from the slightly idiosyncratic wording of the description of the tapering of the furnace (which may have been intended to refer only to the hearth and boshes), Boate's description tallies exactly with what is known of comparable English works (*cf* Schubert 1957, 236*f*: Tylecote 1976, 81*ff*). The description also calls to mind Henri Blès's depictions of ironworks (Schubert 1957, frontspiece and p. 198), and Valkenborch's work 'Clearing the Hearth' (Schubert 1957, 182). His comments on the length of campaign are of interest, since by the 1650's, the market for Irish iron was in decline, although at this point, there may have been sustained demand to meet the needs of the English army while warring on the Irish. He also notes the use of limestone as a flux, also of old slags which Boyle, at least, imported from the Forest of Dean. Again, the use of water to drive hammers and bellows is worthy of note in the context of the process of the industrialisation of Ireland, and has been underplayed in describing the development of the use of water power in Ireland (e.g. Gribbon 1969). In short, Boate presents us with a picture of iron production that could as easily have been lifted from his homeland. Since the whole nature of the industry was English in concept, labour and management, one might be surprised to find otherwise.

From other records, we learn that in addition to smelting and refining iron, many of the ironworks also carried on the manufacture of a variety of goods, including the casting of ordnance and shot, and nail making. In 1613, the East India Company installed a slitting mill at Dondaniel in Co. Cork, and two others were later built in 1626 by Bracknell and Wright at Boyle's nail works at Tallowbridge, (*Cal. SPI* Addenda 1625-1660, 74), and in 1633 by Boyle at Lisfinny, both in Co. Waterford. There seem to be no references to wire-drawing.

Detailed information on output is scant. From figures given in Boyle's diary for 1622 (Grosart 1886), between March and September 1622, the works at Lisfinny, Co. Waterford, and at Kilmacow and Cappoquin in Co. Cork produced respectively 158, 169 and 370 tons, suggesting (at a rough calculation) outputs in the region of between .75 and 1.76 tons per day. In the 1670's, Petty's furnace at Gortamullin was supposedly producing 11 or 12 tons weekly, or around 1.6 tons per day, although due to technical problems campaigns were seldom long. His works at Glanaroughty only managed to produce an average annual output of 120 tons between 1671 and 1675 (Barnard 1982, 18).

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(3) *The rise and decline of iron production: an overview*

One of the acts of the Privy Council of 1591 (*APC* XXI, 213 - 214) was to write to the Bishop of Lismore, Co. Waterford concerning the son of William Carter, deceased. Carter, and a fellow ironmaster, Robert Robin, both from Kent, held a lease of lands and woods for the production of iron. Carter was drowned in passage to Ireland, and the Privy Council enjoined his Lordship to continue on the lease with his son. In 1593, one Thomas Norreys obtained the rights to dig ore and cut wood for iron mills on the estates of Sir Walter Raleigh, who held large tracts of land around the sea-port of Youghal in the province of Munster. By this time, there were probably works on Raleigh's estates at Dromslig, Minehead and Ardmore in Waterford (McCracken 1957, 134), and at Mogelly in Co. Cork owned by Sir Thomas Morris (McCracken 1965, 132). In 1595, Raleigh leased more land and woods to George Goringe and Hubert Pelham for the erection of iron mills (*APC* XXV, 453 - 454). In 1603, Raleigh was imprisoned on a charge of treason, and his estates, which were seized by the Crown, were purchased by the young Richard Boyle. Boyle's estates grew to include areas of Counties Waterford, Cork and Kerry. Others taking advantage of favourable conditions were the East India Company who established works at Dundaniel in Co. Cork in 1612, Sir Charles Coote who went into a short-lived partnership with Boyle in 1629, and Lord Londonderry in Co. Londonderry. Between 1603 and his death in 1643, Boyle's ironworks mirrored the rise and decline of the industry in Ireland, for by that time, opportunities to make major profit had passed.

From McCracken's survey (1957, 1965: *cf* Gribbon 1969, 261*ff*) of charcoal burning ironworks, we may see that during the period under review, some 32 furnace works were established during the period. Of these, at least 11 seem to have been destroyed at the start of the great uprising of 1641. In describing the state of the industry in 1652, Boate described how, during the course of the conflict the ironworks of the English `....whose industry the Irish have been so far from imitating, as since the beginning of this rebellion, they have broke down and demolished almost all of the aforementioned iron works....' (*Boate* 72). Prior to these events, iron, as had been predicted, had proved quite profitable for Boyle and Coote. Boate estimated that Boyle had profited to the sum of £100,000 from his works (a recent study suggests a far lower return: Barnard 1982, 3, note 5): the woes and worries of which he complained did not dissuade him from exploiting iron working as the best way to turn the natural resources available to him into money (*cf* Barnard 1982, 28). While we have no figures for the total of Coote's earnings prior to his death at Irish hands in 1641, average profits were estimated by Boate at around £6 per ton after sale in England. As well as losing its head in the violent events of 1641, however, the Coote family suffered the loss of all of their ironworks.

Ireland was a land in turmoil between 1641 to 1653, and there is no doubt that the destruction wrought on many of the enterprises was a serious blow. We may, however, note that a number of ironworks survived, and indeed some were apparently established during the period. With the restoration of calm, however, it was becoming evident that the destruction of woods in the first forty years of working had begun the process that would lead to the demise of the industry. If Boyle and Coote are seen to have been the principal figures in the first half of the century, Sir William Petty dominates the stage in the second half, with his lengthy and unsuccessful efforts to emulate the first Earl of Cork, and to rival those of his son.

While his estates still were well wooded, his ore supplies were not of a standard to produce iron to compete with the products of the works at Enniscorthy operated by a syndicate. Furthermore, despite being an advocate of the business methods which, in the 19th century, Frederick Taylor advocated as 'Scientific Management', he signally failed to provide the single most important feature of such a scheme, firm standards and control, choosing to run his Irish affairs through a series of agents who proved less than reliable (Barnard 1982, 23f). The low grade of his iron made it uncompetitive both on the shrinking Irish market, and on the stiffly-competitive English market. His Kerry venture at Glanaroughty was initiated around 1666, and finished by 1686. The second half of the 17th century still saw about forty blast-furnace works in action, but the numbers were declining, and in the 18th century, the number throughout Ireland does not seem to have exceeded twenty-five. The last of the charcoal burning furnaces at Drumshanbo was extinguished in 1765 (Meehan 1906, 132).

What then were the reasons for the short-lived success and the decline that followed? Obviously, in the first years, Boyle and his contemporaries gained a head start in establishing themselves at a time when Irish woods were still extensive. Although there had been considerable felling of timber for export of barrel staves, even for charcoal in England and Wales, there was sufficient to allow for twenty or thirty years of intensive activity. Boyle in particular chose his lands well, since Youghal was a good port offering a comparatively short sea-crossing to Britain. Even in these most advantageous times, however, the export market was unsteady. In 1619, he found difficulty selling iron in England, although by 1622 he was able to sell to the Netherlands. He had also apparently cornered much of the market in Ireland, a country which had, in the 16th century, been an importer of iron (Longfield 1929, 167). Others were less fortunate. His partnership with Coote was short (from 1629 to 1630), Boyle buying out at a profit, leaving Coote to bear losses on subsequent operations. Similarly, Wentworth (possibly believing the promise of the surveyors' report) invested in ironworks which lost money (Clarke 1976, 261). Thus, despite superficial appearances, the scope for making profits from the manufacture of iron in Ireland was nowhere near as great as many believed. By the time Petty arrived to lands which were less accessible both to the English markets he wished to sell to, and to the sources of ore which he sought to import, the practicalities of the situation, coupled with his managerial style seems to have doomed him to failure from the start.

It is worth noting that already in January of 1610, Sir Arthur Chichester had been instructed by the Lords of the Council to 'take measures to preserve the timber in His Majesty's woods in Ireland for the use of the ships of His Majesty's navy' (*Cal. SPI* 1625 - 1632, 505). In 1621, an act first brought in under Elizabeth in 1559 for England stating 'that timber shall not be felled to make coles for the making of iron', and preventing felling of oak, beech or ash within 14 miles of the sea or navigable river (Straker 1931, 122) was extended to include Ireland also. A tract, probably of 1623, entitled *Advertisements for Ireland* advocated the restriction of blast-furnace consumption to 'only the worst and unserviceable wood' (O'Brien 1923, 31). There appears to have been little or no effort to conserve stocks of timber from the outset, and even Petty in 1672 felt justified in trying to find out 'how we may destroy the woods of Kiltankin and Kilcashene to our best advantage, viz. how we may engage the ironworks to take them off' (Barnard 1982, 31, note 140). The 'good husbandrie' advocated by Payne never seems to have been put into practice, a sign that even Boyle, the most successful of the iron producers, was less interested in building a long-lasting industry than with short-term profit taking. At the turn of the century, destruction of woods by whatever means was seen as one good way of robbing the Irish of cover from which to wage war, but its longer-term effect was to rob the English of a valuable raw material.

While local ores could be worked economically, and serviceable metal produced (despite the opinion of English ironworkers that 'Irish iron is nothing near so good as ours': Grosart 1886, II, 162), competition in England provided resistance to Irish iron gaining more than a small share of that market. Thus, in 1633, Wentworth and Boyle were experiencing difficulty in selling there (Kearney 1953, 159). In 1665, Sir George Rawdon who owned works in and around Belfast sent a man to Lancashire to seek 'any market for iron. I can sell none here and have worth near £1000: and for these two or three years I have with great difficulty but got money out of it...' (*Cal. SPI* 1663 - 1665, 602).

An important factor in limiting the development of the industry and in bringing it to a premature end was the fact that the industry effectively had no roots in Ireland. Throughout the seventeenth century, blast-furnace production was entirely a foreign concern. Although the owners of the ironworks bought in the necessary skills to ensure that the technical side was well covered, there was neither native involvement nor commitment. Added to this, the potential markets were too small and too precarious to support the number of foreigners who were competing for it in an essentially hostile environment. Long-term considerations were subordinated to short-term gains. In such a climate, only the most determined could have expected to succeed, and lesser men than Boyle either made much smaller profits, or lost out badly. Boyle managed his industry in Ireland, fussing endlessly over it as his diaries make clear (Grosart 1886), and carried it often by his own energy. His family managed to continue it on until the 1670's. Petty, equally energetic, allowed the force of his ideas to be dissipated by his absence in London. The uprising of 1641 and the subsequent upheavals certainly occasioned considerable destruction, but should not have proved so severe a blow. The restoration of peace after 1653 left English power stronger than ever, and should have allowed greater scope for entrepreneurial success. But by this time, the prodigality of earlier deforestation finally began to take effect. Although fuel prices remained cheap in comparison to England, the lack of suitable fuel close to ironworks meant that transport costs rendered it progressively more expensive at the works.

The final factor was market forces. While the period *ca* 1620 - 1630 saw an upsurge in demand for iron which absorbed much of that produced in Ireland, the years that followed were times when European iron production made inroads into the markets formerly dominated by England. Despite an order of 1623 that in Ireland no ironworks were to be erected or used 'for making iron ordnance, or bullets' (Steele 1910, 26 no. 245). Boyle at least was casting guns, and Blacknell's petition to Charles I of 1626 spoke optimistically of the profits to be made from, amongst other things, ordnance. But by 1634, the Lord Treasurer of England was writing to Wentworth telling him that Irish ordnance was no longer the most economic proposition: in 1635 one producer claimed to have been driven out of the market entirely by Swedish ordnance (Kearney 1953, 159). In 1665, one John Beix, who had an entitlement in Co. Laoise including an ironworks, wrote to Joseph Williamson complaining that he could 'find small encouragement in that trade, here being but small vent for iron, also a great deal of foreign iron brought in from Spain and Swedland which beats down our price...' (*Cal. SPI* 1663 - 1665, 540). Beix decided to get out of the iron trade!

In summary, geography and politics together ensured that the 17th century blast-furnace industry provided only the basis for limited profits and short-lived successes, with the asset-strippers themselves often being stripped also.

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SESSION 3

SOCIO-ECONOMIC CONSEQUENCES

THE BEGINNINGS OF THE MEDIEVAL IRON INDUSTRY IN WESTERN EUROPE: CRAFT SPECIALIZATION AND THE DOMESTIC MODE OF PRODUCTION

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SUMMARY

This paper examines some socio-economic implications of the great body of iron objects from early medieval archaeological contexts. It is contended that the production of iron prestige and utilitarian items is consistent with the observed emergence of state societies in western Europe. However, an important dichotomy appears to exist before the 9th. century between items made for gift giving and those used to enhance agrarian production. This has certain historical implications, and some lasting bearing upon peasant society in the later Middle Ages.

In 773, according to the 9th. century monk of St. Gall, as the Franks beseiged Pavia, the Lombardic king, Desiderius on seeing the arms and armour of his enemies exclaimed "Oh the iron! Alas the iron!". Carolingian use of iron, so we are led to believe, won the day (1). But the significance of iron in early medieval Europe, and in particular, its production has received scant attention. In part this accounts for the quite erroneous impression, cited by more than one eminent historian, that iron tools were rare in the early middle ages, and those that existed were to be found only on the great estates (2). Archaeology emphatically demonstrates that this hypothesis, borne of the historian's impoverished samples of written sources, is utterly wrong. Iron objects abound on all categories of early medieval sites in western Europe. After pottery, iron items are the most common discoveries. As such the history of iron production and distribution offers us a rich source of evidence about all aspects of this period.

To some extent, however, the exploitation of iron and the development of smelting technology constitute a major theme of Lynn White jnr.'s contentious book Medieval technology and social change. White boldly asserted that the invention of the (iron) stirrup and the (iron) plough share proved vital for the Franks, enabling them to shed their primitive tribal condition and to establish a feudal regime (3). White's book, however, received hostile treatment and his argument is difficult to sustain. Yet his approach, following in the footsteps of Marc Bloch, and owing much to the great emphasis once placed upon technological divisions in prehistory, offers a germ of an idea that warrants further appraisal.

The 19th. century realization that technology and social change are closely linked is now easy to appreciate as a historical approach to the past. Marx, after all, was influenced by his context, and accordingly laid great stress upon the command of technology in the path to socio-economic change. Similarly 19th. century prehistorians, dividing up the millennia before Christ, were persuaded by the same historical context. The ages of stone, bronze and iron are a product, after all, of the Industrial Revolution! Only after a century of use is the full meaning of this historical typology being assimilated. The transition from a stone age to one using a metal alloy was indeed a great development. Bronze-working was a highly specialized craft which seems to have been controlled by an elite stratum of society, and was manipulated to maintain their status. The transition to iron, however, offered conflicting opportunities. The abundance of iron in temperate Europe on the one hand meant that serviceable iron implements could be made, which enhanced agricultural practise and stimulated population growth in turn (or so goes the simple equation). On the other hand, the general availability of iron weakened the centralized authority which characterized the bronze age (4). The contradictory benefits of iron production have yet to be fully examined; a century of progress has encouraged us to focus only upon agricultural expansion, and to misunderstand the social contradictions. The paradox needs to be kept in mind when we examine the early middle ages following the demise of the classical world.

To examine the place of iron manufacture in post-classical Europe we must put ourselves in the picture. The written sources, as I noted above, give a false impression of iron production and the use of iron tools in the early medieval world. But then the written sources are mainly no more than unassessable impressions of their times. Archaeology, by constrast, potentially offers a measured index of 'how it was'. The material record is composed of settlement systems, production-distribution systems and cognitive systems which have anthropological and historical meaning if we implement appropriate methodologies to interpret it. As I have contended elsewhere (5), this record puts the Dark Ages into perspective; it reveals the framework of society that in turn gives us a context for the hitherto unassessable historical (written) events and peoples of this period.

The archaeological evidence confirms the collapse of the Roman Empire as clearly as it charts its rise. The classical world with its complex market-based relations came to an end in the later 5th. or early 6th. centuries in Gaul; in the later 6th century in most of the west Mediterranean, and in the first quarter of the 7th. century in the east Mediterranean. In the fluid decline of western classical civilization we must envisage small Germanic groups sucked into the vacuum, rather than the raiders and migrants that hitherto have characterized this chapter of European history. Remember too the displaced peasants and the immense social change transacted in this short time. Clearly, western Europe in the 7th. century was in many respects a Neolithic society which retained a few technological aspects of antiquity.

Archaeology reveals a small-scale kin-based society where the domestic mode of production was pre-eminent, and where there exists merely signs of an evolving hierarchy. 8th. and 9th. century Europe is a remarkable period in which the strident lineages in some territories sought to obtain prestige goods to enhance their political statuses. The gift-giving of prestige goods gave rise to the controlled commerce at emporia such as Dorestad, Hamwih, Saxon Southampton and Hedeby. This gift-giving, however, proved a mechanism for the exchange of regional commodities, it would appear. To what extent under Carolingian imperialism, and under Carolingian influence there occurred increased production of commodities for surplus marketing is a matter of some debate. It is certain, nevertheless, that the steps towards a tribute-based society maintained by state rather than chiefly mechanisms were first established during the early 9th. century. The consequences of this have proved far-reaching. A tribute-based society proper appeared in the 10th. and 11th. centuries, with the foundation of regional markets and the appropriate craft production of commodities to sustain state administered market exchange. From this date the European landscape with which we are familiar took shape, and the path towards capitalism was in hand (6).

In short, archaeology measures the scale of socio-economic activity, and if we employ the appropriate methodology we can operationalize these data to establish behavioural patterns that recalibrate the nationalistically conditioned history of these times.

In the light of this sweeping socio-economic trajectory we might expect iron production to be reduced almost to the domestic mode of production in the 6th. and 7th. centuries. Accordingly, we might expect labour costs to be unimportant, and if the ore could be readily obtained, we might predict a few labour-intensive items, and a narrow range of utilitarian products. The technology itself we might expect to be the simplest of those practised in the classical world. We might predict, however, that the unit costs of specialized, labour-intensive items would change as the circulation of prestige iron gifts increased in volume. In particular, we should expect significant changes to the industry within the courts of the aristocratic lineages of the Carolingian era. But the greatest changes must be anticipated when the fabric of European society switched to tribute-based relations. At this point increased production of all categories of iron items; increased variety of products; a related drop in the unit costs of labour and materials, and, of course, the emergence of permanent smiths operating from workshops in the new markets would be expected. In a nutshell we would expect the transition from an industry focused upon the domestic mode of production to one where craft specialization was near-universal. Put in other terms, we are predicting changes in decision-making to be consistent with the socio-economic constraints placed upon units of labour/matter (7). This leads us to ask specific questions of the data to test this model:

1. was there increased production of iron between the 6th. and 11th. centuries?

2. was there an increased variety of products made in this period?

3. are there signs of changes in the unit costs of products?

4. is there evidence of the changing locations of the industry consistent with the model?

1. Contrary to the belief of many historians iron ore (of poor quality) is common in many parts of western Europe. Hence, iron implements occur throughout this post-classical period, and are a hallmark of all categories of sites. Proudfoot showed, for example, that simple iron-smelting took

place on all types of Early Christian Irish settlements (of the 7th.-10th. centuries), though only prestige artifacts appear to have been made at royal and monastic sites (8). Iron nails were used in buildings of the 6th.-7th. centuries, while iron tools, many based on Roman models were available in Migration-period society. Some were placed in pagan graves. It is apparent, however, that the quantity of iron finds increases significantly with the establishment of the urban centres (emporia) for controlling long distance trade. To judge from the excavations at Hamwih, iron was made in more than a dozen households in the emporium. Equally, to judge from my excavations of a great Carolingian-period monastery in Italy, with the vast increase in scale of these places around A.D. 800 great quantities of iron were needed for building purposes - for roofing nails, locks, keys, bolts, hinges. Iron items, however, are absolutely ubiquitous with the emergent market world of the 10th.-11th. centuries. Beyond all doubt this might be christened the iron age.

2. An increasing variety of iron products, and with this variety increasing standardization in the 10th./11th. centuries is well substantiated by the evidence. Iron weapons and a few tools are found on Migration-period sites, but the range is limited. In the age of the emporia, however, the range of weapons increases - a number of new spear-types, for example, were made in the Carolingian-period Europe (9); similarly the range of household and agrarian items increased with the innovation of standardized keys, locks, hinges etc. Moreover, utilitarian items such as these occur on villages like Warendorf (West Germany) or Raunds (England), besides the elite sites of the age.

With the age of markets, however, comes an explosion of diversity. Examine the ironwork from late Saxon towns or the first Scandinavian towns such as Lund or Hedeby (10). Iron items were used as labour/material costs involved in carpentry, bronze-smithing or silver-working escalated. Accordingly, most households have locks and keys, most men wore iron buckles (based on earlier fine metal models) and iron-clamped coffins are a feature of the age. Similarly, iron horse-gear including horse-shoes are regular features of the new age (11). In addition, prestige goods hitherto made of silver or inlaid with silver were now tinned in a cheaper imitation product. Standardization is also clearly observable though no studies of the craft have drawn sufficient attention to this point; only the discoveries of smith's equipment reveal his increasingly uniform tool-kit (12).

3. Evidence of a change in the unit costs of iron implements is readily found for this period. Let me illustrate a few examples. First, the well known pattern-welded swords, those highly distinctive weapons of the Migration and Merovingian periods, were superseded by swords with hardened carbonised edges in the Carolingian period (13). A pattern-welded blade is supposed to have taken about a month to make. About A.D. 800 this labour intensive technique was replaced by one that meant higher quality weapons, produced in a shorter time with less material. The first Carolingian swords were typically marked with the smith's name, such we may assume was the esteem attached to their achievement. This innovation also occurred in knife production (14) and in the making of scramasaxes. The widespread distribution of such items, especially in Scandinavia where the significant ritual destruction of weapons periodically persisted into the Christian age, reveals the success of the manufacturers. Equally, the inception of standardized hone-stones to keep these implements sharpened - and their distribution too - is an additional reflection of the changing craft of the

smith. First, the blue phyllite hones of northern Europe, then about A.D. 1000 the famous Norwegian ragstone hones were quarried, mass-replicated, and widely circulated around the western Baltic and North Sea basins (15).

Another illustration, dating to the same critical age, has been revealed by the royal smithying site at Ramsbury in Wiltshire (16). Excavations in the nineteen-seventies uncovered a succession of late 8th. to early 9th. century smelting hearths. Significantly, however, the first three bowl hearths were superseded after a short interval by a smaller hearth with slag-tapping facilities. About A.D. 800, in other words, on this West Saxon royal estate, some important change was made to the techniques by which specialized iron was produced. The technique, as the excavator comments, points to a rediscovery of a process lost in England since the Roman age. It is no coincidence that it happened in the Carolingian age - as the carbonised steel was replacing pattern-welded weapons - when the ideological fascination for classical antiquity appears to be mirrored in modest, yet directed decisions to implement classical craft technology.

A third illustration has bearing upon the markets of the subsequent era. In this period the quantity of prestige and semi-prestige goods in circulation increased with the demands of a fast-expanding west European community. To meet these requirements pewter or brass was often used instead of silver by Anglo-Saxon smiths; similarly tin-plated spurs are a feature of this period (17), replacing the silver inlaid iron spurs of the earlier period. Gilded iron objects are also known from this time, as are objects with brass inlaid into the iron to give it a prestigious appearance.

However, above all else standardization is a feature of cost-controlling by smiths. The weapons and tools of the late first millennium bear witness to repeated replication for an expanding market. The tool-kits found by chance tend to bear this out. Smiths now could not afford to become engaged in making swords which took a month to finish.

4. The changing location of the industry is the key, of course. In the migration period iron was either made by a few elite smiths attached to the pre-eminent lineages, or by farmers when and if tools were required. Craft specialization, however, became an increasingly prominent feature of the emergence of stratified and state societies. Hence, smiths are well represented in the <u>emporia</u> of the Carolingian age. Smiths are prominent at small <u>emporia</u> like Helgö and Kaupang, under royal protection. They are far commoner still in the great sprawling urban communities at Dorestad and Hamwih (sites ten to twenty times larger than the contemporary Scandinavian <u>emporia</u>). We must establish, however, whether this new group of craftsmen replaced or supplemented smiths attached to the pre-eminent lineages and the great ceremonial centres (i.e. monasteries). In fact, I believe these smiths represent a new breed - an additional tier in the artisan community, generated by some increase in the small-scale commodities' market. It must have been a combination of all these craftsmen who occupied the first planned tenements of the 10th.- 11th. century towns. Nine smiths working iron are recorded for mid-10th. century Winchester (18); excavations in most Anglo-Saxon burhs detect evidence of blacksmithying as well as periodic, domestic iron-working. Remains of smiths are also prominent archaeological discoveries in all other towns of this age around Europe. Like potters, blacksmiths serviced the shift from a kin-based to a tribute-based community.

Conclusion

In some respects, however, the production of iron is very different to potting. Iron ore could, of course, be found in many local contexts, like clays for pots; but good quality iron for fine objects had to be mined.

This was a complex operation with ownership implications. Here certain regions were bound to be at an advantage, colouring their historic development. Iron production in the central Rhineland, as in central Sweden has to be taken into account when reviewing the place of these communities in the trajectory towards statedom. Conversely at Kootwyk in the Netherlands, a village with moderate quality, easily obtained iron ores (19) flourished in Carolingian times; but the discovery of better sources nearer to the Rhenish heartland in the 10th. century led to a marked decline in the community's material standard of living.

The call for iron nails, hinges, locks etc., especially in the emergent market towns, must have had tremendous implications for those communities owning or living by good iron resources. Yet alongside an artisan class of smiths much iron-working of a simple kind was still practised in domestic or, at least, village units. Unlike pottery production which became a specialized regional or sub-regional craft from c. A.D. 1000 all over western Europe, iron-making remained split between the skill of the urban or peripetetic specialist and the casual preparation of implements when and if these were needed in village life. Late medieval villages across Europe bear witness to the persistence of this curious dichotomy.

So what was the role of iron technology in the steps from tribal to state communities? On balance the evidence points to the importance of iron prestige goods as the principal lineages of Europe competed with one another in the 8th. to 10th. centuries. The evidence, however, indicates that the domestic mode of production was so embedded that iron-making was not a rigidly administered elite craft, and therefore there was limited connection between iron weapons for prestige objects/gifts (such as stirrups) and iron tools (such as plough shares) made to intensify production of agrarian commodities. This distinction has far-reaching socio-economic implications as several anthropologists have now noted (20). Only with the social will to effect economic change in the late first millennium did the manufacture of the two categories occur in single workshops. Even then, though, some autonomy of this craft production was retained at domestic levels. As a reflection of the power of the peasantry in early medieval Europe, and as a lesson to the construction of simple equations resting on prehistoric or historic data the archaeology is an important illustration. I should conclude, therefore, where I began: I wonder if that late 9th. century chronicler, fascinated by the escalation of smithying in his age, was colouring his history of an earlier century with his own experiences. The few excavations of Lombardic settlements and cemeteries in Italy leads us to believe that iron was, in fact, readily available. In short, I wonder if in this illustration, archaeology by putting iron production into its context is illuminating why the historian made the remark he did.

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DER EXPORT VON SCHWEDISCHEM EISEN IM SPÄTMITTELALTER UND SEINE BEDEUTUNG FÜR HANDEL UND GEWERBE IN NORD- UND WESTEUROPA

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SUMMARY

This paper is divided into four sections preceded by some introductory remarks.

In the first section, we take a look - figuratively speaking - from the distance of the importing countries at the place of origin of the central Swedish iron exports and its singular structures which combined royal initiatives and those taken by tradesmen and small entrepreneurs.

In the second section, the quantities and different qualities of iron exported from Sweden will be studied; they explain Sweden's competitiveness against the Spanish and South German iron exporters.

The "Osemund" stands out from the other types; in the third section, it will be compared to the South German "Deuchel" and "Graglach". All of them were types of soft iron, by-products of the pig production of direct reduction.

The fourth section suggests that it may have been the "Osemund" export which particularly stimulated the production of sheet metal and wire and, on the basis of that, of needles and rings in North German and West European towns.

Wegen der weiten Verbreitung der oberflächlichen Eisenvorkommen, der Rasen-, Sumpfeisen, Erznischen, war die Eisengewinnung im Mittelalter tendenziell noch ubiquitär, Fernhandel mit Eisen weniger notwendig als jener mit Kupfer, Blei oder Zink. Aber diese oberflächlichen Eisenvorkommen nahmen fortgesetzt ab. Außerdem entstanden mit der fortschreitenden Urbanisation Europas Bedarfszentren, die durch das lokale Eisenvorkommen nicht befriedigt werden konnten. Provoziert dadurch entwickelten sich einige Zentren der Eisenproduktion für den Fernhandel. In Nord- und dem nördlichen Westeuropa wird als Fernhandelsgut im Spätmittelalter am häufigsten das schwedische Eisen genannt. Aufs ganze gesehen dürfte in Europa der Export spanischen Eisens noch bedeutender gewesen sein. Seine Expansion erreichte in den letzten Spitzen Schottland, die Niederlande, ja sogar Lübeck. England und die Niederlande waren Räume der Überschneidung und Konkurrenz zwischen spanischem und schwedischem Eisen (1). Die folgenden Ausführungen sind der vielfältigen Bedeutung des schwedischen Eisens im Export gewidmet. In einem ersten einführenden Teil werfen wir gewissermaßen aus der Ferne der Empfängerländer den Blick auf die mittelschwedische Herkunftsgegend des schwedischen Exporteisens. 2. Sprechen wir von den Mengen und Arten des schwedischen Eisen im Fernhandel. Dabei kommen wir auf das alte - immer ungelöste - Osemund-Problem, dem wir 3. durch einen Blick auf die Eisensorten des mittelalterlichen Europa und ihre Verwendung näherzukommen hoffen. Abschließend 4. ziehen wir daraus einige Folgerungen für das schwedische Eisen und gehen seiner gewerbegeschichtlichen Bedeutung an den Empfängerorten nach.

1. Nach den Arbeiten von John Nihlén aus den 3oer Jahren unseres Jahrhunderts wurde im früheren Mittelalter nicht in Mittelschweden, sondern in Südschweden umfänglich Eisen produziert (2). Allerdings handelt es sich um die Ausbeute von Sumpf- und Seeerzen, die bis zum Hochmittelalter schon weitgehend verschwunden sein dürften. Mit der Verlagerung des Produktionsschwergewichts von Südschweden nach Mittelschweden ist die Umstellung von einer nebenberuflichen Ausbeute oberflächlicher Erzvorkommen auf den großformatigen Bergbaubetrieb verbunden. Ein solcher Bergbaubetrieb war erst möglich, nachdem durch eine gewisse Urbanisierung Mittelschwedens und die Anknüpfung an den Seeexport die entsprechenden Absatzchancen gegeben waren. Eine solche Entwicklung nimmt man nach den bisherigen historischen Forschungen erst für das 13. Jahrhundert an (3). Deswegen bleiben die neuesten archäologischen Entdeckungen in Lapphyttan, die einen großformatigen Betrieb bereits in das 12. Jahrhundert datieren, zunächst noch ein gewisses Rätsel, das weiterer Erklärungen bedarf.

   Die Organisation der Produktion, wie sie uns in den Quellen der Mitte des 14. Jahrhunderts entwickelt entgegentritt, ist gekennzeichnet durch vom König kreierte Bergdistrikte mit einem besonderen Recht, einer Art Bergfreiheit, durch die kleinen Handwerker-Unternehmergruppen, die mehr oder weniger gemeinschaftlich Gruben und Hütten ausbeuten und an Grundbesitzer abgabenpflichtig sind, und durch die dabei in Erscheinung tretende betriebliche Verbindung von Bergbau und Verhüttung (4). Diese Merkmale begegnen auch im übrigen Europa, aber nicht in der gleichen Zusammensetzung. Die Bergfreiheit hat sich in Gebieten der deutschen Ostkolonisation (insbesondere Freiberg in Sachsen) zuerst entwickelt. Auch sonst erinnert die Leute anwerbende Tätigkeit des schwedischen König an die osteuropäischen Fürsten während der Ostkolonisation. Die betriebliche Verknüpfung von Bergbau und Verhüttung begegnet auch am steierischen Erzberg, wo sonst keine Bergfreiheit galt. Die Aufteilung einer Hütte auf mehrere Unternehmer begegnet sonst im Eisenbergbau - im Unterschied zum Buntmetallsektor - selten. Am ehesten ist noch auf das Siegerland hinzuweisen, wo der Landesherr seine Hütte wochenweise an Schmiede verpachtete. Die Stahlschmiedezunft von Schmalkalden betrieb gemeinschaftlich einen Blasofen (5). Aber Korporationszeugnisse fehlen in den mittelschwedischen Bergdistrikten ebenso wie das Vertragsrecht der Unternehmensgesellschaft Süd- und Westeuropas.

   Die eigentümliche Struktur der mittelschwedischen Eisenproduktion erklärt sich zum Teil durch das Interesse des Königs - in das Adel und Kirche hineingezogen werden -, fiskalischen Nutzen aus dem Export von Landesprodukten zu ziehen. Zum anderen ist das fehlende Kapital, die geringe geldwirtschaftliche Entwicklung des Landes während des ganzen Mittelalters kennzeichnend. Die Meistermannen tauschen Eisen gegen

Lebensmittel. Eisenstücke werden als Zahlungsmittel in den verschiedenartigen Kaufverträgen in Dalarne und Västmanland genannt.

Entsprechend dem lange Zeit bedeutenderen Kupfer-Fernhandel war auch für die schwedische Krone und Mittelschweden Kupferproduktion und Kupferexport lange Zeit vorrangig. Die Eisenproduktion wurde von der Kupferproduktion gewissermaßen mit hochgezogen. 1368/1369 verhielten sich in Lübeck die Stockholmer Kupfer- und Eiseneinfuhren wertmäßig wie 3:1, 1492 sogar 4:1 (6).

2. Damit kommen wir zu den Mengen und Arten des Schwedischen Eisenimports in Nord- und Westeuropa. Die verhältnismäßig guten Quellen von den Zöllen Nord- und Westeuropas erlauben es, den Umfang des gesamten mittelschwedischen Eisen-Seeexports zu schätzen, und damit sicherlich einen erheblichen Teil der Produktion überhaupt zu ermitteln. Wir kommen dabei auf wenigstens 4o.ooo Ztr. Schmiedeeisen Jahresproduktion am Ende des Mittelalters. Damit dürfte Mittelschweden - bei dem ein starkes Wachstum im 15. Jahrhundert gerade von den Zollzahlen her anzunehmen ist - das soviel genannte nordspanische Eisen überholt haben. Es bleibt allerdings weit zurück hinter der für die binnenländische Versorgung Mitteleuropas und den Mittelmeerraum wichtigen Produktion der Oberpfalz, der Steiermark und Kärntens. Allein für die Oberpfalz kommt man auf etwa 13o.ooo Ztr., für die österreichischen Alpengebiete auf noch etwas mehr.

Die von der Forschung ausgewerteten Zollisten von Dieppe, Rouen und Southampton ergeben keine Hinweise auf schwedisches Eisen. Für Antwerpen liegen verwertbare Zahlen aus den Jahren 1366-137o vor. In dieser Zeit liegt die Jahresgesamteinfuhr des Brabanter Hafens in Eisen zwischen 1.ooo und 3.ooo Zentnern, der schwedische Anteil liegt zwischen 7o und 13o Zentner. Die Eiseneinfuhr dürfte gerade hier am äußersten Rande der Ausbreitung des schwedischen Eisens damals - im 14. Jahrhundert - im wesentlichen aus Spanien gekommen sein. Aus dem 15. Jahrhundert haben wir zwar keine Zollquelle aus Antwerpen selbst, aber dafür von der Antwerpen vorgelagerten auf der seeländischen Insel Beveland gelegenen Zollstelle Iersekeroord. Dort kamen 1473 21.ooo Ztr. Eisen durch, also etwa 1o x soviel wie 1oo Jahre zuvor. Der Anteil des schwedischen Eisens betrug über 6.ooo Ztr., ist also erheblicher stärker angestiegen.

Für England kommen die Zollquellen der 4 Nordseehäfen, Yarmouth, Kingston, Lynn und Newcastle, in Frage. Die Eisenimportzahlen erstrecken sich über das 14. und 15. Jahrhundert. Sie liegen überall in der gleichen Größenordnung, meistens zwischen 1.ooo und 2.ooo Ztr. pro Jahr. Die schwedischen Anteile daran variieren aber sehr stark; in Yarmouth machen sie etwa die Hälfte aus, in Kingston schwanken sie zwischen 25% und 1oo%. Auch in Lynn werden in einem Jahr 1oo% erreicht, in einem anderen Jahr liegen sie nur wenig darunter. In Newcastle schließlich sind sie erheblich kleiner, bleiben unter 2o%.

Die Zollquellen mit den größten Mengen schwedischen Eisens kommen aus Lübeck. Zahlen, die mit Einschränkungen vergleichbar sind, liegen aus den Jahren 1368-137o, 1398-14oo, 1492-1494 vor. Die erste Zahlengruppe wird bestätigt und ergänzt durch Hamburger Zollisten. Das schwedische Eisen dürfte in Hamburg zum Teil dasselbe gewesen sein, das auch durch Lübeck lief.

Danach muß man in dieser Zeit (1368-137o) mit jährlichen Transporten von 3.ooo-5.ooo Zentnern schwedischen Eisens nach Hamburg und Lübeck rechnen. Nach Hamburg kam gleichzeitig west- und mitteldeutsches Eisen, wahrscheinlich etwa in der gleichen Menge wie schwedisches. In Lübeck dominierte das schwedische. Die Einfuhrzahlen steigen in der nächsten Etappe (1398-14oo) auf 1o.-19.ooo Zentner, also etwa um das dreifache, und in der letzten Etappe (1492-1494) auf 22.ooo-27.ooo, also noch einmal etwa um 5o%-1oo%.

Schließlich sind die Zollisten von Danzig zu erwähnen. Dort konkurrierte das schwedische Eisen mit kleinen Mengen ungarischen und polnischen Eisens. Die zwischen 1474 und 1492 bezeugten Mengen schwedischen Eisens liegen ziemlich gleichbleibend zwischen 3.ooo und 6.ooo Zentnern. Lediglich 1498/1499 fällt eine Zahl von 8.3oo Zentnern auf, die wohl den neuen Aufschwung des schwedischen Eisenexports im 16. Jahrhundert bereits ankündigt, den wir durch die Zollquellen des 16. Jahrhunderts nachdrücklich kennen.

Aus Schweden wurde Eisen verschiedener Sorten exportiert. Dem deutschen Wort Eisen entspricht das schwedische jern, das einerseits generell Eisen bezeichnet, andererseits das gewöhnliche Eisen, dem gegenüber Sondersorten wie Stahl ausgegrenzt werden. Eine Sondersorte war auch Osemund, dessen Bezeichnung aus dem Schwedischen in die deutsche Handelssprache übernommen wurde. Auf dessen Bedeutung kommen wir gleich zurück. Die vorhin genannten Zahlen aus auswärtigen Zollquellen sind im wesentlichen auf die Osemund-Erwähnung gestützt; nur für Lübeck ist daneben Stab- und Stangeneisen aus Schweden bezeugt und in der Statistik verwertet. Im übrigen müssen wir annehmen, daß unter den sonst an den Zollstellen bezeugten Eisenmengen, die keine andere Herkunftsbezeichnung haben, noch andere Sorten schwedischen Eisens verborgen sind. Allerdings ist nicht auszuschließen, daß der Wortgebrauch an einzelnen Orten unscharf war, und daß alle Sorten schwedischen Eisens unter dem Wort Osemund begriffen wurden.

Aus den reichen englischen Quellen über Preise - sowohl von den Zollstellen als auch aus dem englischen Binnenland - wissen wir, daß auf den verschiedenen Preisstufen des Eisens der Osemund im 14. Jahrhundert noch gleichmäßig vertreten ist, aber nach 14oo entschieden die unteren Plätze einnimmt. In den Niederlanden entspricht jedoch auch in der Mitte des 15. Jahrhunderts der Osemund-Preis ungefähr dem Preis spanischen Eisens. In Danzig ist Osemund teurer als polnisches Eisen oder Landeisen. In Hamburg und Lübeck ist im 14. Jahrhundert eine weitgehende Preisgleichheit von Osemund und Stahl festzustellen. Im 15. Jahrhundert liegt dann ähnlich wie in England Osemund deutlich unter spanischem Eisen und anderen Eisensorten.

Eine vergleichende Betrachtung der Preise schwedischen Eisens im Hersteller-Land, in England und in Danzig zeigt, daß mit dem Export erhebliche Gewinne erzielt werden konnten; Gewinne, die offenbar in Danzig noch höher waren als im entfernten England, wo die Konkurrenz des spanischen Eisens groß war und immer größer wurde. Die spanische Konkurrenz griff mit den Spitzen sogar nach Norddeutschland vor. Aber das spanische Eisen war dort wohl doch zu teuer, um dem schwedischen Eisen noch gefährlich werden zu können.

Die internationale Entwicklung der Eisenpreise im Spätmittelalter war depressiv. Die Nachfrage wuchs zwar, aber die Produktion offenbar schneller. Für Schweden war die Situation zusätzlich prekär, weil offenbar in Westeuropa der Druck der Konkurrenz wuchs. Die Preise des schwedischen Eisens sanken im Herstellungsraum fortgesetzt sowohl in internationalem Goldgeld als auch in schwedischer Mark,in Goldfloren zwischen 134o und 148o auf etwa ein Drittel (7).

3. Wir wissen schon, daß der Preisniedergang nicht etwa auf eine nachlassende Bedeutung des schwedischen Eisenexports schließen läßt; im Gegenteil, Preisverzichte ermöglichten offenbar eine Expansion von Produktion und Export.

Weiterhin hat unser Preisüberblick gezeigt, daß die Preisunterschiede zwischen schwedischem Eisen, Osemund und anderem Eisen nicht etwa auf eine bessere oder schlechtere Qualität des Osemund schließen lassen. Regionale und konjunkturelle Bedingungen sind für sie wichtiger.

Osemund war eine Sondersorte des Eisens, die besonders von Schweden aus verbreitet wurde, war hier und dort Bezeichnung für schwedisches Eisen schlechthin und hing als solche vielleicht mit einer besonderen Handelsform schwedischen Eisens zusammen. Es waren normierte kleine jern-Stücke, in Fässern verpackt, die in Innerschweden als Zahlungsmittel dienten. Im Export trifft man den Osemund regelmäßig in Form von kleinen Stücken in Fässern verpackt. Darin unterschied er sich vom Stangeneisen.

Man wird differenzieren müssen zwischen Osemund-Stücken mit gewöhnlicher Eisenqualität und solchen, die ein Sonderprodukt darstellten. Fragen wir nun danach, wodurch sich das Sonderprodukt auszeichnete. Eine weitere Verbreitung fanden die Ausdrücke Osemund und Osemund-Hämmer in der Mitte des 16. Jahrhunderts. Damals waren solche Hämmer in Westfalen spezialisiert auf die Herstellung von Blechen, auch den Grundstoff für Draht (8).

Man ist in der letzten Zeit bei Versuchsschmelzen mehr und mehr darauf aufmerksam geworden, daß im direkten Verfahren keine kompakte Eisenluppe aus Ferrit hergestellt wurde, sondern daß die Ränder der Luppe kohlenstoffhaltiger waren als ihr Kern. Wenn die Luppe ausgehämmert wurde, konnte es geschehen, daß die kohlenstoffhaltigen Ränder gewissermaßen abtropften. In der Luft oxydierten diese Eisentropfen, wodurch ein weiches, gleichmäßiges, gut schmiedbares Eisen entstand (9). In der Oberpfalz wurde dieses Sonderprodukt Deuchel genannt und diente der Blechproduktion. In der Steiermark entstand in den Blaswerken des 15. Jahrhunderts, hohen geschlossenen Reduktionsöfen, neben dem gewöhnlichen Eisen Graglach. Es ist vergleichbar mit den äußeren Bestandteilen der Luppe heutiger Versuchsschmelzen und kommt seiner chemischen Zusammensetzung nach dem heutigen Roheisen nahe. Es ließ sich erst nach einem Frischvorgang, auf den man zunächst nicht eingerichtet war und der wohl nur in einer Geräteschmiede hier oder dort improvisiert stattfand, verschmieden. Von der Geschichte des Osemund und der Osemundschmieden im 16. Jahrhundert her wird man annehmen dürfen, daß Osemund als Sonderprodukt in die Nähe von Deuchel und Graglach zu setzen ist, mit einem vielleicht mehr oder weniger oxydierten Kohlenstoff, entsprechend mehr oder weniger leicht schmiedbar, mehr oder weniger geschätzt, entsprechend auch nach den Fähigkeiten der Empfänger, einen Frischvorgang nachzuholen.

Die Osemundschmieden Danzigs und Westfalens sind vergleichbar mit den ebenfalls im 16. Jahrhundert zuerst bezeugten Welschhämmern und Deutschhämmern des Alpengebietes, von denen es heißt, sie seien auf Deuchel und Graglach spezialisiert gewesen. Die ersteren hätten insbesondere aus Deuchel Weicheisen gemacht.

4. Wir können davon ausgehen, daß im Spätmittelalter mit Osemund an vielen Orten eine Sonderproduktion der schwedischen Eisenerzeugung gemeint war, aus dem Weicheisen hergestellt wurde, das aber in sich unterschiedliche Qualität besaß, mehr oder weniger eines Frischvorganges bedurfte. Wer nahm es auf vor Errichtung der Osemundschmieden? Das Weicheisen war geeignet für die Blech- und Drahtherstellung, für Ringe, Nadeln, Spangen, Harnischplättchen, u. a.

Die Zentren der spätmittelalterlichen deutschen Blech- und Drahtherstellung, das Land um Köln und Nürnberg, wurden allerdings nicht mit schwedischem Eisen versorgt. Man wird die Abnehmer bei den Drahtmachern, Sarwörkern, Plattnern, Nadlern und anderen Blech- und Drahtverarbeitern der englischen, niederländischen und hansischen Städte zu suchen haben. Osemund ist darüber hinaus im deutschen Binnenland in Trier - wohl von den Niederlanden herkommend, in Osnabrück, Hildesheim und Hannover, wohl von Hamburg kommend und im Kloster Preetz, wohl von Lübeck kommend - bezeugt. Neben der generellen Versorgung mit Eisen dürfte die Anregung des Blech- und Drahtgewerbes in den genannten Gegenden die Hauptbedeutung des schwedischen Eisenexports im Spätmittelalter gewesen sein.

An der Spitze steht Lübeck, dank seiner schwedischen Handelsbeziehungen, als Zentrum der Verarbeitung von Weicheisen. Es gab dort die verschiedenen weicheisenverarbeitenden Gewerbe, wie Harnischmacher, Plattner. Am zahlreichsten waren die Nadler, auf die wir besonders den Blick richten wollen. Die Nadler von Lübeck haben 1356 schon ihre geschriebene Zunftordnung. Danach gab es 14 Nadler, die auch ihre Stände auf dem Markt hatten (1o). Der Rat hat der Zunft eine Drahtschmiede gegeben, die Draht - den Grundstoff für Nadeln - schmieden soll, wenn es die Nadler brauchen. Wie bedeutend die Konzentration in Lübeck war, zeigt ein Vergleich mit Nürnberg, dem wohl größten eisenverarbeitenden Zentrum der damaligen Welt. In Nürnberg sind nur 1o Nadler bezeugt (11). Im hansischen Raum war der Abstand Lübecks zu den Nachbarn groß. Im 14. Jahrhundert gab es zwar schon in Rostock und Bremen einzelne Nadler, aber nach unseren Zeugnissen zu urteilen, fehlen sie noch z. B. ganz in Hamburg und Lüneburg. In Hamburg bilden die Nadler 144o eine geistliche Bruderschaft. Aus der gewerblichen Zunft der Schmiede treten sie 1529 mit einer eigenen, geschriebenen Ordnung heraus. Dabei tritt auch eine Aussonderung aus dem übrigen Kleinschmiedewerk (Nägel, Sporen, Schlösser), das eher aus Stahl gemacht wird, ein. Bis zur Aussonderung der Nadler haben in Hamburg die Schmiede Weicheisen und Stahl gemeinsam verarbeitet. In einer Bestimmung der Schmiedeordnung von 1375 heißt es: Niemand in der Zunft soll Osemund oder Stahl entzwei bauen, außer daß er es selber verarbeiten will (12). Dieses Zeugnis läßt vielleicht darauf schließen, daß nicht alle Schmiede gleicherweise geeignet waren, den angelieferten Rohstoff Osemund oder Stahl zu verarbeiten, und daß die Tendenz bestand, die Herstellung eines zubereiteten Zwischenproduktes, insbesondere Draht, in den besser ausgestatteten Schmieden zu konzentrieren. Insbesondere dürften die Plattner hier und in anderen Städten die Bleche von den Schmieden erhalten haben. Die Plattner bilden in Lübeck schon im 14. Jahrhundert eine eigene Zunft, in Hamburg gehören sie einer größeren Sammelzunft, u. a. mit Sattlern und Glasern, an. Einzelne Plattner gab es auch in Rostock, Bremen und Braunschweig (13). Sie treten so selten wie die Nadler als eigene Gruppe hervor. Häufiger ist eine andere Aufgliederung der Schmiede.

Um 14oo untergliederten sich die Lüneburger Schmiede in Schmiede und Messermacher. Um 15oo erst sagen die Schmiede: Unser Amt ist dreiteilig: Grob-, Kleinschmiede und Messermacher. Eine ähnliche Aufgliederung ist in Braunschweig (1342), Riga (1382), Magdeburg (1419) und Reval (1459) zu beobachten. Es bleibt offen, ob hier die Weicheisenverarbeitung, die Blech- und Drahtherstellung bei einem der Zweige des Schmiedegewerbes erfolgte - wie offenbar in Hamburg vor 144o -, oder ob Nadeln und Ringe eingeführt wurden. Der Handel mit Weicheisen-Fertigprodukten nahm während des Spätmittelalters zu und dadurch entstanden für den Absatz von schwedischem Osemund eine neue Konkurrenz und neue Schwierigkeiten. 1469 verhandeln die Lübecker Nadler vor dem Rat gegen die Nürnberger Importeure, erreichen aber kein Verbot des Nürnberger Nadel-Imports, das den Lübecker Handelsinteressen wohl zu sehr geschadet hätte. Allerdings dürfen die Nürnberger Nadeln nur zu Tausenden absetzen. Sie bleiben aus dem Kleinverkauf ausgeschlossen und es sind wohl die Lübecker Nadler selbst, die diesen Kleinverkauf übernehmen, sich dadurch eine neue Erwerbsquelle schaffen.

Abschließend und rückblickend bemerken wir, daß der schwedische Eisenexport im Spätmittelalter in Nord- und Westeuropa große gewerbliche Impulse gegeben hat, gleichzeitig aber gerade an der Wende zur Neuzeit auf eine enge Konkurrenzsituation traf, die durch viel Unternehmungsgeist und Anpassungsfähigkeit überwunden wurde, so daß Schweden in der frühen Neuzeit einer großen industriellen Zukunft entgegengehen konnte.

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Eisenhandel einzelner Jahre in Zentnern

Plätze mit schwedischem Eisen

(Jeweils links schwedisches Eisen, rechts Gesamtmenge, 17 und 18 nur Schwedisches Eisen)

Jahr	Jersekeroord		Antwerpen		Yarmouth		Kingston		Lynn		Newcastle		Hamburg		Lübeck	Danzig
1324/25										760						
1365/66				560												
1366/67			130	2 700												
1367/68			70	1 300												
1368/69			130	2 000											2 900	
1369/70			110	1 000									4 200	12 100	5 400	
1383/84							790	3 200								
1390/91											210	1 500				
1393/94					490	1 000										
1396									1 700	1 700						
1398															12 400	
1399															19 000	
1400															9 900	
1462/63							1 700	1 700								
1466/67									490	660						
1471/72							260	1 200								
1472/73	6 100	21 100														
1474																3 900
1475																5 500
1476																4 100
1490																2 800
1491																5 400
1492															24 200	3 500
1493															27 900	
1494															21 300	
1495															5 000	
1496															680	
1498/99																8 300
1499/1500	(2 000	6 700)														

Preissteigerungen durch den Handel

(Preisunterschiede in derselben Eisensorte zwischen verschiedenen Orten in Zentner und Fiorini.)

Zeit	Ort	Preis	Ort	Preis	Ort	Preis	km Entfernung	Verteuerung pro 100 km	Bemerkungen
Schwedisches Eisen, See- und Landtransporte									
1375	Stockholm	1,19	Hamburg	1,57			1500	0,025	Fahrt durch den Sund.
1375	Stockholm	1,19			Yarmouth	1,78	1700	0,035	Fahrt durch den Sund.
1375			Hamburg	1,57	Yarmouth	1,78	580	0,036	
1375	Stockholm	1,19	Hamburg	1,57			830	0,046	Von Lübeck aus über Land.
1375	Stockholm	1,19			Trier	2,25	1300	0,082	
1375			Hamburg	1,57	Trier	2,25	480	0,14	
1387–1390	Stockholm	0,6	Danzig	1,48			580	0,15	
1387–1390	Stockholm	0,6			Lynn	0,99	1700	0,023	Durch den Sund.
1387–1390			Danzig	1,48	Lynn	0,99	1500	–	Durch den Sund.
1387–1390	Stockholm	0,6	Hamburg	1,2			1500	0,04	Durch den Sund.
1396–1398	Stockholm	0,7	Lübeck	0,59			780	–	
1396–1398	Stockholm	0,7			Lynn	0,74	1700	0,0024	Durch den Sund.
1396–1398			Lübeck	0,59	Lynn	0,74	1300	0,012	Durch den Sund.
1424–1425	Stockholm	0,44	Lübeck	0,66			780	0,028	
1430–1431			Danzig	0,79	Hildesheim	0,72		–	
1430–1431			Danzig	0,79	Southampt.	0,9	1800	0,0061	Durch den Sund.
1436–1440			Danzig	0,98	Cambridge	0,9		–	
			Danzig	0,98	Yarmouth	0,6		–	
			Danzig	0,98	Holland/ England	0,79		–	Preis in fläm. Geld in einem Vertrage zwischen England u. Holland.
1452			Danzig	0,7	Lincoln	0,95	1500	0,017	
1468–1473	Närke (Kumla)	0,34	Lübeck	0,52			950	0,019	
1479–1481	Närke (Kumla)	0,33			Lynn	0,52	1900	0,01	Durch den Sund.

Mittelschwedischer Eisenexport im Spätmittelalter

ROCCA SAN SILVESTRO: AN ARCHAEOLOGICAL PROJECT FOR THE STUDY OF A MINING VILLAGE IN TUSCANY

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SUMMARY

In Italy, despite renewed historical interest in pre-industrial iron and steel industry, archaeologists have given scant attention to the extraction and working of iron in the post-classical age, and even so their interest has been confined to the post-medieval period. Yet, iron metallurgy was of fundamental importance in the Middle Ages, especially in that area of the Tuscan coast that had been mined intensively ever since Etruscan times. In 1984, the Department of Medieval Archaeology of Siena University launched a project for excavating in and around the mining village of Rocca San Silvestro (Campiglia Marittima, Leghorn). The idea, which had been abandoned for over fifty years as far as field work was concerned, is to study the techniques of extracting, processing and working metal within the wider framework of a medieval settlement. So far, only part of the urban structure of the centre of San Silvestro has been investigated in any detail. However, from 1985 on, the intention is to examine the industrial area inside the castle walls (where huge quantities of slag have been found) in order to study the production of iron, copper, lead, zinc and silver.

1. Historical outline

Rocca San Silvestro is on a naturally fortified outcrop (see Fig. 1 and 2) jutting out from Montecalvi, a few kilometres to the north east of Campiglia Marittima in the Populonia hinterland and not far from the Manienti valley that connects it with the coast near San Vincenzo (Fig. 3). The area surrounding the Rocca is one of the most highly developed mining districts in the western Mediterranean, with deposits of copper, iron, tin, lead, silver and antimony. The extraction and working of metal has always been the corner stone of the economy of medieval San Silvestro and, ever since the Iron Age, it was the reason for the area becoming inhabited (Simonin, 1858; Ricerche archeologico-minerarie, 1937). However, Rocca San Silvestro was not the medieval name of the village but was introduced in modern times after the settlement had been deserted, probably making use of the name of the village church. In medieval documents it is called Rocca a Palmento and appears in this guise as early as 1191 in a diploma of Henry VI, who places it in the "*comitato*", or county, of Pisa. A document from Lucca of 906 mentions a place called Palmento, but it would be difficult to identify it as our village and castle since the name can be found, with variations, throughout the area to this very day.

The castle is also mentioned in a few documents dating from the XIIth to the XIVth centuries. In particular, there is a document of 1310 in which "Ranierus dictus Nerius quondam Uberti de Rocca ad Palmentum" sells his rights to the castle to "Raniero di Ranieri comiti de Donoratico" and where the boundries, which coincide with those of San Silvestro, are described as follows: ". . . ex parte meridiani in confinibus et ad confines comunis Campilie, ex parte levantis ad confinem et in confinibus Suvereti, ex partis ponentis versus confines et ad confines Biserni et ex parte tramontane versus confines Preterosse et Montis Ferrantis . . .", and above all among the castle's possessions are mentioned not only "silvis" and "fluminibus" but also "salinis" and "venis, metallis". Thus the document informs us on two essential sources of local economic wealth: the salines, which probably lay along the coast between Baratti and San Vincenzo, and the exploitation of mineral deposits, with the extracted ore probably being worked on the spot, besides an extremely limited form of agriculture based on the local woods and pastureland.

Two later documents, from 1430 and a little after 1434, inform us that Rocca a Palmento, after being used sporadically, was then abandoned once and for all. Although this is all an initial perusal of written sources has revealed so far, local tradition, not yet proven though probably true, says that Rocca San Silvestro was called Castelnuovo before the XIth century and, from the XIth to the end of the XIIth centuries, was mentioned in a series of imperial diplomas under the name of Moncalvo and Monte Calvo castle (for historical details see Francovich *et alia*, 1980, 176-178; Galgani, 1973, 135-140).

2. Objectives

The research is being carried out in various directions: a systematic examination of written sources for the village and the whole surrounding territory, including the Cornia valley; extensive archaeological work on the castle area; a survey of the documents on the region so as to reconstruct when and how it was settled, from prehistory to the present day. Besides, the buildings in the village are so well preserved that a complete survey will allow us to study both the single households and the whole outlay of a rural community, with a unique wealth of detail that is parallelled by very few sites examined so far in the western Mediterranean. Furthermore, the distinctive economy on which the life of this village was based, that is the exploitation of mineral deposits, makes our research particularly significant and original for this area of the Mediterranean, and allows us to deal with a subject that has only recently received the attention of Italian historians (Balestracci, 1984; Ricerche storiche, 14, 1984).

Our objectives, as from the first excavation campaign, have been:

1. to describe the main features of a late medieval settlement and, more specifically,
   a) to trace the urban structure of the village
   b) to discover the distribution of space within the dwellings and functional buildings
   c) to investigate the way the metal industry was organized and the techniques used.
2. to follow the development of the settlement from its beginnings to discover whether these prove to be pre-Roman or medieval.

3. <u>Description of buildings</u>

In 1984, after the area within the walls (a little under a hectare) had been cleared and the trees cut down, a survey of the village outlay was carried out, enabling us to make our first assessment.

The settlement is surrounded by walls, of which long stretches are still in good condition, built "<u>a sacco</u>" (parallel rows of stone masonry with a filling of debris) of hewn blocks of local limestone set in regular courses; these walls are usually lain on the surface bedrock and pierced by narrow splayed slits. As it stands, this wall seems to have been built at various stages and not over a short lapse of time, either. Indeed, at some points, especially in the western section, it coincides with parts that were later used for terracing the village; in others, as in the south-east, the wall was built later than at least two of the dwellings and clambers over these. Finally, on the southern side, the wall, already complete, was enlarged as shown by the different technique used and the presence of battlements. Probably the access to the castle gate had been reorganized, a theory which seems to be borne out by the results of our excavation. Inside the walls the houses and the functional buildings climb steeply up the hillside. The highest point is taken over by military, religious and manor buildings and the whole complex is linked by a regular network of numerous alleys, cut into the bedrock.

The "military" area. At the highest point, on an outcrop of rock, stands the watchtower, its base surrounded by a buttress, probably of the same date as a room set beside it, and lower down the area is encircled by another wall, pierced by a gate beside two parallel cisterns that stand within the wall. The lower wall, built in at least two phases, contains another dwelling with a stone floor, revealed by recent illegal excavation. The tower itself is built "a sacco", of fairly small (4x5) perfectly squared blocks and access was via a door set 3 metres above ground level.

The manor area. This occupies a platform immediately below the "military" complex and above the church. This whole area is surrounded by walls, of which only faint traces are visible, whereas the ruins of the conspicuous dwelling space are clearly visible. Taken together, the military and manor areas were probably known as the "cassero" or keep.

Ecclesia de Rocca a Palmento. The church, which was part of the diocese of Massa Marittima--as we are informed in the tythe book of 1298--is a hall with a trapeze-shaped apse, which is still intact, except for the roof which was probably trussed. There are traces of a wall belfry that has disappeared. Entry is given through two arched portals, one in the façade; the other, on the right side, corresponding to the presbytery, has a striped arched lintel in grey and white stone. The church was lit by a cruciform window in the façade and two narrow single-opening windows, splayed on both sides, one in the apse vault and the other in the right wall. The building's phases, of which scant visible traces exist, show that the church was shorter by about 2.40 metres and was probably built at the end of the XIth century and enlarged in the XIIth or very early XIIIth centuries. The church is typical of Tuscan rural churches (Moretti, 1983) found mostly in the Pisan Maremma, Elba and Corsica.

The bourg. The dwellings are built on various levels along the village streets and around the fortified hilltop (or "keep") and the hamlet developed from north-east to south-west. The survey has shown that buildings were rarely single dwellings, but usually included two or three houses; this proves a minimum of coordination. However, there are exceptions to this rule. Generally, the buildings are of two storeys, rarely (one case only, perhaps) three, each with the same volume of space (27.5 m^2) though not the same plan. An analysis of the building techniques revealed at once that there had been at least two phases in the life of the village; the second phase probably dates from the last decades before the site was abandoned and took the form of the enlargement and reconstruction of buildings (in some cases these were raised). Almost all the buildings of the first phase (which, as we shall see, was also varied and followed a given pattern) were constructed with walls "a sacco", the fairly regular courses made of large squared blocks of stone. In the second phase the technique was much more rudimentary, using small or middle-sized stones with only one flat side, possibly the cleavage surface, lain higgledy-piggledy. In the numerous cases of well-preserved standing walls, the surviving windows belong to two main types, although variants do exist. The most ancient is the splayed window with monolithic lintel, the more recent type a rectangular window (Damians d'Arcimbaud, 1980, 232). The roofs, sloping both ways, with wooden beams, were covered in thin sheets of schistose limestone, quarried from the hillside opposite (to the south-west); that this stone was used locally in medieval times is proved by the church of San Giovanni at Suvereto.

"Industrial" area. Inside the curtain there is a large section to the north west, beneath the tower, where there is no indication of houses, but only terraces and traces of paths and steps cut into the rock. Here we discovered the area where the "industrial" activities must have been concentrated, proof of this being the large quantities of ferrous slag (analysed elsewhere and, in any case, found only sporadically in other parts of the settlement) and the reddened surface of some of the rock faces. Samples of minerals and slag from this zone have been analysed by C. Bernagozzi and T. Mannoni, who have shown that this was the scene of a varied metal industry where iron was smelted (the ore coming from Elba and from local mines), copper was cast and zinc and lead were worked.

Outside the curtain. In this area the woods have only been cleared in a patch to the south and archaeological exploration has still to begin. However, we have come across two large rectangular rooms, as well as terraces destined for a use that cannot be ascertained until after a systematic survey, and the first probes have been carried out.
In the meantime, the roads leading to the castle and the system of terraced fields surrounding the hillock remain problems to be solved in the future.

To sum up this initial descriptive analysis, I think we can advance several hypotheses as to the group of inhabitants living in this settlement. The "military zone" could accommodate from 10 to 15 people, and the same goes for the "manor zone"; whereas the bourg, if we consider that at the peak of its activity from 40 to 46 houses were inhabited, probably contained from 200 to 240 souls.

4. Archaeology

Before setting up a site for the complete excavation of the village, we decided to begin by examining:

1. 3 separate situations within the bourg,
2. the church, already the object of unauthorized excavation,
3. the manor zone, by subjecting it to an initial "clearing",

and to postpone any probing of the "industrial" zone to the following year. For obvious reasons, in this early phase, it was decided to put off the analysis of evidence from outside the curtain which, together with the known mineral deposits, remains one of the main objectives of our project.

4.1 Interior of the church (area 1.000; fig. 5). Our first job was to examine four large holes, the results of illegal excavation (interface 1017, 1019, 1021, 1024), and remove the large piles of earth the illegal excavators had left behind. The holes concerned three quarters of the whole interior surface of the church and had been dug after the floor had been cleared of the debris from the fallen roof. Thus we found only very scant traces of the roof in the form of fragments of thin sheets of schistose limestone. However, it was possible to discern the two main phases of the building's construction: the older church was shorter, by 2.40 metres, than the new church, which, as I have already said, otherwise used the same walls.
Phase I: the partial removal of the uppermost level of *cocciopesto* (*opus signum*) from the floor of the earlier church and the tidying up of the section made by the illegal excavators have revealed: a sequence of flooring strata and their corresponding foundations near the entrance, a small presbytery wall, obliterated in the second phase and moved closer to the façade, as well as the foundations of the first apse.
Phase II. To this phase belong the strips of *cocciopesto* from the last and uppermost floor and those of the other flooring levels, as well as a new small wall, built further from the façade and separating the rear (presbytery) from the hall, of which only the foundations remain.
The very few finds were not chronologically helpful, except that the last re-flooring dates from the last years of the XIIIth or first years of the XIVth centuries. On the other hand, finds from the first phase do not appear to contradict the view that the church was founded at the end of the XIth century and that it was enlarged fairly soon afterwards during the XIIth or in the first decades of the XIIIth centuries. Inside the church we found no trace of burials and it seems that the illegal excavators also drew a blanc; the gap between the lateral walls was filled in with a substantial and uniform mass

of stones, and nothing else. The burial area for the church was probably out in front on the embankment, which seems to have been raised on several occasions and completely filled in. Within the church, and also inside most of the open spaces and other buildings, we came across a system for collecting rain water. In all probability this system served not only to drain off infiltrated rain water, but also to provide a constant supply of water to an area where no spring existed.

4.2 Excavation of the living quarters

4.2.1 Area 3.000 (Fig. 6). The building is on the south side of the Rocca San Silvestro complex. It was chosen because part of the walls are in excellent condition and because a first, rapid, surface survey revealed that it had been occupied over a very long period. The area has been investigated together with the surrounding network of alleys. Both inside and outside the buildings in this area the pattern of collapse was the same; above, the stone materials from the walls, below the sheets of schistose limestone that had covered the construction, together with charred remains and nails, the remnants of rafters of the floors and roof. The period of the collapse is determined here by the presence of both "archaic maiolica" of the late Pisan period and "italomoresca" and "Hispano-Mooresque" (of the Valencia-Manises type) pottery, dating it to the first decades of the XVth century.

This building, together with the tower area, was probably inhabited for the longest period of time, since this is the only site from which such late finds were recovered. In other sites, as we shall see, the finds were all earlier by many decades; while what was discovered in previous years, scattered over the surface of the whole settlement, included nothing as recent as this.

Traces of floor levels came to light only along a short section of the south wall, probably built, or rather rebuilt (under these strips we found a few fragments of "archaic maiolica" from the first productive phase), at the same time as the base of a rectangular, whitewashed structure built on parallel beams of wood, at right-angles to the east wall. A considerable part of the floor consisted of a sloping plane cut into the rock beneath. This had been used, in the most recent phase, as a shed and grain store, if we are to judge by the whitewashed surface that could have been the bottom of a container with wooden sides, of which there are traces round the edges; further proof of this theory would seem to be the absence of fireproof pottery and the presence of bowls and jugs only.

It is hard to tell, until the area excavated has been widened, whether this is an area that was urbanized in the late Middle Ages, or an area that was rebuilt, as its location (the exposure was very favourable and the building stood inside the walls in a section where the latter had been built over preceding buildings) and certain cuts in the rock face would lead us to believe; the latter, if not traces of earlier buildings, would otherwise be inexplicable.

4.2.2 Area 4.000 (Fig. 7). Here our choice was determined by the atypical characteristics of the standing walls of constructions in this area. We felt that, together with areas 3.000 and 5.000, it could provide us with a cross sample of buildings. The archaeological evidence, however, as with area 5.000, did not bear out this hypothesis. In fact, even though it occupies the same space as most of the other houses in the bourg, the house from area 5.000 was not built all in the same period like the other structures, but each new building incorporated previous structures. In area 4.000 too, excavation was carried out both inside and outside the house and uncovered unexpected elements: the gate, with a corner stone and hinge, perhaps the only one into the castle and through which only men and animals passed, as well as four broad steps, on the third of which a nine men's morris is inscribed. The whole gateway had lain sealed beneath rubble from collapsed walls of neighbouring houses, from which late XIVth century material was recovered. It would appear that the section of curtain corresponding to the gate was modified in a later period, whereas the gate itself seems to belong to the earliest phase. The building, with walls on three sides, at least on the ground floor, was a guard room. This is proved by the absence of a wall on the gate side and a hole for a pole at the centre of the internal axis of the step-pavement, which held up the transom supporting the floor of the room above. Within the room, on the side opposite the opening, a stone seat nestles along the north wall. This point was sealed off by falls from the roof, the rafters and the walls. Here, too, the floor was partly in beaten earth, partly hewn out of the rock. Under the floor, between the bedrock and the foundation of the curtain, we found traces of wall foundations filled in with debris, whence we recovered considerable amounts of coarse pottery sherds of both table and fireproof ware, as well as two red-figured fragments.

4.2.3 Area 5.000 (Fig. 8). The building, just inside the south-west section of the walls by the guard room, was built in such a way as to use earlier walls that had served other functions: as the curtain, or as an earlier, more internal curtain, and as the outside wall of a former house leant up against this earlier curtain.
Once the rubble from the roof and parts of the walls had been removed, it was clear the house had only one storey. The front

part, in direct communication with the door, gave onto a small courtyard; it contained a kitchen area, with an almost circular fireplace of baked earth but no chimney, set against the external village wall, under a large niche. Among the strata of ashes and charcoal we found large quantities of cooking ware (ollas and lids), as well as fine table ware, proving that meals were eaten beside the cooking area; among the latter was a Pisan jug "a palla" in archaic maiolica from the first half of the XIVth century. Inside the house, and in the whole surrounding area (guard house and oven), we found large fragments of water containers with long, pointed lips "a beccaccia", in larger amounts than discovered so far elsewhere. This section of the house was the scene of other domestic activities, such as spinning and weaving.

The rear section, probably separated from the front by a pillar and by perishable material such as curtains, was used as sleeping quarters and, probably, also as a shed for tools and farm produce. Numerous iron manufacts, such as hoes and hand scythes, but also a short sword and a spear head, were found here; while keys, locks and hinges were found in the front part. Taken all together, these finds would date the period when the house was abandoned to the first half of the XIVth century.

In the small yard in front of the house, with a wall especially built round it, behind the guard room and along the village wall and the external wall of the house (area 5.500), we discovered and excavated a bread oven (Fig. 9): this is the first medieval example of such an oven to have been found in Italy. The floor is parallelepipedal and made of refractory earth (similar to the baked earth of the fireplace), with a brick vault that is intact almost to its "cervello" or top. The vault is made of tiles and bricks that, after macroscopic examination, would all seem to belong to the classic age. The draught flowed through the low opening to the mouth of the oven. The structure resembles bread ovens in use in the surrounding countryside until very recently and, in some places, even today. Judging by its capacity, the oven could provide bread for a considerable number of "hearths" and, therefore, was used by the community. Furthermore, finds from this section show that the oven ceased to be used several decades after the adjacent house had been abandoned.

4.3 The manor area (area 6.000). The platform directly beneath the tower and behind the wall of the church has been illegally pillaged on a vast scale. Ample evidence of this exists in the area by the church itself, where a hole had been dug, and on the north side, where a deep trench of over three metres had revealed a curtain, built using a more rudimentary technique than the visible walls of San Silvestro. During our first excavation campaign we cleared the surface of the area, uncovering a series of very wide walls belonging to dwellings that had since collapsed; we also cleared the large illegal trench and, at the northern end at the edge of the precipice, the clearance of that section and of the wall enabled us to uncover strata belonging, in all probability, to an ~~late~~ early medieval phase. This clearance also revealed the top of another curtain which separated the "military" zone from the manor area.

5. Conclusions

The archaeological project of 1984 at Rocca San Silvestro confirmed the potential of this settlement, but rather than solving certain problems it has raised new ones that will only find an answer as our work continues. Why was the village deserted? So far our work has given only partial information on this point. Judging from the three areas we have analysed so far, it seems that the village was abandoned gradually, starting at the beginning of the XIVth century (area 5.000); this exodus becomes more widespread in the second half of the same century (areas 5.500 and 4.000) and has its final phase in the XVth century (area 3.000). This slow demise of the village seems to be borne out by several archaeological clues, such as the drystone walls along the minor streets that are probably the traces of the gradual enclosure of areas of the village, even though this interpretation seems to be contradicted by the numerous manufacts, some in iron and therefore of a certain value, that we found in some of the households (area 5.000).

Even if we have no news of catastrophes (whether military or natural) that might have determined the end of the settlement, it seems quite likely that the village wasted away as a result of the new techniques discovered for working metals; the latter required a different organization of workspaces and had to be close to water courses. However, a contributing factor was possibly political expansion in the region, when surviving pockets of manorial power were swept away. Two examples of this expansion are Pisa's abortive attempt to found the "*terra nuova*", or new foundation, of San Vincenzo and also the new prominence of Campiglia, the most populous centre in the region under the sway of Pisa.

We still have to tackle the question of the origins of the settlement. The two fragments of red-figured pottery are not evidence enough for us to hypostatize the existence of a pre-Roman settlement: they might have been picked up and brought there from near-by areas that had certainly existed since Etruscan times. The same may be said of the San Vincenzo "bench", the only example of a slab of stone from a quarry not in the immediate vicinity of San Silvestro, much used in the Etruscan period. However, the latter is hardly sufficient evidence to allow us to hypostatize a burial area in the castle zone because the stone was used only in the last phase of medieval construction and to a very limited extent. So far, we have not discovered with any certainty the earliest phase of this medieval settlement. We do not yet know if what we call the first phase of building for the dwellings did, in fact, belong to a wholesale reconstruction of a site occupied before the XIth century, or whether it was a completely new settlement, as local tradition seems to suggest in claiming the original name of San Silvestro to have been Castelnuovo.

Undoubtedly, San Silvestro was a well-established unit of population in the XIIth century. The lengthening of the church in this period is clear indication that the number of inhabitants had increased. It is interesting to note the coincidence of this increase with a growing demand for metals, which in that century was due both to the new requirements of townsfolk and to those of chivalry.

The question of the origins of the medieval settlement is one of the main issues of our research and we hope to discover a link between manor enterprise and the exploitation of local mineral resources.

One point is worth underscoring: besides San Silvestro, areas of slag from iron smelting have also been found in the prethirteenth century castle of Fornoli, near Roccastrada (in the Grosseto province), together with scrap from the working of metals in the castle of Cugnano, not far from Massa. We also know that the seasonal smelting of metal was carried out along the coast by the Pisan "blacksmiths" (Gelichi, 1984), as well as in the plains near water courses by cistercian monasteries (San Galgano, but above all Giugnano, near Roccastrada, where traces of a smelting oven have been found). In effect, these were two different ways of exploiting mineral resources: one based on the manorial system and centering round the castle areas (incastellamento), the other the result of the enterprise of towns and religious institutions, which slowly developed their systems of production until, during the XIVth century, they took over completely from the manorial system (of which we do not yet possess a clear picture).

Some of the finds we uncovered deserve a few preliminary remarks. Until we get the results of the analysis of the composition of the coarse pottery from the early building phase, which will help us to locate the centres of production where the village bought its supplies, it seems that, from the moment tin glazed pottery of Italian make was placed on the market, San Silvestro was completely dominated by Pisa (for a historical profile of Pisan pottery see Berti, Tongiorgi, 1977), at least until the last years of the XIVth century, or the apogee of this Maremma settlement (see area 5.000). There are very few traces of other kinds of maiolica, only a few fragments that probably belong to the Sienese type of bowl produced in the Volterra region (Francovich, 1982, B.1.1.), whereas the few examples of late medieval pottery may come from areas producing ware of the Pisan type, possibly from the coastal region. The dominance of Pisan pottery is not restricted to tin glazed ware but also includes coarse tableware, of which the small, one-handled bowls in the shape of truncated cones (Busi, 1984, 465-9) are excellent examples. However, the large water containers do pose a problem, because they include both known Pisan amphoras (Mannoni, 1975, 18-20) and amphora-type containers with long beak-like lips (_a beccaccia_), best known in the Florentine region (Francovich, Vannini, 1976, 709-28).

This high dependence on Pisa, rather than proving the economic weakness of the settlement, sheds light on the highly developed market for the mineral products of Rocca a Palmento.

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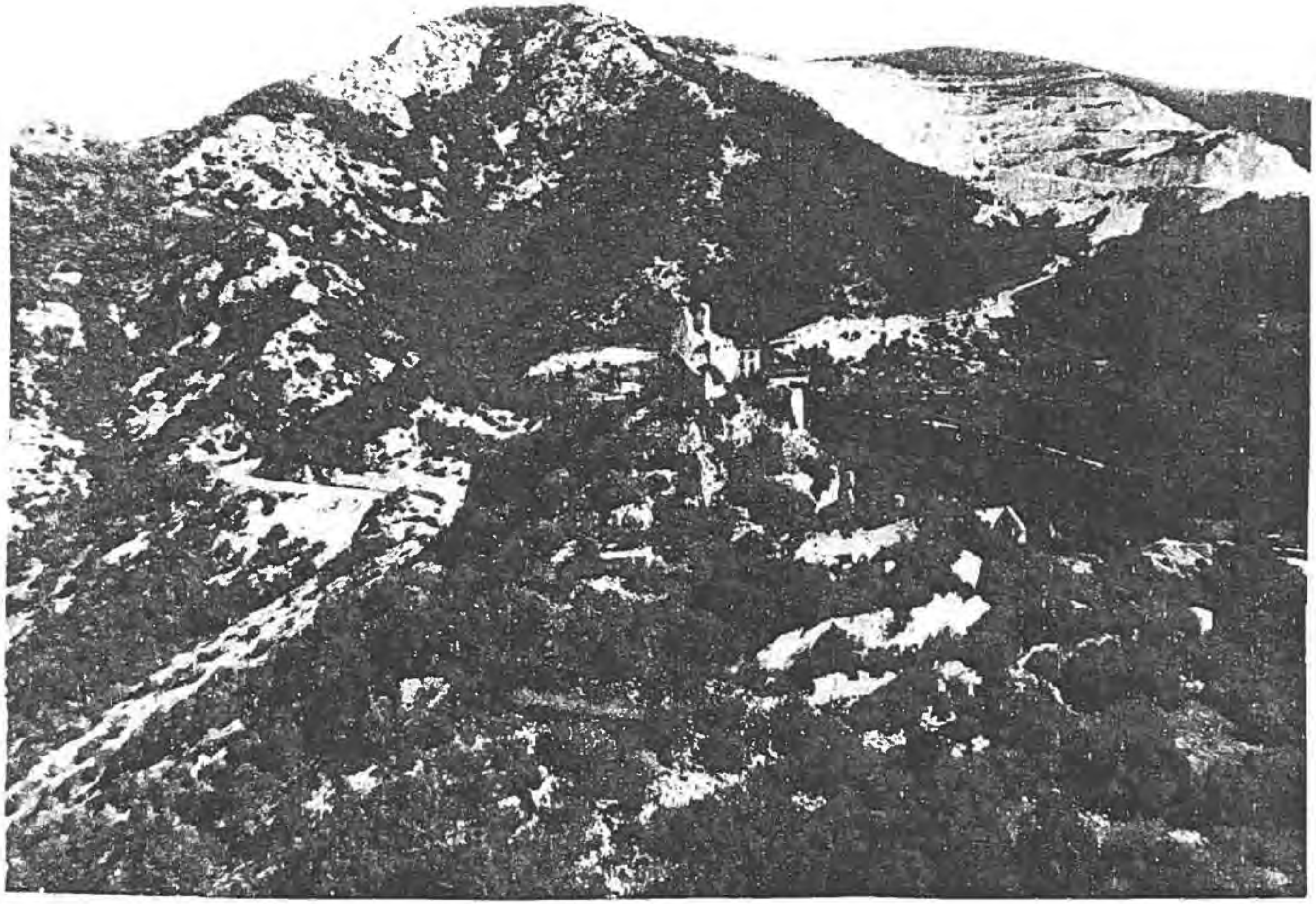
Fig. 1: Rocca San Silvestro seen from the west; in the background the mass of Montecalvi.
Fig. 2: The aerial photograph of San Silvestro.
Fig. 3: Map showing the position of San Silvestro in the mining district of the Colline Metallifere, in the territory of the Etruscan town of Populonia.
Fig. 4: Survey of San Silvestro, each area corresponding to a given function: a) the fortified area, b) the manor area, c) the church, d) the bourg, e) the "industrial" area.
Fig. 5: Part of the excavation in the church's interior.
Fig. 6: The bottom of the grain container inside building 3.000. To one side fragments of the XIIIth century flooring.
Fig. 7: View of the excavation of the guard room (area 4.000).
Fig. 8: The fireplace, inside building 5.000.
Fig. 9: The bread oven, after excavation had been completed.
Fig. 10: The manor area, with excavation in progress.

Fig. 1, 2, 5, 6, 7, 8, 9 and 10 are not available in this working-copy but will be included in the bound volume delivered at Norberg.



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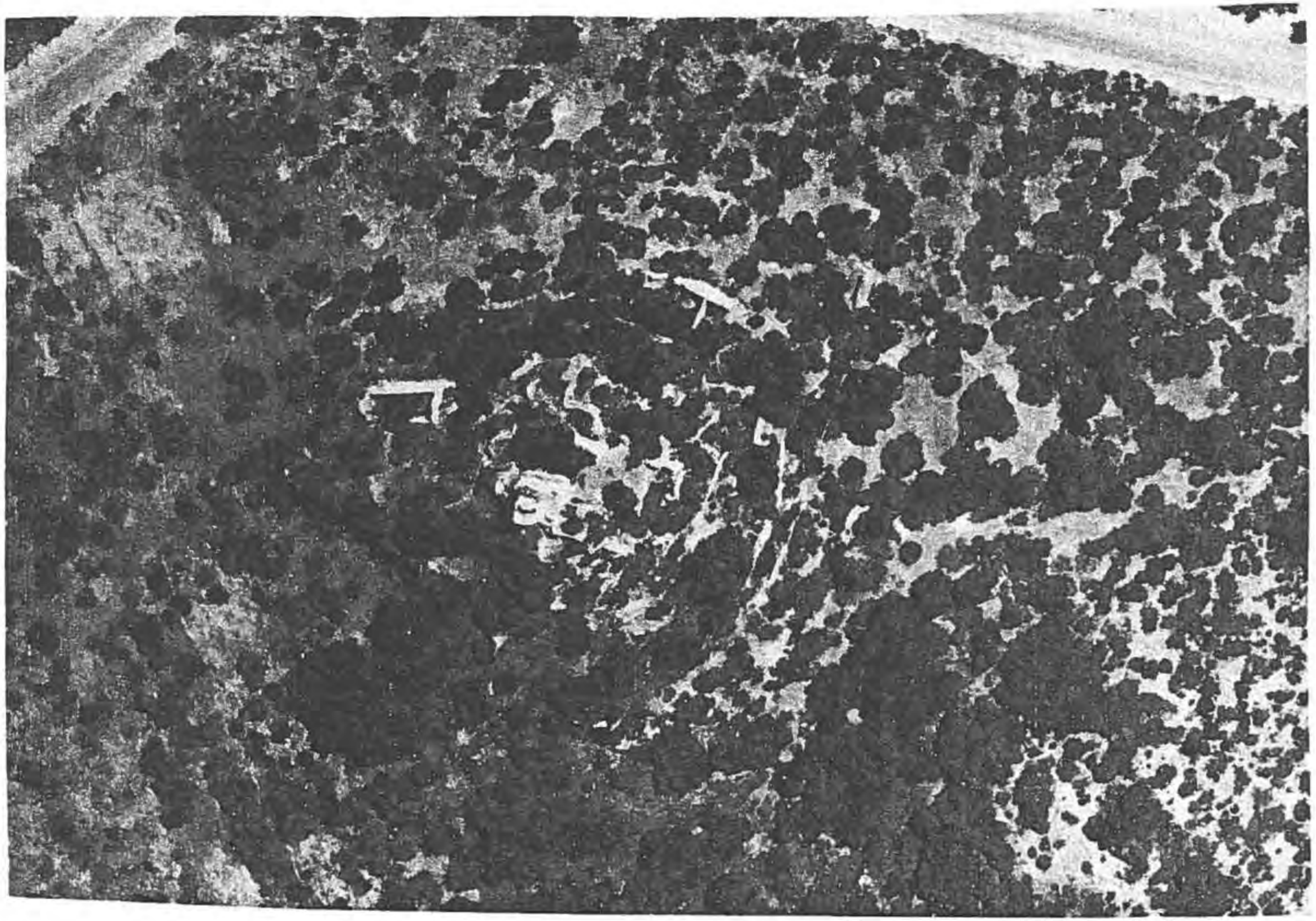

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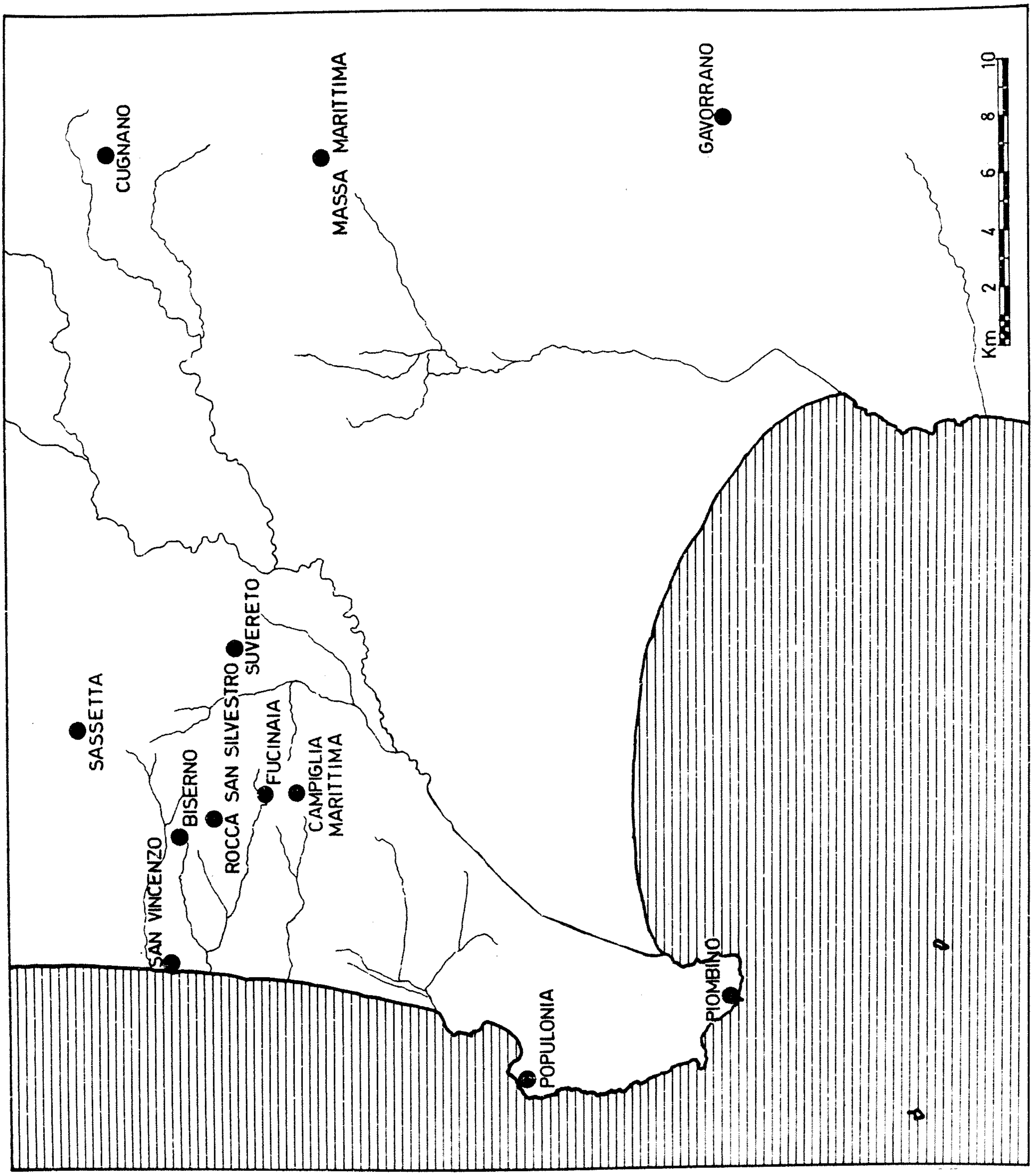

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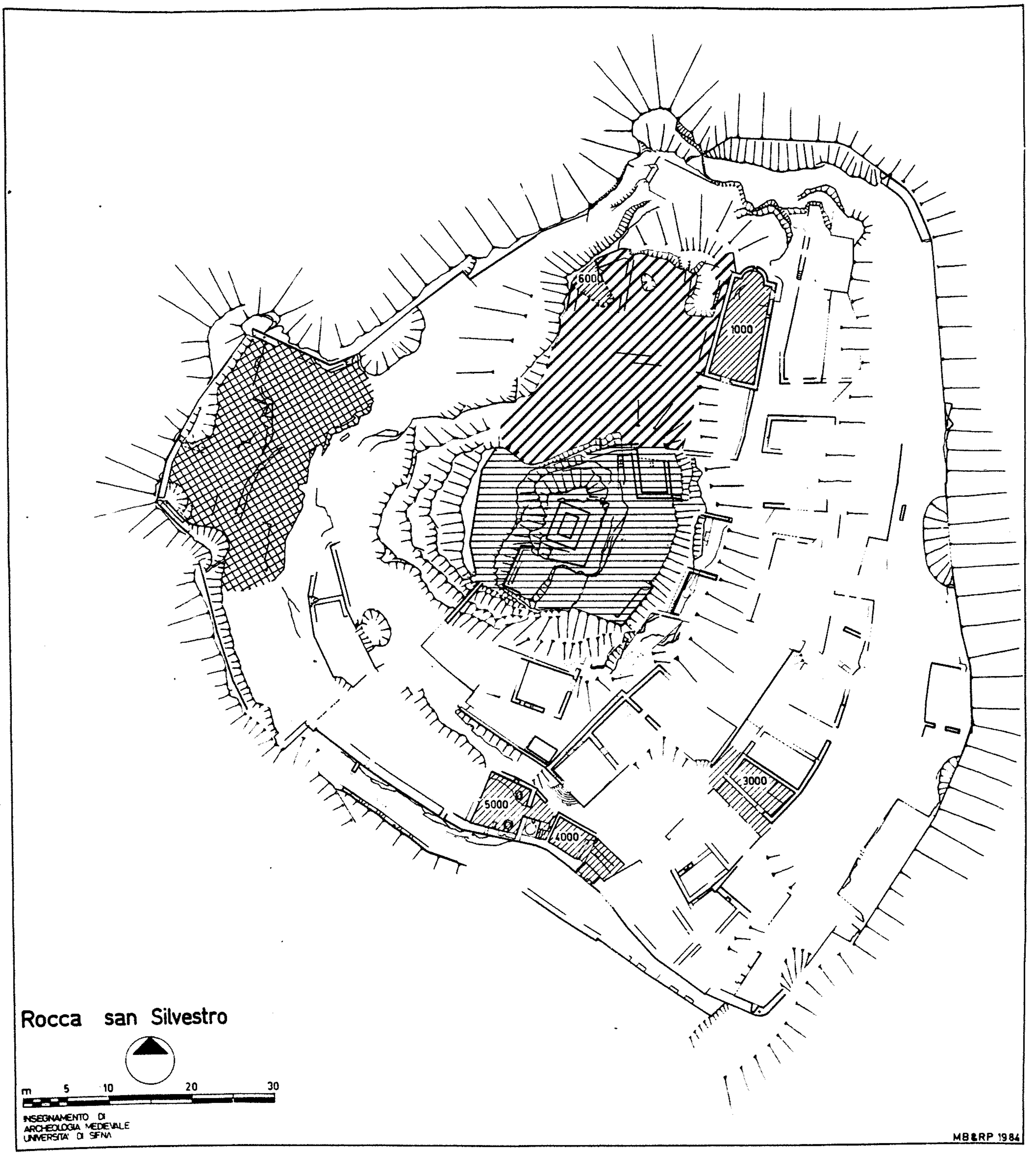

Fig. 4: Survey of San Silvestro, each area corresponding to a given function: a) the fortified area, b) the manor area, c) the church, d) the bourg, e) the "industrial" area.

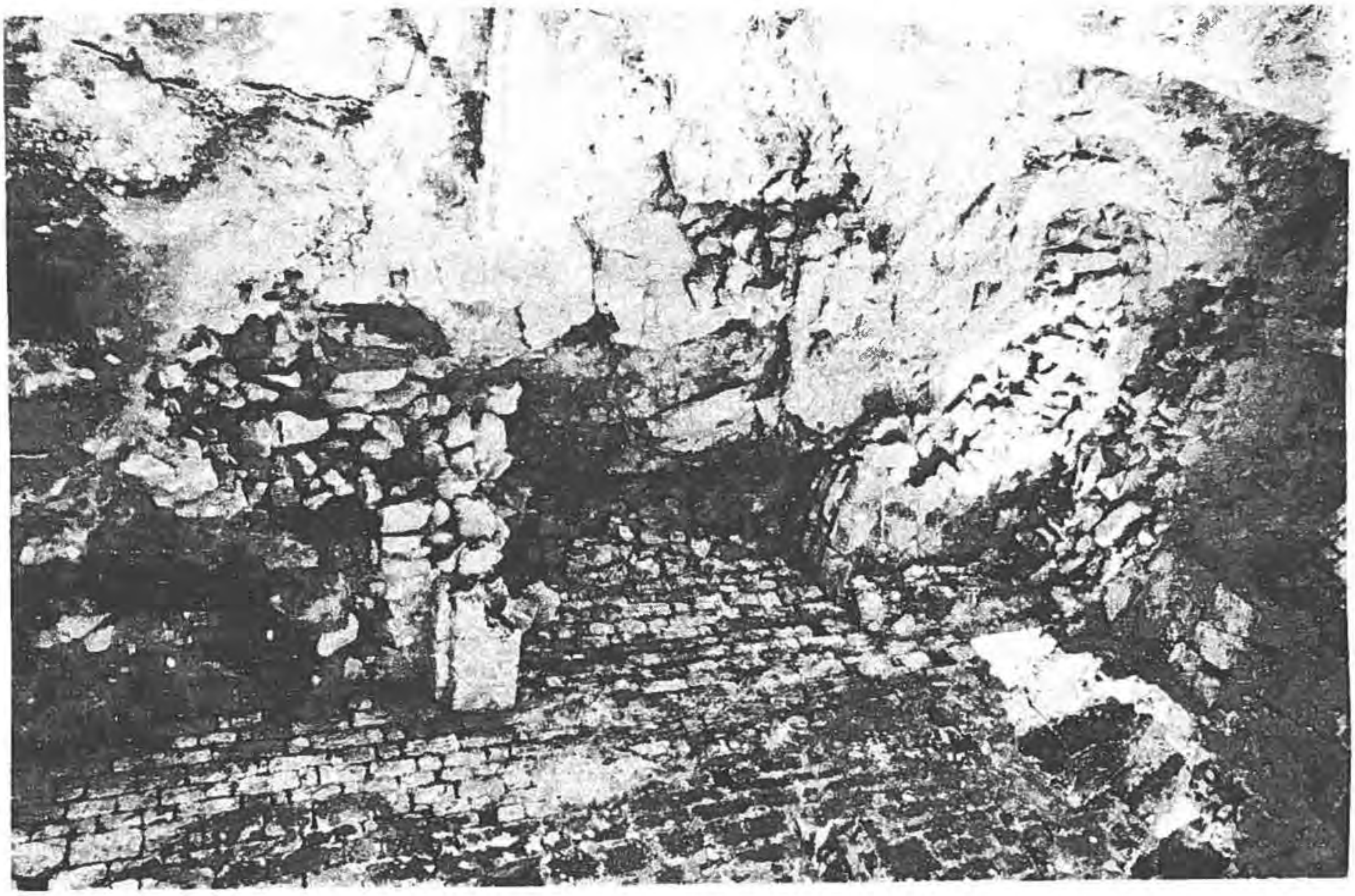

Fig. 5: Part of the excavation in the church's interior.

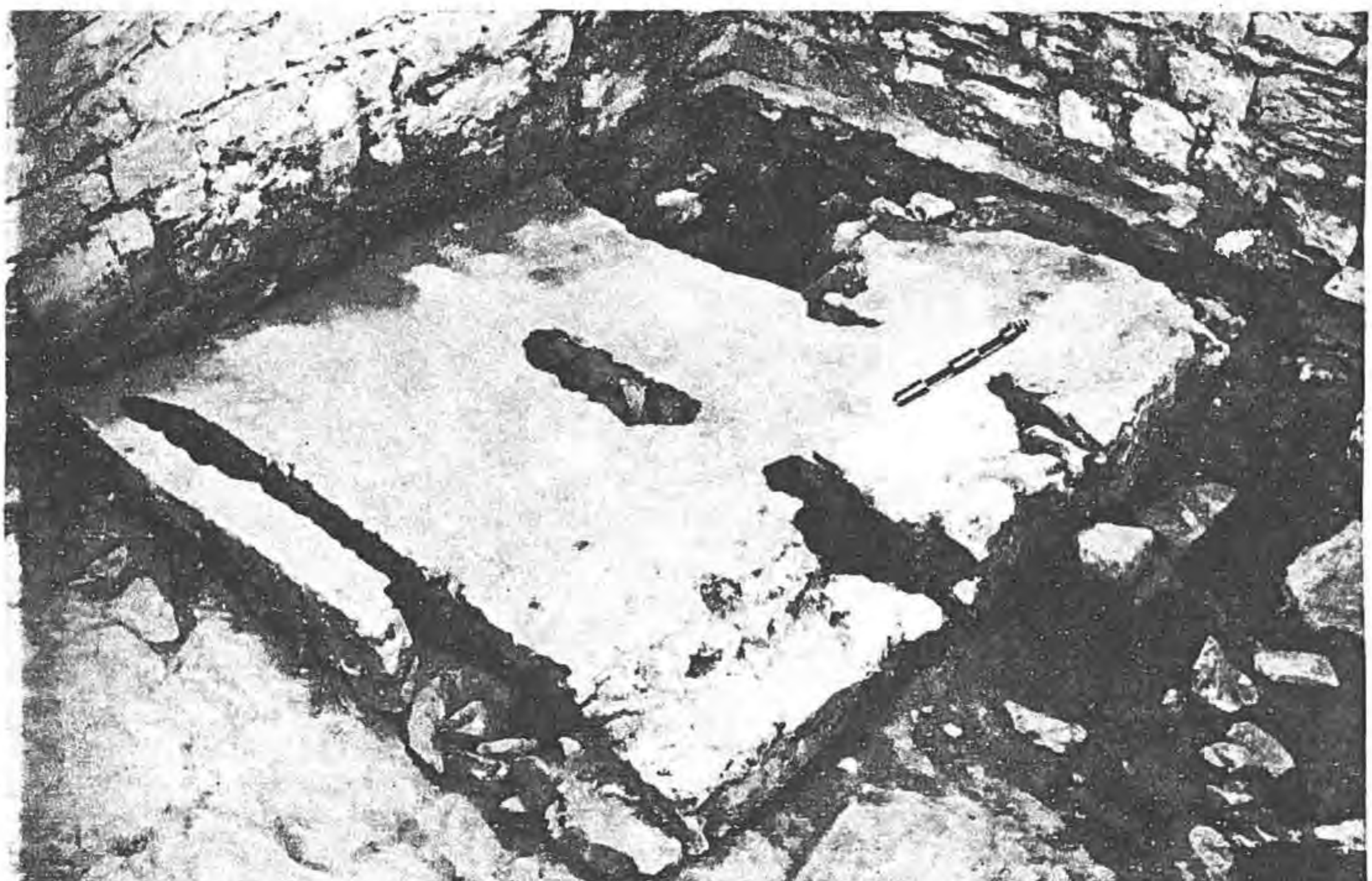

Fig. 6: The bottom of the grain container inside building 3.000. To one side fragments of the XIIIth century flooring.

Fig. 7: View of the excavation of the guard room (area 4.000).

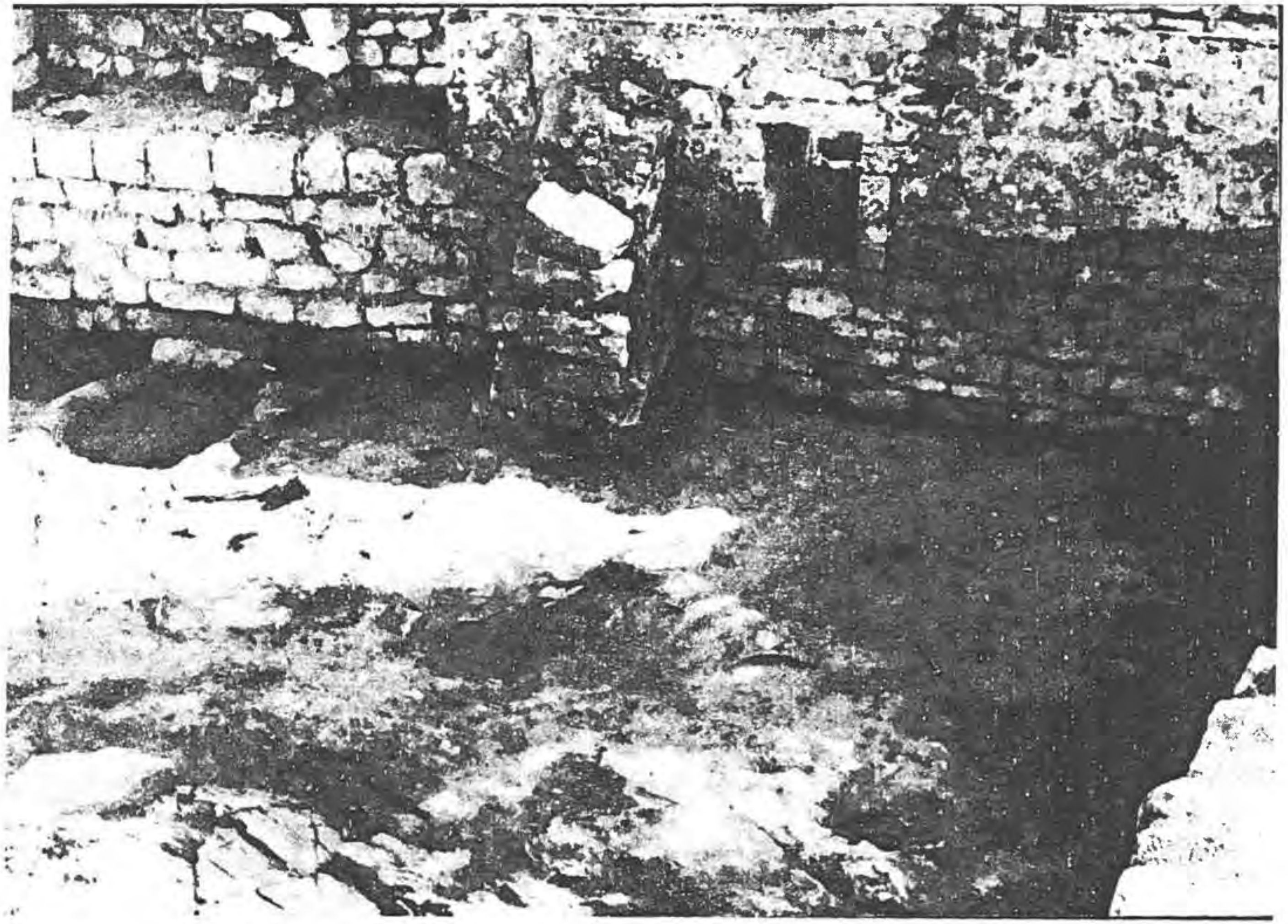

Fig. 8: The fireplace, inside building 5.000.

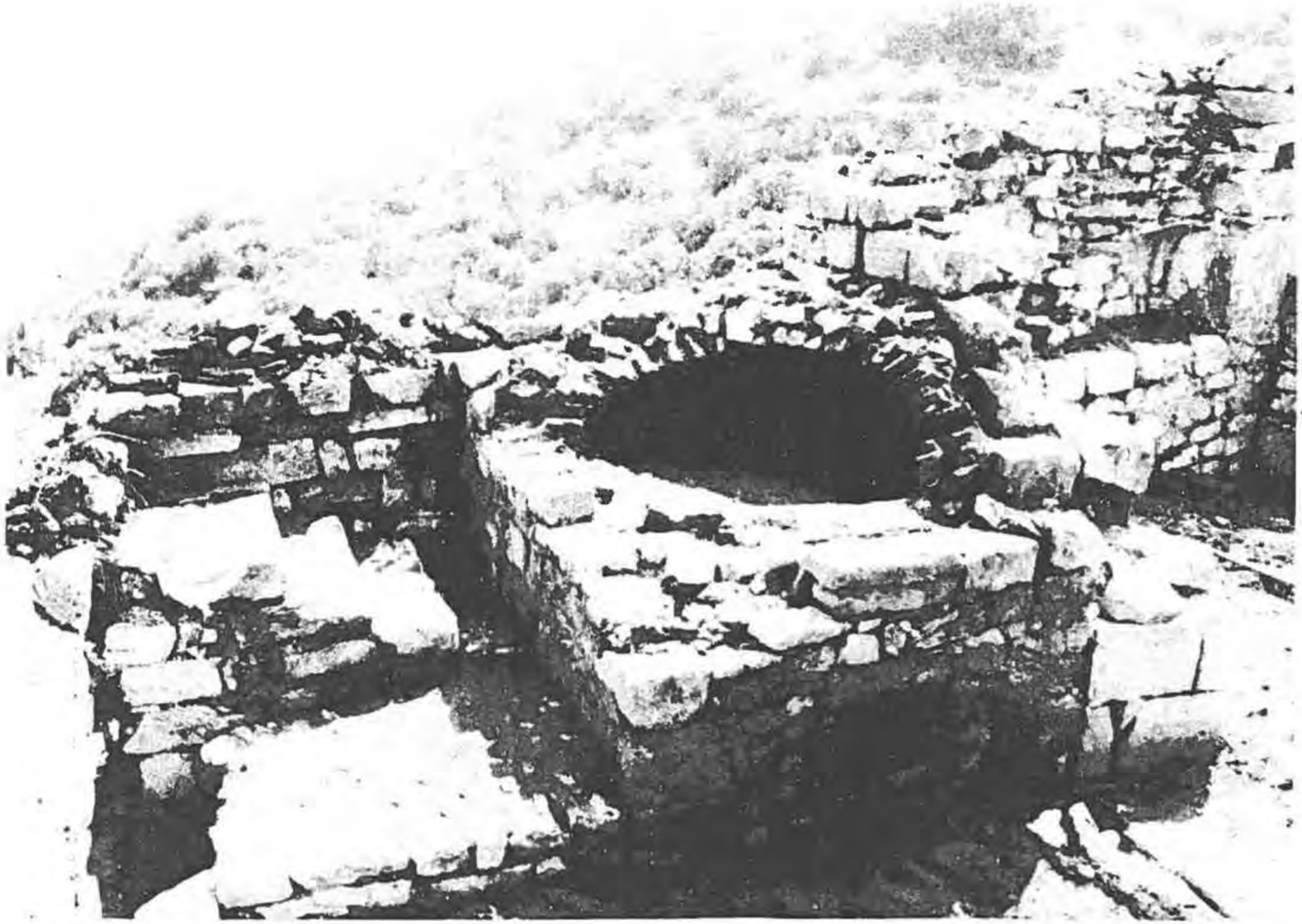

Fig. 9: The bread oven, after excavation had been completed.

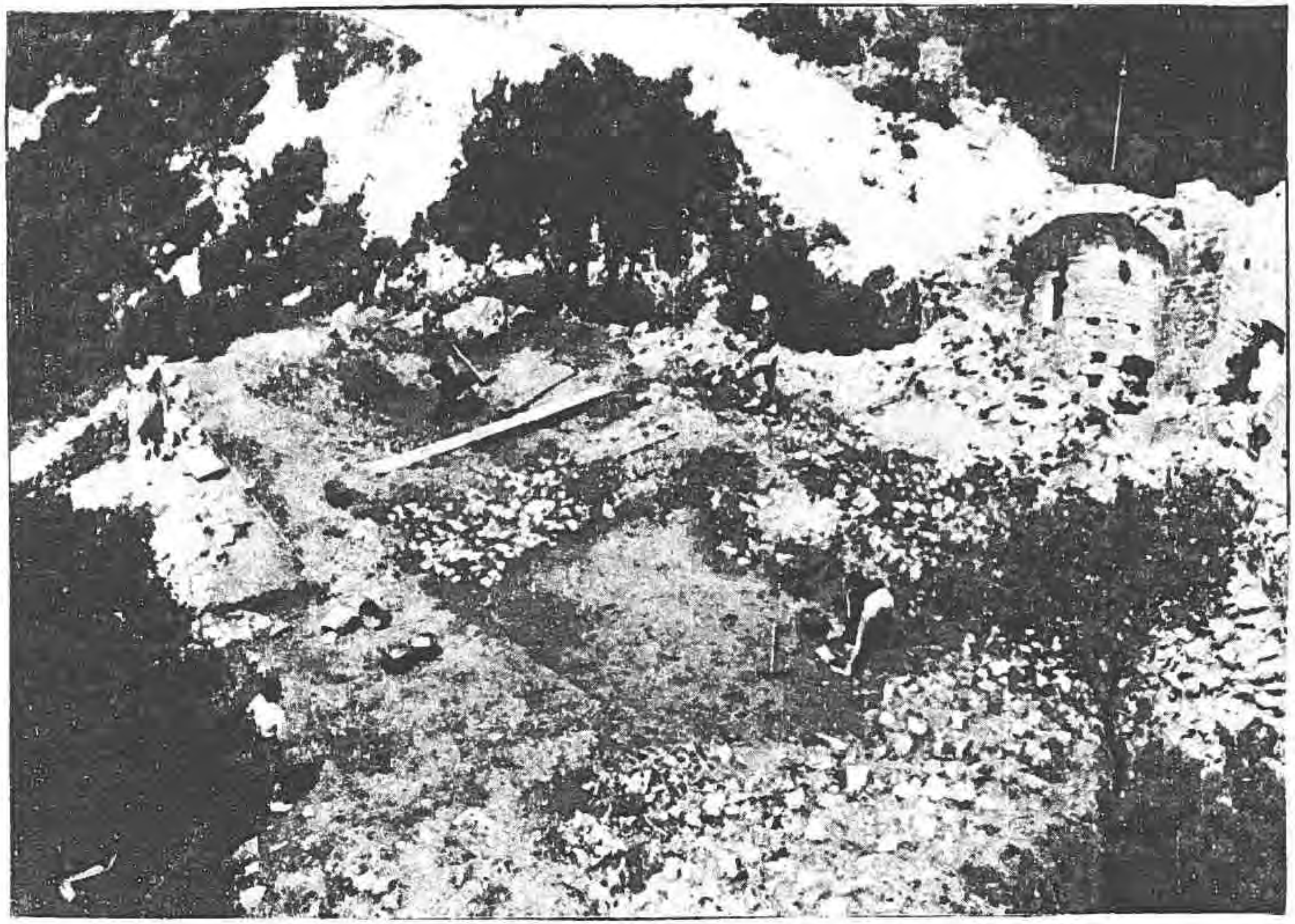

Fig. 10: The manor area, with excavation in progress.

C I S T E R C I A N   I R O N   P R O D U C T I O N

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SUMMARY

In Europe inter-disciplinary medieval research has for a long time taken an interest in the decisive influence the Cistercian order used to have on the economy of the Middle Ages. In recent years particular stress has been laid on the importance of their iron industry in that respect.

Preserved documents show that French and English monasteries successfully carried on a resolute policy with monopolistic ambitions, which led to their dominating European iron production, as regards quantity as well as quality, ever since the middle of the 12th century. 75 per cent of the preserved French concessions for iron mining regard the Cistercians, and the corresponding figure for England is a hundred per cent. English daughter monasteries were localized to already known ore-deposits where they served as mining offices, from which was also systematically carried out further prospecting. Behind this very conscious policy was one of the order´s principal abbeys, *Clairvaux*, which immediately after its foundation in 1115 specialized in iron industry and soon was plying a flourishing trade.

In 1143 monasteries were founded at Alvastra and Nydala, as the 40th and 41st daughters of Clairvaux´. Anders Wallander has studied the Alvastra excavation material and found evidence of a comprehensive iron industry. The site of Nydala Abbey has not yet been excavated, but nevertheless the picture seems unequivocal: it was certainly iron that attracted Europe´s leading iron producer, Clairvaux, to these wilds in Småland, which were otherwise lacking in means of subsistence. But there were the three basic conditions for industrial iron production: *ore, wood and water power* - all three to an unlimited extent.

From the archives of Nydala Abbey over 400 ducuments have been preserved, deeds of gift, judicial decisions, contracts of purchase and concession documents, in which keep returning questions of waterfalls and dams. These documents show clearly that the abbey carried on a conscious policy aiming at procuring landed property and monopolizing the water power of the region. The recurring *molendinum* and *molendinorum locus* of the documents have been translated into *mill* and *mill site* by Swedish scholars and interpreted as corn-mills. Their number is manifestly out of proportion to the very modest agriculture in these parts. A comparison with the use of *molendinum* in the Danish diplomatarium shows that the word often meant *water-wheel*. In other words, that is referred to is the kind of water-wheel working the bellows of the furnaces.

A more detailed version, in Swedish, of this paper has been published in *Imagines Medievales*, Acta Universitatis Upsaliensis, Ars suetica 7, 1983.

During the 13th and 14th centuries there appeared in Gotlandic ornamental ironwork a characteristic motif, unknown elsewhere in Scandinavia. A few components of it can be found in southern Swedish wrought iron from the 12th century, which is known to have influenced the development also in Gotland from the middle of that century, but the working out of details, as well as the way of joining various parts together, differ from older Swedish usage.

The ironwork on Romanesque church doors was often on a high level, aesthetically as well as technically. During the Gothic period, when the motif in question got its particular Gotlandic character, church portals were made both higher and wider than before. It was no longer possible to give every detail the same careful treatment. The general arrangement was still in many cases well balanced; the integrating form elements, however, were not shaped in an individual and varied way, but manufactured in long series and combined into simple patterns, which were repeated all over the door.

In Gotland one such motif was predominant in high medieval ironwork. In its basic form it consists of a horizontal band, which has a C-shape with split curl terminals welded on at either end. At the middle of the band there are two additional C-shapes, placed back to back. As a rule, C-shapes and band have three profound, fullered grooves (fig. 1, 2). This motif is often supplemented with arrow-shaped leaves on short stems, extending from inside the C-shapes (fig. 2, 3). It is generally multiplied to make vertical rows on the doors, which are commonly divided into two leaves (fig. 4).

It has already been mentioned that the various characteristics of the motif, iron band, C-shapes, split curls, arrow-head leaves and grooves, were common even in the Romanesque period. But judging from preserved specimens, the motif was not fully developed until the early Gothic period, in portals dating from little before the middle of the 13th century.

The different components are, with few exceptions, well and deftly wrought, without undue finicking in details. Their character differs a little from one door to another, and it is evident that several smiths have been at work and varied the motif. An early version, on a door from Lokrume which sits in a portal from the second quarter of the 13th century, has open C-shapes with long, thin and originally very elegant curls (fig. 1). But soon the motif was given a more robust and, if I venture to say, more Gotlandic character, often with deep, U-shaped, dextrously fullered grooves (fig. 2). The arrow-shaped leaves on Romanesque doors had long, twisted shafts and differentiated cross-sections: broad central grooves and chamfered sides. The leaves we study are much simpler and usually almost flat (fig. 2, 3). Some of them still have a convincing arrow-head shape, but others rather resemble triangles.

We will not enter upon all the varieties of this motif, but it should be mentioned that it developed in two different directions even before the year 1300. Some varieties are definitely retarded, but there are also well-made versions with vegetative outgrowths. The latter tendency reaches its climax at Stånga, on the door in its south portal, which dates from the middle of the 14th century (fig. 5). In addition to these two divergent trends, the original form of the basic motif also kept alive.

The motif we have seen in its original version on the doors at Lokrume and Fole (fig. 1, 3), is made up of a few simple components with a long history behind them. The straight horizontal bands served as hinge-straps on the early doors, and they each ended in two gently curved curls (fig. 6A). This shape is known from classical antiquity (Liger 1875 fig. 426) and became very common in medieval ironwork.

As early as the 9th century there appeared in Europe another type of hinges, large C-shapes (fig. 6B)(Geddes 1978, 84). In the preserved

Swedish material, however, there is only one door that with reasonable certainty can be said to have had this type of carrying, C-shaped hinges, viz. the one in the south portal of Kaga Church, Östergötland. It is true that a few other doors have large C-shapes in close connection with the hinge-eyes, but in those cases their object is purely ornamental and they intersect with the carrying, horisontal hinge straps. There are several indications, however, that more Romanesque churches, on the mainland and in Gotland as well as in the rest of Europe, originally used to have C-shaped hinges.

Anyhow, the straight and the C-shaped hinges (fig. 6A, B) constitute the basic components of the motif in question. The two constituents appear in several combinations. On English doors they are often welded together into a unity, and thus carry the door together. In Gotland there remain no similar combinations, made for carrying purposes, but there are a number of varieties with a loosely added C-shaped next to the hinge-eye (fig. 6C). These varieties also have another C-shape, usually smaller, instead of the split curl terminal of the band; it is true that this other C-shape is welded on to the band, but in its position it cannot have any carrying function.

Most early Gothic doors either are without a C-shape next to the hinge-eye, or have one which is turned the other way (fig. 6D). At the same time there appeared horizontal bands without any carrying function, bands with C-shapes at both ends (fig. 6E).

The latter combination is most common and would constitute, if integrated in a typological sequence, the very frame of the fully developed motif (fig. 6F), which serves only as an ornament. There are exceptions, doors with different types of hinges; most of these, however, have also been adapted to the basic motif. The horizontal band is lengthened through one of the C-shapes and supplemented with a hinge-eye (fig. 6G).

Several doors are much broader than their portals, which causes the C-shapes next to the hinge-eyes to be partly hidden behind the door-post. This state of affairs counteracted the ornamental designs of the smiths and, consequently, they sometimes preferred to leave out the inner C-shapes (fig. 6H).

If we were to disregard all other aspects, chronological, morphological and aspects of general history of culture, and preferred to interpret the motif in fig 6F as exclusively Gotlandic, we might consider the possibility of an evolution as indicated by fig. 6. But many circumstances contradict such a hypothesis and a satisfactory explanation must be looked for elsewhere.

This motif is most characteristic of Gotlandic ironwork but has no direct parallels in other parts with similar prerequisites - the iron band and the C-shape were common all over Europe in the early Middle Ages. Neither has the motif, considered from a more general aspect of history of art, any specific features that point at Gotland. Because of being so frequent there, it is regarded as typical of Gotland, but it has no place in the stylistic development that was taken by other manifestations of Gotlandic ornamental art.

Medieval art is generally not restricted to any single raw material. What was made of one substance could mostly without inconvenience be made of another. But this very motif is totally dependant on the technical possibilities of iron. Apart from vegetative additions, like the leaves at Stånga (fig. 5), nothing in the motif represents organic forms or stylized nature. Every detail of it derives from consequently using the possibilities offered by the forging techinque of iron. Accordingly the motif is a purely abstract one. Abstract forms are uncommon in Nordic art of that time, when most ornaments originated from forms in nature or from regular patterns of the type which results from e.g. basketry. Neither are there any positive arguments why Gotland should possess particularly advantageous conditions for the development of abstract forms. It will thus be necessary to look for the origin of the motif outside this island.

In other parts of Europe medieval ironwork has been preserved only to a very small extent. The basis for comparative studies will of necessity be unsatisfactory, and as regards our Gotlandic motif it has proved difficult to find direct parallels. In the whole of Europe there is only a small region, a short stretch of the Serein valley east of Auxerre and Avallon in central France, that has retained a few doors with similar motifs.

The most imposing and most consequently decorated door sits in the west portal of the abbey church at Pontigny (fig. 7, 8). It is a double door, as is also often the case in Gotland, but with other proportions. It is rather low but considerably broader than the Gotlandic ones. Each door leaf is carried by three C-shaped hinges of the type showed in fig. 6B. These are ornamentally balanced by mirroring, but otherwise identical C-shapes, placed near the opposite long side. Between each pair of facing C-shapes runs a horizontal iron band, whose ends terminate in *double* split curls. In between have been placed similar but slightly longer horizontal bands, each of which has a pair of C-shapes, smaller and sitting back to back at the middle of the band. Consequently they are applied in the same way as in our Gotlandic motif. The general disposition of the door is also identical. In both cases the basis of the ornamental pattern consists of horizontal bands, regularly spaced, around which are grouped C-shapes. The differences are that some Pontigny C-shapes are placed otherwise and that they serve as hinges, i.e. they are distinctly functional. An additional difference, purely ornamental, is that the horizontal bands have *double* split curl endings, whereas their Gotlandic counterparts have C-shapes.

The same basic motif recurs on other doors in the neighbourhood, e.g. in the wine-growing centre of Chablis, whose door leaves were originally carried by C-shaped hinges, later on substituted with straight, band-shaped ones. Its ironwork is much simpler, aesthetically as well as technically, than that of Pontigny, but it repeats the same theme and the two are certainly directly related to each other.

Outside this little group Pontigny has no close continental counterparts. The porch and west portal have been dated to the middle of the 12th century and the ironwork is contemporaneous (Dimier 1962, 255 ff). Romanesque ironwork is often difficult to date, and there are on the Continent very few doors that are definitely older than that of Pontigny. Thus it would be awkward to sketch its background and relation to other Romanesque ironwork in France.

During the 12th and 13th centuries there were two divergent tendencies of development, which more or less prevailed. On one hand a rustic and popularly rooted ironwork with obviously apotropeic elements, on the other the type which was developed at the large cathedral forges and which was dominated by a skilled vegetative ornamentation with its roots in classical antiquity.

The Pontigny motif is beside these two more frequent tendencies in medieval French ironwork. It has no botanical connection and its purely abstract forms are, even more than the corresponding Gotlandic motif, conditioned by the possibilities offered by material and technique. Considered from this point of view, the two motifs (Fig. 1, 8) offer an evident outer similarity, but they have, moreover, arisen from the same basical conditions.

Above we have observed that Gotland´s cultural situation in the Middle Ages was hardly one to stimulate the growth of abstract patterns. It is true that our motif did not appear there until the period that Roosval (1911, 141) named *the iconoclastic*. It must be emphasized, however, that there is a decisive, fundamental dividing line between this kind of ironwork and the apparent "iconoclastic" currents in Gotland. The latter type of ornamentation may seem highly abstract, but nevertheless it always has its origin in plant forms. These have been stylized and thus made more abstract, whereas our ironwork motif got its form directly from its material and technique.

If conditions in Gotland were unfavourable to abstract ornamentation, what about France? As is well known, Pontigny is a Cistercian abbey, founded in 1115 as number two of the four daughters of Citeaux and thus one of the principal establishments of this order. The Cistercians' aversion to pictures and adornments is too well-known to be commented on here. Their 12th century architecture can be seen as a strong, conscious protest against Cluniac extravagance. Their hostility to pictures was by no means caused by artistic insufficiency. The Cistercian architects and master masons were on the contrary capable of very complicated calculations and aesthetically advanced solutions. They had no chance of hiding eventual tectonic shortcomings under colourful murals and sculptered decorations. For a short period of the Middle Ages was thus awakened a unique sense of the properties of different materials and their aesthetical possibilities. As regards architectural details, this has been obvious and well-known for a long time. The Cistericians' refined and conscious exploitation of the aesthetic potential in one raw material - stone - can still be admired in ruins and preserved churches in the greater part of Europe. In short, Cistercian art was charaterized by a well developed understanding of the material, a sober restraint and an aristocratic desdain for what was considered meaningliess decorations.

In sorroundings with this basic attitude, it is evident that the luxuriant plant decorations of the cathedral forges are inconceivable, as well as the demon-averting representations in popular ironwork. The Pontigny motif (fig. 8) confirms the above description of the Cistercian conception of form. We have already noted down that the Pontigny motif got its shape because of the properties of iron. The long, gently curved split curls have a restrained, aristocratic elegance of the same kind as appears in plastic architectural details. Thus everything indicates that this motif developed in Cistercian surroundings - not necessarily Pontigny but one or other of the early abbeys of that order: Citeaux, La Ferté, Pontigny, Morimond or Clairvaux, which are all situated in a restricted area of central France. Of the five only Pontigny has preserved its original ironwork, but it may safely be supposed that the others used to have iron-mounted doors, too, like a number of their daughter establishments. Fontenay, second daughter of Clairvaux, can boast of still having one of its original doors, though no longer in its portal, with clear "ghosts" of similar ironwork motifs (David-Ray 1979, 65).

The Gotlandic motif (fig. 1, 3) is not identical with the one at Pontigny (fig. 8), but there are undoubtedly a number of remarkable similarities, which justify an examination of possible links between Pontigny and Gotland.

An obvious way of contact is known by anyone who takes an interest in medieval Gotland: in 1143 monks from Clairvaux founded an abbey at Nydala in Småland. Twenty-one years later some of them went on to Roma in Gotland. The abbey church at Nydala has been heavily restored and the one at Roma is nothing but a ruin, but both still tell us, by their unique quality and superior treatment of materials, of a direct French-Cistercian influence. The quality of Roma is far above that of earlier Gotlandic architecture and was to have an important influence on later construction work

(Swartling 1967[2], 58). Everything indicates that not only the basic principles, but also the architect and other specialists working at the building site of Roma, had been fetched, via Nydala, from the mother abbey of Clairvaux.

When the construction of Roma Monastery started, the Cistercian order was in the middle of a rapid economic development. The early monasteries had been set up as self-supporting unities, able to manage without any contact with the common market outside their walls. Each monastery was thus, according to the basic ideology, thrown upon its own resources. Soon, however, things had taken a course away from this strict, isolationist principle of self-sufficiency. Economic realities, as often happens, proved incompatible with an untried theory. In this clash between ideological and economic principles, the latter got the upper hand, a fact which has been differently interpreted by different groups of scholars. Protestant historians of religion have with unveiled disapproval spoken of spiritual decadence, whereas the same development has filled their economically minded colleagues with enthusiasm and admiration.

It is well-known that the Cistercians often sought out remote, sparsely populated regions, in modern literature sometimes depicted as wilds of great natural beauty. The monks are described as detached nature-dreamers and nothing could be more misleading. Their interests in nature were manifold. They were awake to nature´s *all* possibilities, not excluding the economic ones. The various monasteries skilfully exploited the resources their neighbourhood offered. These varied of course - what could be successfully conducted in one monastery was impossible in another. This led to specialization, which was directly contrary to the basic priciple of self-sufficiency. We know the outcome - the principle faded out and specialization was in many cases carried to extremes. Several monasteries gradually developed into productive unities strictly specialized in e.g. salt, wine, cereals, fish or meat. Meaux, in northern France, had shortly after the middle of the 13th century 11000 sheep (Sprandel 1973, 20), which is a considerable number even according to modern standards.

In the early 12th century the Cistercian order seems to have taken an interest in mining and iron trade. The first written evidence dates from about 1140, and from the 1140s and ´50s there is a great number of documents that confirm this inclination to iron industry (Delaine 1975, 33; Sprandel 1968, 359 ff; the latter with an exhaustive list of written evidence). Preserved documents plainly show that French and English Cistercian monasteries pursued a firm and purposeful line of action in economic matters. They had also strong monopolistic ambitions, and were to dominate European iron trade, quantitatively and qualitatively, for a century from the middle of the 12th. Of all the preserved concessions for mining of that time, 75 per cent of the French ones regard the Cistercians, and the corresponding figure for England is 100 per cent (Delaine 1975, 33). British economists and historians of industry have long been emphasizing this order´s decisive importance in this field. Many monasteries were consciously located to known ore-deposits, and from them initiated further prospecting. H.R.Schubert, in his fundamental work *History of the British Iron and Steel Industry* (1957, 87), makes it clear that it was the Cistercians who, through their well-organized and methodical exploitation, laid a firm basis for later British iron industry. In some cases the iron trade of the order attained industrial proportions as early as the 13th century, when Furness in Lancashire, at least at times, had 40 furnaces in operation (Graves 1957, 18).

Furness was a daughter establishment of Clairvaux´. This was not by pure chance, for a few rich ore-deposits near Sheffield were being exploited by six monasteries, all of them issued from Clairvaux. It is evident that this strong interest and proficiency in mining emanated directly from the mother abbey. In the first half of the 12th century Clairvaux was already plying a flourishing iron trade, which had probably started immediately after its foundation in 1115. Our knowledge of the output and technical level of the first two hundred years is limited. In the 14th century, however, Clairvaux alone was running at least eight ironworks with a total yearly output of an estimated 700 tons (Fossier 1961, 7ff), which implies a high technical level and a well-working distribution system. There are several indications that the Clairvaux group even in the 12th century supplied forging-iron to the ecclesiastical building sites. In the 12th and 13th centuries innumerable churches and monasteries were built in all parts of Europe. The demand for forging-iron grew rapidly and the Cistercians, particularly Clairvaux and its duaghter establishments, were not late to make the most of the situation.

When studying the localization of the daughter monasteries (cf. maps in van der Meer 1965, *Atlas de l'ordre Cistercien,* and in Sprandel 1973 fig. 1), it appears very clearly that Clairvaux on purpose established several of them in close connection with known iron deposits. One cannot help suspecting that several monasteries were founded to serve as offices for mines and smelting-houses.

From conecession documents it also appears that the Cistercians were open to new economic solutions. Earlier the mining trade in the densely populated areas in civilized Europe had been in the hands of the various landowners, who mostly lacked the means, economic and technical, of working their property. Also very early the Benedictines had taken a certain interest in mining, but they were reduced to their own grounds or to purchasing mines and ore-deposits, which of necessity limited their possibilities. Clairvaux and its daughter monasteries chose another solution: they contented themselves with resticted *droits d'usage,* i.e. rights to ore and to wood for making charcoal. The landowner could then essentially keep his estate and his valued hunting-grounds (Sprandel 1968, 51). Entire purchases of ground, on the scale necessary for this purpose, would have been out of the question, even for the very wealthy Cistercians. Instead they preferred, at reasonable costs, to gain control of ore-deposits and characoal-making near the monasteries and their foundreis, which latter gradually came to be established very far from the monasteries.

The Cistercians themselves took active part in this iron production, which was also a novelty. Formerly the landowners, among them the Benedictines, had leased out their finds to independent mining contractors and thereby secured a certain income, a percentage on the output, usually insignificant. Through this new and more engaged direct connection and through vigorous development work,a considerable fund of metallurgical expertise was accumulated, which thanks to the centralistic structure of the order, could rapidly be passed on to distant daughter establishments. The iron trade caused the economy of the monasteries to flourish and at the same time a thorough technical development was achieved (Schneider 1977, 568).

These tendencies are most pronounced in England. The 12th century location policy of the Clairvaux group in England was partly governed by the existence of ore-deposits in combination with woods for charcoal-making. Everything indicates that similar facilities helped to give Småland a Cistercian abbey in 1143, viz. Nydala, Clairvaux' 41st daughter. In the same year another daughter of Clairvaux', Alvastra, had been founded a little further north. At Alvastra excavations have been going on for half a century and comprehensive finds have been unearthed, which, though they have not yet been worked up, testify of a very large iron industry[1]. No similar examination has been made at Nydala, so archeology cannot tell us anything about the economic basis of this abbey.

In scientific literature on religion and art the Cistercians are often represented as detached nature-dreamers, avoiding the abodes of men and seeking a lonely existence in the wilderness. And there is no doubt that the immediate neighbourhood of Nydala, Lake Rusken and its surroundings, in the 12th century would fulfil any wants of seclusion. In the region there are traces of early settlements and primitive devices for iron-smelting, but from the Viking Age and early Middle Ages there are no indications of any permanent establishments (Lönnberg 1943, 24). The conditions for agriculture were unfavourable. Apart from fishing in the lake and surrounding rivers, the possibilities of provisioning during the building and colonization stages must have been very limited.

Evidently, what decided the choice of place was crass economy. Here was at hand what the Clairvaux group, in other parts of Europe, had taken most interest in - the three chief conditions for iron industry: ore, woods and water power, all three to a seemingly unlimited extent.

1. Lake Rusken is in a district with Sweden's highest concentration of lake ore, and this also applies to the lake itself. It is still very rich in ore and as late as the 17th century there was in the southern part of it, opposite Nydala, an ironworks which exploited its riches (Lönnberg 1943, 11).
2. On the Continent and in England the woods had already been much exploited and partly ravaged from charcoal-makeing. It was usually want of charcoal, not of ore, that limited the production of iron. Around Nydala there were miles and miles of unspoiled forest-land, which would in the foreseeable future give charcoal enough and to spare.
3. Iron production on a large scale demands furnaces with an ample and continuous supply of oxygen, i.e. mechanically operated blasts, which in those days meant bellows worked by water-wheels. The water system north and west of Nydala, mainly the Härån, tributary to the Lagan, presented a long row of rapids and small falls suited to the simple dams and water-wheels of the time.

We have already seen that Clairvaux, in its operations and its location policy, manifested a pronounced interest in iron industry. Nydala had all the requisites for large-scale production, and there is no doubt that it was the iron that brought the monks to these wilds. The researchers on Swedish mining history, however, have not yet taken any interest in this area. The building-site of the abbey has not been examined by archaeologists, and the surroundings have only been the object of a cursory inventory. Therefore there are only few and vague proofs of the activities carried on by the abbey: in the late 19th century, at Holkaryd, five kilometres east of Nydala, a large slag-heap was cut away, which, according to local belief, had resulted from the iron industry of the abbey (Nihlén 1932, 194); in Nydala itself some cut pieces of bar-iron have been found (Wallander 1977[2], 93ff)[2].

This haphazard evidence, as scarce as it is uncertain, reveals nothing about the output and technical level of the iron production[3]. Pending a systematical examination of the abbey, the banks of Lake Rusken and the rapids in the watercourses north and west of Nydala, we are obliged to resort to the written matter, which fortunately is uncommonly rich. From the abbey archives over 400 documents have been preserved till our days, mostly deeds of gift, judicial decisions, contracts of purchase and concession documents. They are labelled the Nydala letters and are supplemented by a fragmentary copy-book. In its present condition the latter reproduces a little more than 200 documents, the majority of which, however, also exist as originals. This material affords a good survey of Nydala's policy, in some respects most ambitious, as to property and estate. It would, together with the examination suggested above, give an unusually complete picture of the economic basis of a medieval Scandinavian monastery. To go through all the material would be a large undertakeing and take us outside the limits of this study. I confine myself to exemplifying how one of the basic conditions of iron production, the supply of water power, is illustrated in these documents.

Rapids, waterfalls, dams and "mill sites" keep returning in judicial decisions, certificates, deeds of donations and of purchases (Hall, 1898, 128ff; Härenstam 1946, 228ff; Nygren 1943, 40ff; Ek 1962, 31ff). Nydala's charter of foundation (Diplomatarium suecanum 119) shows that it was very early in possession of "mills" and "mill sites". In a deed of gift from 1220, Bishop Bengt Magnusson of Linköping gave away the "mill site" of Långafors in the Härån, which he had received in penalty from seventeen men (DS 210). There is good reason to suspect that the Nydala brethren themselves made the bishop demand this very penalty, and that a consicious policy lay behind this acquisition. Anyhow, the right of use was not to be indesputed. A few decades later Birger Jarl had to intervene and confirm the Nydala rights to the rapids in question (DS 846). In 1288, finally, Abbot Nicolaus of Alvastra maintained that Nydala Abbey alone had the right of use of the Långafors water power (DS 966). In the 1210s Bishop Karl of Linköping had certified that a certain "mill site", today unknown, legally belonged to the abbey (DS 165). From the certificate it appears, moreover, that the country people opposed Nydala's extension plans.

All through the 13th century the abbey tried hard to gain full control of the Härån watersourses, which resulted in conflicts with the inhabitant in the neighbouring parishes. That such a monopoly was of extreme importance to Nydala is clear from the fact that even faked deeds of purchase were made and adduced (Härenstam 1946, 228; Ljungfors 1955, 211ff). From the abovementioned letter of 1288, dispatched by Nicolaus of Alvastra (DS 966), it also appears that the brethren made no scruples to remove what they considered to be pirate establishments in the Härån. In a postscript to the letter, other private claims to a "mill-fall" in the same river are also rejected (Härenstam 1946, 237 note 33). This Nicolaus had formerly been abbot of Nydala and seems to have defended the interests of the abbey in every possible way. At the beginning of the 14th century Nydala was again involved in disputes about the Härån water power, and tried to prove its claims through a number of certificates from influential people (DS 1826, 1840, 1844).

These and other documents clearly show that Nydala needed much water power and was firmly decided to gain complete control in this field. In the documents none of these rapids and "mill-sites" are connected with iron production. Thus the often rucurring *molendinum* and *molendiorum locus* have, by modern commentators, been translated into *mill* and *mill-site* respectively, and without exception interpreted as corn-mills. In some case this is probably true, i.e. water-powered mills for meal. But the modest agriculture in these parts is out of proportion to the large number of "mills", which, accordingly, must have had other uses as well. A contemporaneous Danish document gives a clear indication that Latin *molendinum* had also another meaning.

In 1197 Archbishop Absalon of Lund donated to Sorø Monastery in Zealand an estate at Tvååker in Halland. The donation comprised woods, a watercourse and an ore-deposit, i.e. a property where the brethren could extract iron out of the earth - *de terra ferrum extrahere* (Diplomatarium Danicum I:3:223)[4]. Neither did the contacts with the inhabitants of this region pass off without friction, and after only a few years Absalon's successor had to make clear the powers of the monastery, concerning among other things a wood which the Sorø brethren owned jointly with the local population. One of the fixed points of this delimitation is given as *de molendina ubi ferrum* *fabricatur* (DD I:4:67). The translation practice from the Nydala letters would give *from the mill where iron is manufactured*. What is meant is of course no ordinary mill but a water-wheel working the bellows, indispensible for iron manufacture. The most adequate translation of *molendinum* would in this context be *water-wheel*. Everything indicates that this is also true of the greater part of the many *monendina* of Nydala Abbey.

To sum up it seems clear that Clairvaux′ iron trade was very early a prospering one and that the daughter establishments, expecially the English ones, were consciously located to known ore-deposits. At Nydala lake ore was plentiful and there were woods for charcoal-making as well as water power to provide the furnaces with continuous air supply. Otherwise the region was barren and desolate. Thus there can be no doubt that the good conditions for iron industry was what dicided the localization. Written matter corroborates these indications and shows that the abbey worked methodically to gain total control of the water power in the region. This would have been absurd if nothing but conventional mills had been intended. On the contrary, the aim of Nydala must have been a large-scale iron production and at the same time a local monopoly.

Not until the inventory of ancient monuments is completed will there be a sufficient basis for judging how far the Nydala brethren managed to carry out their intensions. No matter how the result will be, the small party travelling in 1143 from Clairvaux in Burgundy to Nydala in Småland must have counted among its members smelting-house masters as well as smiths, capable and experienced craftsmen who were ready to put to good use and develop the heritage from their mother abbey. In this party there must also have been a forger-master trained in the Cistercian tradition and familiar with its stylistic ideals, among them the specific Cistercian motif which still meets the eye on the door at Pontigny (fig. 8). From the abbey buildings at Nydala no trace is left of this man′s activity - all the medieval wrought iron is gone. It is true that the surrounding churches used to have a wealth of ironwork from the decades around the year 1200, but it can by no means be described as Cistercian [5]. No nearer than in Gotland do we find medieval ironwork that has any connection with the Cistercian tradition.

In 1164 Roma was founded as the first and only daughter of Nydala. Nothing is known as to why this very place was chosen. In this case no interests in mining could have been the reason. Possibly Gotland was regarded as a rich and tempting market for the over-production, if any, of the mother abbey, but as so little is known about the activities at Nydala it is impossible to verify suppositions of this kind.

The monastery church at Roma was probably completed around the year 1200 (Swartling 1967[2], 55). It then had a number of strict, extremely well-hewn portals. The doors have disappeared long ago, and we know nothing of the hinges that used to carry them. Probably they were characterized by the same controlled design and superior treatment of material as were the architectural stone details. Perhaps the smith as well as the architect and the master-mason had been fetched from the French mother abbey, and these doors could then be regarded as a link between the Pontigny motif and our starting-point, the motif we have met on several Gotlandic doors (fig. 9). At Pontigny the motif is in all respects stamped by the surroundings in which it came about, a characteristic product of Cistercian artistic aspiration. The Gotlandic variety is, in spite of its frequency, an enigmatical element, unknown in medieval decorative art outside the Cistercian establishments, and also foreign to other Scandinavian ironwork. The only possible explanation seems to be that the doors of Roma Monastery must had a wrought-iron ornamentation of the same kind as that of Pontigny, and that the motif spread from there to Gotlandic parish churches.

Between the two varieties in fig. 9 there existed two or three intermediate links which are now lost. The impulses hardly came from Pontigny but rather Clairvaux, and they probably came to Nydala before they reached Roma. Clairvaux - Nydala - Roma, three links which today have lost all their ironwork and therefore cannot verify the above hypothesis. On the other hand, we have ground to maintain that the difference between the Pontigny and Fole varieties (fig. 9) is so small that the latter can be looked upon as a rather common rustic usage of the elegant and aristocratic Cistercian forms. The same tendency characterized much of Gotland´s art in other materials.

The original aim of this study was to trace the history of a motif we have met whith in Gotlandic ironwork (fig. 1, 3). I then got into contact with Cistercian iron industry and found a number of indications that the choice of Nydala for a monastery was due to economic rather than religious reasons. Nothing but an archaeological excavation of the former abbey and its surroundings, especially the valley of the Häran, could confirm or refute this hypothesis. Even more interesting, however, is that such an examination could also give a hint of who introduced the blast-furnace into Sweden.

NOTES

1 Antiquarian Anders Wallander has been instructed by Jernkontoret to examine the Alvastra material. In the course of a personal talk he informed me that he had found a great number of objects which bear witness to an extensive iron industry. Cf. also Wallander 1977[1], 1977[2].

2 The area around Nydala Abbey will be the object of an inventory of ancient monuments within a few years, but even the superficial probing Antiquarian Anders Wallander and I undertook in the summer of 1984, disclosed traces of sites along the Härån valley where iron has been produced.

3 Little is known about the methods and types of furnaces used in Cistercian iron production in the early Middle Ages. German scholars maintain that e.g. Fontenay had a blast-furnace and bar-iron hammer as early as 1140 (Spiess 1959, 266; Schneider 1977, 567).

4 Sorø is another Cistercian monastery, founded in 1162 by monks from Esrom, like Nydala a daughter establishment of Clairvaux´. Thus the information on iron trade in the donation documents corroborates what has been said about the policy of the Clairvaux group.

5 The chests from Rydaholm, Ryssby and Voxtorp, like the door at Rogslösa, Östergötland, probably derive their origin from the neighbourhood of Nydala Abbey (Karlsson 1981, 1). About this group Andreas Lindblom writes (1916, 320): "je suis portè à croire qu´elles ont été exécutées par un convers de l´ordre cistercien, d´après les indications d´un moine". This supposition, produced to confirm a hypothesis, is hardly plausible. The ironwork of the Roglösa group, with its folklore and abundance of pictures, represents the very antipole of the Cistercians´ aristocratic iconoclasm.

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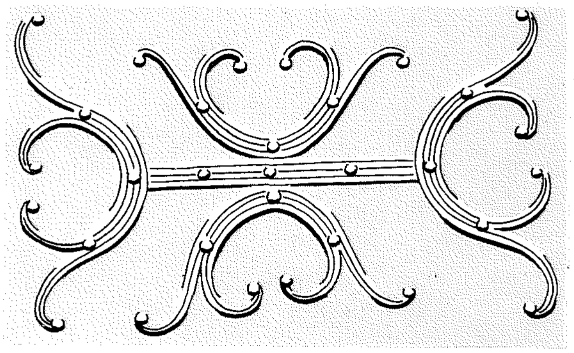
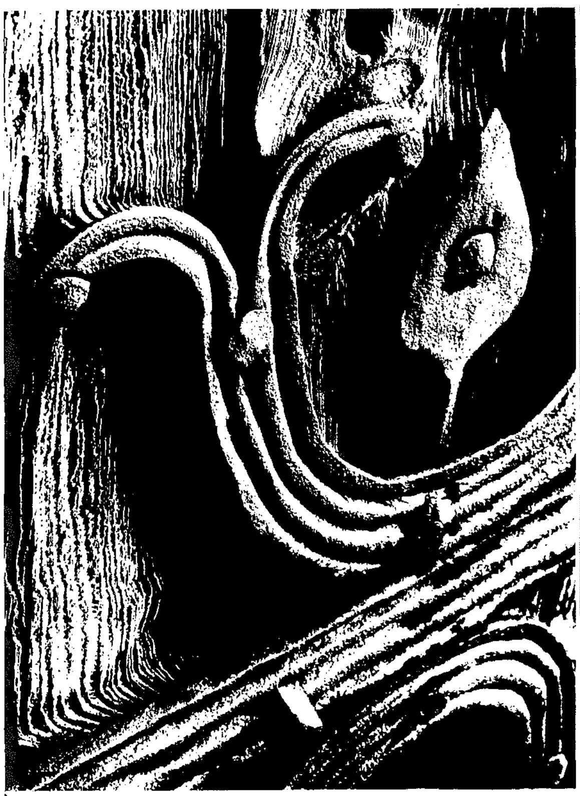
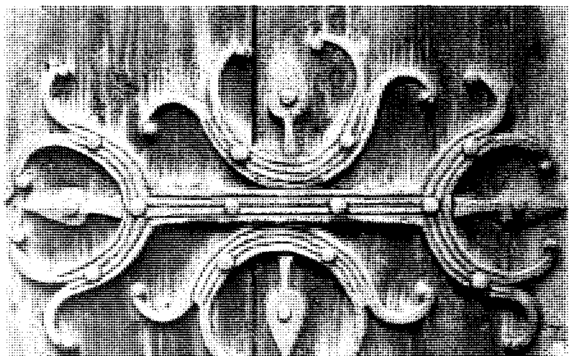




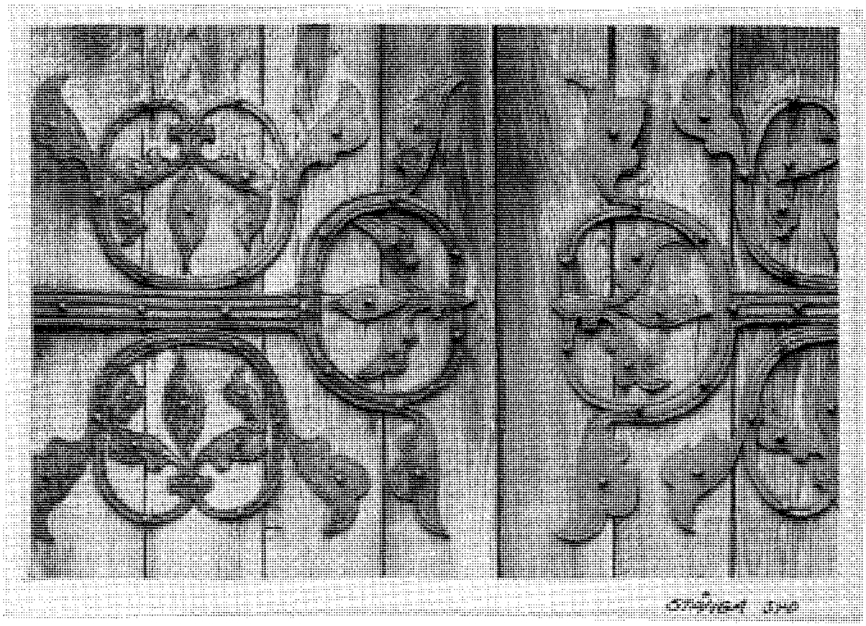


1 Lokrume, Gotland. Detail of door in the west portal.

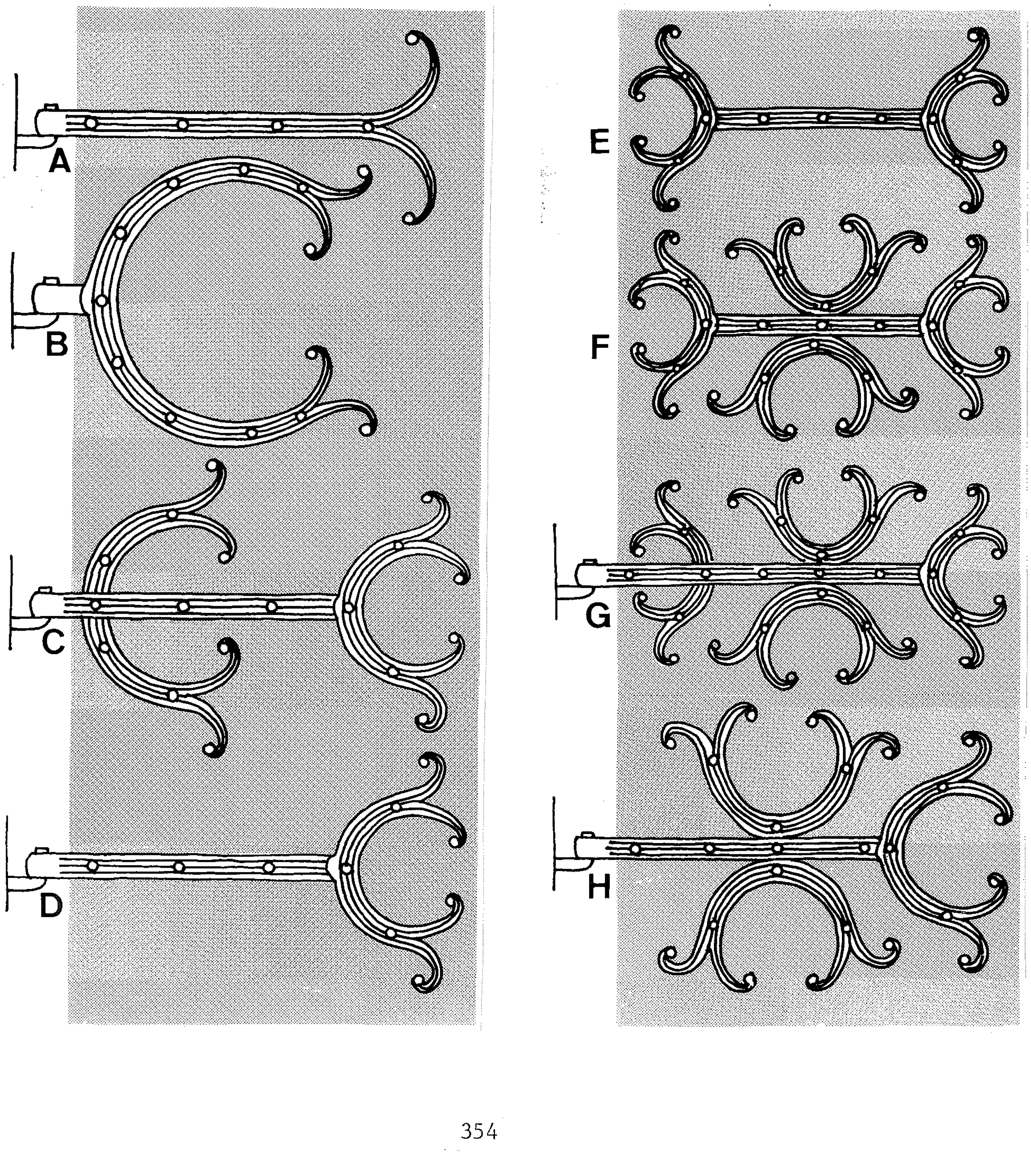
2 Källunge, Gotland. Detail of door in the south portal.

3 Fole, Gotland. Detail of door in the south portal.

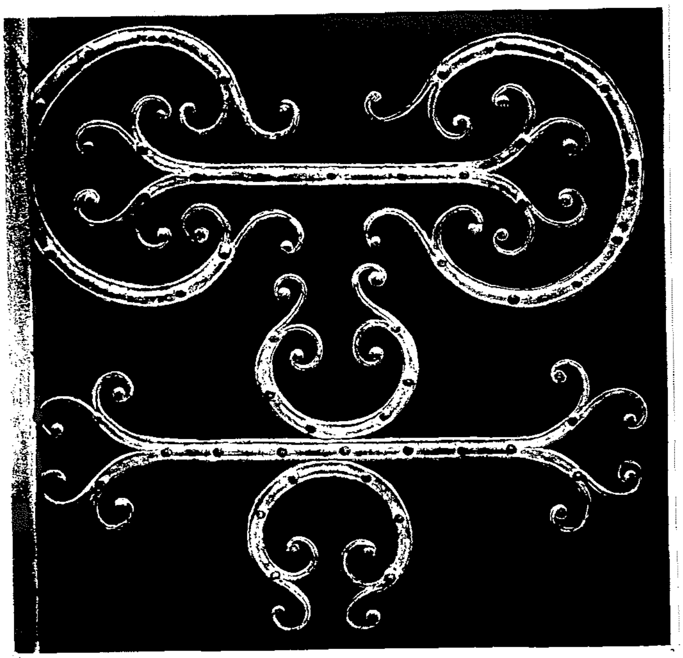
4 Källunge, Gotland. Door in the chancel portal.

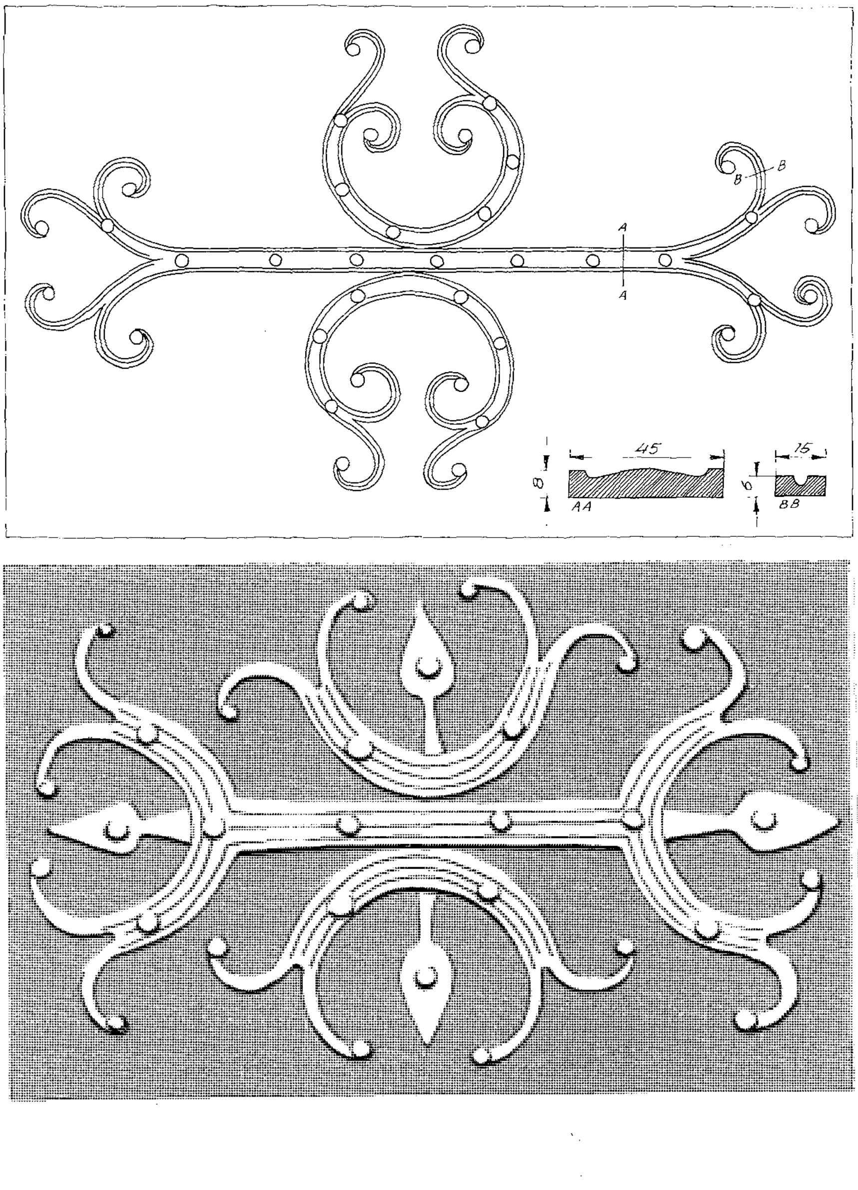


5 Stånga, Gotland. Detail of door in the south portal.



6 Bands and C-shapes in Gotlandic ironwork.





7 Pontigny, France. Door in the west portal. Photo Monuments Historiques.

8 Pontigny, France. Detail of the door in fig. 7.

9 A Cistercian motif and its Gotlandic version. A: Pontigny (cf fig 8). B: Fole (cf fig 3).

EARLY MEDIEVAL MINING AND IRON PRODUCTION IN SWEDEN - SOME SPATIAL ASPECTS

ÅKE HYENSTRAND

SUMMARY

This essay deals with some of the main outlines of social development between 1000 and 1200: the establishment of a national system of government, colonisation, changes in agricultural technology etc. The distribution of mining activities is viewed in comparison with that of the medieval towns, especially in the Mälar region. One important question is whether the apparently dynamic expansion of town life in the first half of the 13th century was connected with the development of the mining industry.

Medieval mining and iron production in Sweden is a rather unique phenomenon. In the course of a couple of centuries it helped to bring about a major transformation of society, converting Sweden from a rather loose federation of sparsely populated agrarian communities to a focal point of economic and political events. In the 14th century sources we can discern various interest groupings with strong claims to control of the mines and furnaces. The economic life of large areas was dominated by a process industry.

During the 14th century the source materials reflect the emergence of a long succession of Bergslags, i.e. organisations for the extraction and processing of ore from important mines. Most of them were located on the western and northern fringes of the Mälar communities, and the whole of this area is generically termed Bergslagen. Stockholm became the principle export harbour in a commercial network based predominantly on market mechanisms in the southern Baltic area, viz the Hanseatic League and Lübeck.

The establishment of the Swedish iron industry would appear to have proceeded rapidly, mainly during the 13th century. Its relationship to an earlier, low-technology method of iron production is unclear. So too are the relations between foreign capital and technology and native conditions. The origins of the industry must be discussed with reference to its attendant circumstances in society and the world at large, in terms of needs and markets, technology and organisation. A great deal of these things were located outside Sweden itself. Sweden had the labour, the logistical possibilities, a political organisation and the raw materials. Then again there were energy resources in the form of water power and fuel. All these factors were favourably combined at an auspicious moment. This, however, is not to say that the real reason for the rapid rise of the iron industry is to be found in a combination of these factors.

When the Icelandic chronicler Snorre Sturlasson visited Sweden in 1219, the lawfinder Eskil of Västergötland supplied him with important information about the country. Historical research during the 19th and 20th centuries has drawn heavily on Snorre's geographical and historical descriptions, but a great deal of what he tells us must be subjected to source criticism. Parts of his historical description are highly questionable. This applies, for example, to his version of the origins of national government in Sweden. Adam of Bremen's ecclesiastical history, written in the 1070s, is a more dependable source on this point.

Snorre's visit coincided with an important juncture in Swedish history. The first half of the 13th century appears to have been a dynamic period, not least in the Baltic area. Numerous towns were expanding rapidly, as a result of trade and the exploitation of raw materials. More about this later. This also seems to have been a period of increasing consolidation for the emergent Swedish state. The centre of political and economic gravity in Sweden had increasingly shifted to the Mälar provinces. During the 11th and 12th centuries, the initial period in the formation of the state, the emphasis had been more on the agrarian regions of Västergötland and Östergötland.

The Mälar provinces faced the Baltic, they were expansive and easily accessible. The area was criss-crossed by natural channels of communication in the form of rivers and ridges. This, of course, simplified the handling of raw materials and transport operations, e.g. iron shipments.

Snorre describes the importance of the Mälar provinces, but he was unaware of the main historical outlines. Nor does he tell us anything about the part which the iron industry possibly played in the 13th century expansion process. The historical sources fail us on this point as far as the period before 1250 is concerned. On the other hand we have the archaeological material, which in Sweden is extremely abundant where the early iron industry is concerned.

Historical and archaeological information can very well be transferred to maps. The actual distribution of a number of factors, such as transport routes, mines, furnaces and towns, can in itself provide partial explanations. Maps, however, are static; they have to be viewed in relation to historical processes. Different historical processes can run parallel to one another, sometimes closely interdependent and sometimes quite independent of one another. Before going any further on the subject of the iron industry, we ought perhaps to say a few words about these different phases.

Above all we have to focus our attention on the 11th, 12th and 13th centuries. This is the period when the Swedish state comes into being, following the dynamic development of a magnate class which provided the foundations of royal power. The background to all this can be found in the expansionist endeavour, trading and missionary activities of the Carolingian empire. Whereas formerly there were spheres of interest under the Carolingian emperor, the Scandinavian countries of Denmark, Norway and Sweden now become federations in their own right. This is a painful and turbulent process. In Sweden, magnate dynasties in Västergötland and Östergötland compete with each other for the royal power. They were also rivals for control of the Mälar provinces. By the mid-12th century, important Cistercian monasteries had developed adjacent to estates belonging to the royal families, viz Varnhem in Västergötland and Alvastra in Östergötland. The Christian mission was particularly powerful in these areas, as witness the intensive building of churches during the 12th century. This in turn meant the development of a completely new building technology in Sweden.

There were great economic changes, above all in agriculture. This is confirmed by surviving fields, not least in Västergötland. Topographical analyses have revealed that large new areas were brought under the plough. This is also connected with watermill technology, which would seem to have been developed first by the towns of southern Scandinavia.

This would seem by all accounts to have been a period of heavy population increase and colonisation of previously uninhabited areas. Comparisons between archaeological and historical source materials show that great changes took place between 1000 and 1300, conspicuously so in large parts of Småland, the Bergslag region, Dalarna, Eastern Hälsingland and other regions. Population increase cannot have been the sole cause of this extensive colonisation. The growth of urban society probably played an important part in the regulation of land ownership. This implies a "freeze" on patterns of settlement in certain areas. In other areas, such as Skåne and Västergötland, it may have caused an aggregation of homesteads in the form of villages. Landless people may have been forced to seek out new areas.

Probably, then, this was a period of great social change. The landholdings of the established magnate families came up against a new system, that of territorial division. The old "lands" and "bygds" were divided into hundreds (<u>härader</u>, <u>hundaren</u>), which in turn were subdivided into parishes. Among other things this may have resulted in the incipient privatisation of land. In addition, it must have increased the potential mobility of labour, which in turn was a precondition of social expansion.

Thus the formative phase of the Scandinavian states was a dynamic period in which the European Middle Ages penetrated these northern fastnesses. The foundations of this process are located in an ancient form of raw material trading, or one might say an exploitation of Scandinavian furs, hides, wool and other raw materials. This trade had existed for centuries, possibly millenia. The archaeological source material bears witness to continuous links with the Continent ever since Roman times. There were established transport routes and trading stations arose at the intersections between them. Contacts between local chieftains and traders or agents from the Continent had led to specialisation, crafts and organisation. This had also contributed to the rise of the magnate dynasties and chiefdoms. It is not inconceivable that trading activities also included iron, manufactured by low-technology methods from bog ore or red earth.

Trading routes and transport systems naturally developed rapidly during the period with which we are now concerned. During the Viking era one could sail from Hedeby to Lake Mälar in a week. Along the Baltic coast of Sweden, from Skåne in the south to Uppland in the north, a number of trading stations laid the foundations of medieval town life. And then there were the inlets penetrating western Sweden, the most important of them being the Göta River linking Lake Väner with the sea.

Roads mean everything to a state, and so there is good reason to assume that great improvements were also made to road connections inland. Adolf Schück's reconstruction of medieval roads shows a system of lines and junctions linking the various regions of the country together. Many of these junctions devloped into towns during the Middle Ages.

This brings us on to one of the most important manifestations of early medieval life: central localities and towns. The 70 or so towns of medieval Sweden have been specifically studied in a major project, generally termed The Medieval Town, in which historical and archaeological data have been combined. The origins and early history of urban life are growing increasingly clear, but for present purposes we need only hint at the complicated process involved.

The background of the medieval towns is not unambiguous. Moreover, there are regional differences. During the 11th century, the Christian mission and the need of the early monarchy for staging posts played a vital part in the rise of certain towns, viz Lund, Skara and Sigtuna. The further development of urban life was fostered by the market economy and territorial divisions. But links with the monarchy, the Church and the needs of the emergent state were clearly apparent throughout this period, down to the 14th century. Many of the towns which achieved prominence in the 13th century were descended from 12th century ecclesiastical centres. This is true not least of the towns developing at such striking regular intervals in the Mälar provinces, Närke and Östergötland. These towns are particularly interesting because they are so near to the mining districts.

The Medieval Town project suggests among other things that Swedish towns were expanding rapidly during the 13th century. Earlier central localities developed and new ones were added. Certain tendencies point to a very rapid process of change in about 1220-1230 (Hans Andersson). This period also marked the beginning of a building boom in Visby which produced hundreds of stone buildings within just a few decades. Baltic trade expanded heavily northward. This makes it natural to ask whether the Swedish iron industry could be one of the factors behind all these developments.

Mining and iron manufacturing demand a great deal of transport organisation, including seaports and shipping. The medieval towns of the region concerned constituted a maritime transport network within a larger region. This was in fact the foundation stone of an advanced mining industry with the Hanseatic League as middleman. We may also recall Snorre's description of Norrström in Stockholm: "When it rains heavily and the snow melts, the water flows so rapidly that a waterfall develops at Stocksund". This illustrates the great importance of Stockholm as an entrepôt and export harbour. The Hanseatic cogs were probably unable to enter Lake Mälar during the 13th century, but they could perfectly well put into other important harbours along the Baltic coast, viz Kalmar, Västervik, Söderköping and Nyköping.

In terms of economic and political background, the Swedish mining and iron industry has to be viewed in relation to the towns and, accordingly, to transport opportunities. A simple map of the various medieval mining districts, natural transport routes and the siting of the medieval towns brings out a number of striking connections. The towns also had another important role to play, namely that of suppliers of important raw materials to the mines - mainly cattle and horses, and perhaps too certain foodstuffs.

Through their geographical distribution, the Swedish mining districts were variously endowed, for example as regards transport and logistics. This had its effects on settlement and colonisation. Some mines were located in completely uninhabited areas, while others were situated close to older agrarian settlements. In many cases, intensive agrarian colonisation had rapidly brought the mines within reach. Logistical opportunities arose as nearby areas were brought under the plough. Kopparberget at Falun, perhaps the oldest and most important of all Swedish mines, is a case in point. Kopparberget is not far from the largest continuous plainland in the province of Dalarna, Tunaslätten, which would seem by all accounts to have been intensively colonised already during the Viking era and early medieval period. There were natural transport routes linking Kopparberget with Västerås.

In Dalarna and Närke there are mines in roughly the same position, i.e. close to agricultural areas. The Bispberg, Vikaberg and Lerbäck bergslags are three such cases. Elsewhere, not least in Norberg, permanent agricultural settlements were further away. This is true of the mines in northern Östergötland, the western mining districts of Dalarna, the west of Västmanland, Gästrikland and above all Värmland. In many such areas, mining could have been entirely responsible for the colonisation of the furnace villages. The resultant demand for grazing land and agricultural produce extensively transformed the local landscape.

Thus the old adage about "iron breaking ground" may be true of certain areas and at local level. In a wider spatial perspective, however, the preconditions of ironworking can be defined as a general and agriculturally based expansion of settlement. Where the Mälar provinces are concerned, this expansion can be traced through the Late Iron Age and early medieval period in a particular direction, westwards and northwestwards. This is especially true of the Svartån River valley going north and of the Dalälv River communities. Along the northern shore of Lake Väner a similar expansion took place from west to east, at the same time as the heart of the Mälar region, round about Köping, expanded along similar lines.

The critical factor of mining development was not local agrarian logistics but the availability of ore. Opportunities of rapidly extracting large quantities of iron, copper or silver probably governed the expansion of transport systems and colonisation. First, though, the ore deposits had to be discovered and appraised, which required prospecting. We still know hardly anything concerning this process. One would like to know whether deposits were systematically searched for, and if so what signals were utilised. One may also ask whether experience of an earlier, low-technology form of iron production could have played any part in this process.

It is certainly surprising that the largest and most important ore deposits in Bergslagen were known during the medieval period and to a great extent probably already in the 13th century. This suggests that indications of ore deposits were distinct and were properly understood. The question then arises whether they were understood by the local population, for example as a result of observations made while hunting and fishing in the "outback", by specialists detailed to explore the terrain or as a result of contact between specialists and the local population. Once a deposit had been found, its extraction demands immediate and heavy capital investment. Labour has to be recruited and organised, facilities have to be built and supplies and transport assured. The availability of water power and fuel has to be investigated and a wider geographical area has to be turned into a production system.

These aspects have been discussed with reference to the Continental examples on which the organisation of Kopparberg was probably modelled. It seems unlikely that mining organisation evolved locally round about the ore deposits. There ought reasonably to have been larger systems and abundant capital behind it all. This brings us back once again to the question of the background and possibly Continental antecedents of the Swedish mining industry.

An interesting research situation prevails at present, as a result of new datings and experience yielded by archaeological sources. What is more, the technical standards of the mining industry would seem to have been high already during the introductory phase. This, of course, is above all true of the blast furnace technology used for reducing the ores. Another important but, as yet, less firm observation concerns the simultaneity of urban expansion and the growth of the mining industry.

The investigation of Lapphyttan has imparted a new dimension to mining research. That research cannot make any further progress without archaeological inquiries, which in turn will have to be based on wide-ranging experience of the field material. Different types of inquiry will have to be viewed in relation to one another. The Lapphyttan type of investigation is very expensive, and is unlikely to be repeated on the same scale within the foreseeable future. Lapphyttan itself, however, has yielded a central corpus of reference material. The experience thus gained can be applied to smaller investigations and analyses focusing on specific problems.

There are also other ways of penetrating the earliest history of mining. Modern topographical studies, e.g. of lake-bed sediments, can yield a more detailed and exact picture of colonisation processes. Suitable sites should be selected for investigations of this kind.

The earliest period in the history of mining should also be viewed in relation to low-technology iron manufacturing. During the early medieval period, iron was produced from bog ores and ferruginous soils in large areas of Sweden, e.g. parts of Småland, the south of Västergötland, and central and southern Halland. Particularly where Småland is concerned, this is thought to be connected with the intensive colonisation of certain outlying areas, not least during the 12th and 13th centuries. In Halland, iron is arguably connected with the appearance of certain early towns, e.g. Halmstad. The same idea has also been put forward concerning Kalmar. A small area of low-technology iron production to the north of Skövde in Västergötland can be associated with local demand for iron following the foundation of the city of Skara and Varnhem Abbey.

These iron production areas may partly have inherited traditions from the Viking era or still further back in time. Local demand may explain a great deal, but the possibility of wider connections cannot be discounted. Parts of the Swedish Bergslagen, moreover, had low-technology iron industries during the Vendel and Viking eras. In the south of Norrland, low-technology methods of iron production survived until well into modern times.

Technically and organisationally speaking, mining is far more complicated than the low-technology methods. There need not be any direct connections, but one cannot exclude the possibility of the low-technology methods in themselves generating experience and insight which, indirectly, contributed to the rapid development of mining. But the most important prerequisites were the political, economic and social conditions of the time, i.e. the influx of medieval civilisation and close links with the Continent. The establishment of a national system of government led to the dissemination of ideas and the setting up of an organisation, the establishment of towns and systems of control, and improved transport apparatus and new social systems. The growth of towns also facilitated technical innovations, and this is the perspective in which Swedish mining is to be studied.

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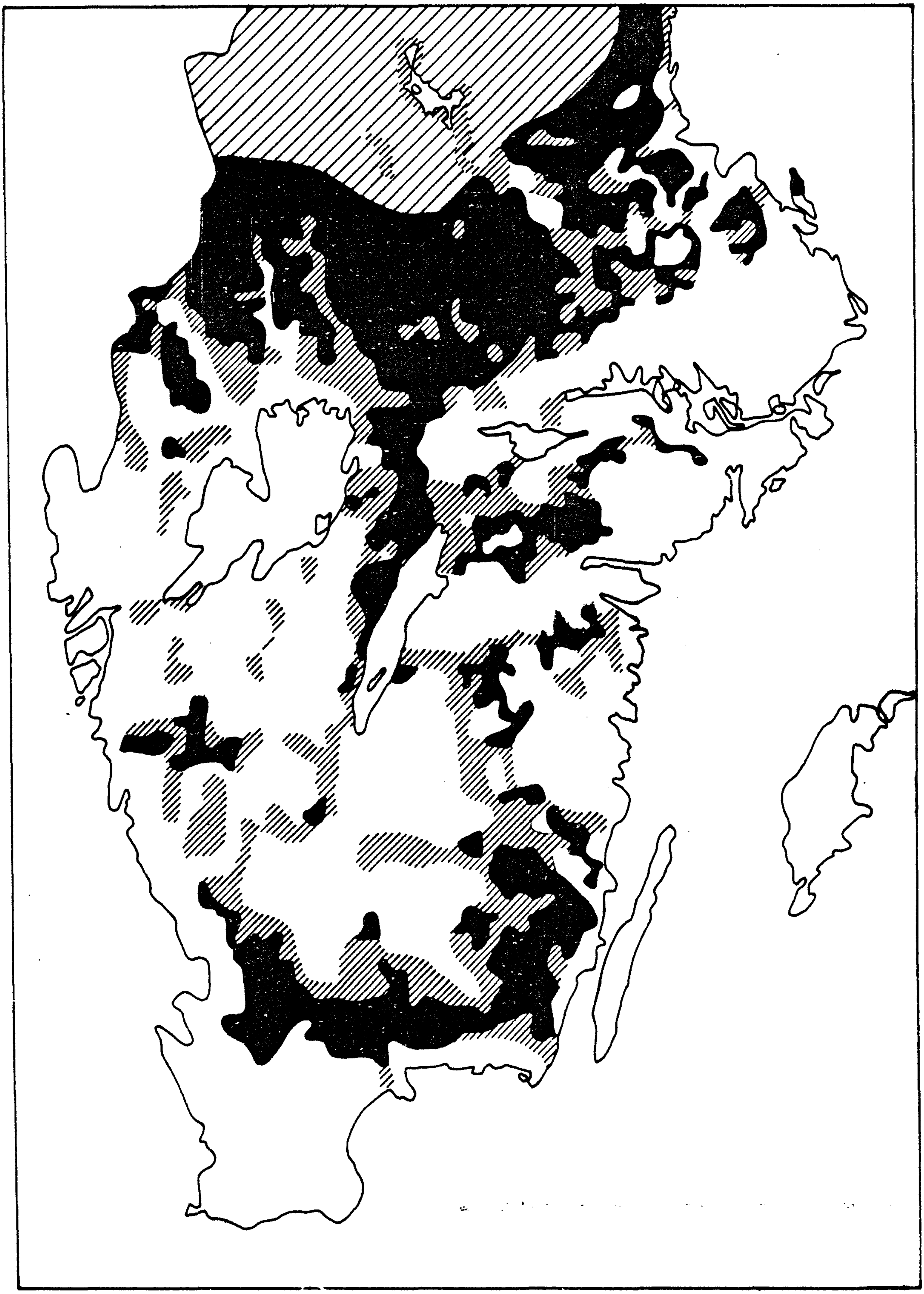
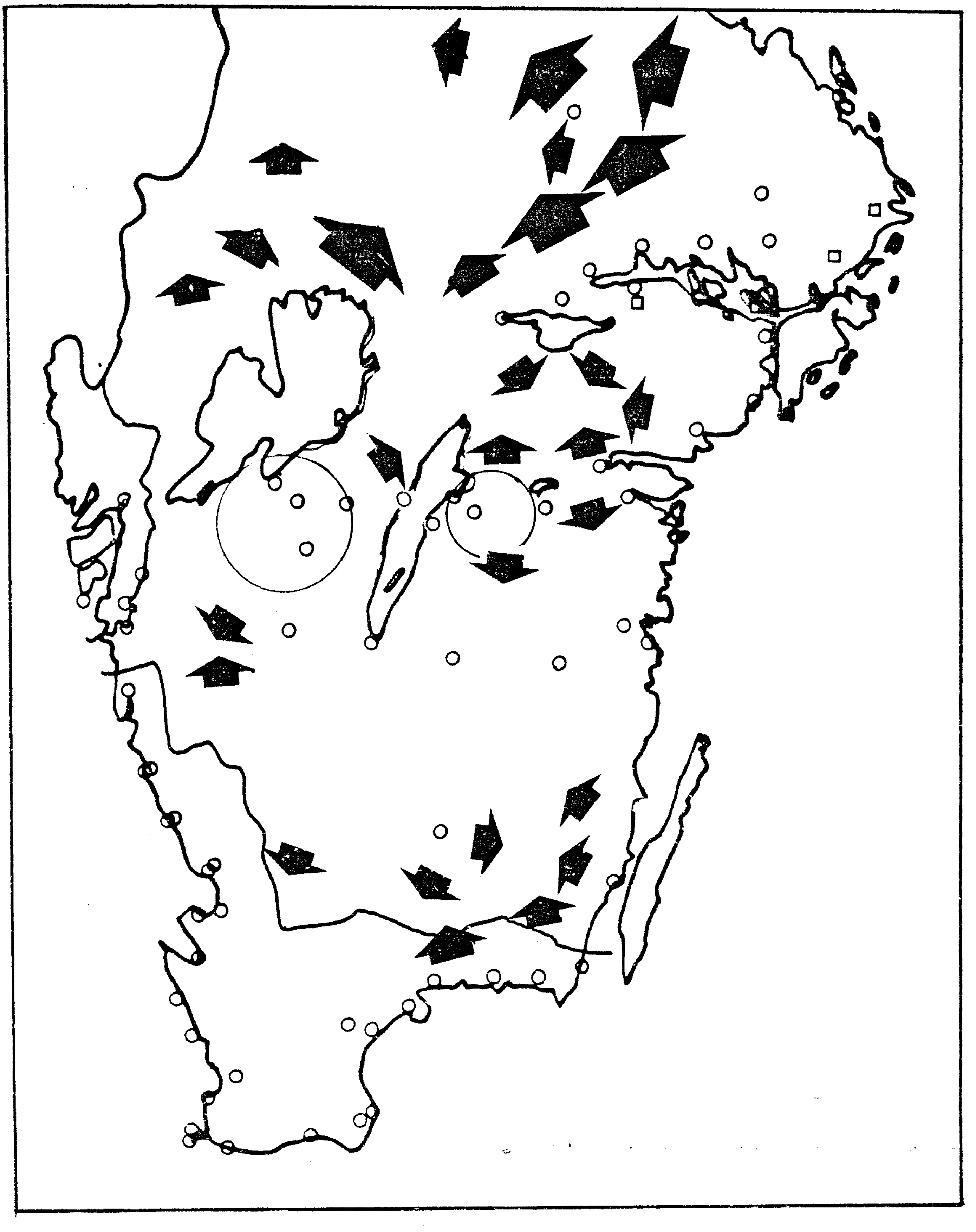


Areas without prehistoric graves (black) and areas with low frequency of graves (1-30 individual graves or 1-4 sites with graves).



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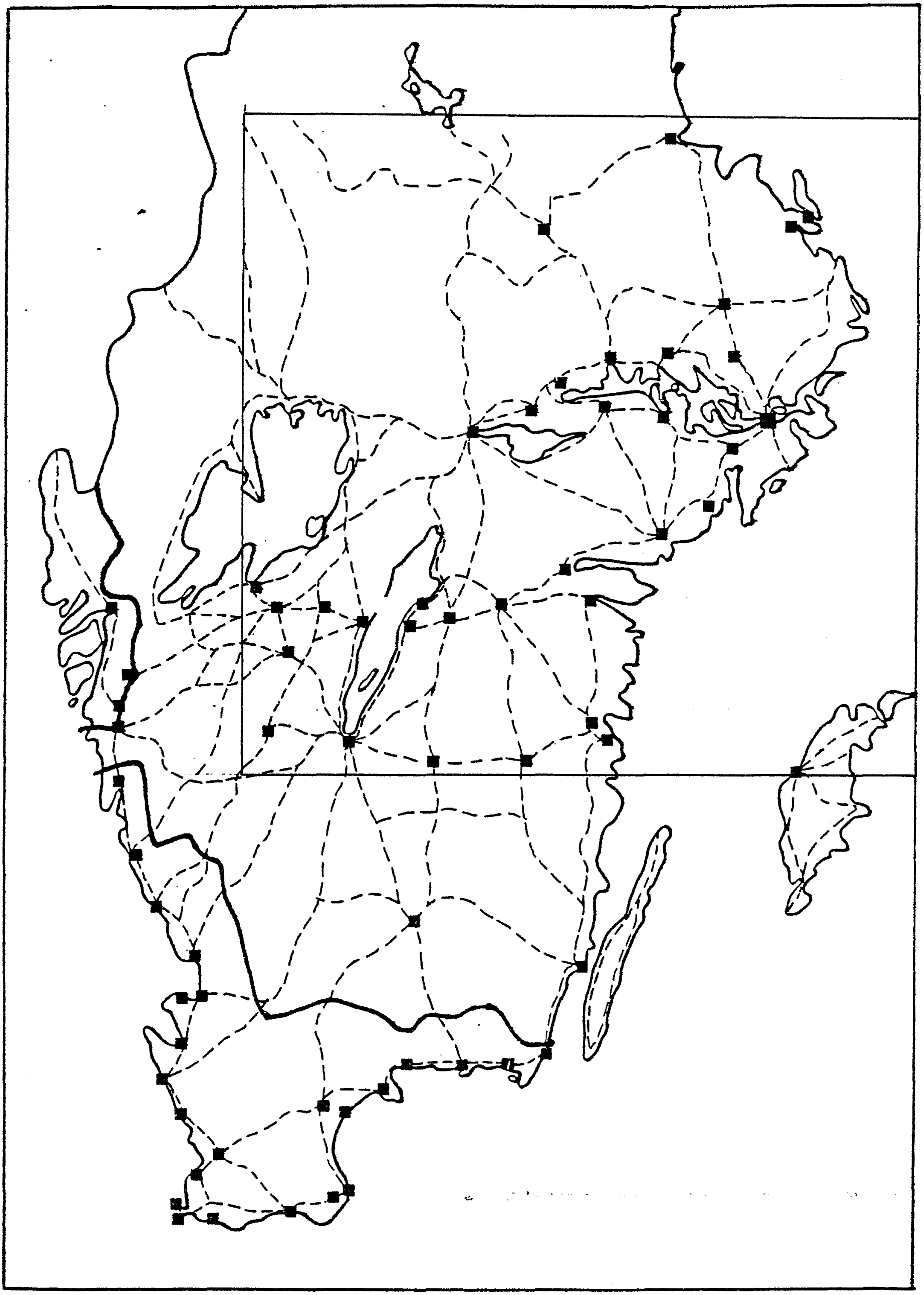

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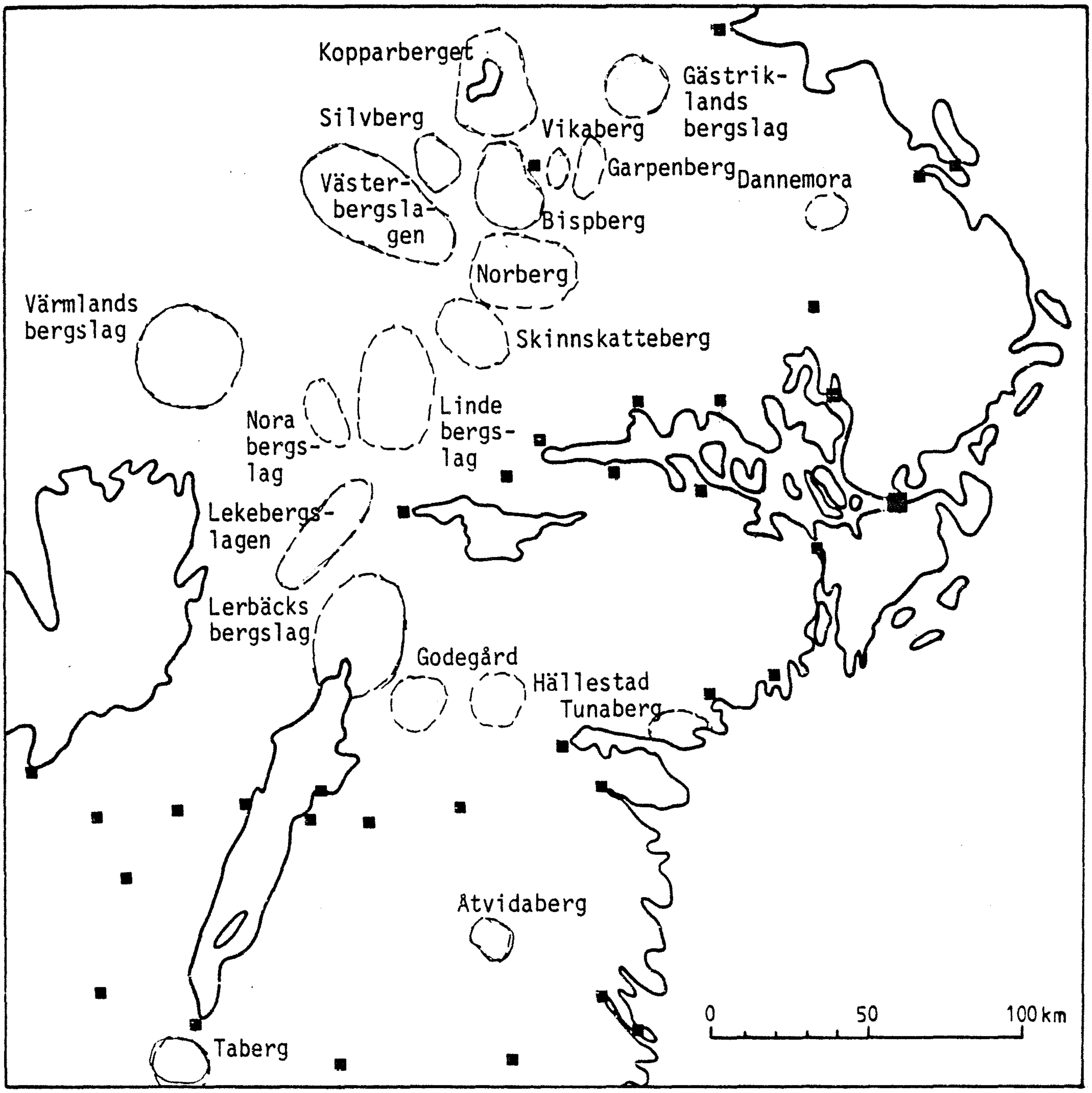

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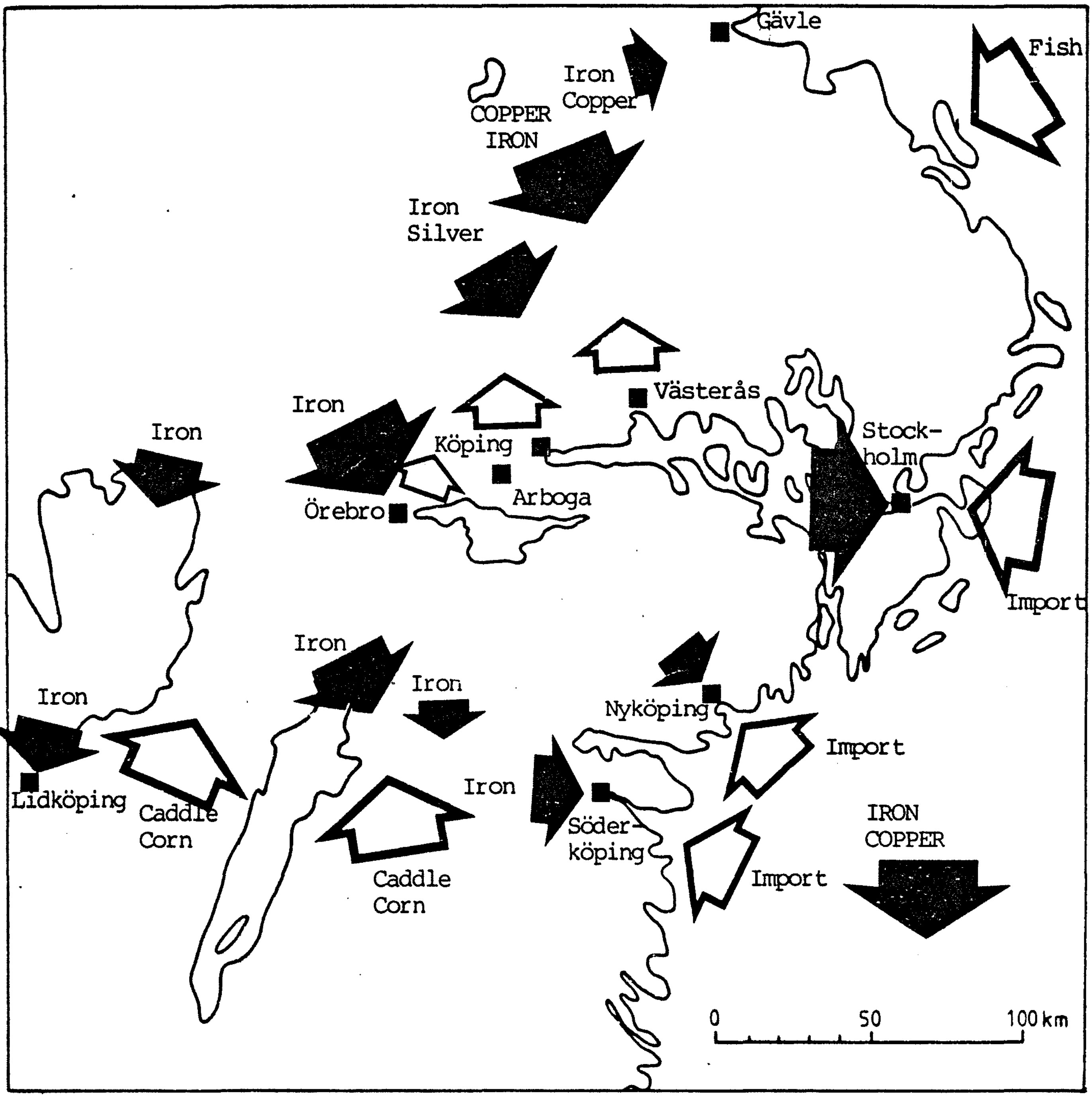

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