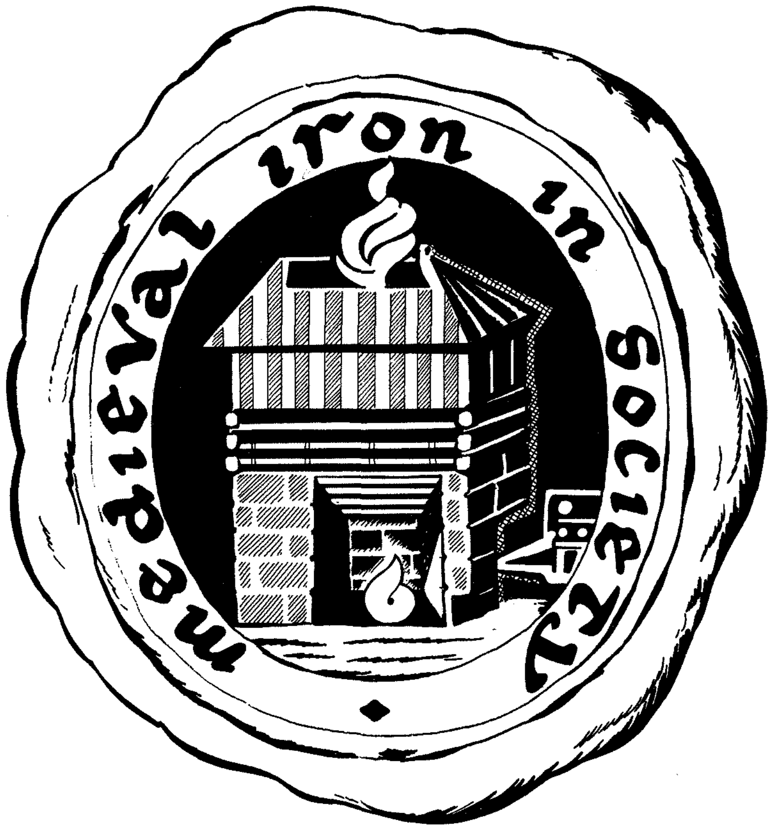
MEDIEVAL IRON IN SOCIETY II



Papers and discussions at the symposium in Norberg

May 6—10, 1985

JERNKONTORET AND RIKSANTIKVARIEÄMBETET

Jernkontorets Forskning H 39

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This volume contains papers not published in the preprints H 34 and discussions from the symposium.

THE DIFFUSION OF THE BLAST FURNACE PROCESS ACROSS WESTERN FRANCE IN THE 15th AND 16th CENTURIES

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S U M M A R Y

This paper deals with the introduction of the blast furnace or indirect process in France, particulary across western France from Normandie to the Loire area between 1450 and 1550. It presents first a rapid survey of the general problem for all the territory of France, and introduce some remarks about the period anterior to the beginning of the indirect process.

Though a few references prior to 1450 do exist, it does not appear that the Walloon type of indirect process was extensively known within the domains of what was then the kingdom of France before the second half of the 15th century. Earlier mentions can certainly be found, particularly in the duchy of

* I thank M. Brian AWTY for his reading and translation of my text from French to English (except the summary and the references).

Burgundy (1), which at that time was a powerful independent principality, and also very probably at an early period in Lorraine (2). But the implantation proper of the new process did not occur until the second half of the century, in some regions during decade of the 1450s, for example in the area of Beauvais and in the eastern part of Berry (3), near to Bourges, capital of the kings of France at the time of the English usurpation, and more generally after 1480, when the final repercussions of the Hundred Years' War had at last subsided.

Before approaching the specific problem of its diffusion in the west of France, a rapid survey of the geographical spread of the new process is necessary. There is no doubt that the blast furnace spread to France from the principality of Liege and that it appears to have spread from the North towards the South. Having been installed probably very early in the Ardennes (4), it spread in the west into Beauvaisis, in the east into to Champagne, and in central France into Berry. By the 1480s it had still reached the area of Châtillon-sur-Seine (5), that is to say the part of Burgundy which adjoins Champagne, and Upper Normandy in the Pays de Bray, in the Pays d'Ouche around Breteuil and in the Perche to the north of Chartres in the neighbourhood of Senonches. There is no doubt that these were the main regions of France which knew the new process from the period of the 15th century. But the expansion of the indirect process did not take place until the first half of the 16th century, which according to contemporary witness was a period of intense metallurgical development. A text of about 1540 points to the existence of around 450 ironworks, most of them established during the previous forty years (6). This development occurred not only towards the west, as we shall see in more detail, but also towards the east in Nivernais and into Franche-Comté, and also towards the west of central France in the western part of Berry, and probably also into Poitou.

This undoubted expansion of the Walloon indirect process, and the predominance which it gained at that time in France and in the neighbouring grand duchies, should not obscure the fact that meanwhile the ancient direct method continued its existence in several forms. Firstly, it is certain that in the areas which had gone over to the new process, small water-powered forges continued to exist throughout the whole of the 16th century alongside the new blast furnaces, operating the direct process under various nomenclatures which varied from region to region (7). It was above all the greater part of the southern part of France which remained faithful to the ancient process. In the Alps, in Dauphiné, a region which knew in the 17th century the Bergamasque process, wide-spread throughout the whole of northern Italy, the precise origin of the indirect process, apparently independent of Walloon technology, is not yet determined. But the first definite mention of a blast furnace of the Bergamasque type in Dauphiné does not date from before the end of the 16th century (8), so it does seem possible that the direct process may have persisted there during the first half of that century.

The situation is clearer for the south-west of France. In the Pyrénées, the direct methode remained up to the end of the 19th century under the name of the Catalan process. But it continued also further north, and even expanded at the time of economic recovery in the 16th century, in areas where metallurgical activity was to disappear later on, such as Aveyron (9), or even where, as in Agenais, it was to waver over ultimately into the indirect process (10). The latter continued to progress southwards, finally reaching the Pyrénées in the 19th century. Where was the frontier between the two processes at the end of the 16th century ? Probably between Poitou and Dordogne, a great metallurgical region in the 17th century, which was to specialize in the production of artillery (11), but of which little is known during the preceding centuries.

Metallurgy in the west before the blast furnace

As in many other regions of France, the west, that is to say Normandy, Maine and Brittany, had been a metal-working area from the most ancient times. It was on the basis of a metallurgical tradition well-attested for Celtic, Gallo-Roman and also Medieval times, that the revolutionary technique of smelting and fining pig iron began to be introduced from the fifteenth century. Though these ancient industries may not so far have been done the object of very profound study, it seems from what work has been done, that there were at least three main areas.

Firstly, in Normandy, the most ancient and most intense area of exploitation appears to have been the region of the Perche and the Ouche, which extended from the forest zone of Senonches north-west of Chartres as far as the neighbourhoods of Conches and Ferrières-sur-Risle in the Pays d'Ouche, taking in the environs of Rugles and l'Aigle. The latter towns were built on accumulations of cinders and slag. A historian of the 19th century, Vaugeois, suggested the existence of huge exploitations in Roman times at Saint-Nicolas-d'Attez and Mézières-de-Tourouvre in this region, well connected by highways to the neighbouring camps and cities (12). One can be equally certain of the continuing importance of this area during the Middel Ages by the existence of guild of Ferons with legal rights and privileges for all the forges situated between the Orne and Avre rivers (13). Exclusive rights to the proprietorship of all these forges belonged to six powerful lords called Barons fossiers, of whom three were ecclesiastics, and the concession of these powers proves the importance accorded to this metallurgical region by the dukes of Normandy, and later by the kings of France.

Another ancient centre was located to the north-west of Le Mans. An industrialist and engineer of the last century, Marcel Hedin, made a note of the localities where accumulations of scories and the remains of furnaces are to be found, particularly in the neighbourhood of the Forest of Sillé, some of which date from Gallo-Roman times (14). More recently, other remains of furnaces have been found in the woods of Lavardin, for which a Merovingian date (7th century) has been established by Carbon 14 dating (15).

The third centre was in the region of Châteaubriand in Brittany, to the south of Rennes. This important ironworking zone includes very many accumulations of scories, some of which were re-exploited in the 19th century. The engineer, L. Davy, used this opportunity to survey them systematically, and also attempted to establish celtic, Gallo-Roman and mediaeval datings for them, based on the pottery and coins found alongside. This region has recently been the subject of new work carried out under the auspices of the Inventaire général des monuments et richesses artistiques de la France, during which Jean-Yves Tinevez made a survey of all the metallurgical and mining remains in one of the forests, the Forest of Juigné (16). Similarly Claudie Herbaut has studied a 15th century text from which it has been possible to demonstrate the existence of manually operated forges in a neighbouring zone near to Ancenis (17).

These three ancient centres of metalworking, though they may prove to have been the most important, were not of course the only ones. Numerous place-names in the woodlands of Normandy, such as La Ferrière-aux-Etangs and Sept-Forges, are evocative of exploitation at least in mediaeval times. Mathieu Arnoux has studied activity during the 15th century at an important mine, that of Beaumont, near there, from which numerous local manually operated forges were supplied (18).

The spreading of the blast furnace in the West

The point has already been made that the indirect process progressed across France, especially in the West, from north to south. We shall see also that this progression clearly took place as a result of the process of local contact.

The point of departure was apparently the region of Beauvais, in the east of the Pays de Bray, where by 1451 three Walloon technicians had established a forge on the Avelon stream at a place called Le Becquet and a blast furnace or "fonderie" higher up the same stream (19).

Based on this initial centre, three neighbouring zones were newly converted to the indirect process, but not before the decade of the 1480s, which corresponds with the end in France of the wars between king Louis XI and the Duke of Burgundy, the veritable beginning of the modern age. The first of these zones is the western part, or Norman part of the Pays de Bray. The English researcher, Brian Awty, has located several blast furnaces and forges in the vicinity of Neufchâtel-en-Bray, principally at Neufchâtel itself, at Neuville-Ferrières, Nesle-Hodeng and Beaussault (20). The existence of ironworks in all these parishes is proved by documents of 1486.

A second zone is located in the Pays d'Ouche, to the west and south of Evreux. For these areas there are available two unquestionable references, the first of 1480 for Breteuil-sur-Iton, part of the royal domain (21), the second of 1489 for Trisay on the Risle, belonging to the abbey of Lyre (22). In addition to these definite mentions, it is possible that there were also very early blast furnaces at Bourth and at Ferrières-Saint-Hilaire, this last site in particular being a dependency of one of the Baronnies fossières, where we know that the ancient forges of the direct process were very rapidly displaced by blast furnaces (23). The abbey of Saint-Evroult, another Baronnie fossière, may have possessed one in the 15th century also, though the reference to a forge in 1493 is not itself sufficient proof (24).

The third and last zone is that of the Perche. There two indirect reduction sites are mentioned in unquestionable references. That of Randonnai on the Avre, near to Mortagne and the Abbey of Grande Trappe, from 1486 (25), and that of Dampierre-sur-Blevy, to the north of the Forest of Senonches going towards Dreux, of the same year, though in the latter case the proof of the indirect process is available only from the start of the 16th century (26). Nevertheless, here too, other early sites may be suspected, notably at Moulicent near to Longny-au-Perche, where there was an ironworks at the site of the present mill, and even more probably at Longny itself, where the well-known ironworks of the 17th century at the Beaumont site is referred to from 1537 (27), and may well have been built at the end of the 15th century. In these same region near to Mortagne, a "forge grossière a faire fert" was established in 1488 at Maison-Maugis, though it is still not possible to determine whether this is anything more than a water-powered bloomery (28).

Further to the east, as we approach the Forest of Senonches and the Pays Chartrain, that is to say, to the south-west of the attested site at Dampierre-sur-Blevy, the blast furnace of Moulin Renault at La Madeleine-Bouvet is regarded as one of the most ancient of the region (29). Moving towards the north-west on the fringes of the southern edge of the Forest of Senonches, the site of Ferrière at Manou on the river Eure is still obviously the site of what was an important forge.

Finally on the Avre, downstream from Verneuil, the forge of Bêrou is also considered as dating from the 15th century, though without authentic proof (30).

From all these mentions, certain or supposed, it seems incontrovertible that the indirect process was established in the Pays d'Ouche and the Perche from the last quarter of the 15th century, leaving aside for the moment the exact magnitude of the change and the extent to which the direct process survived. Furthermore, one can be sure that the blast furnace continued its expansion from the beginning of the 16th century, for example at Lallier near to Breteuil -a probable reference from 1500 (31)- and more certainly at l'Aigle, where a deposition of 9th June 1500 mentions that the Baronnie had the "right to large forges and to a blast furnace for making iron", a fact confirmed by a survey of 1530, "In the same Baronnie, there is a blast furnace where iron is made in sows ...; the said lord has the right and can have built on the said river (the Risle) a little below his blast furnace, a great forge for hammering and fining (the iron)" (32).

On the other hand the two most western zones of metal-working Normandy, that is to say the zone of Alençon which extends along the valley of the Sarthe as far as Le Mans, and the zone which runs from Argentan to Domfront, crosses the Mayenne and ends to the west of Laval, acquired the technology associated with the blast furnace, later than the Pays de Bray, d'Ouche and the Perche.

Clearly the area between Alençon and Le Mans acquired the new technology during the first third of the sixteenth century, with two references to its existence in 1534 for the ironworks of l'Aune at Douillet-le-Joly (33) and in 1537 for those at La Gaudinière at Sougé-le-Ganelon (34). both situated in the province of Maine. Probably the nearby Norman sites of La Roche Mabile and of La Bataille (at Saint-Céneri-le-Geret), reputed very ancient in the 18th century, were their contemporaries.

On the other hand, it seems that the group of more important works which extends from the vicinity of Carrouges into Mayenne was not properly converted to the indirect process until the second half of the 16th century. There is, in fact, a collection of almost certain reference for this zone; Carrouges, very probably 1556 (35); Cossé at Saint-Patrice-du-Désert, 1573 (36); Thury, 1580 (37); Rânes, a little before 1588 (38); Champ-de-la-Pierre, 1593 (39); Port Brillet, 1619 (40). In fact there is only one reference from before 1550, that of the ironworks of Halouze, which is said, with powerful arguments to have been built about 1530 (41); a hypothesis which accords well with the positive attitude, observed by Mathieu Arnoux, of the barons of Flers, proprietors of this works and of the forest of the same name, who had opened a mine and had a manually operated forge built in the same forest by 1474 (42). A little to the south, the ironworks of Chailland belonging to the duchy of Mayenne, and the property of the powerful dukes of Guise, are also referred to in 1550 (43). It seems possible, then, that a small centre of indirect iron-working may have appeared at a very early period in this western part of Normandy and Maine.

Further to the west, the heart of Brittany clearly remained faithful to the direct method for a long time yet, that is to say until the beginning of the 17th century in the central forests of Paimpont and the principality of Rohan (Loudeac, Lanouée, Quénécan), since the first large ironworks of the region, those of Salles, date from 1623 (44). Meanwhile, however, we know of two much earlier examples, both of them situated on the edge of the Armorican massif, and so much more easily accessible by river or from the sea. There seems no doubt that the very earliest site is that of La Poitevinière, near Ancenis, and to the north of Nantes. Thanks to the chatellenie accounts, Claude Herbaut has been able to work out an almost certain date for the introduction of the indirect process of around 1515 (45). The evidence suggests that this very early date is to be explained by the relative proximity of the port of Nantes, and also of the river Loire, which guaranteed communication with the more advanced provinces such as Maine, Berry, and even Poitou. The other site definitely converted to the indirect process, according to another document, before 1560, was that of Avaugour, near to Saint-Brieuc in northern Brittany (46). There too, proximity to the sea has obviously been the decisive factor.

CONCLUSION

This work of compilation, based almost entirely on the juxtaposition of information from archival sources, did not have as its final aim more than to establish a chronology for the diffusion of a technology, the introduction of which obviously had very important repercussions on industrial techniques and on the national economy. But quite naturally it raises more questions than it furnishes answers for.

As regards, first of all, the concrete description of the arrangement of blast furnace and finery forge, we remain very ill-provided because almost no archaeological work has yet been done on the ironworks of this period. One can presume simply that in the 15th and 16th centuries the furnace and the forge were usually placed at two quite distinct water-powered sites, and that the conjunction of the two which can be seen later at many ironworks was the result of a rearrangement made at the start of the 17th century, presumably as a consequence of increased mastery of water-power techniques. The separate situation is one that can be seen on the very early plan showing the iron-works at Rainvilliers near to Beauvais in 1508 (47). This plan shows a finery forge of a kind quite comparable with those which we know from the 17th century , but with only two wheels instead of four. Certainly we have here a representation which is to some extent only symbolic, but it does suggest the question as to whether the finery forge of that time had the same number of hearths as the later one. And as for the furnace (called at that time the fonderie in the pays de Bray, though the term haut fourneau was being used in the same period in the Pays d'Ouche), it appears to be rounded and not very high to judge from the number steps accorded to the ladder or charging ramp.

In addition to these technical problems, one can ask a larger number of related questions in the economic and social fields. Did the diffusion of the blast furnace perhaps change the relationship between ironworking and the forests; did it bring with it, as was to be the case later on, the appearence of new techniques of forestry management, with the gradual extrusion of all competing usages of wood from those forests which were directly linked to the ironworks ? The very early disappearance of the ironworks of the Pays de Bray, probably caused by an insupportable increase in the price of wood, seems to show that viability of wood supply had already become an essential factor in ironworking prosperity (48).

Another question, this time in the social field, is that of who were the proprietors and exploiters of the new ironworks. A knowledge of this might help us to understand better what were the agents through which diffusion of the new technology occurred. In some cases, the ironworks belonged to very powerful personnages, the King himself in the case of Breteuil, the dukes of Guise at Chailland, who could ensure inter-regional, even international exchanges. The Guise family notably were cousins of the dukes of Lorraine, a province very advanced in the mining, metallurgical and even forestry spheres.

But the evidence seems to be that it was the ironmasters themselves who were the decisive factor. We have seen earlier, that modern ironworking was brought to the Beauvais region by technicians from Liège and Namur. Others may also have operated in the eastern part of the Pays de Bray. Nevertheless, it seems probable that a network of autocthonous entrepreneurs must soon have been formed, familiar by long experience with all aspects of the new technology. It was they, rather than the foreigners who had taught them, who transferred the industry to neighbouring regions in its second phase (and even to England as shown by Brian Awty (49)),where once more the baton was taken up again by new ironmasters of local origin. These are nothing but hypotheses, but some examples can be cited in support : notably the case of Michel Le Feron who during the 1530s was involved in starting the ironworks of l'Aune (50), and who was probably descended from Henry Le Feron of Namur, one of the workers who set up the forge at Le Becquet in the Beauvaisis around 1450; or the case of Jacques Tremblay, one of the first ironmasters at La Poitevinière, presumably related to Gervais Tremblay (51), ironmaster at Randonnai from 1486, an excellent example of a very long migration, from the Perche to Brittany, until then totally without experience of the indirect process.

These are examples of some of the questions set us by this major problem of industrial history, and we must hope that they will lead on to the fruitful researches which are to come.

R E F E R E N C E S

1. Serge Benoît has found about the forge of the Abbey of Bèze near Dijon the mention : "fondre, affiner et forger" in 1427. Unpublished paper.
2. Alain Girardot : A propos d'un bail de forge en 1391 : fonte et forges hydrauliques en Lorraine au XIVe siècle. Annales de l'Est, tome XXVIII.
   This paper proves the existence of water-powered forges and production of pig iron, but not of the indirect process.
3. Mention of a lease in February 1451 of a "fondouère" and two "affinouères" at Précy, Archives of Cher, E 120 (reference communicated by Patrick Léon).
4. In fact no evidence had been yet discovered before the beginning of the 16th century (I refer to the work in progress of Louis André).
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   Denis Cailleaux has schown, for example, the persistency of the direct process in the area of Sens (Western Burgundy) in the first half of the XVIth century, despite a intensive development during this period.
   Denis Cailleaux : L'industrie du fer en Senonais et forêt d'Othe à la fin du moyen-âge. Actes du 109ème Congrès des Sociétés Savantes. Dijon (1984).
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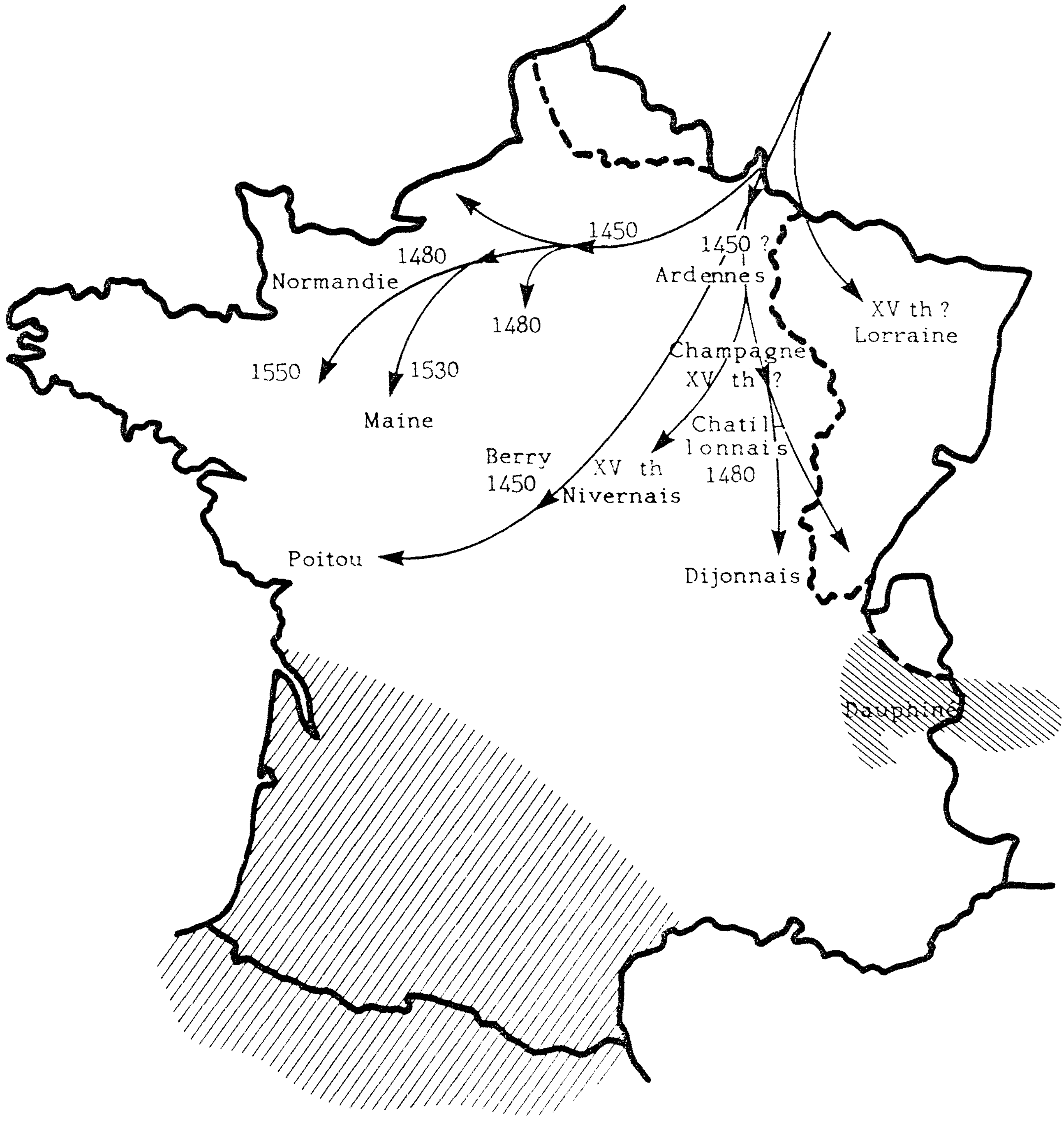
THE SPREADING OF THE BLAST FURNACE ACCROSS THE FRENCH TERRITORY

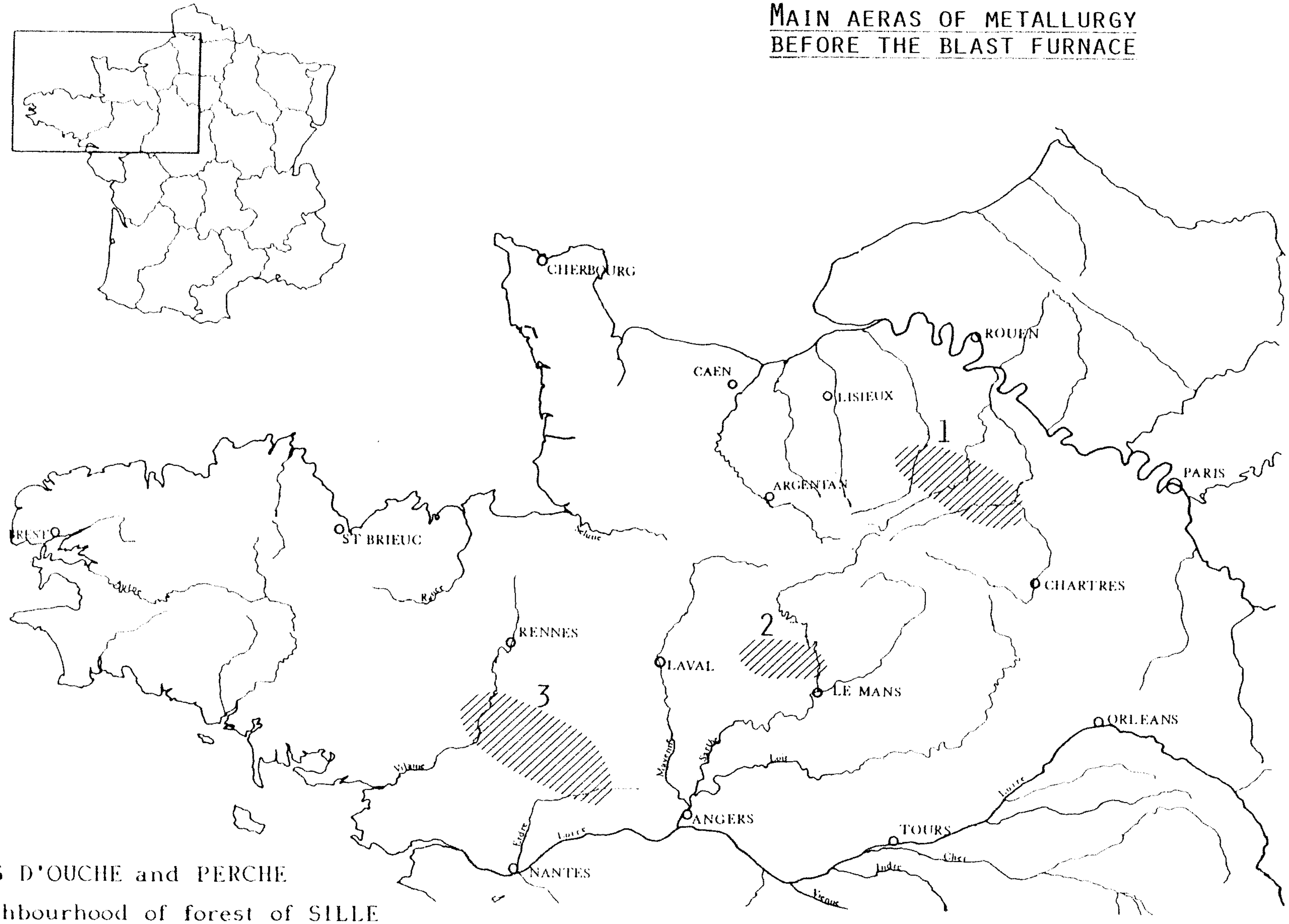


▬ ▬ Approximate boundary of the kingdom of France in 1500

\\\\ Bergamasque process

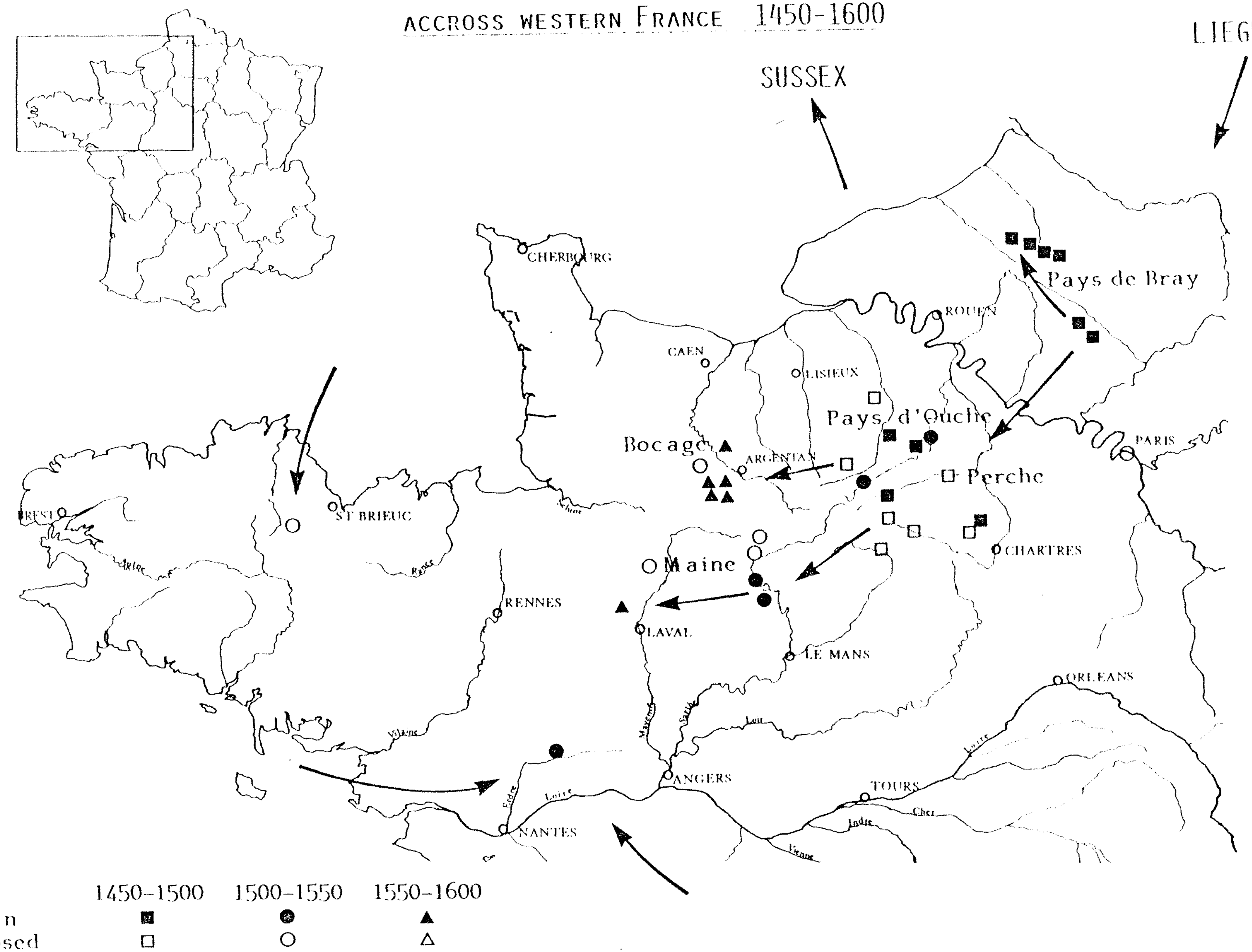
//// Catalan process

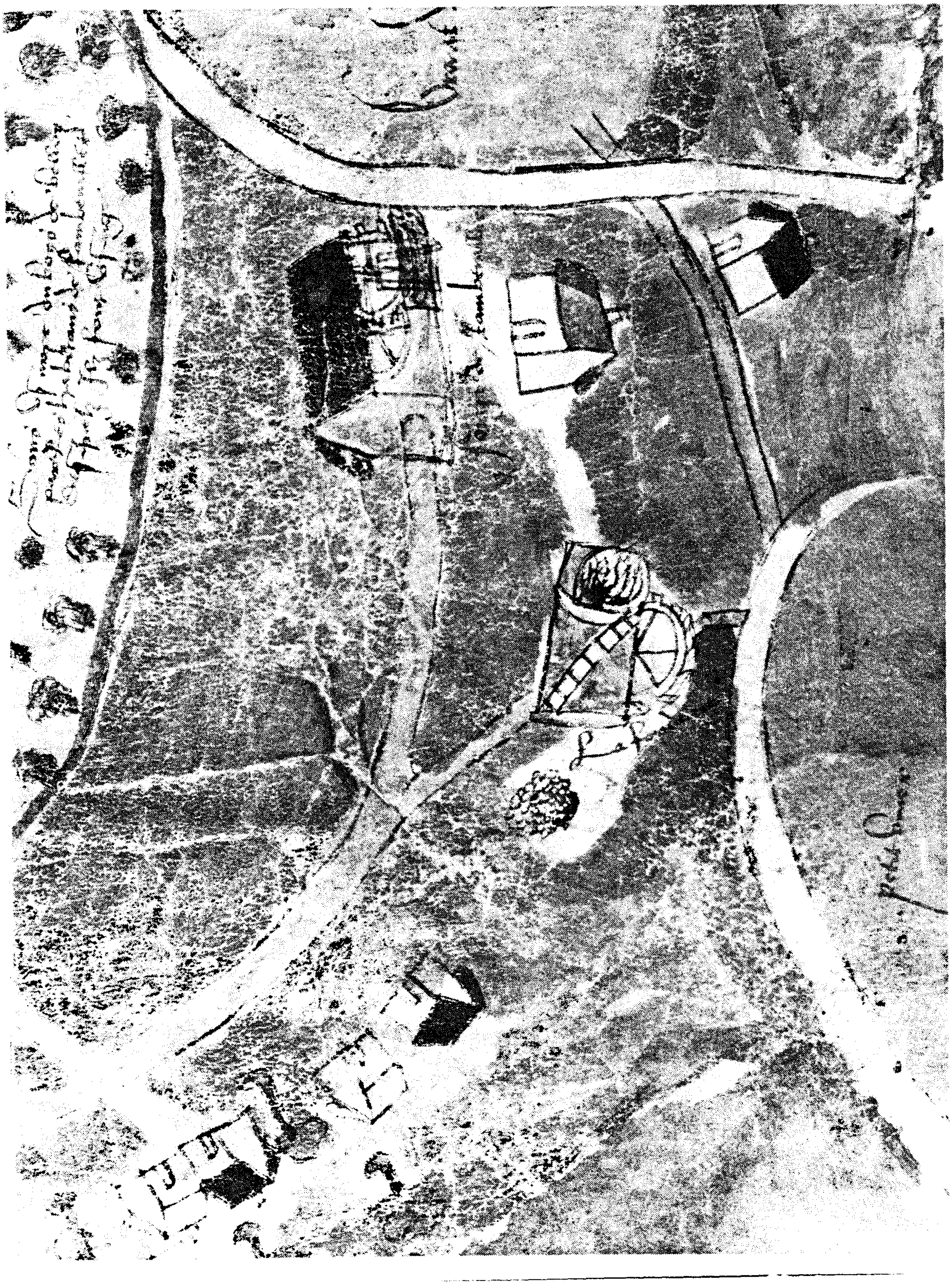
MAIN AERAS OF METALLURGY BEFORE THE BLAST FURNACE



1 PAYS D'OUCHE and PERCHE
2 Neighbourhood of forest of SILLE
3 PAYS DE CHATEAUBRIANT

THE DIFFUSION OF INDIRECT PROCESS ACCROSS WESTERN FRANCE 1450-1600





1. Detail of a map of the forest of Belloy, 1508 (Archives de l'Oise). It shows the "fonderie" and the "forge" on separate sites, below two ponds. Note the two wheels of the forge and the seven steps of the charging ramp (communicated by Jean Cartier, Ecomusée du Beauvaisis).

2. The mill of Hodeng, near Neufchâtel-en-Bray, with the foundations of the ancient blast furnace (XVth or XVIth century) (discovered by M. Brian Awty). (Cliché Inventaire général de Haute-Normandie, C. Kollmann).

3. The site of the blast furnace of Beaussault : Vestiges of the furnace and the dyke of the ancient pond. A very interesting example for an excavation. (Discovered by M. Brian Awty). (Cliché Inventaire général de Haute-Normandie, C. Kollmann).

EARLY IRON PRODUCTION IN NORTH WEST WALES

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'As the hunger for fuel increased ironmasters were forced to migrate into more remote lands; salvation could only be found in solitude, and the industry of smelting and refining was literally fleeing to the wilderness to escape destruction.'

Public Record Office, Star Chamber, 8/223/17 (1606)

SUMMARY

Mineral extraction has always been one of the mainstays of the Welsh economy. The development of the iron and steel industry in the south and north-east of Wales in well known. The north-west is best known for its non-ferrous metals - gold, copper and lead - and the production of iron has been limited to a very small number of sites of little economic importance. There are, however, a well preserved range of field monuments dating from the prehistoric period to the early eighteenth century which illustrate the technological development in the production of iron.

These include an important group of medieval bloomeries situated on the monastic lands of the Cistercian abbey of Cymmer, near Dolgellau. The abbey was founded in 1199 and was endowed with extensive tracts of land by the native Welsh Princes. The abbey's charter includes specific privileges for the extraction of minerals. There are also two bloomeries of 14th century date on Crown land, one of which was excavated by Oliver Davies some 50 years ago.

The earliest blast furnaces in Wales are of mid-16th century date and the ruins of a number of these survive today. The only example in the north developed from one of the Cistercian sites at Dol y Clochydd, which may have been built for the production of arms for Ireland. Dol y Clochydd is the best preserved complex of its date now surviving in Wales and recent excavations have provided new data on the form of the early blast furnace.

Introduction

Much of north-west Wales is mountainous country of marginal agricultural value. This has resulted in the survival of a very wide range of field monuments from all periods, including those for iron production, which in other areas have generally suffered from the effects of agriculture or subsequent industrial development. We have, then, in this region a number of well preserved iron-working sites of a variety of dates, which are particularly valuable for the archaeological information they can provide (Fig. 1). The earliest so far recognised is the late-prehistoric hillfort of Bryn y Castell, which is producing extensive evidence for iron smelting and bloom smithing (Crew, 1985) and there are a number of Romano-British farmsteads at which iron production seems to have formed an integral part of their activities (Kelly, 1976). Recent fieldwork has resulted in the discovery of a number of bloomeries on the lands of Cymmer Abbey and a late 16th century blast furnace which developed from one of these Cistercian sites. These are described further in this paper. The latest surviving site is the early 18th century charcoal blast furnace at Dolgun, designed and built by the famous Abraham Darby on Quaker land near Dolgellau, well known from the diaries of its manager John Kelsall (Raistrick, 1950, 125). This site has recently been excavated and consolidated by the Snowdonia National Park Study Centre (Crew and Williams, 1983).

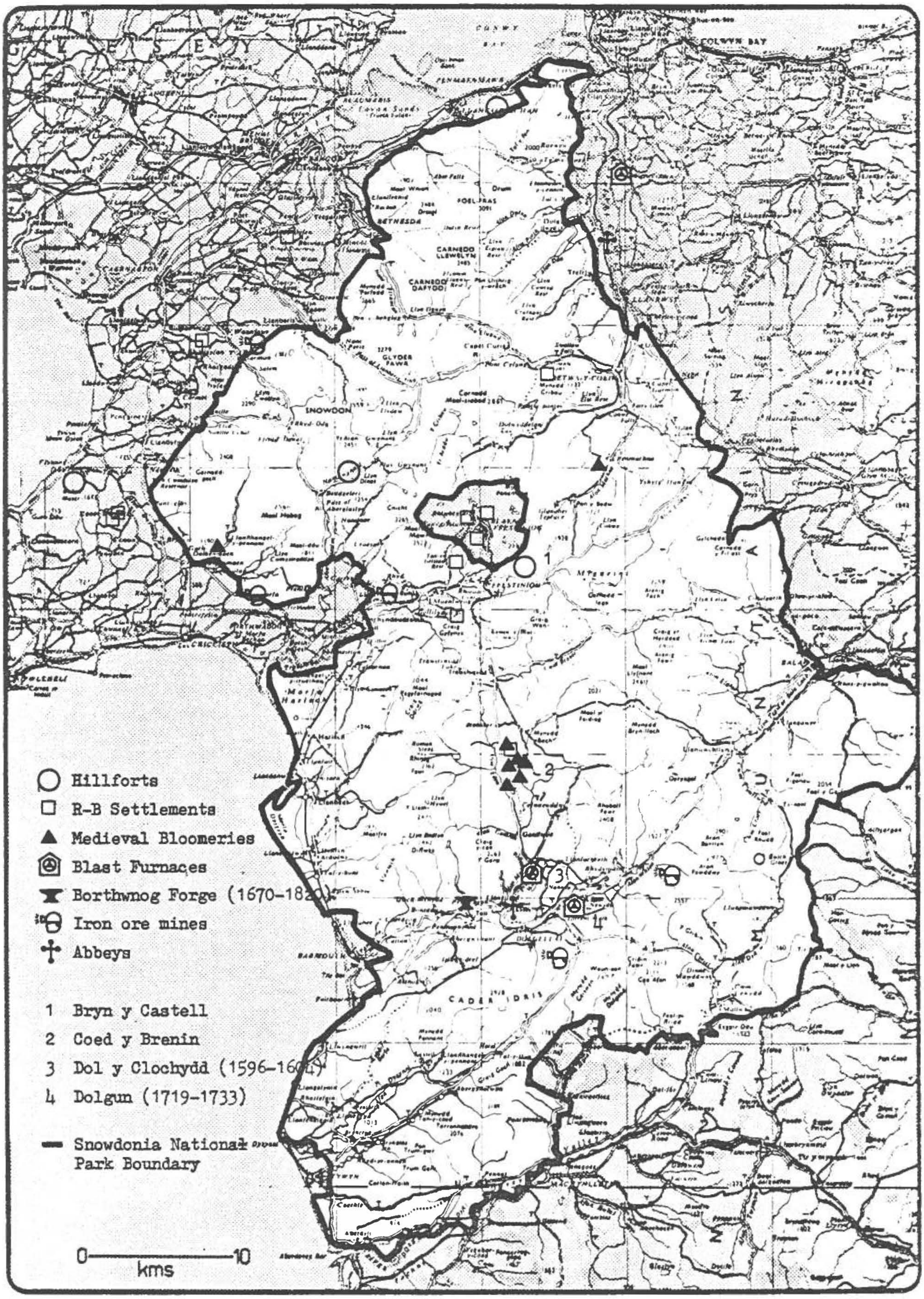

Fig. 1 Iron working sites in north-west Wales

Medieval Bloomeries

The historical documentation for these sites is sparse and has not yet been studied in detail. Two bloomeries are known to have been in operation on Crown land during the 14th century (Rees, 1968, 37, 40). The site of one of these is known, in the medieval township of Dolbenmaen, and was excavated in 1939 by Oliver Davies (Davies, 1948). It consisted of an oval mound of characteristic bloomery slag, some 25m by 15m and up to 2m high, with a central depression in which the base of a furnace was found. It was estimated that the weight of slag in the mound was some 200 tons, perhaps indicating that as many as 1000 charges of ore would have been smelted. This bloomery is situated on an exposed shelf, high on the slopes of Y Garn, where there is no source of water capable of driving a wheel. As it is unlikely that there are any suitable local sources of ore, the siting would appear to have been chosen for its abundant local timber supplies.

Further south, in the area now known as Coed y Brenin (King's Wood), a number of bloomery sites survive amongst the modern conifer plantations of the Forestry Commission. In medieval times this area formed part of the lands of the Cistercian abbey of Cymmer, founded in 1199 and endowed with extensive tracts of land by the native Welsh Princes. The abbey's charter survives in a later inspeximus and among the privileges were 'as a lasting gift ... the rights in digging out and carrying away metals and treasures in mountains and groves' (Williams-Jones, 1957). The Cistercians in Wales, as elsewhere, were engaged in the mining and smelting of various minerals (Williams, 1969, 78). The Coed y Brenin area is, of course, well known for its production of copper and gold in the 19th century, but there is little evidence for any earlier activity. However, recent discovery of crushed and washed fines in a stream bank immediately adjacent to the abbey may indicate a monastic involvement with non-ferrous metals. There are, unfortunately, few documentary references to iron working, though it is known that Cymmer had two forges in the late 14th century in the parishes of Llanfachreth and Trawsfynydd (Schubert, 1957, 129). In 1392 the latter produced 82 'twelfth pieces' of iron (Williams, 1981, 154). These forges were said to be 7½ and 8 miles from the furnace, though this statement is difficult to reconcile with the field evidence presently available.

In the Mining Journal (1887, 1519-21) is a description of the Gwynfynydd Gold Mine area which mentions 'eight hillocks of iron slag' on the crest of the ridge to the west of the mine. Six of these have now been discovered, all comprising of characteristic bloomery slag, and these seem likely to have been furnaces for the Cymmer forges (Crew, 1984). The best preserved of these is some 2m high, with an associated charcoal burning platform. All of the sites have one element in common in that they are situated in exposed locations away from water sources, which suggests that the bellows were man-powered. All of the sites are situated quite close to each other, along the line of the early (and putative Roman) road through this area, within a distance of 1.5km. This may suggest that the furnaces were being opened in sequence, using locally coppiced timber in a regulated cycle. It is also notable that each of the bloomeries lies on the land of different (modern) farmsteads. Whether this might have been the case in medieval times is not yet clear, but it may have some bearing on the way in which the furnaces were operated.

The sites of the two forges mentioned in the documentary evidence are not known, but there are two further sites which have produced bloomery slags whose locations are markedly in contrast to the six bloomeries mentioned above. These are both situated in low-lying positions adjacent to large rivers, at Dol y Gefeiliau (the smith's meadow) and Dol y Clochydd (the sexton's meadow). The former is traditionally a site where the drovers of later centuries shoed their cattle for the long trek to the English markets but the quantity and type of slag seems more in keeping with medieval iron production. Unfortunately the site has been destroyed by recent road works through this narrow valley. The latter site, which will now be described, was converted into a blast furnace in the late 16th century.

Dol y Clochydd - historical notes

The first half of the 16th century was a time of radical change in the political, social and economic aspects of Wales. The Act of Union between England and Wales and the Dissolution of the Monasteries provided two of the stimuli which enabled the Welsh gentry to prosper and build up their estates. One such family was that of Nannau, near Dolgellau, whose estate was enlarged by the aquisition of much of the lands of the abbey of Cymmer. One of the parcels of land aquired by this family was leased by the last abbot of Cymmer in 1534, eventually to become the property of Hugh Nanney and his son (Rees, 1968, 282) and this included the iron works at Dol y Clochydd.

In 1588 the iron works was leased by Hugh Nanney to two English speculators, John Smith of Newcastle-under-Lyme and William Dale, a London grocer, together with all the trees on Penrhos Common, a low hill 'adjoining the said iron mill'. Although Hugh Nanney was sheriff of Merioneth from 1586 and was busily establishing himself as one of the most prominent men in the county he does not appear to have been over scrupulous since the trees on Penrhos Common in fact belonged to the Crown! Hugh Nanney eventually found himself facing a charge of the theft of this timber in the court of Star Chamber, for which he was to receive two years in the Fleet Prison and a fine of £1500, which was later reduced to £800. Fortunately, from our point of view, the Star Chamber records include some details of interest in relation to the iron works. These documents have been studied in some detail by Bryn Parry (1963; 1967) on whose work this summary is based.

It was claimed that, between 1588 and 1603, some 30,000 oaks were taken from Penrhos Common. Hugh Nanney and his son were found guilty of taking 10,000 of these, valued at three shillings each, hence the £1500 fine. There was some dispute, however, over the quality of the trees, which were claimed not to be suitable for coaling and difficult to remove from the steep rocky hill. The carpenter, brought by John Smith from Shropshire, claimed that the wood was of such poor quality and size when squared, that much of the 150 tons of timber used to build the iron-works was brought from elsewhere. It would seem that from 1588 to 1596 the site was being operated as a bloomery, for in that year Smith took out a new lease for 21 years on the iron works and modernised it by converting it into a 'blast furnace with forges' using capital obtained from William Dale and a William Grosvenor of Shropshire. This project appears to not have been successful, however, as Smith made no profits and the furnace ceased to be worked in 1604.

It is of interest to speculate why these Englishmen came to build their blast furnace in this particular part of north-west Wales, which as late as 1700 was referred to, perhaps unkindly, as the 'fag-end of creation'. The mid-16th century expansion of the iron industry outwards from the Weald, under the dual stimulus of timber shortages and an increased demand for naval ordnance, was primarily concentrated in areas like the Forest of Dean, Glamorganshire and the Midlands where the new timber supplies were augumented by local sources of ore (Schubert, 1957, 173 ff.).

In Merioneth there are no rich sources of local ore and additional factors must have played a part. Furthermore, although there were quite substantial imports of both Spanish and English iron into North Wales during the late 16th century, the former probably to supply the growing shipping industry (Lewis, 1927; Rees, 1968, 299), local demand would not seem to have been sufficient stimulus.

The answer may lie in Hugh Nanney's entrepreneurial activities, coupled with a knowledge of the local tradition of iron production and a desire to capitalise on the resources at his disposal. Amongst his contacts in London he was patronised by Sir James Croft, formerly Lord Deputy of Ireland and Comptroller of the Royal Household under Elizabeth (Parry, 1967, 194) and William Grosvenor, one of the backers of the project, had forges and warehouses in Chester, for the supply of arms for use in Ireland. It seems probable that the Dol y Clochydd furnace was built to supply iron for Grosvenor's forges if, indeed, the furnace was not used for casting ordnance, as would be quite likely at this date.

From an archaeological point of view, of course, this furnace is especially interesting in that it was only in use for a very short period of time, for some eight years only. It is thus likely to provide useful data on the form of the late 16th century blast furnace in Britain, as relatively few sites of this date survive much above foundation level. It is only recently that this site has been correctly identified and its potential realised. Both the Royal Commission (R.C.A.M., 1921, 106) and Schubert (1957, 129) thought it to be one of the forges or furnaces attached to Cymmer Abbey. The discovery of glassy slags in the river bank and, now, excavation have proved that Dol y Clochydd is the blast furnace referred to in the Star Chamber case.

Dol y Clochydd - site description (Fig. 2)

The ironworks are situated on a narrow shelf on the east bank of the River Mawddach, some 4km north of Dolgellau (SH 734 220). This shelf is backed by very steep slopes preventing access to agricultural machinery, which is undoubtedly the reason why the site survives in good condition. There is little evidence for activity since the abandonment of the furnace, apart from a small level and buddle for copper extraction of 19th century date and a series of narrow ridges across part of the site, probably due to spade cultivation but of unknown date. The area is now heavily wooded and used only for rough grazing.

The furnace survives as an oval grass-grown mound, 12m by 10m, standing some 2m above the surrounding ground level. The centre of the furnace had been partly dug out on some previous occasion, for which there is no record, exposing a section through the boshes and the upper part of the hearth. The excavations carried out in 1984 were limited by the presence of large trees but a half-section across the mound fell fortuitously across the blowing arch and enabled the complete excavation of the tapping arch. Using this information a tentative reconstruction of the layout of the site can be attempted.

Some 5m up the steep bank to the east of the furnace is a large level platform, some 20m by 6m, which is undoubtedly the site of the charging platform. Spilling downslope from the south end of this platform is a scatter of fragments of bloomery slag broken to a small size, typically 2cms maximum, presumably for addition to the charge. At the north end of this platform is a marked gully cutting into it, and the slope above, perhaps indicating the take-off point for a launder to drive the wheel. The 19th century buddle is some 200m to the north and was driven by a small waterwheel fed by a well-constructed leat. This may have followed the same course as the leat for the furnace, but there is now no trace of it on the very steep slopes between the two sites.

Although there are no indications of the wheelpit visible at ground level (there are substantial deposits of hillwash at the foot of the steep slope) its position can be inferred from the location of the blowing arch and the gully on the charging platform. This would allow room for the tail race to pass behind the furnace debouching, via the wet hollow, into the flood channel. A tail race in this position would also accumulate ground water from the steep slopes above, perhaps explaining why the furnace was built so far away from the foot of the

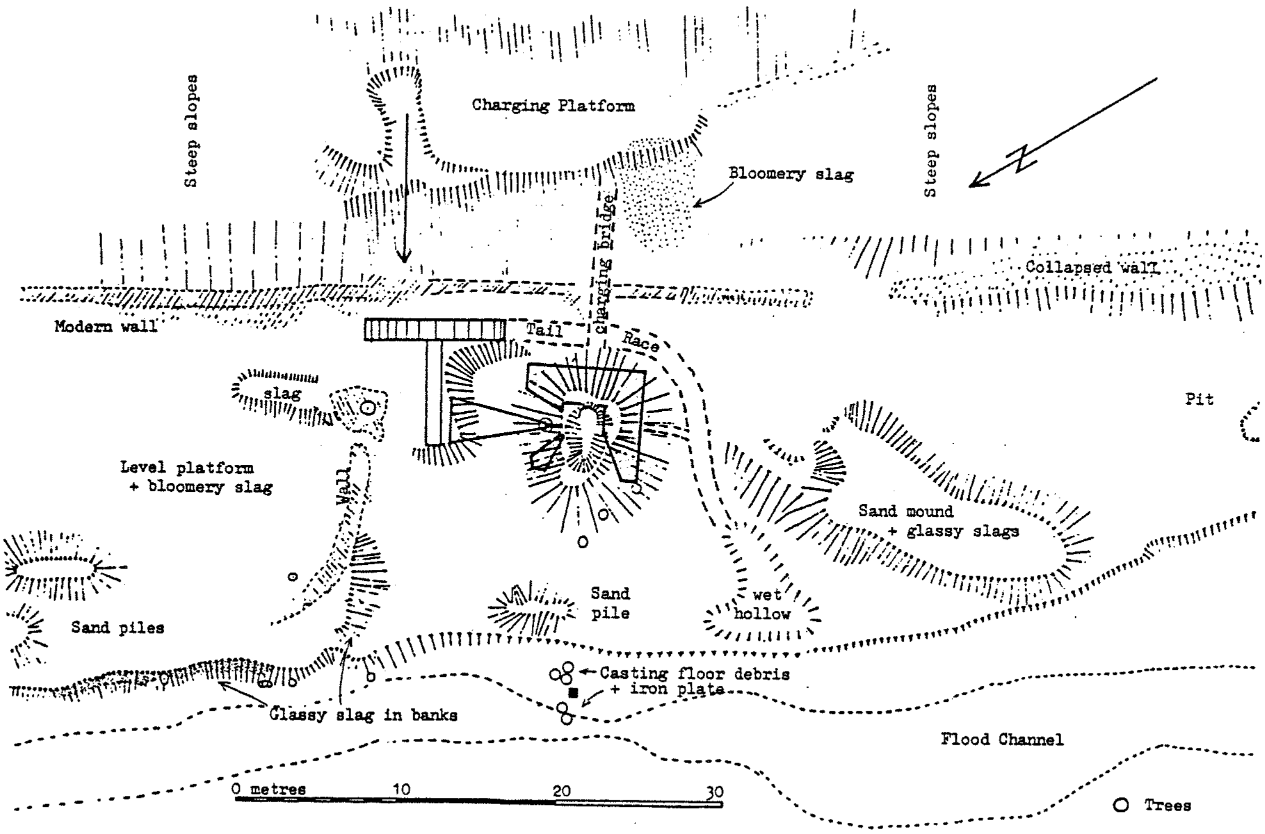

Fig. 2 Dol y Clochydd site plan

bank. The distance from the front of the platform to the furnace centre is some 16m, which gap was presumably bridged by a timber barrow run. The height difference between the platform and the hearth slab is 5.1m, indicating the effective height of the furnace.

There are a number of other features surviving, of less certain function. To the immediate north-east of the furnace is a short steep slope, an angular S-shape in plan, which probably reflects the position of the bellows house. To the north of this, at a slightly higher level, is an area some 20m square covered by small fragments of bloomery and blast furnace slag. This area seems to have been levelled and was probably the site of ancilliary buildings. The western edge of this area has been partly eroded away by a flood channel of the main river, exposing large quantities of transluscent green glassy slags. To the south of the furnace is a long irregularly shaped, but level topped, mound of sand. Inspection of part of this mound, where it has been eroded away, showed it to contain small fragments of glassy slag. It seems likely, therefore, that this mound comprises of dumps of sand from the casting floor, though the quality of the sand does not seem especially suitable. To the south again is a 1m deep steep-sided pit, though it is not certain if this is a contemporary feature.

<u>Dol y Clochydd - 1984 excavations</u> (Figs. 3,4)

The overall dimensions of the furnace are approx. 6.8m. The furnace pillar is especially slender and does not appear to extend to the full limit of the corresponding sides of the tapping and blowing arches. It may be that a series of vertically set timbers, as at Sharpley Pool Furnace, Worcestershire, or timber strapping based on corner posts, as at Chingley Furnace (Crossley, 1975) may have completed the design, but examination was limited by tree roots which will be removed in 1985. The furnace casing was built of rounded river boulders,

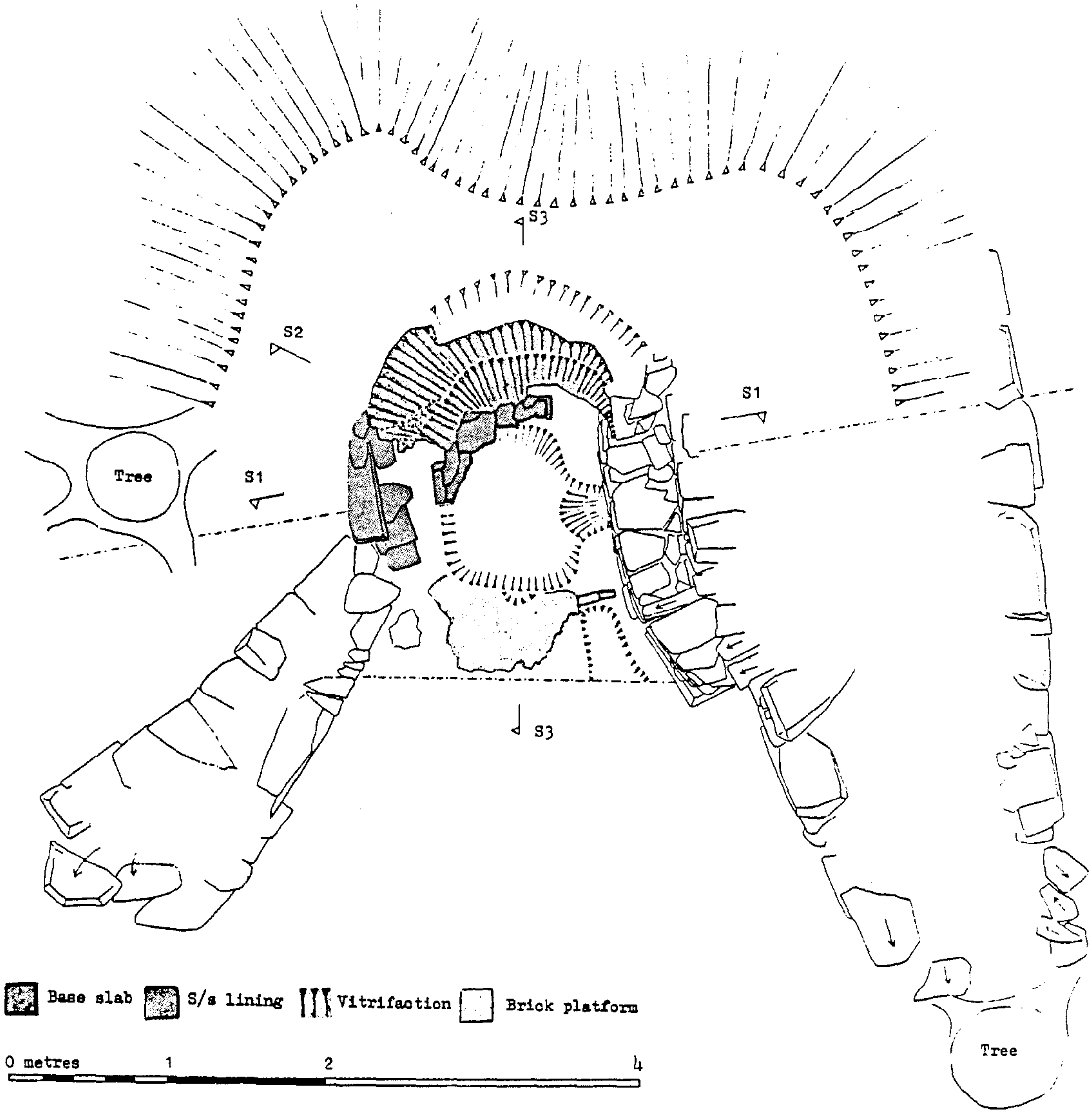

Fig. 3 Dol y Clochydd, 1984 excavation plan

roughly coursed, with a rubble core. The hearth cavity was originally 1.8m square, but with an inserted wall reducing the width on the tuyere axis to 1.3m. It is not clear if this was an original design feature, or a later amendment, but it recalls a similar reduction in size at Chingley (Crossley, 1975, Fig. 17) though in this case apparently on the tapping axis. This inserted wall was extended into the tapping arch area by a pillar of similar width, which may have been a secondary repair to provide additional support for the (unknown) roofing arrangements over the tapping arch. It is notable that the splay of the walls of the tapping arch and blowing arch are not symmetrical.

It was found that the front wall, the hearth slab and most of the contents of the drainage pit had been removed in antiquity. The drainage arrangements seem to have been very simple. Beneath the hearth slab was a rectangular pit filled with a coarse grey sand, with a 30cm diameter channel leading away under the south wall of the furnace. This was completely choked with yellow clay and may indicate that the demolition of the furnace was due to a failure of the drain and an intention to repair the hearth. This appears not to have been carried out, however, as the furnace superstructure subsequently collapsed into the empty drainage pit. Despite this demolition, enough detail of the hearth survived to attempt a three-dimensional reconstruction.

The lining was constructed of dressed red sandstone blocks, which material does not occur locally and was probably imported from Cheshire or the Midlands. Just

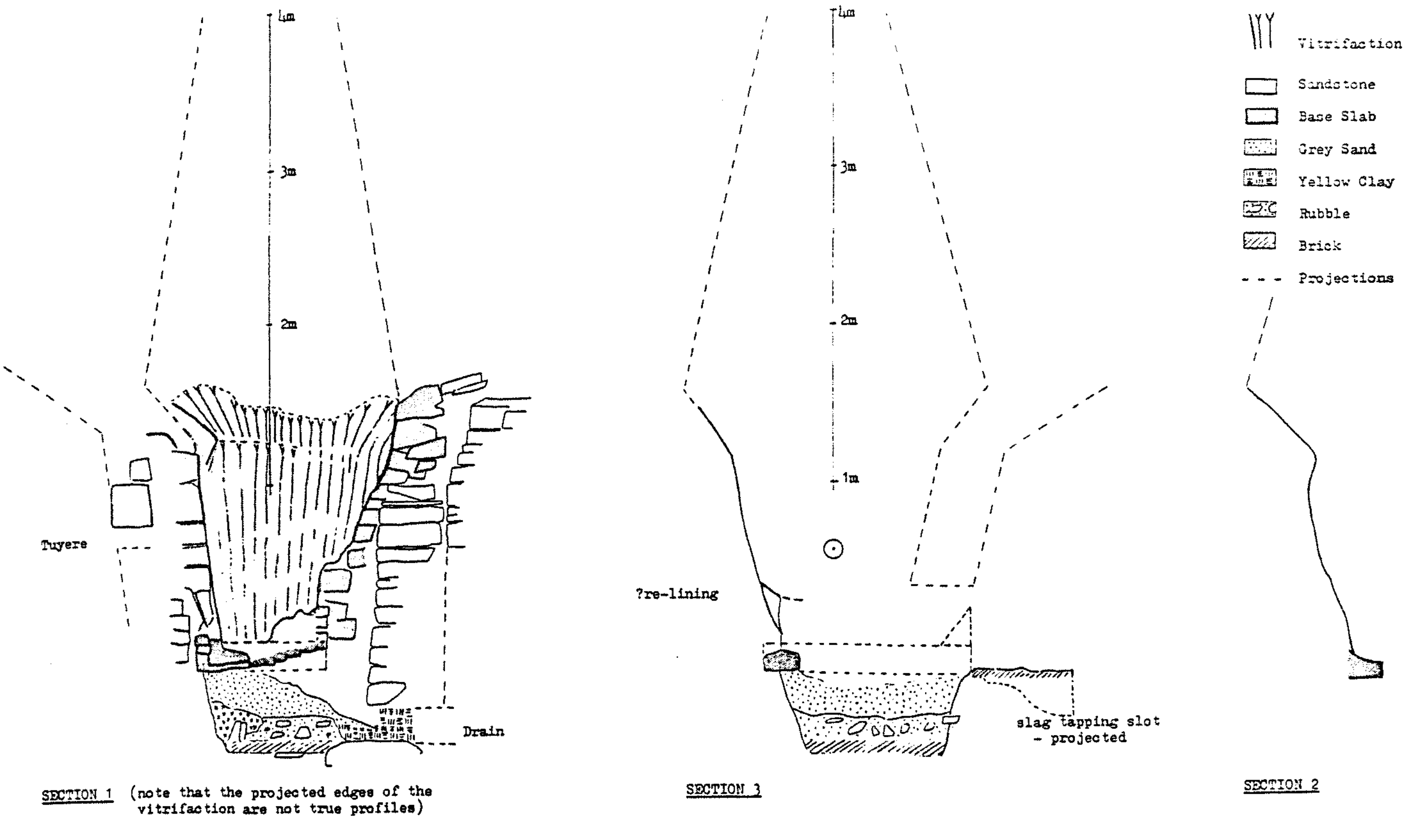

Fig. 4 Dol y Clochydd, 1984 sections

under a half-section of the hearth and boshes survive, giving a very clear indication of the profile of the furnace. The hearth angle was approximately 80° to a height of 1.30m and the boshes were between 45° and 50° to a height of 1.60m above the surviving base slab. The upper part of the profile in sections 1,2,3, are conjectural. The resulting profile is somewhat different to that given by Schubert (1957, Fig. 22), purportedly of a typical 16th century furnace, and that sketched by Swedenborg (Straker, 1931, 78), but is remarkably similar to a contemporary drawing of the late 16th century furnace at Coity, Glamorganshire, which apparently had a square hearth (Rees, 1968, Fig. on p. 180, 265). The lining opposite the tuyere has clearly been eaten back from the original profile so that the hearth and boshes form a nearly continuous curve. It was undoubtedly observation of this kind of wear which lead to the gradual change in the shape of the lining in furnaces of later date.

The hearth base was a large grey sandstone flag, a minimum of 20cm thick. This slab was some 80cm wide and its length could be estimated at some 1.25m from the drainage pit beneath and the burnt brick platform forming the edge of the casting floor, which would have butted up to the edge of the base slab. Allowing for the extent to which the lining would have overlapped the base slab, gives nominal dimensions of 85cm by 60cm for the bottom of the hearth. Not enough of the side walls of the hearth and boshes survives to give a confident estimate of their plan higher up the furnace, especially as the one possible corner may have been altered by the operation of the furnace.

As mentioned above, the position of the tapping edge of the base slab was clearly indicated by a platform of burnt brick forming the edge of the casting floor. Only some 50cm of the casting floor itself could be excavated, due to tree roots, but this appeared to be in good condition with the beginning of a slag-tapping slot towards one side. It was clear from the deposits on the burnt brick platform that the front wall of the furnace was built entirely on the edge of the base slab and that the dam stone must also have been on the base slab, directly beneath the tapping wall. This is at variance with Schubert's schematic drawing of the forehearth, with the dam stone set part-way into the tapping arch, though the thickness of the front wall itself effectively gives a forehearth, if only a small one. Exactly the same arrangement was used in the early 18th century site at Dolgun, only a few miles away. Even allowing for the effective forehearth formed by the front wall, the maximum dimensions of the hearth would be of the order of 1.0m by 60cm. This is at variance with the figures quoted by Straker (1931, 78) for the Wealden furnaces. However, given a nominal height of 30cm for the dam stone, the capacity of the furnace would be about 0.1m^3, giving about 0.8 tons of metal. This would appear to be adequate to cast the small ordnance currently in use, being mainly falcons, minions and sakers, up to 13cwts in weight (Schubert, 1957, 249).

One remaining feature remains to be described. Although the blowing arch itself could not be excavated, due to a very large oak tree rooted in the collapsed rubble, the tuyere wall survives (in a very fragile state) and its inside face could be examined and recorded. A large well dressed sandstone block formed a lintol over a rectangular cavity, which seems most likely to have been the tuyere hole. This is difficult to reconcile with the other surviving fragments of the hearth, as the centre line of a tuyere in this position would be some 60cm above the top of the grey sandstone base slab. There is, however, a possible explanation for this anomaly. There is clear evidence for a major repair of the hearth with large pieces of old lining re-used in new positions. Amongst the debris recovered from the flood channel to the west of the furnace was a broken plate of iron, 50cm by 35cm and up to 8cm thick. This plate is most likely to have been used in the structure of the furnace and it could well have formed part of the arrangements for the base of the reconstructed hearth, set at a higher level than the surviving grey sandstone slab. In other words, the surviving sandstone base slab is not from the same phase of use as the surviving tuyere hole. A further indication of this is given by a fragment of a higher shelf of vitrifaction, shown in fig.4, indicating that the base of the furnace may have been only 30cm below the surviving tuyere hole. If these premises are correct, therefore, the vertical dimensions of the hearth and boshes given earlier need reducing by 30cm.

The cast plate has been kindly examined by Professor Tylecote, and I quote from his report:

> 'This is a graphite cast iron with the usual coarse graphite flakes which have undergone little corrosion. The matrix is almost all pearlite with complete absence of ferrite, even along the graphite flakes, which makes it a relatively hard iron for a grey cast iron. A considerable amount of the phosphide eutectic is present which suggests that this iron contains at least 1% P. There is a small amount of manganese sulphide in the usual crystal form. The hardness of the pearlite is 330 HV1 and the phosphide 460 HV1. This could be a modern pearlitic iron of high quality. It contains about 3% carbon of which 0.8% is in the combined form, the rest as graphite. Impurities are approx. 1% p and a small amount of Mn and sulphur.
> This is certainly not a 100% haematite cast iron, although it might have been made from a mixture of haematite and old bloomery slag which had been smelted from phosphoric ores. This is quite a common way of introducing phosphorous into an otherwise phosphorous-free iron.'

The relevance of the penultimate comment lies in a large block of haematite found during the excavations. This is of some interest, in that there are certainly no local sources of ore of this quality and it would have to have been imported from elsewhere. At this date a south Welsh source seems likely (North, 1962, 43).

There are a variety of sources of pisolitic iron ores in north-west Wales, some containing phosphorous, but there is no evidence of their exploitation until the 18th century, when they were used to feed the Dolgun furnace (North, 1962, 85-87). Even then the ores were not of sufficient quality or quantity and haematite was imported from Lancashire. That haematite had to be imported to the area in the 16th century merely increases the puzzle of the furnace's location. It has already been suggested, on the basis of the broken fragments of bloomery slag on the slope below the charging platform, that bloomery slag was being added to the charge, so the materials needed to produce cast iron of the quality demonstrated by the iron plate were at hand. The siting of the furnace may have been anomalous and in economic terms it may have been a short-lived failure, but from a technological point of view its operation appears to have been successful.

Postscript

The second season of excavation is due to start on the day after the end of this conference. The trees will be removed from the blowing arch and the casting floor, and the excavation of the furnace will be completed. Hopefully some of the difficulties of interpretation may thus be cleared up. The intention is to continue excavations over a number of years, with gradual consolidation of the remains as they are uncovered. Thus, this rare survival of an early blast furnace will ultimately provide a useful addition to the body of data available for study and a fine field monument to illustrate one stage in the development of iron technology. In this region it can be set against the background of a series of conserved sites from the prehistoric period to the early 18th century.

On completion of the Dol y Clochydd excavations we hope to turn our attention to the medieval bloomeries in Coed y Brenin. The Forestry Commission have recently agreed to remove the trees around most of the sites, thus ensuring their preservation and availability for study. These, in their turn, will add significantly to the story of early iron-production in north-west Wales.

Dol y Clochydd, tapping arch, 1984 excavation

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INTRODUCTION OF THE BLAST FURNACE TO BOHEMIA;

A SHORT SURVEY

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I do not exaggerate by stressing the fact that historians of metallurgy were surprised by the new Swedish discoveries which pushed the first application of the indirect process of iron making back into the past. Therefore, it would be useful to remind us of the beginnings of the blast furnace technology in the very centre of Europe which thus had become belated by some four or five centuries. I take the liberty to present some abridged remarks on this topic. Since my special field does not concern this chapter of the metallurgy of iron, I have to state beforehand that my short contribution is based principally on treatises by professor Jan Kořan, a leading Czech historian of mining and metallurgy, who devoted to these problems his books and many papers.

Central Europe, the heart of which is Bohemia as the western part of Czechoslovakia, has a far reaching tradition in the use of iron, going back to the Bronze Age. The metallurgy of iron ores started some centuries later, definitely during the Hallstatt period D and the La Tène period A, somewhen before 500 BC. Since that times it was the bloomery process which dominated in that field of industrial activities. As a part of the Celtic domain, this area participated in progressive trends in making iron, and also later, in the Early Middle Ages, the Slavic metallurgy of iron in Bohemia and Moravia is to be considered as fairly developed, especially as regards the primary production of medium and hard steel.

Further medieval development is not well elucidated by the already excavated iron making plants. What we know until the present day, comes mostly from written records, as well as from legal transactions concerning individual iron works, and from reports of economical nature.

The bloomery process continued to be predominant until the 17th century, at least till its early years, having been proceeded in shaft furnaces, not dissimilar to - but apperently not identical with - the Stück- or Blauöfen in the western neighbourhood, or in the smelting hearths. As a matter of fact, the technology in general was successful enough, if we take into account the extremely bad quality of Bohemian acid ores, having been at one's disposal in that period, low in iron oxides, rich in silica and very often high in phosphorus. On the other hand, it must be admitted that Bohemian metallurgy had been overshadowed by metallurgical events in Europe.

The new technological approaches, connected with the introduction of the indirect process, appeared relatively very late. As to the testimony of written sources, the first two plants equipped with blast furnaces, producing pig iron, were built at the very end of the 16th century by foreign experts: the first was erected in 1595 at Králův Dvůr /SW vicinity of Prague/ by Heinrich or Henri Gaspard de Sart, an experienced foundry-man in service of the Emperor Rudolf II. The second plant was at Kovářská, formerly Schmiedeberg in the Ore Mountains in the North West /Krušné Hory, Erzgebirge/. In 1598 its founder was Zacharias Munich or München who, evidently stood under the Saxonian influence. Both plants started production of cast iron gun balls.

These first blast furnaces were situated in the two leading iron producing areas of that time: Králův Dvůr in the iron ore bearing belt of the Ordovician /Barrandian/, reaching from Plzeň up to the capital of Prague - yielding hematites, siderites and pelosiderites /recently 26-29 % Fe and 20-30 % SiO_2/. The bloomery tradition there reaches back into the Romano-Barbarian period, at least. Kovářská is placed in the northwestern ore bearing region, where the production of iron was based on exploiting hematites and magnetites, since the Middle Ages. Other regions were far less important.

No blast furnaces were working in the territory of Bohemia until the nineties of the 16th century because a contemporary source concerning the rebuilding of the plant at Strašice /bought by de Sart in 1603/ states explicitly that similar furnaces /i.e. blast furnaces/ were never seen in Bohemia before. They produced 12 or 14 pigs a week, which represented about 3 tons of pig iron. The early iron works consisted usually of one or two blast furnaces, of several water wheels for driving bellows and hammers, of ore and hammerscale stamps, and of one more or two bloomery furnaces or hearths. In order to convert a part of smelted pig iron into wrought iron or steel, they used to be further equipped with finery hearths. Another special hearth is to be mentioned: the Zerrenfeuer /krénfajer/ which served for resmelting slags produced by the finery, in order to obtain iron bloom called Knedl, apparently of a very good quality. In the course of improving the blast furnace technology the iron content of slags decreased, so that the operation with the Zerrenfeuer was gradually abandoned. Stores of ore and fuel as well as dwelling houses for the crew also use to be mentioned in various bills of sale concerning the changes of plantowners. Beside these documents there is a unique source dealing with the blast furnace plant equipment and operation written by Jakub Optalius, the Mayor of the town of Rokycany who was a renowned expert in the metallurgy of iron. His booklet in Czech is entitled - in a paraphrased form -: "A very simple and short description of an iron smelting plant", edited in 1647. More than thirty years later, in 1679, it was translated into German as: Kurtze und einfeltige Beschreibung von denen Eisenhütten und Hämmern".

All these facts, as well as the terminology of different furnace parts /preserved usually in a dialectic German/ prove that a fully developed blast furnace construction was introduced, probably from eastern France,Waloon, Bavaria, Thuringia and Saxony. The Bohemian blast furnace of that period was represented by a stone-walled structure. Until the 18th century it used to be 5 - 8 m high, its inner space was divided into classical zones or parts: the tunnel of the shaft and boshes in its lower part, lined with refractory stones, and with a mouth at the top. At the bottom the boshes pointed into a narrow hearth and a crucible below the tuyere level. The working aperture in the front of the furnace was open, blocked by a dam. Molten slag was removed, through a notch, over the rim, meanwhile the liquid iron used to be tapped through a hole in the lower part of the dam.

The ore was smelted by means of charcoal up to the beginning of the 19th century. Some earlier trials with mineral coal and coke, recorded in 1797 and 1821, were not successful. Charcoal wood, predominantly hard sorts for blast furnaces, was burnt in piles, containing 160-200 meter cube in campaigns, lasting 8 - 20 days.

As regards the technology of the blast furnace process, as practized in Bohemia during the 17th century, it should be remarked that a cycle of smelting lasted about 15 weeks /20 weeks were the maximum/. Weeks of intermissions followed. The period of continuous smelting increased to about 60 weeks at about 1700. The yield of one furnace used to achieve about 3 tons per week, in the 18th century 5-6 tons of pig iron, the metal having been tapped once a day, in the 18th century twice a day.

As already mentioned, production of blast furnaces initially supplied material for casting gun ammunition, later in addition, water tubes were produced and then, in the 18th century decorative cast ironwork, oven plates, grids, statues and candelabra were the principal kinds of cast products.

A part of smelted pig iron used to be converted into steel or wrought iron in finery hearths. In Bohemia, as well as in France and southern Germany, the poling of the molten metal with an iron bar was practized. Particles of malleable iron adhering to the bar, were collected and worked. Water driven hammer mills were an integral part of installations of iron works. Heavy belly-helved types were in use in iron-smelting areas.

The 17th century saw a gradually increasing number of charcoal-fueled blast furnaces: the documents indicate new established plants in various sites, the names of which I shall not reproduce, for years 1607, 1614, 1620, 1648, 1662 etc. For example, the complex of iron-smelting plants within the large estate of Zbiroh, in the Southwestern industrial area, comprised, about 1650, 7 blast furnaces, 9 hammer-mills; in about 1780 there worked in the same region 11 blast furnaces and 23 hammer-mills.

In my short survey I have omitted some other important themes as the general organization of the iron industry of Bohemia and its economical relations, the problems of education of experts, the trade in iron and the social position of workers of different ranks who were engaged in iron smelting in the period before the industrial revolution which came about the mid-ninsteenth century.

What I'd like to underline is that the introduction of the blast furnace technology in Bohemia took place in a period of a deep economical crisis, marked by the events of the 30 Years' War. However, the need of iron, involving cast iron, increased steadily. The iron works were owned only partly by the Royal Chamber within the early Austrian Monarchy. To a greater extent they were owned by aristocracy like the Counts of Vrbno, the families of Fürstenberg, Lobkowitz, Coloredo-Mansfeld and of other immigrated nobility who controlled large territories rich in fuel and ore resources as well as in manpower. Nevertheless, a small group recruited from free middle-class craftsmen, hammer-smiths, who were accorded privileges by landlords against fix fees. Just these people were inclined to support the introduction of the new technology. This was the case of Münich and de Sart, who were the real founders of the first blast furnaces in Bohemia.

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A BRIEF ACCOUNT OF IRONMAKING IN NORWAY IN PREHISTORIC AND HISTORIC TIMES. RECENT FINDS. EXPERIMENTAL WORK.

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It seems to be of interest to present a brief and personal survey of the present state of knowledge about early ironmaking in Norway, in connection with the discoveries and the dating of Lapphyttan, Vinarhyttan and Juteboda blast furnaces in Sweden.

The introduction of the blast furnace must be linked with mining operations. There is no written source mentioning mining of rock iron ore in Norway prior to 1538. True blast furnace operations seem to have started in 1625 at Fossum near the city of Skien. During the years 1538-1622 ironmaking appears to have taken place in "Rennöfen" (1).

During this period Norway and Denmark were united. The king Christian III, residing in Copenhagen, imported craftsmen from Saxonia, where his uncle was ruling. In Saxonia the first blast furnaces started operating in 1575 (1).

As in Sweden the first industry with large scale operation and shift work was introduced at the iron works. They numbered a maximum of about 20 in operation at the same time. There is no indication of any other organization than capitalist ownership and administrative pattern, this being in contrast to Sweden, where also some cooperatively run blast furnaces are well known, e.g. Löa hytta (2), possibly reflecting the pattern for the small scale Osmund furnace operation.

Norwegian iron works had certain privileges on the Danish market. After the Napoleonic wars, notably 1814, such privileges were abandoned. We had to face competition with the iron industry in Sweden, where the forests were more extensive and charcoal cheaper. The Norwegian iron works were faced with a grim economy. One blast furnace after the other was shut down during the 19th century. A renaissance for the Norwegian metallurgy started after the development of cheap hydroelectric power in this century, while there is a continuous history in Sweden from present day blast furnaces and indirect steelmaking back to the operations at Lapphyttan, Vinarhyttan and Juteboda.

A full study of the small scale direct ironmaking in Norway has yet to be carried out. The extensive work by Irmelin Martens at Mösstrond has given the impression that Norway was producing iron mainly in the period from the great migration to the 14th century (3-5). However, later finds at Fet, Sysendalen (6), Eg near Kristiansand (7), Seltuftvatn in Flåmsdalen (8) and Hoset and Navlus in Tröndelag (9) are all from operations during the iron age, as found by the 14 C method. The information about the type of furnace and mode of operation at all these places is scant and no convincing comprehensive picture has been presented yet.

In connection with ironmaking as a school project, however, a site for iron production with well preserved furnaces was revealed at Heglesvollen in Tröndelag in the year 1982. Excavations during the years 1982-84 have shown that four furnaces lying apart are practically identical and that four adjacent furnaces all belonged to the same production unit. The furnaces must have been built and operated by skilled ironmakers. The state of conservation is extremely good, in part due to the stabilizing effect of in situ slag in the furnaces, amounting to up to 55 kg (10). All 14 C datings are from the Roman iron age.

The approximately 10 m high slope facing a bog and a little river contains some 100 tons of slag, reflecting the total production in the set of four furnaces.

It appears that the furnaces have been equipped with a shaft as a superstructure and that the stone-lined lower part acted as a recipient for liquid slag. The produced bloom was removed through a wide slot. This opening must have incorporated also the necessary tuyeres.

The site is being studied by a group of archeologists associated with a botanist, a geologist and a metallurgist from the University in Trondheim. It seems to be numerous places in Tröndelag with the Heglesvoll type furnace (11).

Now turning to the end of the period of the bloomery process, iron seems to have been produced as late as in 1890 in this type of furnace (12). There are a great number of furnaces from this late period in the area near the Swedish border south of Röros. The etnology of iron making and blacksmith technique in the greater area is extremely well documented in the Swedish book from Lima and Transtrand (13). In addition, the book by Ole Evenstad from 1782 gives a full description of the state of art at his time (14). Following his advice, iron has been produced from bog iron ore as a part of a school project in three different furnaces recently (11, 15). The Evenstad process is also being studied in the Metallurgy department at Norway's institute of technology by the present author (11).

The aim of the experimental work is to obtain quantitative data on the operating conditions of the Evenstad furnace and to compare with metallurgical theory, taking other experimental work into consideration. This in turn may lead to an explanation of the practice in the Heglesvoll type furnace. Special attention is paid to the principle "reduction before melting" and the need for a discontinuous operation.

The iron production in Mediaval type bloomery furnaces appears to be the most difficult to explain, judging from the state of conservation at the archaeological sites and the ideas which have been presented. It is hoped that a full understanding of both pre- and post-mediaval processes shall lead to a full explanation of ironmaking in the important intermediate period - The Viking age up to the 14th century.

The author feels that furnaces ought to be classified according to functional criteria, among others the separation of slag and metal and the disposal of the two products. It appears that the Heglesvollen furnace had a sink for slag under the section at which iron was produced and subsequently removed. During post-mediaval times the produced bloom and the slag were removed from the top through a relatively wide opening. In the intermediate period at least one of the types of furnaces was based upon tapping of the slag, leaving a relatively open and unprotected furnace to the effect of frost and other detrimental influences.

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Characteristic furnace from Roman Iron Age at Heglesvollen in Tröndelag, Norway, after removal of in-situ slag.
Photo: A. Espelund.

CONTRIBUTION TO THE DISCUSSION

Jean-François BELHOSTE (*)

Bearing in mind the impressive results of work on Laphyttan and also taking into consideration the long period of development that led up to the large Swedish blast furnaces of the 16th century - because leaving aside the question of whether or not cast-iron was deliberately produced there, there cannot be the slightest doubt that the installations at Laphyttan were very advanced in their size and in their capacity to extract a very high proportion of the iron content of the ore-, I would like to make two related observations from the history of the introduction of the indirect process in France.

1°) I would firstly like to recall that between the stage of the bloomery with hand-operated bellows and the stage of blast furnaces with finery forges, several French and Swiss regions were familiar with large furnaces equipped with water-powered bellows during the 14th and 15th centuries. These furnaces were from 2 to 3 metres high and produced not cast-iron but blooms of iron and were therefore using the direct method. The cinder in these blooms was got rid of by a kind of finery process using a water-powered hammer ("martinet"). These is an obvious relationship between these furnaces and the Austrian Stückofen. It has been difficult to get to grips with this intermediate stage, both because it lasted a relatively short time and because of the scarcity of manuscript sources and the lack of archaelogical investigations, but it has been remarkably described for the western Jura in French-speaking Switzerland by Paul-Louis PELET (fer, charbon, acier dans le Pays de Vaud, tome II, La lente victoire du haut fourneau, Lausanne, 1978). These installations are called "ferrieres hydrauliques" (water-powered bloomeries) by the author. Their slags contain not more than 20 to 30% of iron. The lease of a forge of 1391 in Lorraine, studied by Alain GIRARDOT (Annales de l'Est, Tome 28), probably relates to an establishment of the same type. We may also infer their existence in the Pays d'Ouche (Normandy) at the beginning of the 15th century under the name "renardière", which is also to be found in Franche-Comté.

(*) The translation is due to M. Brian AWTY.

*) Supplanted from the end of the 15th century and the beginning of the 16th century by the blast furnace, having a larger productive capacity and allowing the use of less rich ores and those containing more impurities even despite its much greater consumption of charcoal, these "ferrières hydrauliques" had a quite brief existence. But their existence does show that the final arrival of the indirect process in France as in Sweden came at the end of a period of gradual evolution.

2°) My second remark relates to the characteristics of the indirect process in France. The works adopting this process in the second half of the 15th century consisted of establishments which were already very important, belonging almost always to great lords or important merchants on account of the necessity of providing them with large quantities of charcoal. In addition they were provided with two distinct water supplies, sometimes several kilometres apart, firstly that of the furnace and secondly that of the finery forge containing one or more hearths and a "great hammer". Now it is striking to observe that it was this last which contemporaries considered to be the most important of these installations. In addition the forge master often lived in the immediate vicinity. In the West it is above all the employment of the term "grosse forge" which signifies the finery forge in contemporary texts, and by extension it is often applied to the complete establishment, that is to say to the blast furnace and the finery together, so the term forms one of the best written indications of the introduction of the indirect process. However, the expression "grosse forge" obviously originally indicated the presence of a large water-driven hammer, so that we can see that the installation which appeared novel and basic was the finery forge with its hammer mill, the blast furnace initially perhaps being thought of as an improved kind of "ferrières hydraulique". The novelty which was going to facilitate an enormous growth in French iron production was the fact that it was now possible to fine and convert into bar iron large quantities of an already known product, cast-iron, the utility of which up to then had been very restricted.

ON THE WEIGHT DISTRIBUTION OF SLAG FROM LAPPHYTTAN

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The aim of the investigation presented here is to see if more information can be obtained by sorting the slag lumps after weight in the slag concentrations on a site than chemical analyses and metallographic examinations supply.

About half a cubicmeter of material from each of three slag heaps have been examined. The slag heaps belong to construction no A3, A4 and A17. Construction A17 is supposed to contain refinary slag and A3 as well as A4 blast furnace slag.

Table 1 shows the weight and the number of slag weighing more than 1 gram.

Table 1 - Examined slags from Lapphyttan

Construction No	Slag $\geq$ 1 g kilo	Slag $\geq$ 1 g number
A3	381	13 799
A4	313	6 553
A17	280	78 802

Weight distribution

Figure 1 shows the weight distribution of the slag lumps. For example, 20 % of the slag weight from construction A17 have a lump weight higher than or equal to 31 grams and 50 % of the slag weight have a lump weight higher than or equal to 8 grams.

The medium weight of the slag lumps based on the weight of the slag lumps is given in table 2.

Table 2 - Medium weight of the slag lumps

Construction No	Medium weight gram
A3	144
A4	212
A17	8

As can be seen it is a big difference between the weight of slag lumps from construction A17, i.e refinary slag, and the slag lumps from construction A3 and A4, i.e blast furnace slag.

Appearance of the slag

Table 3 shows how much of the slag that is vitrious, partly vitrious and not vitrious. Remarkable is that more than 94 % of the blast furnace slag are not vitrious at all. As expected the refinary slag from construction A17 is not vitrious.

Table 3 - Per cent weighing > 1 g

Construction No	Vitrious	Partly vitrious	Not vitrious	Total
A3	0,3	4,3	95,4	100
A4	0,7	5,0	94,3	100
A17	0,0	0,0	100	100

Representative slag analyses of blast furnace slag from Lapphyttan

Slag lumps of medium weight from construction no 3 have been chemically analysed. From the chemical analyses of vitrious, partly vitrious and not vitrious slag and from the percentage of slag weight from these three groups, a representative slag analyses has been calculated, se table 4.

Discussion

The examination of about 100 000 pieces of slag have taken a considerable time. Many more slag producing units must be examined in order to ascertain if an approximate determination of the medium weight of the slag lumps can give information on the type of slag studied. A method is presented below.

An approximative way of determine the medium weight of slag lumps

1 Take about 100 kg of material from a slag heap.

2 Sort out everything that is not slag as well as all slag lumps weighing less than 1 gram.

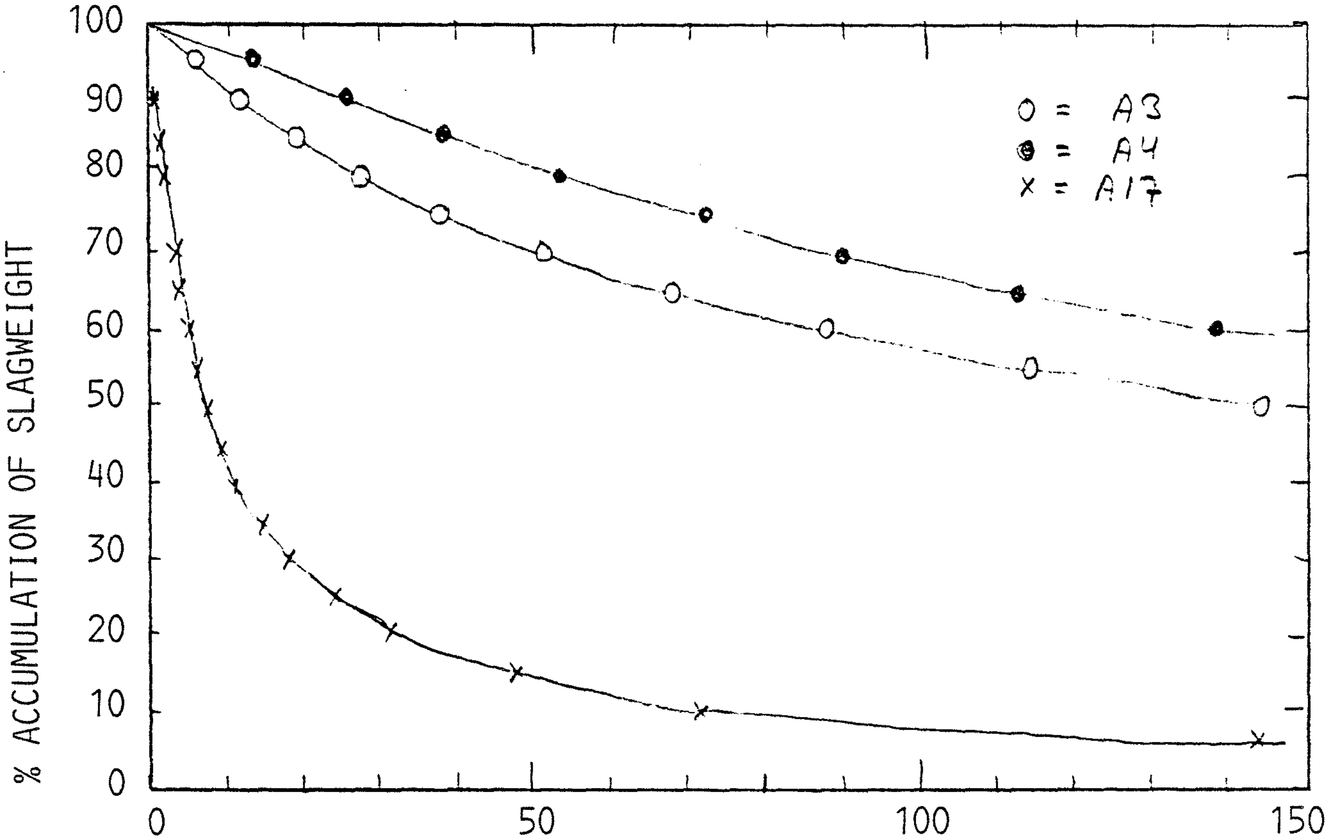
3 Place the slag lumps in a box and determine the total weight of slag lumps.

4 Remove the heaviest lump and than the second heaviest lump and so on until the half of slag weight remain The next lump of slag you sort out will have the approximate medium weight.

Table 4 - Construction no 3

Representative slag analyses

Element	%
Fe_{met}	2,5
FeO	2,2
Fe_2O_3	4,3
SiO_2	45,9
CaO	11,7
Al_2O_3	6,0
MgO	10,1
MnO	12,4
TiO_2	0,16
V_2O_5	0,03
K_2O	0,94
Na_2O	0,85
P_2O_5	$<$ 0,01
S	0,04
Loss of ignition	2,35
Total	99,48



WEIGHT OF SLAG LUMP GRAM

FIGURE 1

The transmission of the blast furnace from China to Europe: Some notes to complement Prof. Tylecote's paper

Symposium Medieval iron in society, Norberg, 6-10 May 1985.

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Prof. Tylecote's paper has presented the basic framework of the problem. I shall present here some complementary considerations.

I have never personally had any real doubt that the blast furnace came to the West from China. Work on diffusion of ideas and techniques, however, has a peculiar bias which should be kept in mind: diffusion can often be argued convincingly and sometimes be proved conclusively, but independent invention can virtually never be proved conclusively. Those who favor dffusion have a special responsibility to insist on strong arguments and to fill out as many links in the chain as possible. I have been gathering material on this subject for some years now, and present below some material to complement Prof. Tylecote's. Like him I think the case for diffusion is now strong, but a great deal of work needs to be done to complete a real proof.

More than forty years ago Otto Johannsen (1941) argued that blast furnaces were used in Sweden earlier than anywhere else in Europe. His arguments were not very strong, but the new excavations have beautifully confirmed his contention. Central to his argument was that the early Swedish blast furnaces were of a more primitive construction, with a sandstone shaft, a wooden outer frame, and tamped earth in between; a somewhat later type has stonework "feet" and wood only on the upper part (figure 1). This construction has no parallel elsewhere in Europe.

Johannsen suggested somewhat hesitantly that the blast furnace may have come to Sweden from the Arab world. Very little is known about how iron was made in the Middle East in early times, primarily, I think, because most Arabists are totally uninterested in technology. Parry (1970:224) has some interesting remarks on the subject, but nothing, as far as I can see, relevant to the question of the blast furnace vs. the bloomery. He notes two descriptions of ironworks in the Lebanon: Seetzen (1854-5: 145, 188) describes briefly and obscurely what seems to be a large bloomery; I have not yet seen Brocchi (1841-3:187-94, 283-4)

Erich Böhne (1928) describes a small blast furnace in northern Iran, in the mountains just south of the Caspian Sea; see figure 2. Compare especially the blast apparatus with that of Filarete. "The impetus is transmitted directly with the help of a wooden connecting rod and short iron cranks through a standing water wheel, a kind of turbine, as is found in all north Persian mills. On the vertical axle 24 wooden scoops are mounted with carefully fluted blades at an angle of 55°. The removable connecting piece between the bellows and the tuyère is of leather with sheet-iron ends. ..." (Böhne 1928:1579).

According to Böhne this traditional industry was dying out because of competition with cheap Russian iron. He saw only three furnaces in blast, but vast slag heaps and furnace ruins indicated a much larger production in the past. At the beginning of the nineteenth century Trezel (1824:449, cited Böhne 1928: 1579) had seen thirty furnaces in blast.

Molten iron from this furnace was granulated by pouring it from a ladle onto a damp floor. Daily production was never more than 120 kg. This granulated pig iron was in Böhne's time used only in foundrywork, but he was told that in former times it had also been converted to wrought iron in small fining hearths by itinerant smiths.

There is a certain family resemblance between this blast furnace and some traditional Chinese "dwarf" blast furnaces used in the twentieth century (Wagner 1984; 1985, chapt. 5.1).

We might very well see in this furnace the origin of the Italian blast furnace described by Filarete. In this connection we may note a curious passage in Vannoccio Biringuccio's Pirotechnia (published 1540) on the iron "ore" of Elba: "this ore is of such a nature that, in order to extract the iron from it and then to reduce it to purity, it is not subjected to the force of violent fires or many devices and extraordinary efforts as are the others. By merely placing it on a forge in front of the tuyère where the blast issues, a very soft and malleable iron can be extracted with an ordinary smelting fire. ... After the ore has been broken in little nutlike pieces it is arranged on the said place in a heap and around this a circular enclosure is made of the larger pieces of ore or of other dead rocks... The amount that it is wished to reduce is well covered with charcoal and then an arrangement of bellows connected with a water wheel which moves them is caused to blow. With a fire of only eight or ten hours' duration the ore is smelted and cleansed of the earthiness which it contains..." (tr. Smith & Gnudi 1943:62).

This is clearly a description of fining, not smelting. Apparently Biringuccio had seen granulated pig iron in "little nutlike pieces" and mistaken it for ore. Biringuccio also describes a process for making steel by immersing wrought iron in a bath of molten cast iron (Smith & Gnudi 1943:68-70). It is virtually identical to the Chinese "co-fusion" (guan gang) process, which was in use by the early sixth century A.D. (Needham 1958:26-31) and was still in use in the twentieth century.

There is not a great deal of resemblance between the early Swedish blast furnaces and the Iranian furnace described by Böhne, but this need not negate the hypothesis of a connection. A common phenomenon in the competition between traditional iron industries and modern imports (in this case from Russia) is that the traditional industry can compete only in price, rarely in quality. Profits decline, and the largest-scale enterprises, with the largest capital investment, are the first to disappear. Small-scale labor-intensive enterprises can continue because of the depression of wages resulting from foreign competition in all fields of economic activity. It is quite possible that much larger and more sophisticated blast furnaces were in use in Iran in earlier times.

Furthermore modern competition can be expected to have had a differential effect on the geography of the traditional iron industry. Large-scale ironworks with an output on the order of tons per day require a large market, and therefore tend to be located in regions with good transportation possibilities. Precisely such areas are most easily penetrated by foreign competi Thus in 1928 the only blast furnaces in the region may have been the three seen by Böhne in northern Iran, but a few centuries earlier they may have been much more widely distributed. We should look especially for early blast furnaces in the Caucasus and in modern Turkey (the Byzantine Empire). There seems to have been some Scandinavian trade with the Caspian region, but the trade with the Black Sea region was intense and is well docume

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Looking now directly to China, figures 2-5 show some traditional blast furnaces in Sichuan and Hunan which are remarkably similar to the early Swedish furnaces. In particular they are wood-faced. Széchenyi's description of a blast furnace in Sichuan in about 1880 (figure 3) is the earliest Western description I have been able to find of a Chinese blast furnace. This furnace is also the only one described which uses water power. Here again we have the problem of the differential effect of foreign competitio on traditional iron industries: Széchenyi saw this furnace only a few years before steamboat traffic was introduced on the upper reaches of the Changjiang (Yangtze River) and suddenly made impor iron cheap enough to compete with the local product. The immedia effect was to lower the return on capital; investment in water-power was no longer attractive, and only labor-intensive methods survived.

How early were blast furnaces built with wooden facing like these? There has been very little archaeological work in China on the iron industry of recent centuries. A few blast furnaces of the Song period (960-1279) have been reported, but with very little detail. Figure 6 shows a Song blast furnace excavated in Handan, Hebei; it seems possible that this furnace might origi have had a wooden facing.

* * * * *

It is important in this discussion to keep the subject of iron-casting separate from that of blast-furnace iron production. The earliest cast-iron artifacts in Europe (Johannsen 1911-17) appear not to have had much economic significance; not enough, at any rate, to warrant the introduction of the blast furnace. The earliest European iron castings may have been made by carburi and melting iron blooms in a cupola furnace of the type used for bronze-casting. A German manuscript of 1454 describes precis this (Johannsen 1910). I have been told that the first ironfound in Europe were Gypsies in the service of a Hungarian prince; can anyone tell me more about this? (Simson (1865:234) describes the iron-founding techniques of a group of Gypsies in Scotland; see also Andree 1884:79-84, "Die Zigeuner als Metallarbeiter".)

It is most likely that the blast furnace and the finery were introduced together in Europe. A combination of blast furnace and finery could produce wrought iron which could compete directl with bloomery iron in both quality and price. This is again a contention of Otto Johannsen's which has been borne out by the new excavations.

Recent Chinese work (reviewed in Wagner 1985, chapter 6.3) indicates that it is possible to distinguish fined iron from bloomery iron metallographically, by the form and distribution of slag inclusions. There has been almost no work along these lines in Europe (but cf. Johannsen 1953:148), but almost any major museum would have enough well-dated medieval wrought iron to allow a determination of the date of the introduction of the finery. If the museum keepers would allow it!

A wide variety of evidence indicates that the finery was introduced in China in about the first century B.C. The evidence includes metallographic studies, written sources, a second-century A.D. tomb relief which may show a finery, and excavations of at least twenty actual fineries (Wagner 1985, chapter 6.3). Fineries then do not seem to have been much different from the traditional Chinese fineries of the twentieth century shown in figures 7-9. They consisted of a small hole in the ground, protected by a low mound of earth or bricks, with blast blown in from the top. The fineries at Lapphyttan seem remarkably similar.

* * * * *

The Lapphyttan dates correspond to the Song period in China. This was the time of a great commercial revolution; among other things annual iron production rose to an estimated 125,000 tons, or about 1.4 kg per capita (Hartwell 1962; 1966; 1967). It was also the time that coal was first used in iron-smelting, and this fact gives an interesting perspective on our problem.

By early in the Tang period (A.D. 618-907) problems of deforestatio seem to have become very serious. In Borneo and in various places on the east coast of Africa there are signs of ancient large-scale iron industries (Harrisson 1969). Sherds of Chinese export porcelain allow a very reliable dating of iron production in Borneo to the period from the Tang to the beginning of the Song. The sherds of course also indicate contact with China, and there are also some signs of contacts with the Middle East. I suggest as a working hypothesis that these were "iron production colonies" established by Chinese merchants to take advantage of large local wood supplies, and that they lost their Chinese market after the introduction of the use of coal in iron-smelting in the Song.

These colonies, if such they were, clearly would have provided a place where Islamic merchants could see and study Chinese iron-production techniques far more easily than in China itself. On the other hand no sign of anything like a blast furnace has been found in the Borneo excavations - the only ones which have been published in any detail. Only slag (estimated at 40.000 tons) and crucible sherds have been found. (The slag is 57% iron oxides, so it is also necessary to ask whether this really is iron-smelting slag rather than from copper smelting fluxed with iron ore; but in Harrisson's review of the geology of the region there is no mention of copper ores.)

The Borneo iron industry may have used the Chinese crucible smelting technique, which was not used in Europe until Emil Sieurin invented the "Höganäs process" in 1911.

Despite the present lack of evidence of blast furnaces in Borneo the idea of a Chinese iron-production colony here still seems attractive. Perhaps further work will reveal Chinese blast furnaces somewhere along the maritime trade route between China and the Middle East. An especially interesting place to look will be Sri Lanka, where early Chinese trade is well documented. British colonial officials and others seem to have studied the traditional siderurgical techniques here in considerable detail, but I have not yet looked into this material.

There are also various possibilities along the land route. In particular the blast furnaces described by Böhne may have come to Iran in the thirteenth century, when the area was under Mongol rule. This is too late to account for an influence in Sweden, but quite reasonable for Italy.

Northern India must also be studied in this connection. Too much attention has been paid to wootz steel, and the production of iron for ordinary purposes has been neglected by scholars of Indian technology. A curious example of the sort of thing which can be found when one begins searching is a remark by the traveller Abū Dulaf Mis'ar. In Kashmir, about A.D. 940, "they have a large observatory in a building constructed of Chinese iron, on which time has no effect" (i.e. it does not rust) (Ferrand 1913, 1:224). The term "Chinese iron" seems to have had various meanings in Arabic scientific writings, but here it clearly refers to cast iron. Compare the large cast-iron pagodas cast in China at least from the Tang period (Needham 1958).

* * * * *

It seems to me that a very good case can be made for an Iranian or Byzantine origin of the Italian blast furnace, and a moderately good case for a Chinese origin of the Iranian blast furnace described by Böhne. The Swedish blast furnace, which strikingly resembles some Chinese blast furnaces, may have come from China through the Middle East; it may, however, have come to Sweden by a different route.

If there were Chinese iron-production colonies in the South Seas, there may also have been in the northwest, perhaps in the great forests of Siberia. Blast-furnace iron production generally requires a large market to be economically viable. It is difficult to imagine a sufficient local demand in Siberia, and production for the Chinese market would have been hampered by the high cost of land transport. Nevertheless the possibility seems worth further investigation.

One lesson to be learned from the recent Swedish excavations is that evidence does not appear by itself, but must be dug after, either in the ground or in written sources. One excavation has now entirely changed our view of the development of the blast furnace in Europe: further excavations (of both kinds) focussed on Siberia, southern Russia, and northwestern China, as well as the other areas mentioned here, may well provide material to test the various hypotheses presented above; or it may provide new surprises which lead us in entirely new directions.

* * * * *

In the Byzantine Empire, Iran, or Siberia there may have been a chance for Swedish merchants to see Chinese blast furnaces. There is also a record of a visit to the Song court of a group of merchants who were tall, blonde, and blue-eyed, and who came from a land so far north that in the summer the sun never sets (Needham 1985).

* * * * *

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Figure 1. Ruin of a blast furnace at Nya Prästhytta, Vännebo, Sweden (Johannsen 1941, plate 32.1).

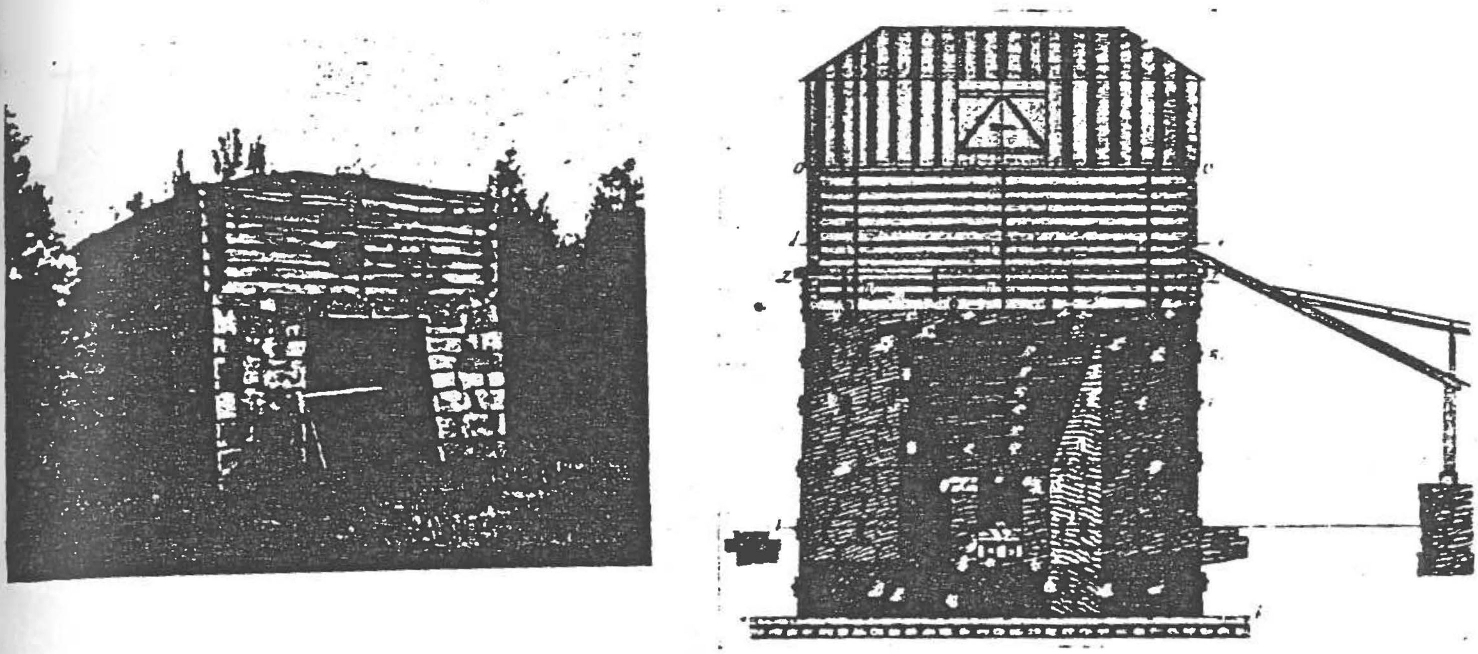


Figure 2. Blast furnace in Masenderan, northern Iran, 1927 (Böhne 1928:1579).

Abbildung 4.
Ansichtsskizze
eines
Hochofens.

Figure 3. Blast furnace in Sichuan, ca. 1880 (Széchenyi 1893:678).

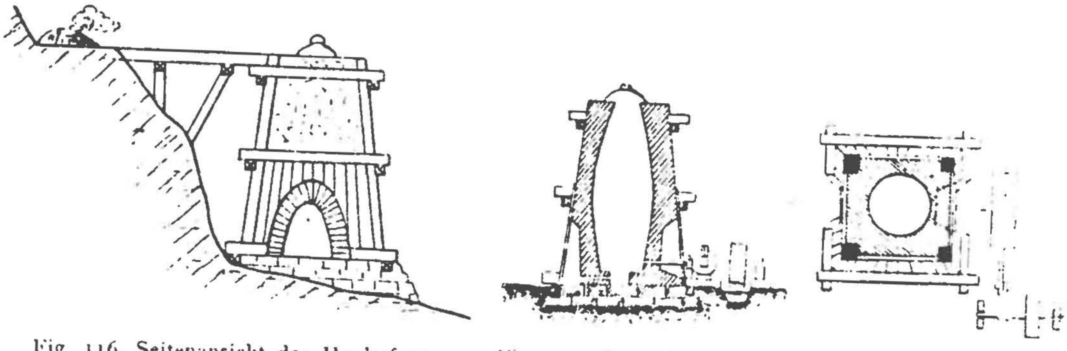


Fig. 116. Seitenansicht des Hochofens.

Fig. 117. Querschnitt durch den Hochofen
Massstab 1 : 35...

Fig. 118. Grundriss des Hochofens.

Figure 4. Blast furnaces in Hunan, 1958 (Alley 1961b, no. 10).

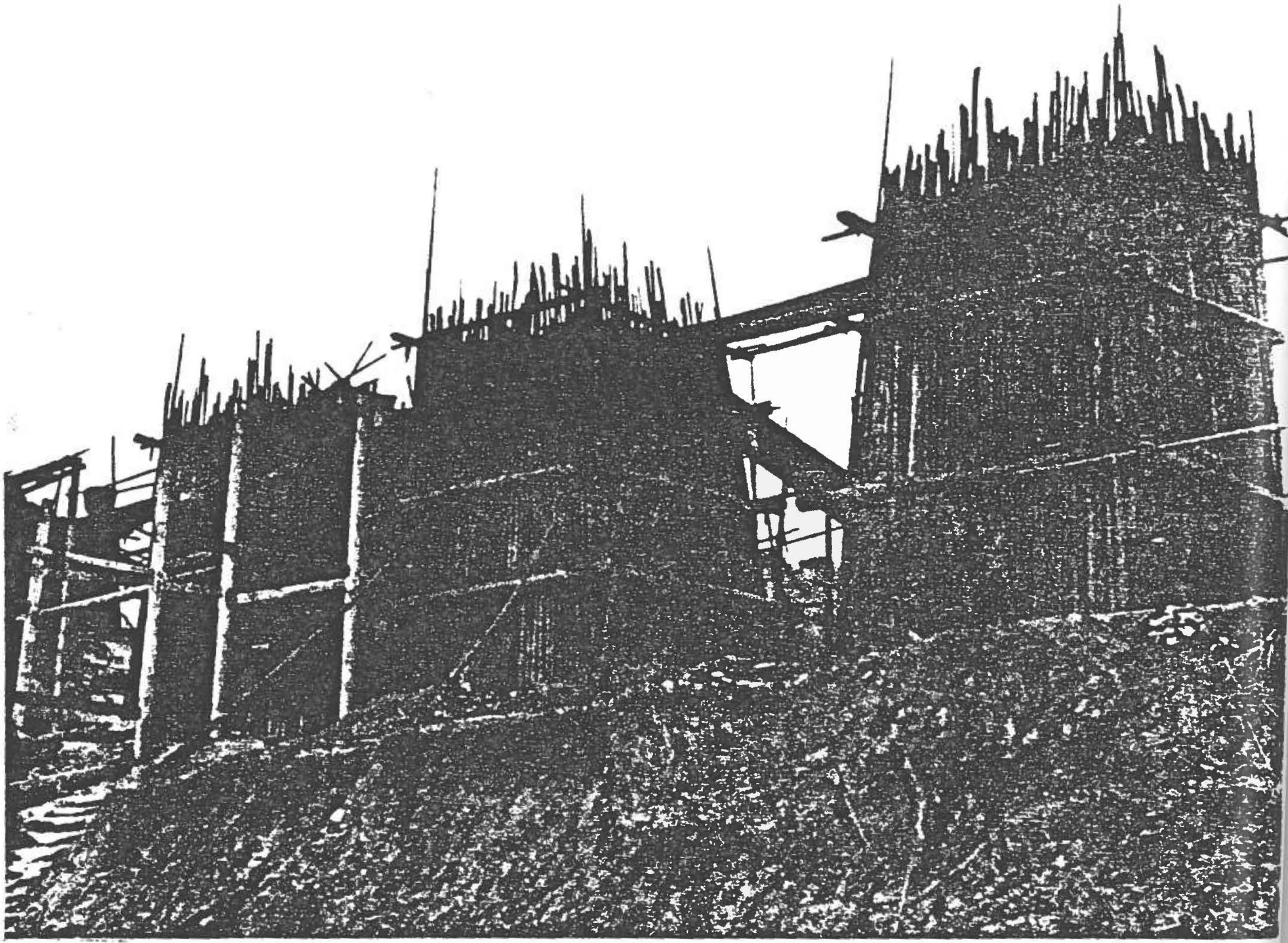


Figure 5. Blast furnace in Sichuan, 1958 (Yang Kuan 1982:185).

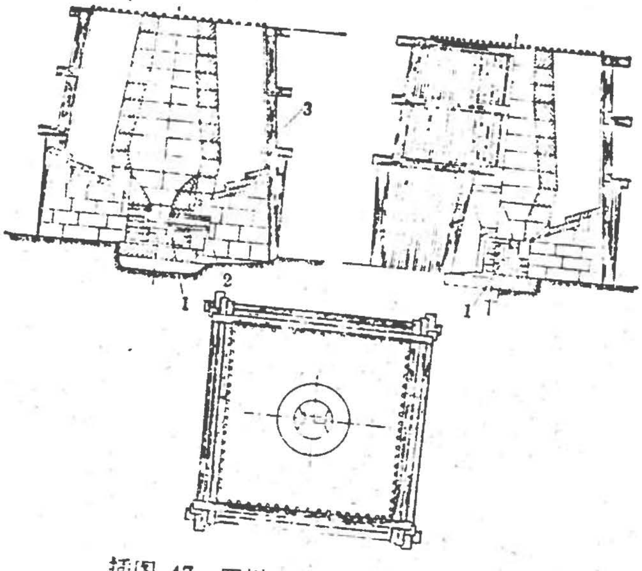
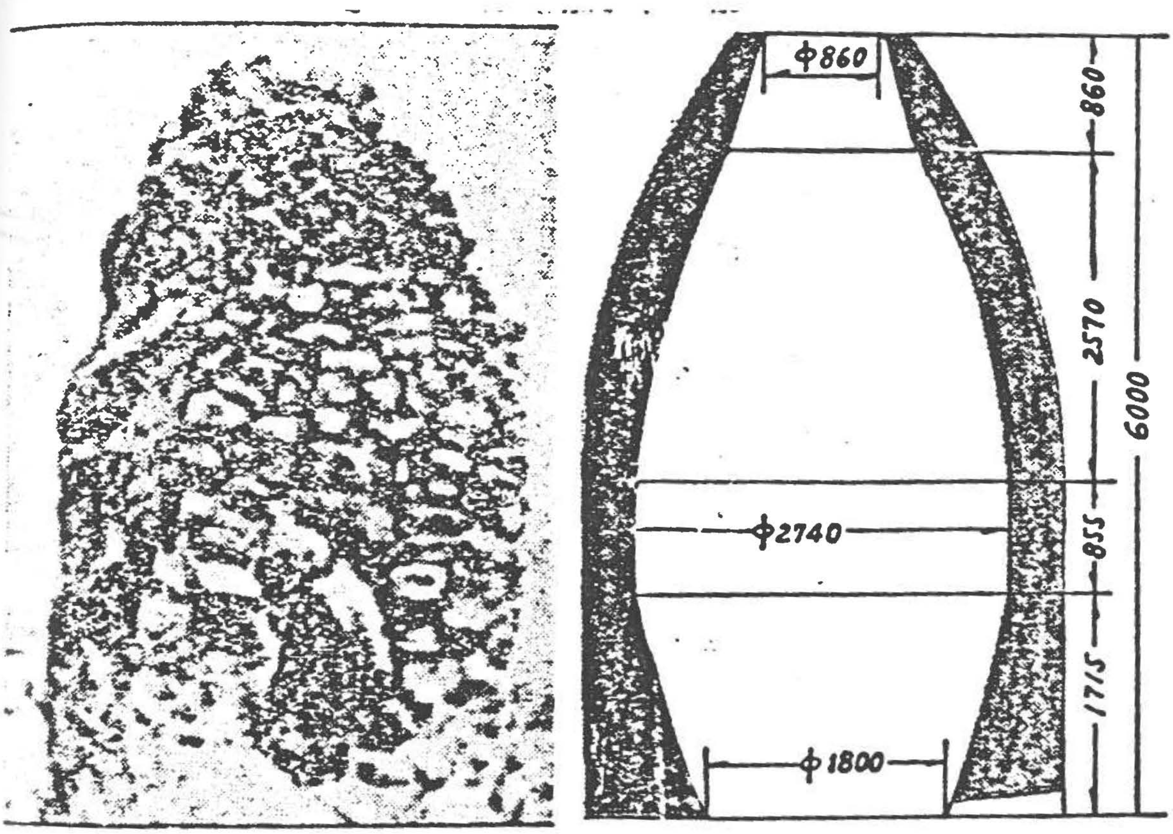


插图 47 四川省石砌的高型土高炉
部位名称：1.金池 2.风嘴 3.木保护匣
（这炉为炼铜用，但结构是和炼铁用的石砌土高炉相同的。采自四川省工业建设经验交流展览会编"土法冶炼"）

Figure 6. Blast furnace of the Song period excavated in Handan, Hebei. Left: photograph of the furnace (reproduced by Liu Yuncai from Chen Yingqi 1959). Right: Reconstruction by Liu Yuncai (1978:23). Dimensions are in mm



图八　矿山村宋代高炉　左：实物遗存　右：复原简式图

Figure 7. Operation of a traditional type of finery in Shanxi, 1958 (Alley 1961a).

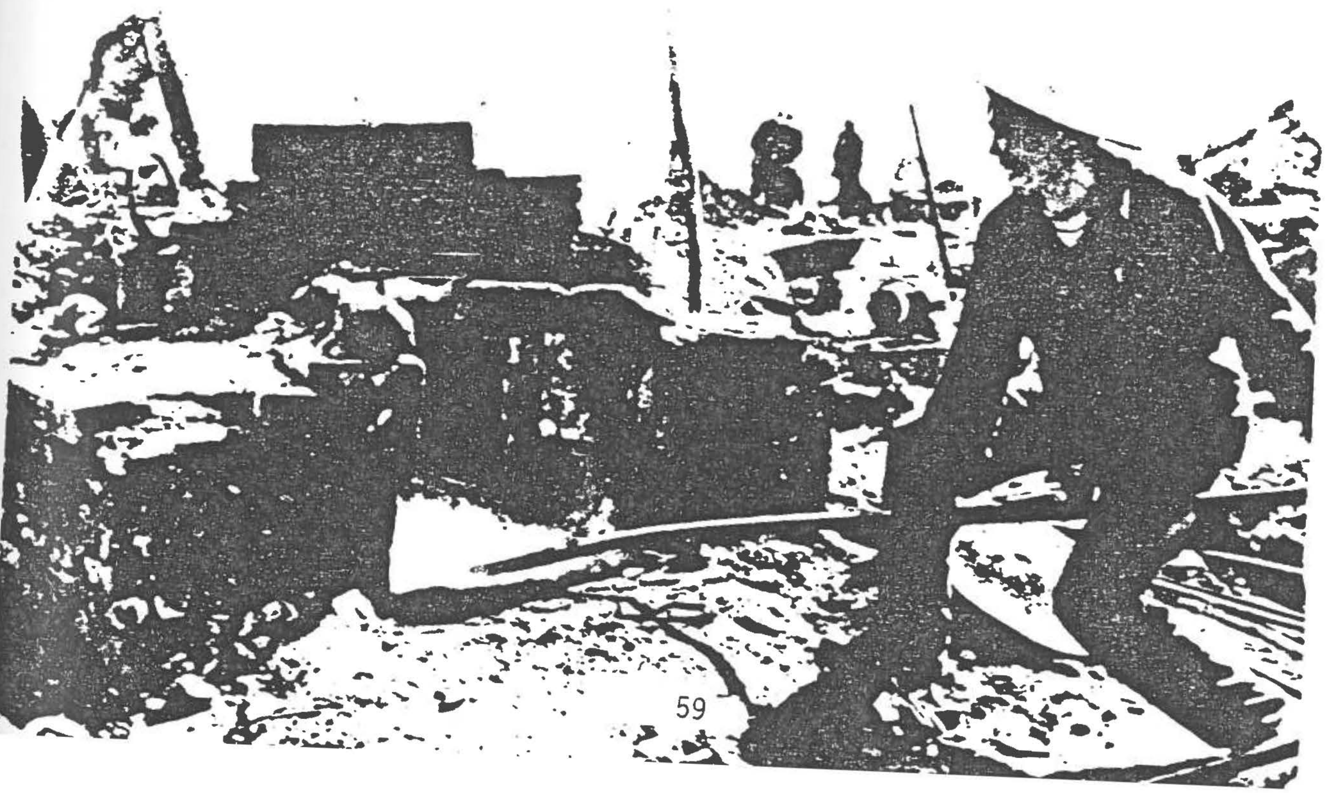


Figure 8. Drawing by E.T.Nyström of a pair of finery hearths in southern Henan, ca. 1917. In the background a traditional Chinese "windbox" (double-acting piston bellows). Courtesy of Tom Nyström and the Museum of Far Eastern Antiquities, Stockholm.

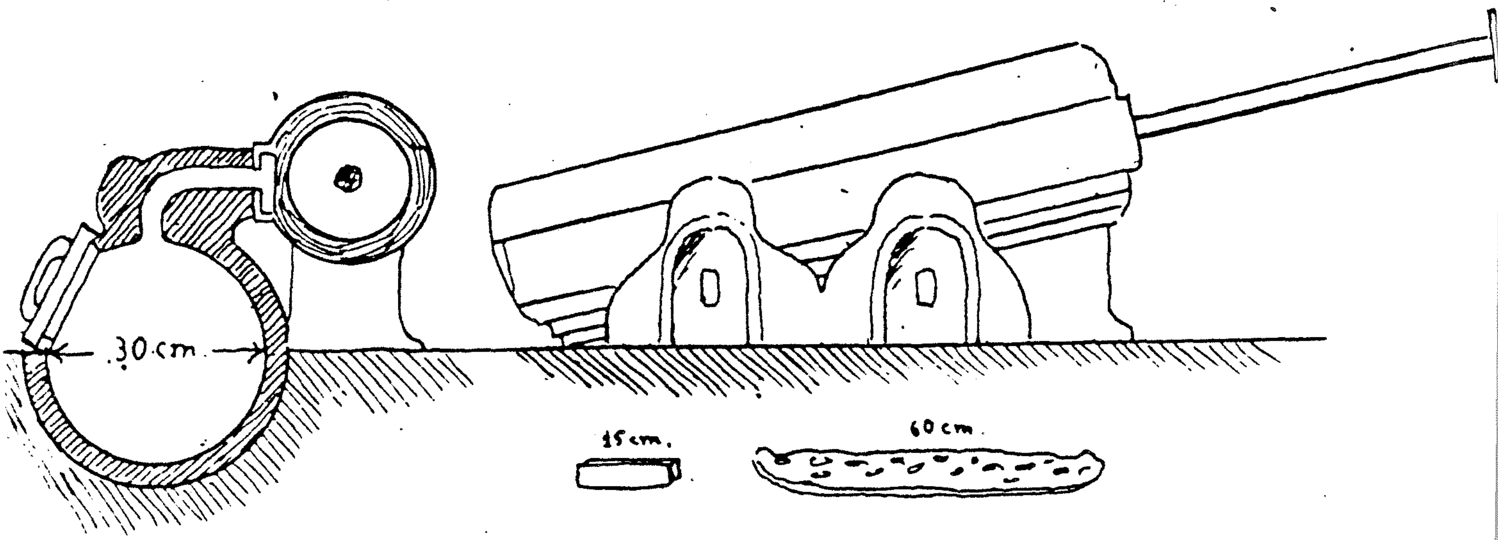


Figure 9. Diagram of a fining hearth used in Shangcheng, Henan, 1958 (Yang Kuan 1982:225). 1. Hearth. 2. Tamped fireclay. 3. Furnace opening. 4. Cover. 5. Windpipe. 6. Furnace opening. 7. Iron reinforcements. 8. Nest. 9. Ground level.

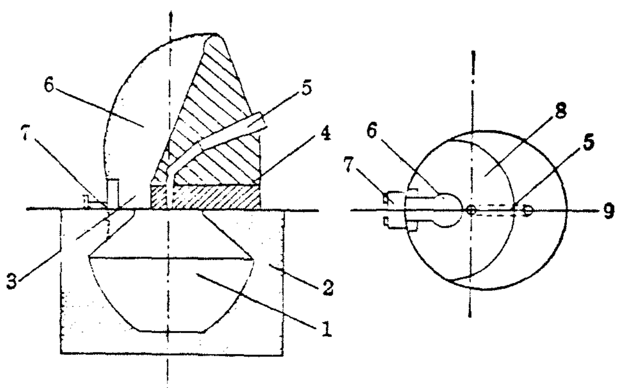


插图 60 河南省商城县土法炒钢炉的正视图和剖视图
(采自冶金工业出版社编《土铁土法炼钢》1958 年 10 月号,
第一篇《河南商城县的土法低温炼钢》)
部位名称: 1.炉缸 2.夯实的耐火泥 3.炉门口 4.天门盖 5.通风管
6.炉门 7.炉门铁 8.炉窝 9.地面

CLASP ARMS VERSUS COMPASS ARMS IN WATER WHEELS: REGIONAL PATTERNS OR TIMBER PROBLEMS?

[A Comment on the Paper of David Crossley]

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In his paper "The Construction and Installation of Water Wheels: Medieval to Post-Medieval" (Medieval Iron in Society, Jernkontorets Forskning H34, 1985, pp. 107-123) David Crossley presents the most comprehensive overview yet published of the results of English excavations of water wheels dating from the period 1300-1700, many of which powered iron production facilities. His evaluation of the construction techniques used on these water wheels and their water supply systems is excellent.

However, in the same paper Professor Crossley also suggests (pp. 108, 110, 112) the intriguing possibility that two sharply different patterns of vertical water wheel construction existed in Europe. One pattern, that found on all of the wheels thus far excavated in England and seemingly also reflected in the seventeenth-century landscape paintings of the Flemish artist Henry Bles, was characterized by:

(1) compass arms (p. 110),
(2) narrow cross-sections (p. 112),
(3) longitudinal sole planks (p. 112), and
(4) spokes, or arms, attached to the center of the sole on the rim of the wheel (p. 112).

The other pattern, reflected by the illustrations in Agricola's De re metallica (Basel, 1556) and respresenting a central European style, was sharply different and characterized by:

(1) clasp arms,
(2) broader cross-sections,
(3) cross-planked soles, and
(4) spokes attached to the inner edges of the shrouds instead of the center of the sole.

Because of the sparsity of excavated water wheel remains from the period 1300-1700 and the nearly total absence of excavation reports on water wheels from central Europe, the only data base by which Professor Crossley's hypothesis can be tested is water wheel illustrations. There are a number of these, some contained in medieval manuscripts, more in Renaissance theatres of machines, and some in other technical works published in the eighteenth and nineteenth centuries. Unfortunately, however, most illustrations of water wheels before 1800 lack sufficient detail to test adequately all of the parameters mentioned by Professor Crossley. For example, nearly all of the medieval illustrations of water wheels are so sketchy that one can not determine sole construction or how spokes were attached to wheel rims. Moreover, it is difficult to determine the dimensions of water wheels, such as width, from the unmeasured drawings of early technical works. Only one of the differences noted by Crossley between the excavated English wheels and Agricola's wheels shows up quite clearly in most water wheel illustrations prior to 1800, even the crude medieval sketches--the compass/clasp arm distinction.

All of the water wheels unearthed by English archeologists and dated to the period 1300-1700 were compass arm wheels (Crossley, p. 110). Nearly all of the water wheels pictured by Agricola in De re metallica are clasp arm (the exception is a compass arm wheel on p. 191, Hoover ed., New York, 1912). But is this difference due to broad regional patterns--i.e., western Europe vs. central Europe--or to some other factor?

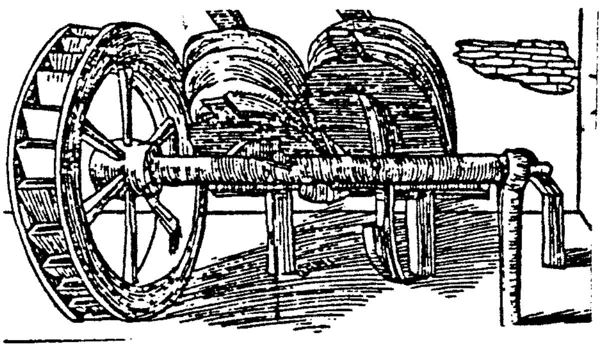

Fig. 1: Compass Arm Wheel (from Biringuccio, 1540)

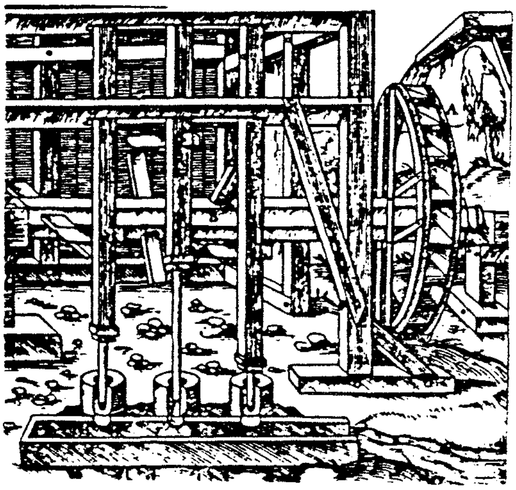

Fig. 2: Clasp Arm Wheel (from Agricola, 1556)

Extant water wheel illustrations suggest that regional patterns are not the explanation for Professor Crossley's observations. For instance, the few surviving medieval manuscripts which picture water wheels show only compass arm wheels. This statement applies even to those manuscripts originating from central Europe, such as the Hortus Deliciarum of the Abbess Harrad of Landsberg, (c1190), the Dresdener Bilderhandshrift des Sachsenspiegels (c1350), Das Mittelalterlich Hausbuch (c1450), and the notebooks of the engineer Conrad Kyeser (c1405).

Water wheel illustrations become more numerous after the introduction of printing. But of all the Renaissance theatres of machines with which I am familiar, only Agricola's

De re metallica and Fausto Veranzio's Machinae novae (Venice, c1615), which contains only around three water wheel illustrations, picture mainly clasp arm wheels. All of the remainder, including those published by German authors, picture either mainly or entirely compass arm wheels. Among those I have surveyed are Georgius Böckler's Theatrum machinarum novum (Nuremburg, 1661), Vittorio Zonca's Novo teatro di machine et edificii (Padua, 1607), and Agostino Ramelli's Le diverse et artificiose machine (Paris, 1588), as well as a number of lesser known works. Even Vannoccio Biringuccio, who travelled extensively in central European mining districts, pictures only compass arm water wheels in his Pirotechnia (Venice, 1540).

This is not to say, of course, that the clasp design does not appear at all other than in Agricola and Veranzio. Zonca depicts a boat, or floating, mill with clasp arms; Ramelli illustrates a water wheel, with clasp arms, powering a pump. But, in general, compass arm water wheels are pictured much more frequently than clasp arm water wheels. This same trend continues in eighteenth century technical works like Jacob Leupold's Theatrum machinarum generale (Leipzig, 1724), Johannes Beyer's Theatrum machinarum molarium (Dresden, 1767), Bernard Forest de Bélidor's Architecture hydraulique (v. 1, Paris, 1737), and others.

In the nineteenth century, however, the clasp design clearly began to replace the compass design in popularity in wooden water wheels over much of Europe. Rees's Cyclopaedia (v. 38, London, 1819, art. "Water") declared, for example, that the clasp design was better than the compass. The French hydraulician d'Aubuisson de Voisins, somewhat later, also condemned the compass design (Treatise on Hydraulics, Boston, 1852, p. 369, Bennett transl.). David Scott, shortly after, discussed only clasp designed wooden water wheels in his Engineer and Machinist's Assistant (2nd ed., v. 1, Glasgow, 1856, p. 213). Finally, and later in the century, Julius Weisbach noted that the clasp method was used on wooden wheels more often than the compass method (Manual of the Mechanics of Engineering, 4th ed., v. 2, New York, 1877, p. 176).

But in some regions, the compass arm wheel retained its traditional popularity. This was particularly the case in the United States. The American millwright Robert Grimshaw in his Miller, Millwright and Mill Furnisher (New York, 1882, pp. 505-506) provided his readers only with instructions on clasp arm construction. And slightly later, another American writer observed that clasp arm wheels were not common in his country (J.P. Frizell, Trans. Am. Society of Civil Engineers, v. 28, 1893, p. 238).

The data outlined above and based mainly on surviving early water wheel illustrations do not, I believe, support the hypothesis that broad regional building styles explain the compass arm/clasp arm distinction. What, then, could account for the facts noted above and the differences between excavated English wheels and Agricola's illustrations pointed out by Crossley?

In order to answer this question, it is necessary to first review the advantages and disadvantages of the compass and clasp arm building techniques. The compass technique required mortising, or cutting a passage through, a water wheel's axle for its arms or spokes. Arms intersecting at the axle were joined by notching within the mortises, and oak keys were used to fill any gap left after the spokes were inserted and joined. The clasp technique, on the other hand, required no mortising. A portion of the axle was squared off and sets of spokes, or arms, were run in parallel pairs from one side of the wheel to the other so that they gripped, or "clasped," the squared portion of the axle between them. A tight link between these arms and the axle was insured by inserting wedges.

The compass technique clearly possessed one major advantage over the clasp technique. The link between the water wheel's axle and its rim was stronger. Because of this a compass arm wheel could be built lighter than a clasp arm wheel. With the clasp technique, especially under conditions of intermittent loading, the wedges which provided a tight fit between spokes and axle were likely to work loose, requiring regular readjustment. And the less direct linkage between axle and rim required a heavier arm construction. One of the chief advantages of the clasp arm design, however, was that it did not require the same high quality timber shafts for axles that the compass arm design did, since clasp arm axles were not weakened by mortises.

These considerations suggest the following:

(1) Most medieval water wheels were of compass design because good oak shafts suitable for water wheel axles were readily available.

(2) This continued to be the case in most of Europe in the period 1500-1800. With good axle shafts available, the better link and lighter construction of the compass design continued to be the preferred style. In some areas of Europe, however, local shortages of good oak shafts had led to the adoption of the clasp design, with its poorer link between rim and axle and heavier arm construction, because it had the compensating advantage of using oak shafts of lesser quality. Probably the metallurgical districts with which Agricola was familiar were among such areas. These districts had contained mining and smelting works for several centuries before Agricola, and these works had probably exhausted the local supply of high quality oak timber.

(3) Similar considerations probably explain the scattered appearances of clasp arm wheels in other European published works between 1500 and 1800.

(4) By the 1800s, however, supplies of large oak trees for high quality shafts had been exhausted more widely in Europe. This explains why European writers in the nineteenth century began to recommend the clasp arm design over the compass arm for constructing wooden water wheels.

(5) In regions where timber supplies remained plentiful, as the United States, the compass arm design continued to dominate.

In brief, I postulate that the differences in construction patterns noted by David Crossley in his contribution can be explained better by the local timber supply situation than by assuming the existence of broad regional water wheel building patterns, although the limited data we have available certainly do not completely rule out Professor Crossley's explanation.

Because the illustrations of water wheels in technical works published prior to 1800 are not as clear on the other stylistic differences pointed out by Professor Crossley, I am, unfortunately, not able to extend my argument much further. But I would like to make two other points. First, is it not possible that the longitudinal planking for soles in the excavated English water wheels and the cross planking for soles in Agricola's water wheels were also dependent on the quality of local timber supplies? The soles of the English wheels had been hewn to the diameter of the wheels by adze. This would have required having timber available in larger dimensions than the simple cross-planked soles of Agricola's wheels. Thus the differences in sole design may also reflect local timber situations instead of regional patterns. Second, the extraordinary narrowness (typically 0.4 to 0.5 m) of the eleven excavated English wheels described by David Crossley may not be indicative of a regional tradition either, but simply a reflection of the types of water wheels likely to be available for archeologists to excavate. Sites with a moderate to good water supply were likely to have relatively broad wheels to make use of such supplies. These sites, because of their good supplies, were also likely to be reused and have their wheels replaced. Sites with small to marginal water supplies, and hence narrow wheels appropriate to such limited supplies, were the ones likely to be completely abandoned and left for archeologists. Thus the archeologists' sample of wheel width is likely to be biased towards smaller wheels.

Discussion of the paper by Nils Björkenstam and Sven Fornander:

'Metallurgy and technology at Lapphyttan'

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In the verbal discussion on May 8th, 1985, I gave a short general introduction, which was also partly devoted to Mr Gert Magnusson, who's lecture on May 6th not was open for discussion. That part is not repeated here because I have delivered a written contribution also to the discussion of Mr Magnussons paper. My two questions to Messrs. Björkenstam & Fornander now have been reformulated and parted between the two papers. Here I would like to address Mr Björkenstam and Dr Fornander (B.&F.) with the following comments and questions.

On the history and some contemporary sources

In their historical survey (p.185), B.&F. have left out completely one of the most important historical features, namely the German influence for centuries, beginning in the second half of the 12th century. See e.g. Boethius (1951). There is still much research to be done to get the whole view from king Knut Eriksson and his treaty in the 1170s with the prince of Lübeck, Heinrich der Löwe, the following period of building German colonies in several Swedish ports on the Baltic, the growing export trade with iron over Kalmar and Ronneby and the establishment of Bergslagen districts such as Godegård, Hellestad, Lerbäck, Norberg etc. See e.g. Boethius (1951), Carlberg (1879) and others.

When referring Peder Månsson (p.186), B.&F. do not mention that there are two interpretations of his description of how the iron was produced. Because of the last part being clearly dealing with the refining of pig iron (named 'skärsten' and not 'järn' because it was non-malleable), B.&F. did not consider the previous part: "they let the lumps out" after "at first have let the 'skärsten' run". The medieval Swedish language deviates considerably from modern Swedish, especially the grammar, but a careful interpretation must, in my opinion, follow the line quoted here as I have shown earlier, Tholander (1973, 1977). That means that the furnace described was a High bloomery, not a Blast furnace. Today we know that the Swedish term 'masugn' still in the 18th century was used for both types of tall furnace. See e.g. Winge (1938), Tholander (1979).

To the official records started under king Gustaf I, B.&F. only give a very general hint. There is in fact some very interesting information to find by considering certain details and making a few simple calculations. Take for instance the very first four decades recorded for Österby and Leufsta iron-works in Roslagen, Uppland, or from 1550 - 1590 AD, where the king was a private partner in Österby in the first decade. It is true that only the first and the last decades show real production figures, but to compare them is of interest here (the two between being out of production by different reasons). The statistic material used here is based on Tyrén (1982).

For the six years in the 1550s (1551,-52,-53,-54,-55,-57), when king Gustaf was still active, the iron production had a quite different character than later on. The total production of pig iron in these years was 16.7 skp ('skeppund' of about 150 kg) or only about 2.5 metric tons. In the same period 469.5 skp of bar iron and other forgings were produced, or ab. 70.4 metric tons making in average 11.7 tons/year. The single furnace at this time, named 'masugn' and producing in average only 3.6 % pig iron and 96.4 % forged iron, cannot have been a blast furnace in modern sense. It ought to have been a type of High bloomery giving mainly malleable iron directly from the ore.

In 1580, however, the iron production seems to have started again under improved conditions, but still with one single ore-smelting furnace and two hammers. The pig and cast iron production soon began to exceed the tonnage from the forges. Due to a certain increase, from 1583, of the number of furnaces and hammers, the production figures for pig and bar iron rised rapidly as is seen in Table I. In less than 10 years the tonnage of finished forged products in the 1580s was multified by 11.3 or from 12 tons/year to 137 tons/year. The pig and cast iron production was multified by 8.9 or from 23 to 205 tons/year.

Table I. Iron production and main industrial equipment at the two iron-works Österby and Leufsta during parts of the period 1551 - 1588 AD. Tabulated figures are calculated from a base table in Tyrén (1982).

Years	Pig iron	Castings A	Castings B	Forged products Bar iron	Forged products A	Forged products B	Equipment M units	Equipment H units	Production pig & cast per unit
1551 - 1557	16.7			390.0		79.5	1	2	
1580 - 1582	73.4	386	2.8	101.6	135.5	5.5	1	2	154 skp/yr
1583 - 1585	908.5	986	22	880.8	454	126.6	3	3	213 "/year
1586	707.2			456.8		22.2	5	3	
1587 - 1588	2072	560	96	1446	357	26.8	5	4	273 "/year

Symbols: A = Cannon shot; B = Other castings or forgings; M = "Masugn", "Blast furnace"; H = Waterpowered hammer

Note: a. Production weight figures in Swedish "skeppund" (skp), ab. 150 kg

b. Years with equal equipment are put together here. Production "pig and cast per unit" is the Sum (skp) div. by M pcs. and the number of years on the line.

In Table I at first one important event can be noted, namely the remarkable change, between the figures of the 1550s and those of the 1580s, in the production content as well as in quantities and yield, indicating some great change in the technology used. In my opinion, that change may well be the introduction of the blast furnace in modern sense.

Secondly, the rapid production increase per furnace unit during the 1580s also is of great interest, because it might indicate the smelting process to be in a phase of strong development.

On the necessary conditions for the blast furnace process

The introduction of water power was certainly not the immediate incitement for the introduction of the Blast furnace in modern sense. The direct consequence must have been, that the enlargement of the antique bloomery into the High bloomery, starting in the Alps according to T.S. Reynolds,(1985), resulted in the capability of smelting rock ores in coarser piece-size than had previously been possible. Not until the knowledge of how to refine pig and cast iron into wrought iron was established, the continous production of liquid, non-forgeable iron could be economically accepted.

The reasoning by B.&F. (p.186) on the influence of phosphorus is not relevant in this context because there are no signs in the Swedish Bergslagen on a competition between a primitive smelting practice and the new medieval technology for the smelting of rock ores. Instead, the authors ought to have considered the historical fact of a specific sort of Swedish iron, the "loppejärn", which in records from the 1460s to the 1530s is mentioned as the reason for punishment, when somebody was unmasked to have mixed 'loppejärn' with 'osmundsjärn' in the same barrel.

In my opinion, the 'loppejärn' was a refined pig-iron product inferior to the 'osmundsjärn' because of the finery process not yet being known well enough to give a wrought iron of equal good quality as the 'osmundsjärn'. My reasons in the case were reported to Osmundsgruppen, Tholander (1972).

On the Lapphyttan furnace being a blast furnace or not

From a general scientific point of view it is very remarkable, that B.&F. without any discussion of possible reasons, for and against, have appointed Lapphyttan as a "blast furnace" in modern sense, i.e. giving a continous production of liquid pig iron. In the discussion of Mr Magnusson's paper, I have expressed my disagreement to his conception on reasons founded on observations of my own and some constructional matters in his report.

To this point of the paper by B.&F., there are not many matters open to a relevant discussion because of the lack of information on significant details recorded at the excavation. Under the heading "Blast furnace" (p.189) however, the first paragraph and Fig. 5 are devoted to the stages of blast furnace development in the 17th and late 18th centuries, half a millenium later than the period claimed to be the active time at Lapphyttan. To the statement on the lines 1 - 3, p.189; "In Sweden ... two patterns for ... furnaces of the kind ... in fig. 5, ... Old Swedish ... or the younger ... German blast furnace ...", I must ask:

Question 1: Because the above statement quoted gives to the reader the impression of the two patterns being both very similar to Garney's drawing in Fig. 5, do the authors have another source for the design of the "Old Swedish blast furnace" than the well known one published by Odelstierna (1913) ?

Further on, when the authors are discussing the inner cross-section shape of the furnace, they claim it to have been impossible to build exactly an circular shaft without a supply of "accurately machine-made bricks". This obvious under-estimation of medieval furnace-builders makes another actual:

Question 2: I find it difficult, on the basis of Fig:s 6, 7, to denominate the horizontal inner cross-section profile of the Lapphyttan furnace as "eight-sided" or even "square with cut-away corners". Would it be possible to you to present, in this volume, actual photographs and sketches from the excavation material, which could better support the readers of the report ?

The authors are also (p.190) discussing the tuyere and its position relatively the sole. Because no information is given on the assumed design of these matters, I would like to ask:

<u>Question 3</u>: Are there any photographs available for showing the indicated position and eventual details connected with the tuyere in the north wall ?

If in Lapphyttan ruin, as is said on p. 190: "nothing is left of the hearth" it would have been of great interest to know something of the authors' reasons to be able to claim the original shape of the hearth to be so similar to the hearth-model being modern in the 18th century, when described and shown in drawings by Swedenborg, Rinman and Garney. Finally, it would be of value to get an answer to the following question:

<u>Question 4</u>: Three reconstruction sketches were shown by Mr Magnusson in his Fig:s 7, 8, 9 over an inserted, rectangular hearth. You are describing the hearth as being "badly damaged" at the removal of the "bear".
How do you then explain the slag-clad wall to be so well preserved down to the very sole, that a sharp horizontal line was visible along which the slag-cover on the wall surface had what looks like its ending against the bottom sole ?

<u>Summing up</u>:

The authors of this paper have claimed, that the Lapphyttan furnace has been a blast furnace in modern sense, continuously producing liquid pig and cast iron. If that is true, the furnace is the hitherto eldest known example of the type. The burden of proof, however, is on the authors. In my opinion, it would be much easier to prove, that the furnace in this case belongs to the type: High bloomery.

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REPLY TO ERIK THOLANDER'S DISCUSSION PAPER CONCERNING METALLURGY AND TECHNOLOGY AT LAPPHYTTAN. - Nils Björkenstam

The sole purpose of our essay is that indicated by the heading, namely to interpret the metallurgical processes occurring at Lapphyttan and the technology otherwise employed there. Accordingly, there is no reason in this connection to go into detail about the reasons for the introduction of the blast furnace process and any precursors or predecessors of the old Swedish blast furnace, mediaeval Swedish trading relations or the exact historical development of the Swedish iron industry. In our historical account we have only sought to highlight important conditions with a bearing on our subject.

The commercial treaty of the 1170s

Tholander puts forward outmoded hypotheses, which have since been abandoned (cf. Rosén 1962), concerning an epoch-making German influence on the iron trade which, the argument goes, also affected the production of iron in Sweden. But the trading activities of the Viking era also continued during the 11th and 12th centuries, and so this trade never ceased altogether. Consequently the German infiltration of the Baltic area was able to use trading routes which had been known for a long time and it formed part of the same process as the German eastward expansion, e.g. into Poland and Hungary, where there were also outposts of German trade.

German merchants were already trading with Nordic markets in the early years of the 12th century. The trading agreement concluded during the 1170s between Henry the Lion of Saxony and King Knut Eriksson of Sweden is not extant but is only mentioned in a subsequent commercial treaty signed by the Swedish regent Birger Jarl with Lübeck in 1252 ("Svenskt Diplomatarium" part I, No. 246). Thus we know nothing about the content of the treaty between Henry the Lion and Knut

Eriksson. Birger Jarl granted Lübeck a certain measure of tax and customs exemption in Swedish ports. The only conclusion which can be safely drawn about the content of the previous treaty is that, like Birger Jarl's, it referred solely to the status of German merchants in Sweden. Obviously, though, the rulers of Sweden had an interest in the continuance of trade. This being so, they must have had something to export, e.g. surplus livestock produce in the south of Sweden and copper and iron from the mines of central Sweden (Rosén, p. 183), and at the same time of course there were certain other things which had to be imported.

Peder Månsson's description of a blast furnace, "masugn"

Tholander deplores our omission, in reproducing this description of a blast furnace from about 1500, of his own personal opinion that the description must be taken to refer to a high bloomery furnace.

Peder Månsson was living abroad between 1508 and 1524, the period when he wrote his account of the Swedish iron industry and other matters. His description, then, probably relies on personal observations in Sweden at the end of the 15th century. There is a sentence of this description which Tholander wishes to interpret differently from philologists, historians and technologists generally: "läte the smelterne ut förste reessen rinna thett som kallas skärsten". Tholander does not deny that "skärsten" (Eng. matte) refers to pig iron, but he puts a full stop after "läte the smelterne ut" and takes "smelterne" to mean the melts, resulting in the following translation: "They let the melts out after at first have let the 'skärsten' out". Dr Calissendorff, who has examined this text linguistically (1974, p. 33), has the following to say concerning Tholander's interpretation:

"Peder Månsson's is the oldest known description of the process. Everybody nowadays agrees that pig iron was produced in this furnace, and the passage does not provide support for any other theories. The conception of Peder Månsson's '<u>skärsten</u>' and '<u>smelterne</u>' referring to two different products is based on a misunderstanding. Peder Månsson refers to '<u>bergsmännen</u>' as 'the <u>begzmennene</u>', and 'the <u>smelterne</u>' as used here refers to the craftsmen and not to their product."

Peder Månsson's description is of great interest and, translated into English, the section dealing with the blast furnace process used in the Norberg mining district and elsewhere reads as follows:

"... There they have big round furnaces eight ell deep (4.8 m. approx.) and they carry the ore to the furnace broken up with hammers after it has been extracted from the rocks, and when it has been blown sufficiently, the melters first[1] allow what is called "matte" (<u>skärsten</u>)[2] to run out into a pit. They then lift out slice after slice as it cools. This blast furnace (<u>masugn</u>) has three holes, just like the copper furnaces. They then break up the matte and put it piece after piece into the fire (in the finery hearth) while blowing it with hand bellows, and this turns into iron, which they break up into small pieces, osmunds."

Since it was first published by R. Geete in 1916, this text has been reproduced and similarly interpreted by many writers, e.g. Winge, whom Tholander quotes in another connection but without stating Winge's conviction that Peder Månsson's

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(1) <u>Tackjärn</u> (pig iron), denoting iron from a blast furnace cast in pigs, does not occur before 1496 (Liedgren 1965).

(2) In the next operation, of course, the slag runs out of the furnace positioned above the pig iron in the hearth.

furnace only produced pig iron, which was then refined into osmund iron. One very great weakness indeed with Tholander's theory is that Peder Månsson does not say a single word about what happened to Tholander's main product, the bloom; he only tells us what was done with the pig iron.

It is sheer nonsense to say that high bloomery furnaces existed in Sweden as late as the 18th century, and this is merely an assertion of Tholander's originally based on his misjudgement of a blast furnace ruin called Harhyttan. That furnace was excavated between 1979 and 1981 under the direction of Dr Inga Serning (Wedberg et al 1985). It was concluded that Harhyttan was a charcoal blast furnace, of a type described frequently in the literature. The furnace had a square section, with the stack partly dug into the hill slope. The front part, with tapping arch and tuyere opening, was constructed of solid blocks. Air was blown into the furnace by one tuyere, with water-wheel-driven bellows. Slag and cast iron have been tapped in the same direction. The slag samples analysed are typical blast furnace slags and the iron found at the site is cast iron. Comprehensive written documentation has survived concerning this blast furnace site between the period when the regent Sten Sture the Elder (d. 1503) owned Harhyttan and until 1697, when Harhyttan paid its production tax in pig iron.

Tholander refers to Winge in the same breath as himself, thereby giving the impression that Winge shares his opinions on high bloomery furnaces in 18th-century Sweden. What Winge (1938, p. 315 et seq.) actually says is that the Swedish name for a blast furnace, masugn, originally referred to a furnace in which a forgeable bloom, Mas or Mass, was produced, but that in time the same name came to be applied to furnaces producing pig iron only. Winge rounds off his essay by saying that the mere occurrence of the word masugn in a document is insufficient to warrant the conclusion that pig iron was being made in Sweden when the document was written.

H. Sundholm (1938, p. 425) objected to this, observing that the word masugn was so rare in our mediaeval documents that it only occurred twice - once in the 1440s and again in 1461. Sundholm asks Winge, therefore, whether the word masugn as used in these years can be interpreted in a different sense from that used by Peder Månsson in about 1480. To this Winge replies: "It is obvious that the furnaces he (Peder Månsson) calls "masugnar" were pig-iron furnaces." On the other hand he gives an evasive answer to the question about the other two furnaces, and he says that objectivity precludes a categorical statement as to what kind of furnace they were.

From the end of the 15th century down to our own time, masugn has denoted a blast furnace producing pig iron. Before that the word hytta was applied to iron furnaces in central Sweden. In 1328, for example, St Bridget inherited two hyttis in monte ferreo - furnaces using iron bedrock ores - in Närke (Wernstedt 1957, p. 36).

Iron production in Österby 1551-1588

Mention of the exceptional opportunities in Sweden of acquiring detailed information on the technology of the 16th-century iron industry implies that we have drawn on this source in order to interpret and understand the activities carried on at Lapphyttan. Tholander himself, unfortunately, does not take this opportunity of conducting researches in our national archives.

The two authors to whom he refers, Douhan and Tyrén, base their accounts predominantly on E. W. Dahlgren's "De uppländska bruken Österby, Forsmark, Leufsta och Gimo under äldre tid" (1928) and on Professor N. G. Sefström's excerpts, published in Jernkontorets Annaler 1845, from the Uppland documents, now in the National Archives, referring to the Österby, Forsmark and Wattholma ironworks between 1547 and 1599.

In 1545 King Gustav Vasa took the initiative in testing a direct reduction method, rännverk, at Österby. This method has a long history in Germany, where it was extensively used in the Middle Ages and even later. The Rennwerk, otherwise known as Zerennhütte, consisted of one or more hearths for reducing the iron ore (Zerennherd), one or more re-melting hearths (Löschherd) and one or more hammers for forging bars, sheet, etc. Beck (II, pp. 782-783) tells us that a Rennwerk hearth was 8 feet long, 4 feet wide and 1 1/2 feet deep. The ore was crushed and screened to a very fine-grained gauge. Big, pure charcoal was similarly pulverised. The ore and charcoal were mixed and deposited in the hearth until the charge rose far above the hearth edges (Johannsen, p. 122). In this way the charge also came well above the tuyere in the rear wall of the hearth, thus forming a furnace wall round the reduction zone. A new charge was added continuously while the ore was being reduced and the slag, which contained a large proportion of iron oxide, flowed out from the channel-shaped hearth. The iron thus obtained was re-melted, or rather its composition was equalised, in another hearth (Löschherd) lined with slag from the first. Johannsen puts the forged bar return at 17-18 per cent.

JkA 1845 states that bar iron was produced from a Rennwerk hearth at Österby. In 1553 the ore input was four tuns per old Swedish ship-pound (skeppund) of bar iron. One tun of ore was normally taken to weigh two skeppund (fine-grained ore was doubtless heavier). If, then, the ore contained about 50 per cent Fe, the return would be 25 per cent at most. To produce this amount of bar iron took 120 tuns of charcoal per skeppund, which converted into modern terms makes 132 m^3 charcoal, i.e. roughly 20 tonnes charcoal per tonne pig iron!

Otto Dress (1687, pp. 77-78) has quite an exhaustive description of the Rennwerk method. He states, for example, that unless you have a very rich, easily melted ore, you obtain very little iron per day but consume a great deal of charcoal. This method is said to have the following advantages:

1. Low capital cost compared with blast furnaces and finery hearths.
2. Less capital tied up in the production process because, assuming the mine to be very close at hand, bar iron can be forged the same day as the ore is extracted, or the day after.

This direct method of iron production, however, was eliminated by the blast furnace process, due to its inadequate yield, and Österby was no exception.

In Table I, Tholander states that 16.7 skeppund of pig iron was produced in a blast furnace between 1551 and 1557. But Österby did not have a blast furnace at that time. In the surviving accounts, the Rennwerk hearths there are referred to as "hytta" (cf. Zerenhütte) and this has been misunderstood by Douhan. Consequently Douhan's table (Douhan, p. 33) includes a blast furnace which is supposed to have produced 2 skeppund and 13 lispund of pig iron (about 500 kg!) in 1552 and 14 skeppund of pig iron (about 2,700 kg) in 1553. Tholander has added these two figures together, making 16.7 skeppund.

Now in the National Archives there is a document called "Bergsbruk. Jern i Uppland - 168 - 1552-1553" which expressly states that 2 skeppund and 13 lispund of pig iron were produced in 1552 from ore in a Rennwerk hearth. The accounts for Dannemora and Wattholma furnaces in 1553, compiled by Hans von Ligniz, are reproduced in JkA 1845, p. 57 et seq. The name Dannemora here refers to the Dannemora mines and Österby bruk. That year Österby had an opening stock of 14 skeppund and 9 1/2 lispund of pig iron. During the year, Marcus Stålsmed ("Steel smith") was supplied with 5 lispund of pig iron for experiments in steel production. The closing stock is therefore given as 14 skeppund and 4 1/2 lispund of pig iron. No pig iron was produced this year at all. The closing stock is the quantity erroneously given as 14 skeppund of pig iron produced.

Until 1570 (Dahlgren, p. 9) Österby was run by the Crown, and after this it was leased to private persons. When, on 15th December 1579, Österby was resumed by the Crown, the inventory stated that the retiring foreman, who took office in 1576, had rebuilt the works entirely. Now, according to the inventory, the facilities include a blast furnace, which must therefore have been constructed between 1576 and 1579. The number of blast furnaces then increased, as shown in Tholander's Table I. The figures in this table come from Douhan, who in turn transcribed Dahlgren's Table II, p. 86. There is a difference, however. Dahlgren has a number of queries concerning several years for which the sources do not give any production figures. Douhan has omitted to note this. Tholander, therefore, has added years for which the output of pig iron, shot, etc. is unknown to years for which we have production figures. As a result his figures are uncertain if not completely inaccurate. Thus there is no cause to comment on his conjecture regarding the capacity of the blast furnaces. It must be pointed out, however, that no such appraisal is possible without taking into account the length of time for which every individual blast furnace was operated during the year. There is material of this kind available for study. Dahlgren, for example, has noted on pages 14 and 15 that three blast furnaces were operating for a total of 305 days and 29 blowing periods in 1584. Their total output was 1,218 skeppund and 5 lispund. This meant an average blowing time of 10 1/2 effective blowing days per campaign, yielding an average of 4 skeppund pig iron (not quite 800 kg). The total charcoal consumption in modern figures was about 450 hl (roughly 7 tonnes) per tonne pig iron.

The blast-furnace process and pig-iron refining

On page 186 of our lecture, we refer to the availability of mechanically operated bellows as an essential prerequisite of the blast furnace process. A furnace which is to produce nothing but molten pig iron has to be operated continuously, day after day, under heavily reducing conditions. Hand- and foot-powered bellows are not suitable for this purpose.

During the discussion which followed the lecture, the author pointed to the difficulty of preventing the occurrence of cast iron in direct reduction processes (cf. Björkenstam 1983). The same observation has been made by practically all scientists and authors concerned with prehistoric iron production. In a letter of 2nd June this year to the author, Professor Eketorp writes: "I myself produce iron (steel) here at Benhamra on a regular basis (once annually for newly admitted students at the Royal Institute of Technology in Stockholm). If we bungle things, the result is both reduced slag and drops of pig iron." Cast iron, then, can never have been an unknown product when it began to be obtained in larger quantities from high bloomery furnaces, not later than the early years of the 12th century in Germany. For reasons of pure operational economics, steps must soon have been taken to convert this product into malleable iron.

Long before this, it was realised when making copper from sulphide ores that the copper accompanied the matte when the roasted copper was melted in shaft furnaces and that copper could be extracted from the matte by means of oxidising re-melting. The blast furnace is based on exactly the same principle. Roasted iron ore reduced in the shaft furnace yields an unworkable product which Peder Månsson called "skärsten" (matte), in which the iron is "concealed" and, just as in the copper process, the iron can be extracted by oxidating re-melting in a second furnace. A hearth of this kind was of course available in every early direct-reduction furnace, where it was used for reheating the bloom to give a more consistent end product containing less slag.

As our text makes clear, our reason for discussing the phosphorus content of limonite ores had nothing to do with any rivalry between limonite ores and bedrock ores in central Sweden. Our one and only reason for treating this subject is that stated on page 186. The general and popular explanation of the transition from direct to indirect reduction of iron ores - that the earlier furnaces were enlarged in situ and still charged with limonite ore - cannot be true. The blast furnace is a completely new type of furnace and it was built in a completely new location, namely in bedrock ore districts.

"Loppejärn"

The unusual wealth of documentation from the mediaeval period down to the present day does not include anything to suggest that high bloomery furnaces existed in Sweden. From the considerable number of products mentioned, therefore, Tholander must at least be able to point out one which was made using iron from a high bloomery furnace. He has chosen "loppejärn".

In JkA 1844, Professor Sefström published a synopsis of the total amount of iron collected by the Crown in 1557, both in the form of taxation and as products delivered that year by Crown ironworks. The list has 11 main headings: osmund iron, pig iron, bar iron, steel, thick iron wire, thin iron wire, iron plates, bolt iron, spikes, horse shoes and nails.

"Osmund iron" includes osmund iron broken up into osmund pieces, quantities of which were traditionally stated in numerical terms even where it is quite clear that they were weighed (one barrel = one skeppund) and loppejärn, known as vägt (weighed) osmundjärn. The reason for loppejärn being called vägt osmundjärn is of course that the blooms are unbroken and of variable size, so that the quantity can only be stated in units of weight. One of the quantities, reported by the bailiff Bengt Skrivare for the Nora and Linde bailiwick, shows how this bloom was produced: 78 skeppund and 18 1/2 lispund of pig iron yielded 74 skeppund, 14 lispund and 16 marker loppejärn. The examples could be multiplied indefinitely. It will suffice to refer to an excerpt from a list of Crown ironworks in 1564, published in Blad för Bergshandteringens vänner No. 20, p. 168. At Bornshyttan, pig iron was produced in the blast furnace there and turned into loppejärn, bar iron and steel as well as all manner of other necessary products. The same thing happened at the Guldsmedshyttan blast furnace where, for example, Stripa rock ore was used to produce the pig iron, which again was converted into loppejärn, bar iron and steel and other, unspecified products.

In cases where the osmund iron was to be hammered out into bar, sheet or suchlike, the bloom (Sw. loppan) was not reheated in the finery for further refinement, nor was it broken up into small pieces. The second, necessary refining took place during the opening stages of fabricating the bar etc. Bengt Skrivare describes how he uses loppejärn, JkA 1844, pp. 143-144. He has sheet hammered into armour, welded into pistol and musket barrels, turned into saws and dampers and used for furnace hearths. Here, then, we have a number of products which have to conform to very high standards of quality.

The inferior quality of "loppejärn" such as bloom compared with the twice-refined osmunds is an obvious reason why it cannot be packed into barrels designated osmund, another reason being that these pieces were not broken into osmund sizes. Many kinds of sharp practice were indulged in on the hopeful assumption that the osmund barrels would not be opened for inspection when they were weighed in. We know from judicial records that inspection revealed the presence not only of "loppejärn" but also lumps of ice and stones.

Reasons why Lapphyttan cannot be anything but a blast furnace producing only molten pig iron

Our conviction that Lapphyttan is a blast furnace rests first and foremost on the very extensive examination which has been made of the shaft-furnace slagheaps. As has been reported in detail, this slag is extremely well reduced and has such a low FeO content that it can only have come from a furnace producing nothing but pig iron. A reduction furnace mainly producing malleable blooms and small quantities of pig iron as a by-product has an average FeO content of 20-30 per cent. The exceedingly careful scrutiny of Lapphyttan has revealed only two types of slag, one with an average of 5.7 per cent FeO and one containing 7.3 per cent FeO. The sample series includes values as low as 1.7 per cent and 2.1 per cent FeO.

Garney (I, p. 12) has a passage which is very interesting with reference to the Lapphyttan study:

> "The heavily quartziferous ores which are still being worked in the Risberg and Morberg mines are unlikely to have been worked in old Norberg. At all events, traditions referred to in the earliest Norberg documents tell us that the old mines were situated at Klackberg, which is on the western side of the lake. It is also probable that our earliest furnace men preferred these fusible ores to the refractory quartzite ores. The green, glassy slag which is still to be found in the oldest slagheaps also appears to corroborate this assumption, and it also seems to prove that the slag resulted from pig-iron blowing, because all other melting methods produce a slag which is more or less black, due to the larger quantity of iron (ferrous oxide) which it contains."

Garney, of course, is influenced by the historiography of his time, and he reiterates (I, p. 7 et seq.) the then accepted view that Oden and his Aesir brought the art of ironworking to Sweden and began producing osmund from bog ore in small, low furnaces. From the passage quoted above, however, he concludes that the Lübeck merchants, who had complete control of the Swedish iron trade in their day, found it more profitable to introduce pig-iron production here and to sell the iron thus produced under the designation of osmund. This was a bold conjecture at a time when the sole credit was given to Gustav Vasa in the 16th century.

Other factors of process metallurgy indicating that the site excavated at Lapphyttan was a blast furnace are of course the finds of cast iron, the eight pig-iron fineries and the non-occurrence of any blooms which can have resulted from direct reduction of iron ore.

Fortunately the furnace ruin which has been uncovered is so well preserved that, without any doubt, its design fully agrees with our knowledge of early Swedish blast furnaces. Figure 5 in our lecture shows a furnace design known in Sweden as the German blast furnace. That picture dates from the end of the 18th century. The furnace was introduced in the 17th century but lived on until the mid-19th. Dress' and Garney's descriptions of the type of furnace which preceded the German blast furnace, known as the Swedish blast furnace, indicates quite clearly that this earlier Swedish furnace was of essentially the same design as the German variety. The horizontal section of the Lappyhyttan furnace in Fig. 7 tallies perfectly with the corresponding section of the "German" blast furnace in Fig. 5. Thus we are not merely trying to give the impression that Fig. 5 and Fig. 7 are similar. We maintain that Fig. 5 and Fig. 7 are examples of one and the same principal type of blast furnace, producing nothing but molten pig iron.

Otto Dress was born before 1630 (possibly in 1626). His father, André Dress, migrated to Sweden at the beginning of the 1620s and was employed at a succession of Swedish ironworks, eventually becoming a bruk proprietor himself. Otto Dress was manager of Kroppa bruk in Värmland at first, but he purchased it in 1659. He owned several blast furnaces and was a part-owner of at least two bergsman furnaces. In addition, he built blast furnaces himself. He lived in Värmland until 1684. Here, then, we have a credible eye witness concerning the appearance of blast furnaces in the 17th century.

Carl Johan Garney was born in 1740 in Älvkarleby in Uppland, where his father owned an ironworks. Boethius, in his "Jernkontorets Historia" part III:1, p. 65, writes: "Garney wrote a detailed description, based on direct observation, of the old Swedish timber-clad blast furnaces, the improved 'German' blast furnaces built by Germans who settled in Sweden during the reign of Gustavus Adolphus and differing only in their greater dimensions, superior construction and more powerful blast - not in terms of essential principle - from the old Swedish blast furnaces, and finally the 'French' blast furnaces of the Walloons." Garney's textbook includes not only an enumeration of the advantages and disadvantages of the various types of furnace but also advice and instructions to those who still had blast furnaces based on the old Swedish model.

Question 1

The answer to this question is that Dress'and Garney's descriptions are source materials. This is not true, however, of Odelstierna's picture (PL XXV, Fig. 2) of a furnace, where he himself puts quotation marks round the word masugn (p. 251). Odelstierna states that this drawing is reproduced from a transcript, made in 1776, from a manuscript of 1673 which has since been lost, "Om Jern Ugnar och Masugns

Byggningar" (About Iron Furnaces and Blast Furnaces). This type of furnace has come to play an important and remarkable part, both nationally and internationally, in descriptions of the early Swedish iron industry, and so a brief résumé of its origins will probably not be out of place.

Lars T. Schulze, an official of Bergskollegium, submitted a report, dated 15th April 1732, concerning furnaces for the melting of bog ore in certain places in Dalarna. The original account, complete with its appertinent drawings, is still extant (Bergskollegie Arkiv, Riksarkivet, Bergverks-relationer. Öster- och Västerbergslagen. EII 9:4 1717-1732) but is also reproduced *in extenso* in JkA 1845, p. 4. The enclosed pictures, Nos. 1, 2 and 3, have been taken from this version. Now the remarkable thing is that not the slightest trace of this type of furnace has been detectable in the comprehensive inventories undertaken by the Central Board of National Antiquities (see p. 185 of our lecture). This has prompted doubts as to whether the furnace really existed. Tholander (1979, p. 37) was one of those who are certain that it never did exist: "One is bound to conclude that Schultze's furnace cannot have existed, and so essential parts of his account must be fictitious." (Tholander actually goes on to broach the suspicion that Schultze made a deliberately inaccurate drawing of the furnace, thereby helping to conceal from the authorities the fact of secret rural production of osmund iron in high bloomery furnaces!)

Swedenborg, however, in his "Opera Philosophica et Mineralia", printed in 1734, uses Schultze's account and drawings, though without acknowledgement. In another chapter Swedenborg also describes the earliest production of osmund in keeping with current historical theories. This passage comes from Saxholm, who says that bog ore is traditionally supposed to have been used. The furnace described in 1725 by Saxholm (p. 80) and, accordingly, by Swedenborg, bears no resemblance to Schultze's.

Ludwig Beck then uses Swedenborg's Latin text to describe the early iron industry in Sweden. Instead of translating this text exactly into German, Beck summarises several chapters, adding data from other writers. Schultze's furnace has now become an osmund furnace. The next stage of evolution is for Odelstierna to translate Beck's description into Swedish, referring to it as German translation of Swedenborg's Latin (p. 26 in O. Already in 1904 this text was incorporated in Wiborgh, "Järnets Metallurgi", edited by O., p. 394). Odelstierna accompanies this text with Beck's illustrations in PL V (picture 4). Both Schultze's furnace and Beck's, Fig. 3, as well as Swedenborg's drawing of the same furnace, Fig. 4, carry the legend: Svensk osmundsugn, "Wolfsugn". Fig. 5 shows a furnace of the same essential design as the vertical section of Schultze's furnace, but this time built into sloping ground. This furnace is called a bog ore furnace and Beck has taken the picture from Evenstad, 1782, who built the furnace in Norway to Schultze's drawings, though with the dimensions somewhat altered.

Following this excursion to Germany, Schultze's furnace has come to serve the dual purpose of an osmund furnace and a more primitive furnace for producing blooms from bog ore. As recently as 1976, in Tylecote's "A History of Metallurgy", one finds Schultze's furnace as an example of an osmund furnace with a reference to Percy 1864 and in Fig. 73 as an example of a Scandinavian bloomery furnace after Evenstad.

Odelstierna's furnace in PL XXV, as can be seen from picture 5, is virtually an exact copy of Schultze's furnace (picture 2).

Newly appointed officials of Bergskollegium had to spend their first years of apprenticeship studying and transcribing historic documents. The person who in 1776 transcribed the essay from 1673 had access to Schultze's drawings. It is unlikely that Schultze, an official of Bergskollegium, could have accompanied his account with copies of the 1673 account and got away with it. It is more likely that the copyist in 1776 appended Schultze's drawings to his transcript. No distinction was made at this time between iron furnaces and blast furnaces. A search has been made of the National Archives for the 1776 transcript, unfortunately without success. In no circumstances can this dubious transcript rank as source material. This has been pointed out previously but is neither mentioned nor refuted by Tholander. (Björkenstam 1978, p. 48).

Question 2

As mentioned in our lecture, the fire-resistant natural stone used at Lapphyttan was a mica schist. This is easy to split after it has been divided into strata, but very difficult to divide regularly at right angles. Bricks made from this rock display maximum fire resistance when the stratified, rough side is turned facing the inside of the furnace. (Garney I, p. 213).

Mortar usually has a lower melting point than fireproof brick, and this is also true of Lapphyttan. Modern brick, therefore, is made to very close dimensions and large radial bricks are obtainable for every furnace diameter, so as to minimise the number of vertical (and horizontal) joints. Today, then, furnaces can be lined without mortar. In a furnace like Lapphyttan, the stratified natural stone gives relatively thin horizontal joints, but very large vertical crevices occur between the stones, as Garney observes, emphasising that these crevices must be very carefully pointed with mortar and with mica schist shards. In a furnace like Lapphyttan, owing to its small diameter, circular masonry would produce a very large number of vertical joints. A square or octagonal section makes it possible to use larger stones, resulting in a much smaller number of vertical joints. In this latter case the stones must either alternately overlap in the different courses, or else the corners have to be cut off by building octagonally, so as to avoid a vertical joint reaching from the top all the way down through the shaft.

The side of the furnace over the tapping arch has collapsed and the shaft has disintegrated, with the result that the northern and southern walls have been pushed out by the collapsing masonry and by the pressure of ice forming there during the winter. Visualising these walls erect in their original position, it is quite obvious that the furnace had a mainly square cross-section. Studies of the design have convinced me that the furnace, when newly built, cannot have had sharply right-angled corners.

Dress writes on p. 60 that the Swedes usually built octagonal furnaces to a vertical pattern (known in Sweden as a stege, ladder). He says it is much better to follow the French example of using a horizontal, circular pattern, because each individual stone can then be adjusted and rectified accordingly.

A circular shaft makes for a better distribution of the charge and more equal distribution of the gas flow, which in turn means a steadier process. A square or octagonal furnace gradually, as a result of fusion and wear, acquires a circular section. The shafts of earlier blast furnaces could be used for several decades without any repairs being needed, the reason being that for most of their service life they were operated with a virtually round cross-section. The choice between a circular or angular structure, therefore, is a matter of operating economics, and it is completely irrelevant to the question of blast furnace or high bloomery furnace.

Question 3

The roofs of the arches had been made up of flat stones. In later furnaces of this kind, the stones rested on iron girders, but Garney (I, p. 155) says that formerly they were supported by wooden beams. The stones, of course, would then be positioned over the beams so as to protect them from the flames, but they still had a short service life. This probably accounts for the complete collapse of the tuyere arch. To deduce the original appearance of this arch, the fallen masonry had to be removed and carefully recorded. The size of the arch could then be uncovered, as shown in Fig. 7, and the bottom of the arch was found to be a sooty floor of heavily flattened clay.

Dress (pp. 55-56) says that one disadvantage of the old Swedish blast furnace, which was dug deep into sloping ground, was that the bellows occupied a fixed position and could only be driven from the water-wheel shaft direct. He goes on to say (p. 59) that the Nora mining district still had blast furnaces driven with small leather bellows which were only 2 1/2-2 3/4 feet (75-82.5 cm) wide. Bellows of this width fit nicely into the "shelf" outside the arch. The distance from the point where the waterwheel shaft must have been is judged sufficient for the bellows to have been of acceptable length. We have therefore concluded that the blow-out pipes of the bellows rested on the floor of the arch. So much for the lower edge of the tuyere. The original position of the furnace floor is determined by the level of the teeming floor and the bottom of the tapping hole, where there were two solidified streams of pig iron. The centre line of the tuyere was thus 25 cm $\pm$ 5 cm above the floor.

In early times the tuyere was a tapered opening let into the fire-resistant stone of the hearth wall and "roofed" with another type of fire-resistant stone. The final area of the tuyere was shaped by clay. It required that the clay tuyere could be replaced while blowing was in progress and shaped in such a way as to aim the air jet in different directions in the hearth (Garney I, p. 269). This, of course, did something to compensate for the immobility of the blow-out pipes. Since the hearth is completely burnt out in the tuyere wall, nothing of the tuyere remains, nor is this to be expected if it was of the design usual in the old Swedish blast furnaces.

Question 4

There are a number of latter-day post-campaign scale drawings of blast furnaces with one tuyere. Wedberg (1985) shows in Fig. 10 how the fusion of the hearth altered the Hällsjö blast furnace in 1873. The bottom area then increased from 2'5" to 4'7" on average. Thus by the time blowing has finished, the area has almost quadrupled. There is a similar drawing of the Uddeholm furnace in 1864 (Björkenstam 1983, p. 25). Here the bottom diameter increased from 73 cm to 128 cm and the hearth diameter from 73 cm to 140 cm. Although these furnaces were larger and were worked harder, their lining of stamped quartz should have made them more flame-resistant than the Lapphyttan furnace.

At the level of the Lapphyttan furnace occupied by the original floor, the distance from the rear wall to the inside of the taphole in the hearth is 6-6.5 dm and the distance between blower wall and tuyere wall about 4.5 dm. At tuyere level the distance between these two walls is about 8 dm. Due to the walls having been pushed outwards, the distance is now slightly greater than immediately after the furnace was taken off blast, but this still shows that the tuyere was entirely or almost entirely burnt away.

Concerning the shape and size of the hearth, there is older evidence than that quoted by Tholander. Dress 1687 (p. 63) quotes, for furnaces about 7 m high, a hearth which is 95 cm to the dam stone but only 58.5 cm to the tymp plate measured from the rear wall, and 37.5 cm wide at the rear wall and 40 cm wide at the taphole. "Iron and Steel on the European Market in the 17th Century", 1982, gives hearth measurements for furnaces about 7 m high, e.g. 80 cm from rear wall to dam, which should mean about 50 cm to the tymp, at the same time as the breadth here is 35 cm. Hearthstone measurements are given on pages 155 and 156. The bottom slab should be 90-105 cm long, 75 cm wide and over 20 cm thick. Proportionally smaller stones can be used for the sides.

The floor of Lapphyttan is oval, measuring about 65 x 45 cm. Since the hearth, inevitably, has melted away in part, it can hardly have measured more than about 5 x 3 dm. The melting presumed here is substantially less than in the two furnaces mentioned above. Considering the smallness of the furnace at Lapphyttan, the calculated area is large in relation to 17th-century furnaces, which were 58.5 x 37.5 to 40 cm and about 50 x 35 cm.

For the reasons already given with regard to the construction of shafts, care is taken not to build a circular hearth in furnaces with only one tuyere. The number of vertical joints is minimised if the hearth is given a square section. The width is determined by the strength of the air inlet. The blast flame has to reach the blast wall if the rising gas is to be evenly distributed through-out the entire shaft area. The tuyere has to be positioned low down in order for slag and pig iron to be kept molten. Beck II, p. 175, mentions that in a German furnace alternately producing blooms and pig iron at the end of the 18th century, the tuyere was lowered two inches for blowing pig iron. For technical reasons, however, the hearth had to accommodate as much slag and pig iron as possible. The only way of enlarging the volume of a given furnace was then to maximise the distance between the rear wall and the taphole, i.e. make the hearth rectangular.

The bear is known in Sweden as "*hyttklot*" or "*masugnsklot*" because the low-carbon iron formed during the oxidising process of blowing down fused with blast furnace slag and with molten clay and heat-resistant stone from the burnt-out hearth something which was very often spherical (*klot*) in shape. This sphere is normally in the middle of the hearth, surrounded by molten slag containing a great deal of iron oxide. The bear, then, is detached from the hearth walls when work begins on pulling it out. If the bear is bigger than the taphole, the latter has to be enlarged. When this happens, slag and bear can solidify against the floor and sides, but this does not usually happen on the hot rear wall, with the result that this is well preserved in most cases. This explains why we say that the hearth is damaged at the same time as the rear wall is lined with slag right down to the original floor. At Saxhyttan in the County of Örebro, for example, there are two bears to be seen from the blast furnace there, which remained in operation until 1864.

Summary

There is no doubt that the reduction furnace at Lapphyttan is a blast furnace. There is nothing remarkable about this observation, considering the extensive written materials which are extant in Sweden from earlier times and the appreciable number of blast furnace ruins which can be studied in this country. The remarkable thing is the dating. This was the reason for organising a symposium immediately after the excavations and studies of Lapphyttan had been completed and before the final report had been put together. The symposium yielded many valuable contributions to our knowledge of the mediaeval iron industry. This, unfortunately, is more than could be said of the contribution which has been refuted here, but this has had the benefit of enabling us, on a number of points, to give an account of the documentation underlying the brief report which we presented during the symposium.

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A. Kransen.

B. Öfversta kanten af väggen.

D. Nedersta kanten af väggen.

B.C.& D.E. Timrets tjocklek af det öfre och undre hvarfvet af väggen.

F.G. Pipmurens tjocklek.

G.G. Pipans vidd öfverst vid brädden.

H. Ställe

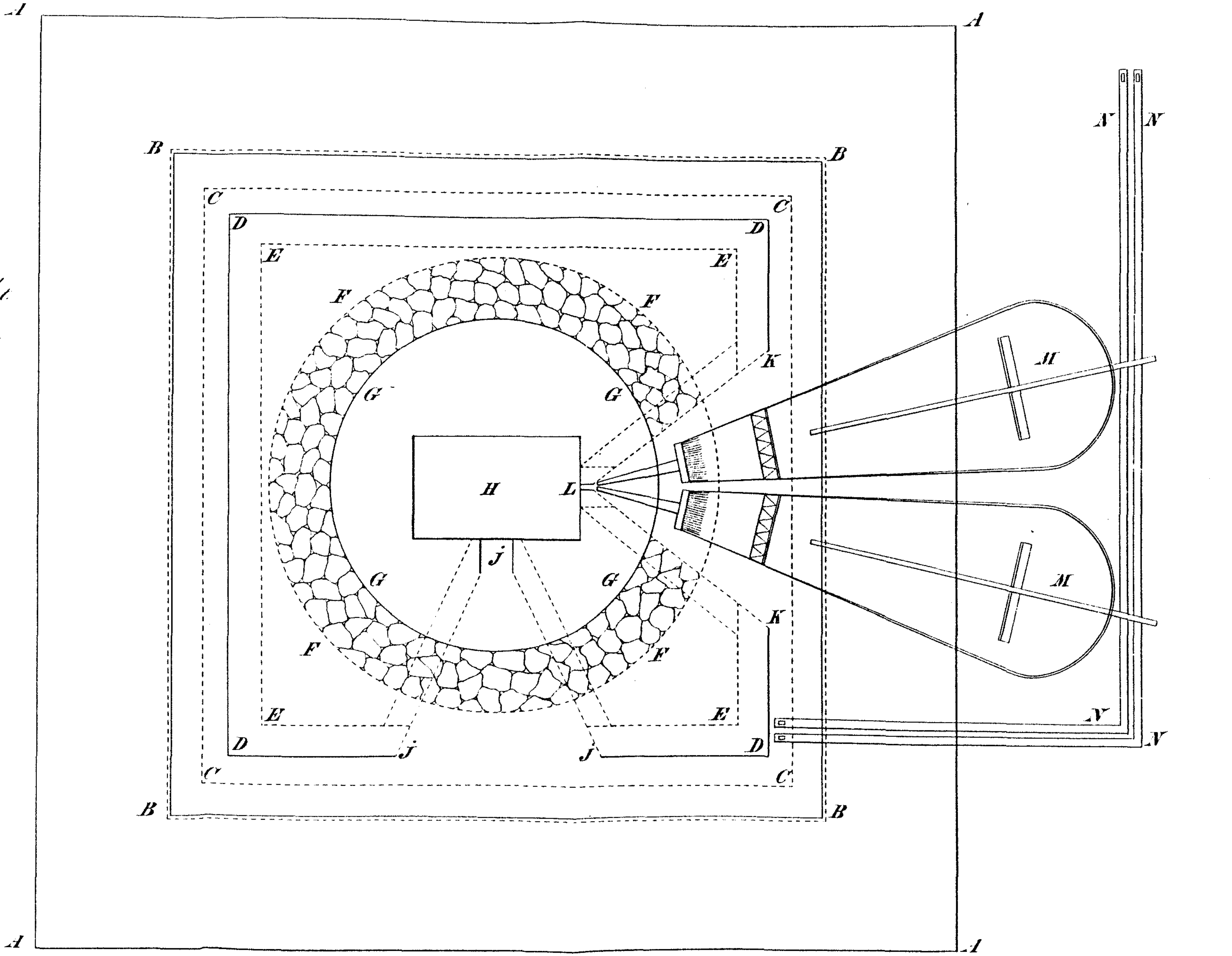
J. Slagghålet.

K.K. Puststaden

L. Forman.

M. 2ne Enkla Pustar.

N. Tramperne.



PICTURE 1

Copy of original drawing by Schultze. Horizontal section.

Scal. = 1/24.

A.B. Kransen.

B.C.&D.E. Timringen af väggen.

E.E. Grunden till Ställe.

C.F. Fyllningen af mull.

F.G. Pipmurens tjocklek.

G.G. Pipans vidd.

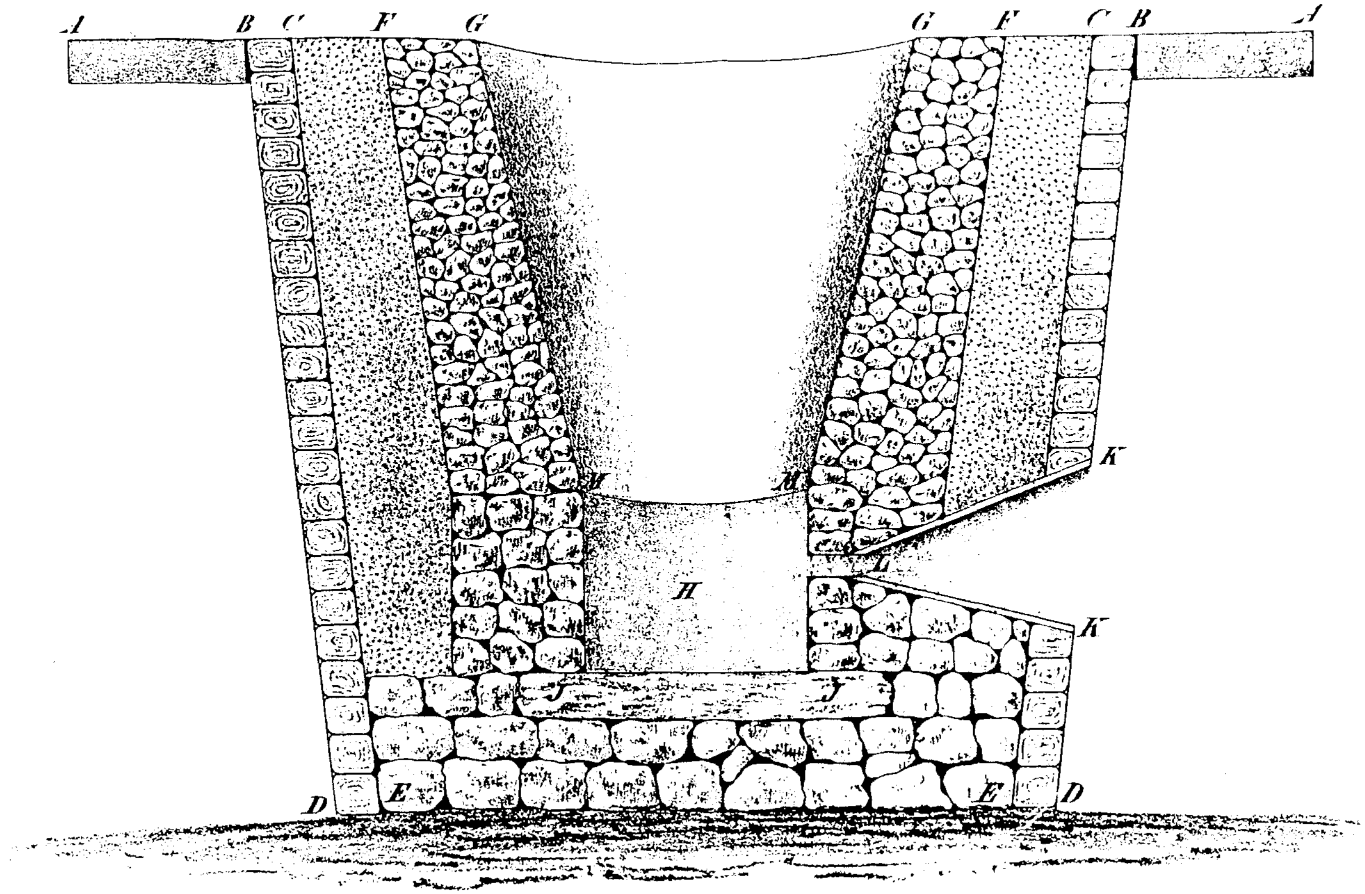
H. Ställe.

J. Ställ-hällen.

K. Raststaden.

L. Forman.

M. Ralyet.



PICTURE 2

Copy of original drawing by Schultze. Vertical section.

PICTURE 3

Copy of original drawing by Schultze.
Total view of the plant.

A. Orästadt Orke.
B. Själfva Rösten.
C. Rästadt Orke
D. Jordborr.
E. Stöhl Häckan
F. Skyffelen.
G. Blåss Tång
H. Opptag- och slagg Stick.
J. Ugns-spett.

K. Form- och Slagghols-Spett.
L. Knästret eller Släggan.
M. Blåss- eller Järnklimpen, som blifvit utwerkad.
N. Yxan.
O. Tramporne till Pustarne.
P. Bron upp till Ugnen.
Q. Slagghålet.
R. Forman.
S. Skäfvel, hwarmed öreket uppsättes.

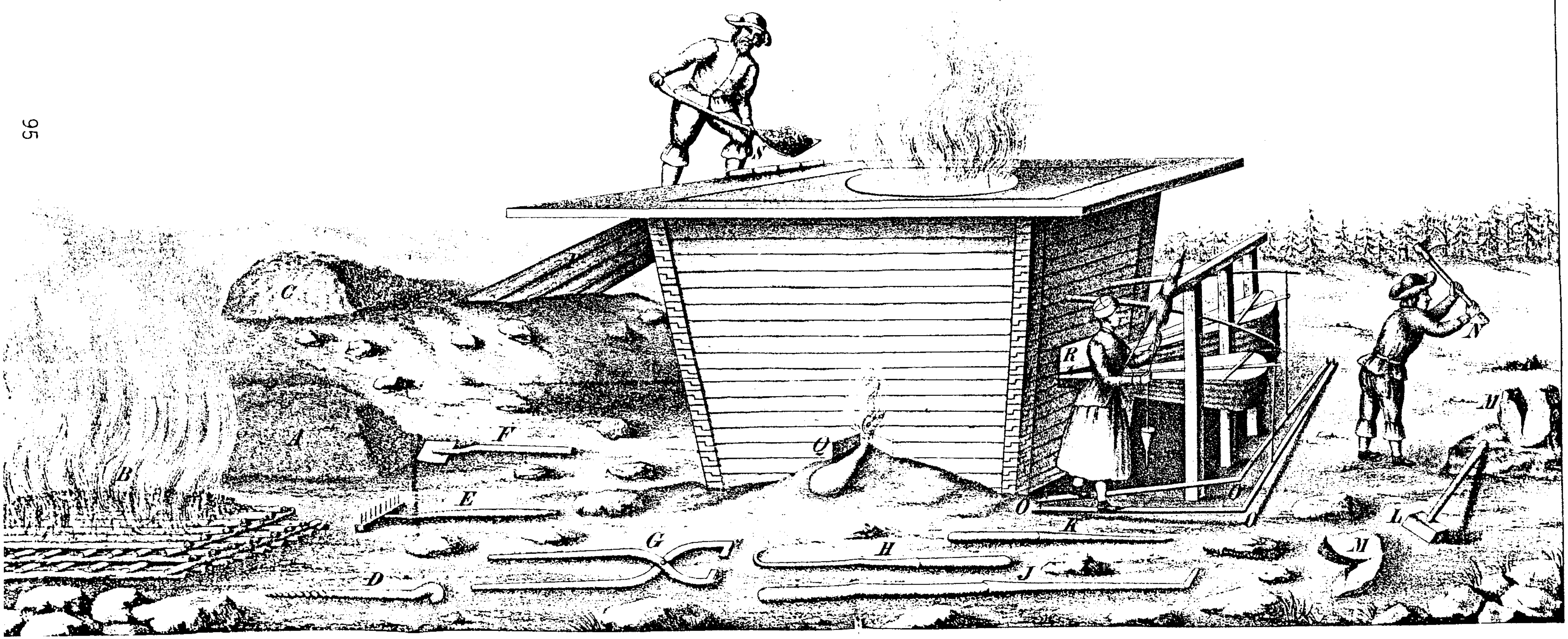
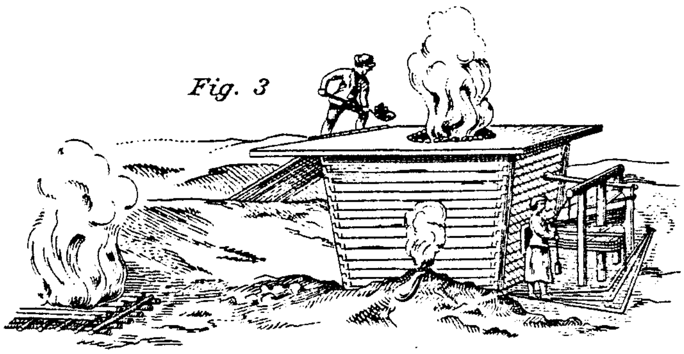


Fig. 3



Svensk Osmundugn,
"Wolfsugn"

Fig. 4

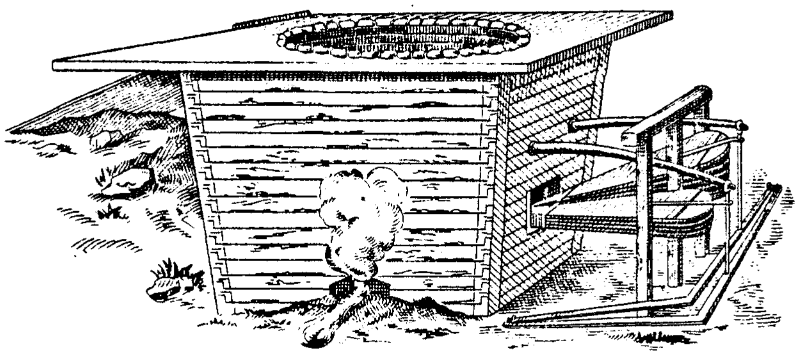
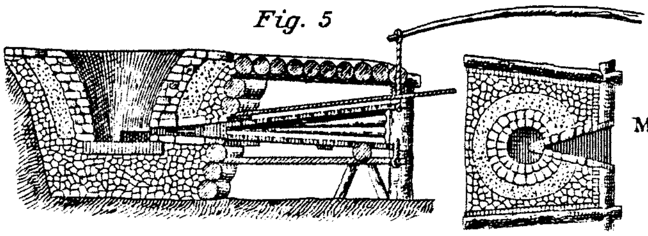


Fig. 5



Myrmalm-
ugn

PICTURE 4

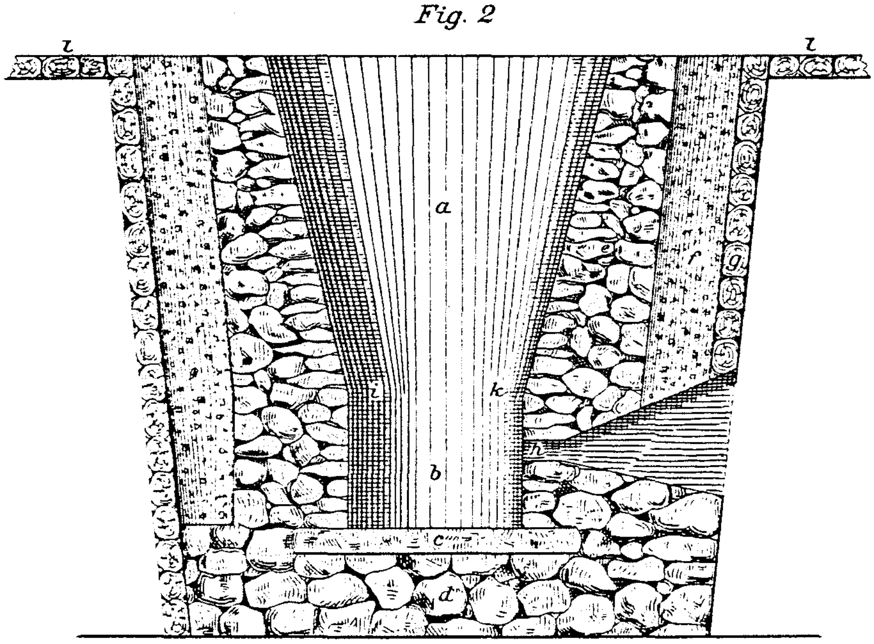
Odelstierna PL V.

Fig 3. Compare with PICTURE 3.

Fig 4. This is Swedenborg's version of Schultze's oven. Tab X. De Ferro.

Fig 5. This is Evenstad's oven.

Fig. 2



PICTURE 5

Odelstierna PL XXV. Compare with PICTURE 2.

Discussion of the paper by Nils Björkenstam and Sven Fornander.

Sven Eketorp

1. The Swedes, I guess, must be very proud when they hear that the blast furnace process was "invented" or at least first used in Sweden about 300 years earlier than in any other (European) country.

What I don´t understand is how such a remarkable technical progress could be made without anyone in Sweden making some sort of a note of it and no one abroad getting to know about it. Certainly, the oral and written communications 1200 - 1500 AD were not that bad. Is it possible that the buyers of the iron (steel) product never asked how it was made?

2. In the papers by Björkenstam and Fornander as well as that by Inga Serning the appearance of high-carbon iron pieces close to the furnaces have been mentioned. The authors take this as an evidence of the process being a blast furnace process producing 100 % molten product.

Such a conclusion seems to me rather risky, when we know that it is possible to obtain a high-carbon molten product in all furnaces from the bloomery to the blast furnace as shown for instance by Tylecote.

The findings of a product which has been molten and left at the furnace could much more logically be explained by this iron being a material which could not be used. It would also have been easy for the melters to recirculate these pieces in the process if the end product really was 100 % molten.

REPLY TO PROFESSOR EKETORP'S DISCUSSION PAPER - Nils Björkenstam

Professor Eketorp returns here to exactly the same questions which he asked during the symposium and to which he then received answers.

1. As Professor Eketorp himself states in connection with question 2, cast iron can appear in all furnaces in the reduction of iron ores. Pig iron, then, cannot have been an unknown product during the mediaeval period. A Stückofen, i.e. a shaft furnace so high that the bloom has to be pulled out horizontally through an opening at the bottom of the furnace, is mentioned in Germany in 1130. A Stückofen in Austria is mentioned in 1164 (Johannsen, 1953). As is well known, quite a lot of molten pig iron is usually obtained as a by-product in these furnaces. According to Johannsen (p. 152), pig iron was already being refined into malleable iron in about 1320 in Mark, Westphalia. Sönnecken (p. 17), however, has shown in archaeological excavations in Mark, that a furnace with a water-powered blast which, intermittently at least, produced nothing but pig iron (NB the low iron content figures of the slag in Table 1 by Sönnecken). This pig iron was refined into malleable iron.

The situation in Europe at large resembled that in Sweden. Detailed technical information in writing is very meagre during the mediaeval period. Archaeological investigations are the only possible way of improving our knowledge of the technology of this period. During the symposium, Dr Nisser and others pointed out to Professor Eketorp that written documentation very rarely occurred in any connection in Sweden at this time and that even less is still extant. In this respect one is bound to say that Professor Eketorp's paper betrays a remarkable lack of historical insight.

We have never claimed that the blast furnace is a Swedish invention. Lapphyttan is just one example of the way in which furnaces producing nothing but pig iron developed in Sweden. Due to the earliest blast furnaces, located beside small watercourses in sparsely populated areas, having been abandoned early on, Sweden presents much greater opportunity of discovering relatively well-preserved remains of such furnaces than corresponding sites in densely populated industrialised countries.

2. Professor Eketorp omits to mention that the decisive proof of Lapphyttan being a blast furnace is the fact of the only slag produced by this furnace being a well-reduced blast-furnace slag, added to which pieces of pig iron weighing up to 5 kg have been recovered, as was illustrated graphically and analytically in my verbal presentation. The mention of droplets is connected with our wishing to show that the viscous slag contained a large amount of pig iron which was recovered and refined, and also with our wishing to dismiss the theory of pig-iron granulation having already occurred during the mediaeval period.

About 5,000 droplets have been found in an area measuring some 1,000 m^2 at a furnace which was probably working for about 200 years. Thus on average about five droplets per m^2 were trodden into various levels of the ground surface. If the furnace was operative for as little as ten days annually, between two and three droplets must have been lost every day.

Lapphyttan has a blast furnace which produced 100 per cent cast iron and eight fineries. The pig iron had to be loaded into these fineries in small pieces for rapid melting and refining. In these circumstances it would be economically indefensible to recycle droplets of pig iron and to go to the expense of re-melting them to no useful purpose.

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REPLY TO THOLANDER-EKETORP'S DISCUSSION PAPER

Sven Fornander

The blast furnace process har a characteristic feature, which is not to be found in other processes for the reduction of iron ores. Its slag has an FeO-content, which is lower than that of other processes.

It is easy to identify a blast furnace slag because its colour is light: a fresh fracture surface is often light grey, sometimes greenish or blue. This light colour is an indication of a low FeO-content. At least 9/10 of the slag heaps at Lapphyttan consist of this kind of slag.

There is no doubt therefore that blast furnaces have been operated at Lapphyttan. The size of the slag heaps show that blast furnaces have been in operation there for quite a long time, probably for hundreds of years.

Discussion of the paper

"Metallurgy and technology at Lapphyttan"
by N. Björkenstam and S. Fornander

Stig Blomgren, Sven Rinman Laboratory, Eskilstuna, Sweden:

During the presentation of the lecture Mr. Björkenstam supposed that such low figures for the phosphorous content, 0,005-0,031%, which occur in the iron items presented in table 11, hardly can exist in iron emanating from a direct reduction process. However, there are iron artifacts having a low P-content which are so old that they must consist of directly produced iron.

An example is the socketed iron axe (1) found in Kjula outside Eskilstuna, Sweden, which for typological reasons have been dated to 0-400 A.D. by archaeologists. A chemical analysis gave a P-content of only 0,020% P.

So, the low phosphorous content of the iron items in table 11 does not exclude the possibility that these objects originate from directly reduced iron.

Reference:

1. Hermelin E., Tholander E., Blomgren S., "A prehistoric nickel-alloyed Iron Axe", J. Historical Metallurgy Soc. 13(1979) pp 69-94.

REPLY TO STIG BLOMGREN'S DISCUSSION PAPER - Nils Björkenstam

Quite clearly there is a misunderstanding involved here. The published essay was too long to be read in its entirety. The verbal account was an abbreviated version in which I described some of the most interesting observations from studies of activities at Lapphyttan. Thus Table 11 was never shown as an overhead transparency; all that was shown was an excerpt containing the first five analyses.

Composition of iron items, %.

C	Si	Mn	P	S
0.58	0.04	0.03	0.024	0.005
0.16	0.07	0.03	0.017	0.005
0.51	0.10	0.06	0.011	0.019
0.34	0.10	0.08	0.012	0.024
0.97	0.03	0.01	0.009	0.007

In view of the relatively high manganese content of this pig iron, the following is all that was mentioned with reference to the above table:

> "Manganese in the pig iron makes the slag more fluid and delays the reduction of carbon, or contrarywise it can be said to assist in producing more blooms of a steely composition as shown in the table. You can also see that the low temperature in the hearth has given a slight decrease in the phosphorus content of the pig iron."

After this a slide was shown of a bloom which had been analysed only recently and, consequently, could not be included in the written lecture:

> "A far-fetched example concerning a too high oxidation at a very low temperature in the hearth is this bloom weighing about 3 kg. The composition is 0.45% C, 0.11%

Si, 0.013% Mn, 0.015% S and less than 0.001% of phosphorous. The result has been a very porous slaggy product and this is probably the reason why it is left. It must have been rejected. The extremely low phosphorous content is a further indication that this bloom comes from an oxidation process. It is hardly possible to achieve such a low phosphorus content in a reduction furnace."

I should have added "assuming the phosphorus content of the iron ore to be on a level with the ores here at Lapphyttan". If there is no phosphorus in the iron ore, then of course a reduction furnace can yield blooms with only traces of phosphorus, derived from the charcoal. (See Dr Nosak's essay from the symposium).

The phosphorus content of malleable iron depends on the iron ore used and the reduction process which it has undergone. When pig iron is refined in furnaces of the Lapphyttan type, low phosphorus levels are only obtainable if the iron ore used has had a relatively low phosphorus content. In the direct reduction process, on the other hand, low phosphorus levels are still attainable if the phosphorus content of the ore is substantially higher. On the other hand, malleable iron from both processes contains very large amounts of phosphorus if highly phosphoric ores are used. Phosphorus content alone can never serve as a criterion of the way in which a malleable iron object was manufactured.

As can be seen from our essay, we used completely different arguments from the phosphorus content of the malleable iron in order to establish that the processes used at Lapphyttan were blast-furnace pig iron production and refining of this pig iron in the hearths existing there.

Discussion of the paper by Gert Magnusson:

'<u>Lapphyttan - an example of medieval iron production</u>'

ERIK THOLANDER, Royal Institute of Technology, Stockholm

From a general point of view the excavation work made on the Lapphyttan site is admirable because of the size of the area, the numerous human activities displayed and the many details brought into the light by Mr. Magnusson and his archaeologists team in order to explain the activity employed there half a millenium ago.

After having heard the lecture and read the preprinted paper, however, there still are some matters seeming unclear and causing some questions, which I would like to put to the author. Because of the additional information signed by Mr Magnusson on page 6 in the coloured appendix (AMW) or 'ASEA Metallurgy Worldwide News', March 1985, enclosed with the Symposium printings received at our arrival in Norberg, a few other matters derive from there. As being a metallurgist and not an archaeologist, I will limit my remarks to such points where metallurgical judgements have to be considered as well as the archaeologic.

On the excavation method used at the furnace ruin

Hither to, very few big old smelting furnaces have been excavated in Sweden. As far as I know, Lapphyttan is number four after the following:

1. Kolebäcksugnen, Fritsla parish, Västergötland 1927. Gösta Ahlström (1)
2. Harhyttan, Säter kommun, Dalarna 1972. Erik Tholander (2)
3. Kåperyd, Månsarp parish, Småland 1974, 1975. Lena Thålin-Bergman (3)

The first aim at an excavation of metallurgic furnace remains must be to perform the work so carefully, that every sign of hearth construction, walls design and apertures for air-blast inlet and the removal of products can be recognized, recorded and preserved as far as possible.

In Lapphyttan the excavation method seems me somewhat doubtful in these respects. Therefore, I have two questions founded on the information obtained at the first display of the site on September 25th, 1981:

<u>Question 1</u>: Why was the work started by breaking into the furnace mound from outside the east wall instead of using the shaft mouth on the top for a successive emtying from top to bottom, which would have given the possibility of an inside inspection of walls and hearth in their original positions ?

By the choice made, unnecessary damage must have been caused on delicate parts of the east wall and the front opening to be expected there.

<u>Question 2</u>: Why has the north wall, which in 1981 not was much damaged, since then got severe breakage and finally been partly rebuilt ?

Parts of this wall are shown in the figures on pp. 53-55, but there is in the paper no picture of the entire north wall. In AMW (p. 7) the colour-photo indicates the north-wall damage a little more.

On the reporting method on furnace details

Mr Magnusson on page 23 mentions the existence of two main schools of thought in the Swedish debate on the History of technology concerning the medieval iron production, especially the so called 'osmund iron'. At the Norberg symposium I declared, that I am representing the (2nd) school, which is favouring the direct smelting of malleable iron from the ore. My reasons have been published in 1973. (2)

In his paper, Mr M. takes no notice of the 2nd school in reporting design details or making his own interpretations. He doesn't even try to assign any reasons for his own answer to the question: "Pig iron or lump ?" At every point of reporting details or drawing conclusions he assumes the iron production to have been 'pig iron'. Because of that he, in my opinion, is drifting further away in the wrong direction without checking the reliability of his "compass". By not following the tradition, at the writing of scientific reports, to present the reasons for his conclusions drawn, Mr M. has missed the possibility of self-checking his claims.

In order to avoid any misconception, however, I below will put some further questions, the next one being:

Question 3: On which reasons is Mr M. founding the interpretation of Lapphyttan as being a blast furnace in the modern sense, i.e. producing pig iron only ?

Considering now the 'furnace ruin', the last lines on page 23 tell of a 'blast furnace', a 'blowing arch' and a 'tapping arch'. Unfortunately, no photographic or other evidence is shown to prove the findings behind these suppositions. Instead, in Fig. 7, a "Reconstruction" is shown of an assumed horizontal section at the bottom level containing a rectangular hearth and two outer "arch areas". No indications are given of how this schematic section coincides with the excavated details, e.g. the square cross-section.

Regarding the vertical sections in Fig:s 8, 9, two different contours of the shaft wall are seen in Fig. 8 and three similar contours in Fig. 9. In both cases the outer one of the vertical contours is marked as being slag-clad from an excavated top-level down to different end-levels, which in Fig. 8 is about 0.3 m beneath the hearth bottom (!) but in Fig. 9 varies from about 0.2 m to 0.5 m above that bottom.

The inner contours show a straight cylinder of about 1 m width, downwards transferred into "boshes" in the shape of an inverted truncated cone standing upon the straight-sided rectangular hearth, the bottom of which is on the present, excavated bottom-level, 1.95 m beneath the top of the wall.

In addition, Fig. 9 shows a third vertical contour line, somewhat bulbed to a maximum width of 1.2 m or 1.3 m, from which the present slag-clad wall seems to deviate outwards considerably or to a top width of about 1.9 m. To me, however, this great deviation seems very doubtful. Because no horizontal sections are presented, the reader has no possibility to check the matter. The questions arising here are:

Question 4: a. By what reason has the inner contour in both sketches, Fig:s 8, 9, been modelled as a straight cylinder ?

b. Does the great upward deviation of the slag-clad wall in Fig. 9 represent the real width determined by measurement or is it an estimation only ?

Finally, in both figures (8, 9) the furnace height has been extended by about 1 m, which is not commented in the text but just mentioned on page 26, paragraph 3, reading: "The furnace shaft ... was square in shape ... and 3 m high ...". It would be of value here to get some additional information, e.g. a sketch on the horizontal cross-section shaft-profile on a level about 1.2 m above the sole as well as an answer to the next question:

Question 5: a. Is there some specific reason for the square shaft cross-section in Fig. 7 ?

b. What is the reason for the assumption of an original shaft height of 3 m, or 50 % more than the excavated measure ?

On the interpretation of metallurgical matters

When reporting (p. 25) that the "blowing wall" was intact "up to 1.9 m above the bottom of the hearth", Mr M. also gives the real level of the original hearth sole. This level happens to be very well marked on the wall also by a sharp horizontal line where the slag-coat ends around the bottom periphery, which there measured a diameter of 0.7 m to 0.8 m. The interpretation then of the ruin as a 'blast furnace', consequently followed up by the "reconstruction" sketches in Fig:s 7, 8, 9 with an inserted rectangular hearth founded on the sole, does to me not seem realistic. That hearth, which of course not could be free-standing, is by the imaginary conical 'boshes' assumed to have been connected with the main inner wall at a level about 0.75 m above the sole, according to Fig:s 8, 9. Then the inner wall could not have been covered by slag below the upper border of the boshes, i.e. about 0.75 m above the bottom.

Because of the reality that the slag-coat is covering the inside wall until the very bottom, the "reconstructed" insert-hearth cannot have existed ! The remaining possibility is, that the original hearth in Lapphyttan was a round or oval cylinder of about 0.75 m "diameter". Consequently, in my opinion, the furnace must have been a high bloomery, i.e. a "Stückofen".

A front opening large enough for the removal of a solid lump of wrought iron also must have existed in the east wall, a rather great aperture necessary also for the extraction of the "bears" mentioned by Mr M. (p. 24), which certainly not could have passed through a taphole for liquid iron.

Another interpretation displayed by Mr Magnusson (p. 28) without any reservation is the occurrence of eight "fineries", where the pig iron should have been converted into wrought iron or steel. Evidences said to prove, that the refining process was regularly used at Lapphyttan, should be the great amount of 'iron shot' on the ground as well as findings of 'refining slag'. As far as the iron is concerned, no regard is payed to the fact, that the high bloomery also produced some pig iron as a by-product. The decisive point here must be wether the Lapphyttan people could utilize the pig iron or not. And regarding the iron shot a final question may be:

Question 6: Would it not be realistic to consider iron remains left on the ground to be waste products not having enough value to take care of ?

In the AMW (p.6) Mr M. tells of the 'Refining' as an oxidizing procedure "performed in solid state in a shallow pit furnace". That description is not correct and such a process would not have delivered any slag. In fact, finery slag left behind as a wasted by-product could have been a useful evidence on a regular activity of pig iron refining, if only such slag in sufficient amounts and with significant properties had been found. Any information of such kind has not been presented.

I have recently had the opportunity to examine microscopically three samples of "finery slag" supplied from the site by Mr M. The result was, that the microstructure indicated the slag to originate from an incomplete refining process probably able to deliver a steel of various carbon content but not a wrought iron low in carbon.
The absence of quantity figures for the occurrence of such slag makes it doubtful, whether pig iron refining has been in regular use at Lapphyttan.

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1985-06-27

E. Tholander

REPLY TO ERIK THOLANDER'S DISCUSSION PAPER

Gert Magnusson

Question 1

In his introduction to the questions, Tholander states that three furnaces have been investigated before Lapphyttan. This is partly true, but none of those investigations, judging by reports and publications, can be termed more than a probe. Kolebäck and Kåperyd have yet to be completed. Neither of these furnaces has a clear medieval dating, which is a problem. It is of course always the last furnace on the site one is able to study. In Harhyttan's case this means the 18th century, while for the Kolebäck furnace it means the 16th or 17th century and for Kåperyd probably the 16th. The early documentation does not measure up to modern requirements. On the other hand Serning's publications of Vinarhyttan and Björkenstam and Serning and Wedberg's publication on Harhyttan are up to standard.

The actual reducing furnace ruin was investigated by stages. The outer wall to the south and about 2 m of the west wall were uncovered during the first year of the investigation. This work took a very long time to complete because it came partly to involve collapsed furnace sections with a somewhat complicated stratigraphy. Owing to shortage of time and money, we were unable that year to carry out any investigation in the part of the furnace where the actual stack was located.

It was during the second period of investigation in 1979 that the stack came to be excavated. The investigation involved unearthing the stack, most of which was completely clogged with fine sand and occasional stones. After this excavation of the stack we were perfectly able to observe and document all the walls. The wall near the tapping arch was severely eroded, had collapsed and was extensively cracked. The stack wall could be studied on this side. It had been heavily damaged by falling stones in the furnace due to the collapse of the tapping arch, probably already during the medieval period. When excavating the stack, we also came to excavate the actual hearth. There were a group of stones here still in situ. These were not in any way affected by heat. They must have been protected during those periods when the furnace was in use, otherwise the heat would have affected them. It is reasonable to suppose that they were protected by a stone lining, which must have been inside the stones obviously belonging to the structure. Assuming that these lining stones must have been at least 10 cm thick, the hearth cannot have measured more than 0.5 x 0.3 m and its depth cannot have exceeded 0.23 m. It is impossible to say whether the hearth was oval, rectangular or square within these maximum dimensions. It cannot have exceeded them. Part of the west wall is all that survives of the hearth walls today.

Work during the third season concentrated entirely on the actual tapping arch and on the stream to the east of it. In order to find out how the inner part and the connection between the outer wall structure and the hearth had been constructed, it was necessary to dig through the rubble on top of this part. This rubble included numerous parts of the collapsed stack wall. Unfortunately we were obliged to commit this "damage" so as to investigate the structure of the inner parts of the tapping arch. Everything has been measured and photographed in detail, and a full account will be given in the final report.

Field work in 1981-1983 was mainly concerned with the actual blowing arch and its structures. This section was excavated very slowly and carefully. After discussing the problem in the Lapphyttan Committee at Jernkontoret, we decided to break through the stack wall at the tuyere so as to be able to document it in detail. We made this decision after observing that the blowing wall was very fragile now that the ruins had been excavated all round. There was a danger of this wall collapsing, in which case it would have become quite impossible to document this part of the furnace. This section was excavated by Björkenstam, Fornander and Magnusson.

The area round the blowing arch has been amply documented and will be described in detail in the final report on the investigation. All that can be mentioned here is that the wall above the tuyere was badly damaged and had been repaired at least five times during the medieval period because of burn-outs.

During the last field season, work was concluded by digging round the entire furnace ruins so as to investigate its foundations.

Question 2

This has already been answered in question 1.

Question 3

My use of the term blast furnace is based on the technical assessments made by Fornander and Björkenstam in the article published in Medieval Iron in Society, 1985.

At the same time I also wish to draw attention to a number of structural details of the furnace ruin which relate directly to similar structures in later furnaces in the Norberg Bergslag and other Bergslag regions. Structurally speaking, the furnace ruin at Lapphyttan is entirely reminiscent of the timber-clad furnace so reliably documented from a later period. The massive stone base, with a timber superstructure. The shape of the arch and their positioning at right-angles to one another horizontally, which is directly associated with blast furnace constructions. The positioning of the waterwheel and the bellows in relation to the furnace. Looking at the Stückofen furnaces documented from Austria, one cannot help noticing that they often have just one arch, in which the bellows were installed and from which the finished bloom was extracted (Tylecote, 1976:86).

I realise of course that these elements of form are only indirect evidence of a blast furnace; the stronger evidence in this respect is provided by Fornander and Björkenstam in their studies of metallurgy at Lapphyttan.

Question 4

We turn now to my suggested reconstructions of the different parts of the blast furnace.

Figure 7 in my article shows a reconstruction of the layout of the Lapphyttan furnace. The sketch is simplified, but that does not make it misleading. The furnace is located in a partly steep moraine slope, which means that some sides are projected to a level somewhat lower than the real structure. This is quite apparent from the two profiles. The outer contours of the furnace are drawn on the basis of directly observable stones on the excavated furnace, which were still in situ. The shape of the internal structure is deduced from a tower photograph analysis of the tower photograph in Fig. 7 of Björkenstam's article. The blowing arch is narrower than the tapping arch, not because of an error of measurement or any inaccuracy in the reconstruction drawing, but because this tallies completely with the foundation stones in this part of the furnace.

Now for the two reconstruction drawings of the actual furnace in profile.

In Figure 8 I attempted to reconstruct those parts of the furnace which can only be indirectly described. Allow me then to begin with the outward structure of the furnace. The rear wall, shown on the left in the figure, is virtually intact. Here in the furnace ruins there are preserved a line of stones extending the full length of this side and virtually flat on top. This layout was constructed from the outer line of stones, which I maintain to have been the foundation of a timber structure. In the rubble outside this wall the remains were found of a timber beam the same length as the wall of the stone base. By measuring the volume of the rubble outside this west wall and placing it in an area between the established stack wall and the established outer wall, I obtained an approximation of the height of the furnace. This is followed by a further assumption, to the effect that the top of the furnace was flat. I do not know of any early furnaces with sloping tops, and so I feel that this is a reasonable assumption to make.

The western stack wall is completely undamaged up to a height of 1.87 m above the bottom of the hearth. As to the shape of the stack, in a notional circular reconstruction I have obtained a possible shape and a possible diameter for the lower part of the stack in its burned-out state. It is clear from the sandstone lining still in situ that stack wall was heavily burned at this point. The uppermost stones of the surviving section of the furnace wall have relatively little superficial slag and provide an indication of the possible thickness of the sandstone lining. On measuring the sandstone lining further down, one finds that they are heavily melted and a good deal thinner. Judging by the profiles of the stack of more recent blast furnaces, we may assume that the difference in thickness between the different stones was due to the furnace wall melting away. The wall was never repaired, but the stack wall immediately above the tuyere was repaired at least five times on account of burn-out.

The contraction of the stack down towards the hearth is an assumption based on the general shape of the surviving stack wall and the structure of the rear wall or circular wall behind it. The slag-coated furnace walls in Fig. 9 are a good deal more dilapidated, owing to the general state of the surviving ruins. But we can see from the projected surviving stack wall that its burned-out state does not come outside such parts of these furnace walls as are still in situ.

Question 5

Tholander's fifth question concerns the square shape of the stack. The shape of the stack has been reconstructed entirely in accordance with the tower photograph published in Björkenstam's lecture. From it one can clearly see, from the shape of the slag-coated furnace wall, that there is a corner in the southwest part of the slag-coated stack wall.

The second part of the fifth question has already been answered with reference to question 4.

Question 6

In his final paragraph, to which question 6 refers, Tholander deals with the entire question of the fineries. Quite obviously, this is an extremely important and delicate question to Tholander. We are concerned here with archaeological material which quite definitely points to the indirect production of iron at Lapphyttan.

The entire furnace site at Lapphyttan has been excavated and more than 8,000 finds salvaged as a result. Ninety-nine per cent of them comprise iron objects of various kinds. About 5,000 of these are small balls of iron which analysis showed to be pig iron with various carbon contents. Exactly how they were formed has yet to be ascertained. The entire Lapphyttan area has been excavated in the same way. The turf was stripped with a spade and the ground was then cleared and finally investigated with trowels in technical strata of 3-5 cm. This gives us quite a clear picture of the distribution of different groups of finds throughout the site. The balls of iron occur in very large quantities round the tapping arch, above all in the space once occupied by the axle bar of the waterwheel. These balls of iron were also found, in their hundreds, round about the fineries. This means that they are connected with those operations in the process of iron production which took place at the blast furnace and the fineries. But there is an essential difference between the appearance of finds at the fineries and at the blast furnace. At the fineries one also finds larger lumps of iron. The distribution of the different categories of find shows which operations took place on the spot. The heavy accumulation of iron balls near the axle mark can prompt the hypothesis that there may have been a slag crusher here for extracting some of the balls of pig iron which had formed in the slag and been discharged with it. As I see it, the migration of these iron balls to the fineries mainly indicates that they can have been used for reducing the pig iron. They were collected for use during the finery process. The appearance of a number of iron balls studied by Sven Fornander suggests as much.

There is something in Tholander's idea of as much iron as possible having been salvaged, but we have to bear in mind that Lapphyttan was an industrial plant. Anybody with experience of industrial employment knows that things get lost and that a certain amount of waste, for various reasons, is not made use of. This is the way things are today, and there is no reason to suppose that they were any different at a medieval furnace. The character of the work, the season of the year, light conditions, the pace of work and the production process etc. all, in their various ways, prevent the workers from being impeccably tidy. The impressive quantity of finds in not really impressive at all. Assuming that Lapphyttan was in use for 200 years, the amount of finds implies that one ball of iron was lost here every ten days. Or assuming that work here was limited for two months in the year, then in principle one ball of iron was lost or forging waste was produced and discarded every two days. This simple calculation shows that very little was in fact wasted, though a ball of iron the size of a pea was lost every two days. The human factor is not to be overlooked!

Tholander maintains that, in principle, the Lapphyttan furnace site has no finery slag. This is incorrect. Two slag heaps (A16) and (A17) in the southern part of the area are both located to either side of finery (A15). One of these slag heaps (A17) is about 1.4 m thick and the other (A16) about 0.5 m thick. In other words, these two slag heaps between them contain more than 11 m^3 finery slag. Close to finery (A14), slag heap (A3) contains quite sizeable quantities of finery slag, mingled with the glassy blast furnace slag.

It is worth noting, however, that only small quantities of finery slag occur near the other fineries. There are finery slags, but mostly in small volumes, viz 20-80 litres of slag per furnace.

There is probably a chronological reason for this. Lapphyttan seems only to have had one, possible two fineries during the earlier period. Towards the end of its history, six more were built.

Finally a short comment on Tholander´s last paragraph, in which he presents the result of a microscopic study of finery slags. I have received his report in which these conclusions are stated:
"In some kind of finery hearth some pig iron apparently has been used in more or less succesful trials on transforming the ´sow metal´ into steel.
For the time actual in the 14th century, a successful refining of the pig iron into steel most probably would have been welcomed and appreciated."

Tholander classifies three studied specimens as slags from an incomplete decarburization of pig iron resulting in high carbon iron instead of wrought iron. It is necessary to point out, that slag is running out of the hearth during the length of the process and it is impossible to know at which time during the process these specimens of slag were produced. Björkenstam and Fornander have also shown, that a considerable part of the produced iron must have been steel because of the manganese content in the pig iron. (p 201 and table 11).

As Tholander has not observed and taken notice of the big amount of refining slag, mentioned above, his objections have the opposite effect and underline the interpretation of Lapphyttan as a site with a blast furnace and fineries.

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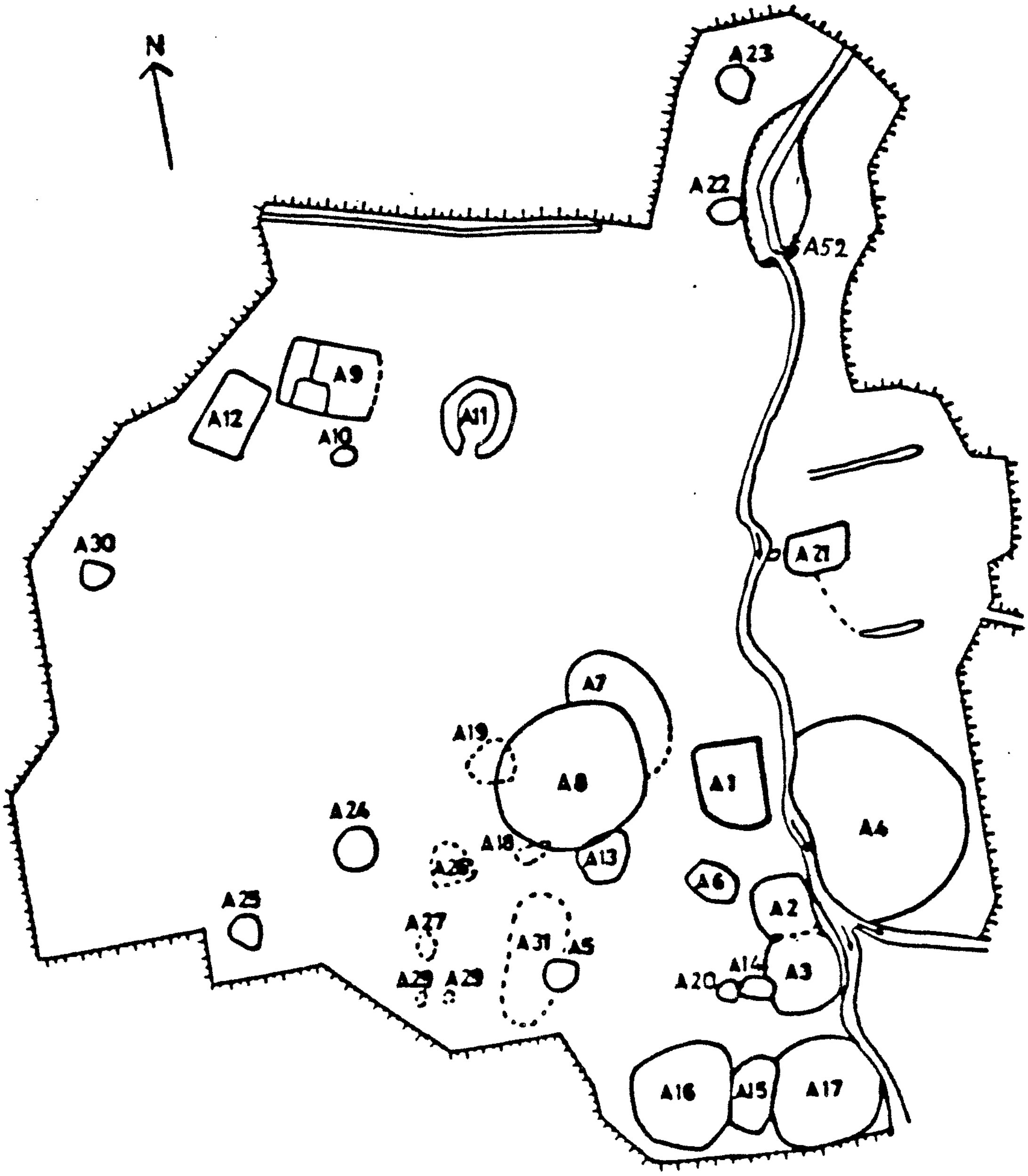
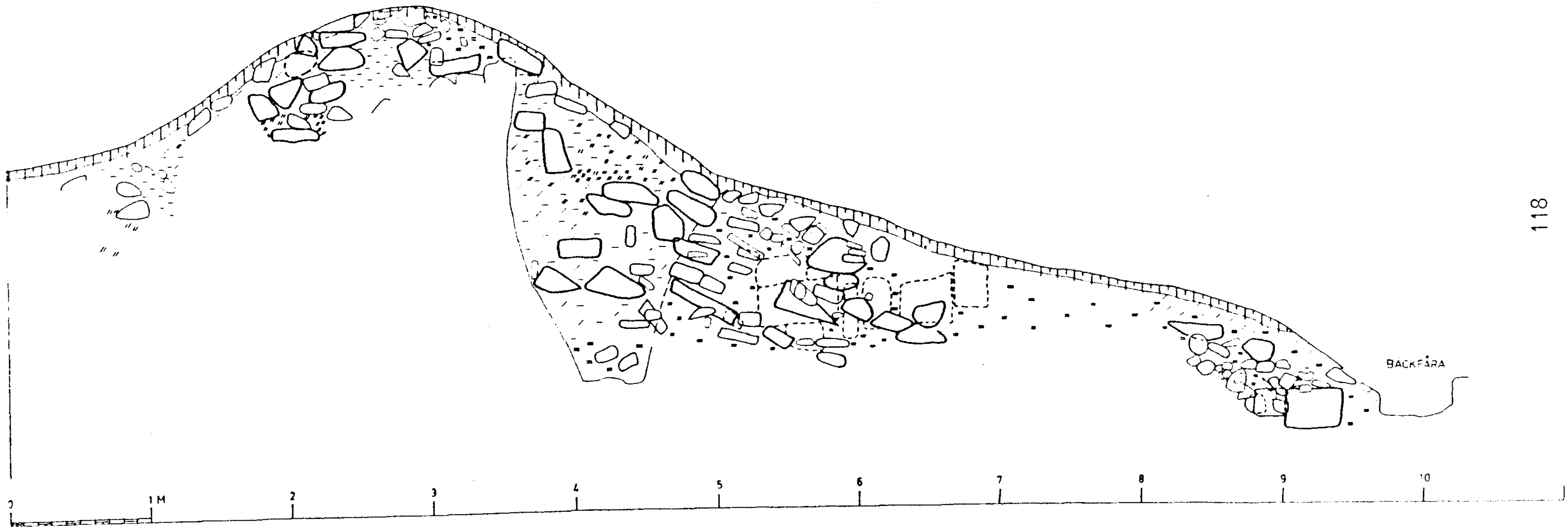
FIGURES

Figures from Magnusson's paper "Lapphyttan - an example of medieval iron production" printed earlier in "Medieval Iron in Society" (H 34).



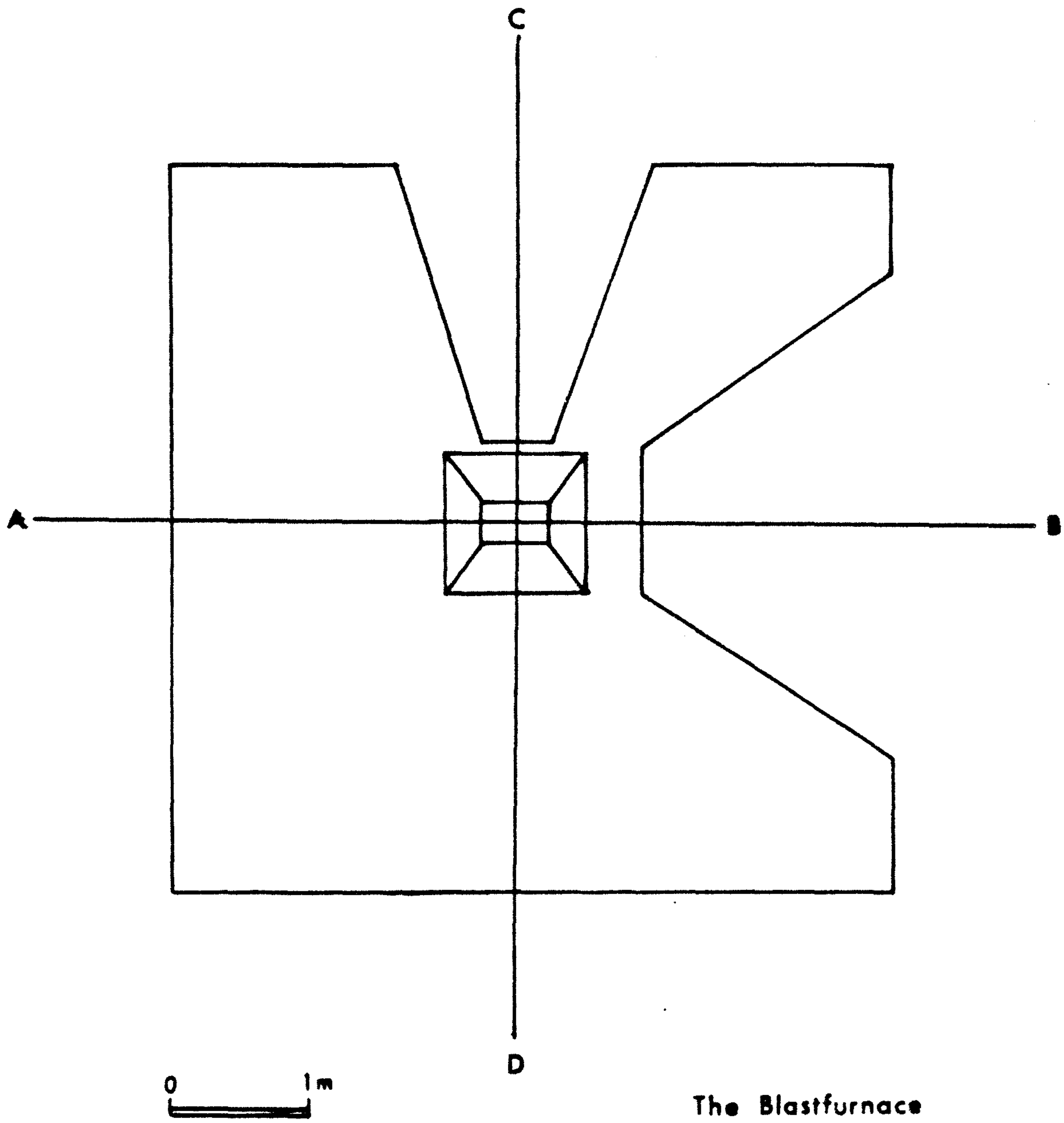
A I = Blast furnace ruin
A 2 = Slag heap
A 3 = Slag heap
A 4 = Slag heap
A 5 = Slag pieces
A 6 = Roasting pit
A 7 = Charcoal stack
A 8 = Charcoal stack
A 9 = Dwelling house
AI0 = Hearth
AII = Iron shed
AI2 = Stable
AI3 = Charcoal shed
AI4 = Finery
AI5 = Finery
AI6 = Slag heap
AI7 = Slag heap
AI8 = Heap 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

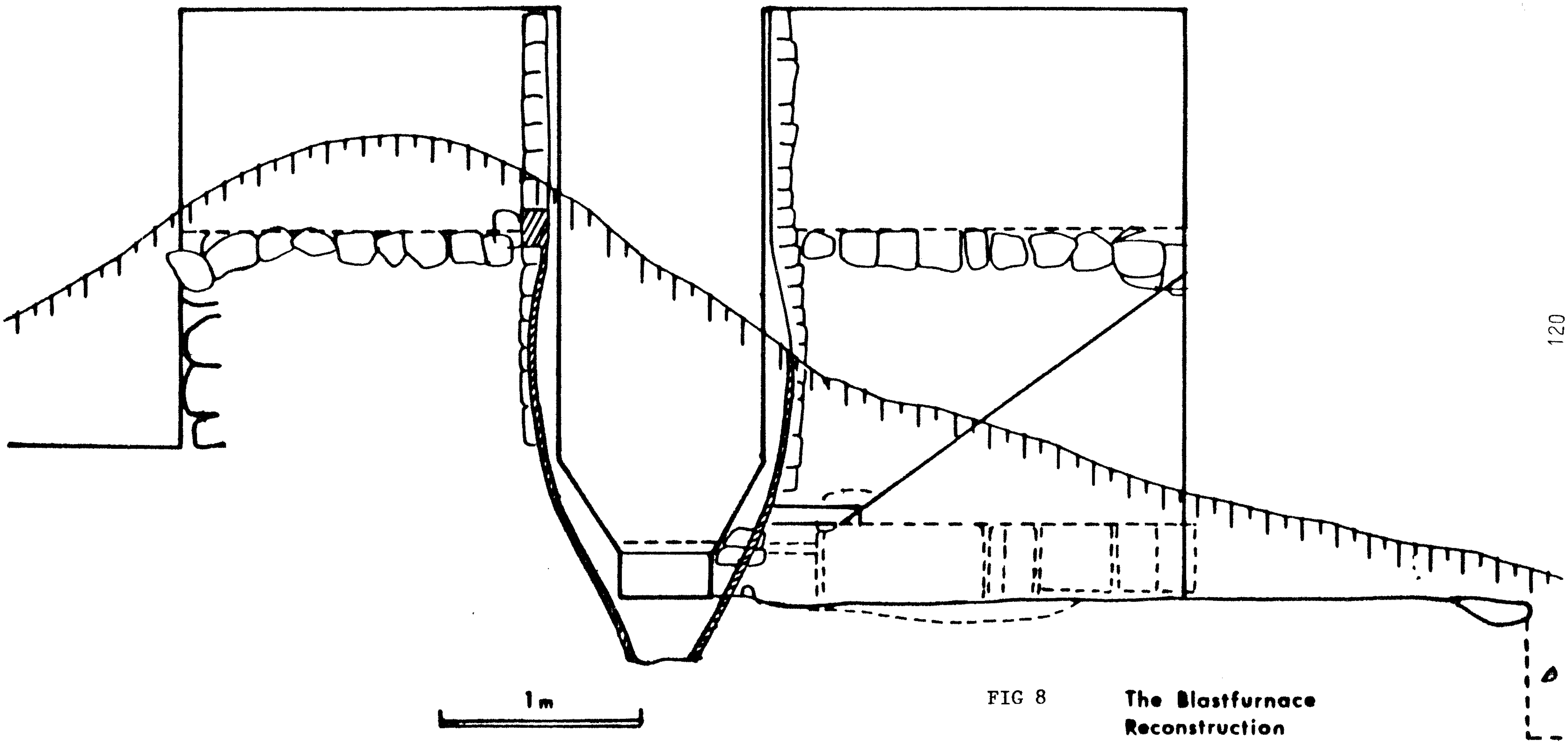


FIG 8 **The Blastfurnace Reconstruction Lapphyttan Profile A-B**

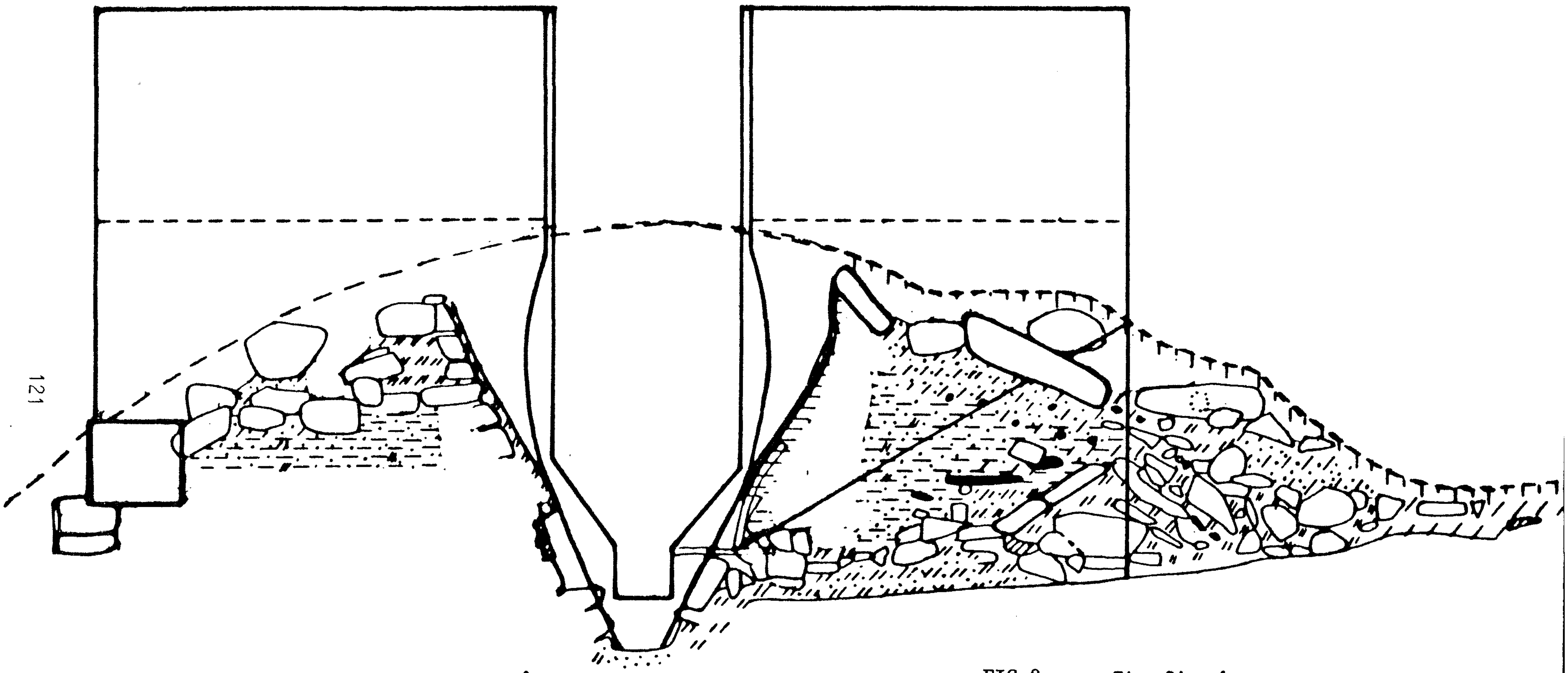


FIG 9 **The Blastfurnace Reconstruction Profile C-D**

THOLANDER´S DISCUSSION OF THE LECTURE BY FORNANDER AND BJÖRKENSTAM

Gert Magnusson

Question 2

Tholander finds it very difficult to understand and see the shape of the stack from Figures 6 and 7 in Björkenstam's and Fornander's lecture. Figure 7 is a tower photograph of the actual furnace ruin, taken from a height of about 12 m. In this picture the square or slightly octagonal shape of the stack is very clearly apparent in the southwest corner of the remaining and heavily slag-coated stack wall. The north wall towards the blowing arch has fallen out and it is impossible to make any such assessment in this direction. The same goes for the heavily collapsed wall towards the tapping arch.

Figure from Björkenstam's paper "Metallurgy and technology at Lapphyttan" printed earlier in "Medieval Iron in Society"(H 34).

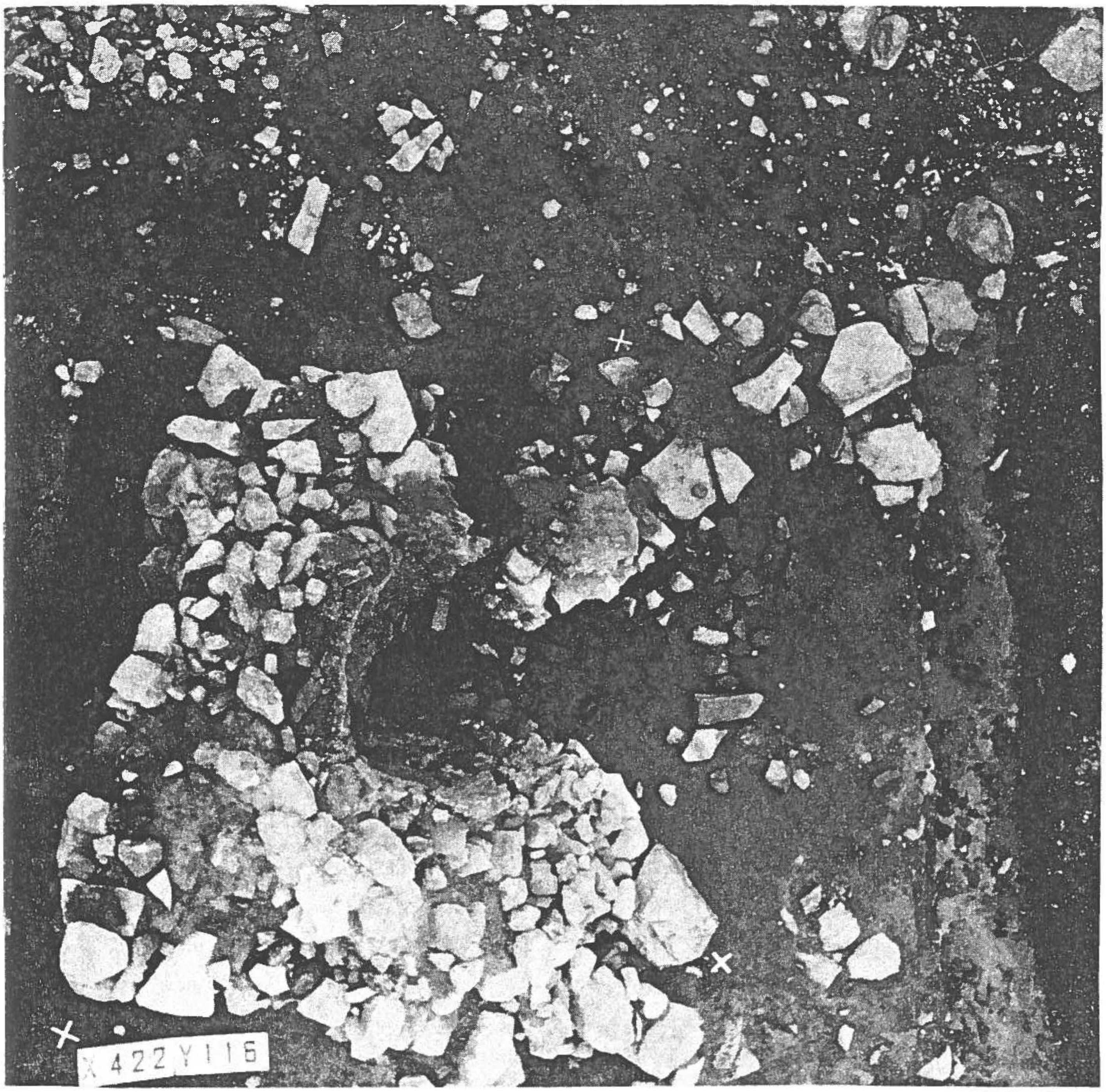


Fig. 7. The blast furnace as seen from above.

COMMENTS CONCERNING THE DATING OF LAPPHYTTAN

Gert Magnusson

This was one of the big questions concerning Lapphyttan and I was asked to elaborate somewhat on the question of its dating.

The dating methods available and used are C_{14} dating, TL dating, artifact dating and dendrochronology.

The dendrochronological dating has not yielded any results. Unfortunately, the timber analysed has too few growth rings.

Objects recovered, above all early red earthenware pottery, indicate the second half of the 13th century and the first half of the 14th.

TL dating indicates, in principle, that the furnace was abandoned in the second half of the 14th century.

There remained 27 C_{14} datings. These were presented in my lecture partly as bars, showing the range of the analysed specimens. I also put these datings together into a curve, which took the form of a normal distribution curve with a certain negative gradient. What I did not do in this situation was to divide up the C_{14} specimens according to the circumstances in which they were found, i.e. distinguishing between specimens from the upper strata and those from the bottom strata or from directly beneath the remains. It should be made clear in this connection that, in principle, no specimens were taken from the intermediate strata or horizons. We refrained from doing so because it is not really possible to obtain any further knowledge in this way. If these specimens are converted into a bar chart along a time axis, one finds two distinct peaks. One of these comes between 1150 and 1225, the other between 1325 and 1400. The latter peak in the C_{14} curve is verified by the TL datings. The first peak is not verified by any other dating method, but in principle it is presented in the same way as the second peak. This leads me to assert that Lapphyttan was established some time between 1150 and 1225.

The earlier dating can also be discussed with reference to the amount of slag produced at the Lapphyttan furnace site, which per se takes some time to accumulate.

Another indirect proof is the pollen curve compiled for the nearby Lake Bågen. This curve indicates extensive clearance and opening-up of the forest landscape here during the second half of the 12th century. It has not been established conclusively that these clearances were really connected with iron production, but that is the likeliest explanation.

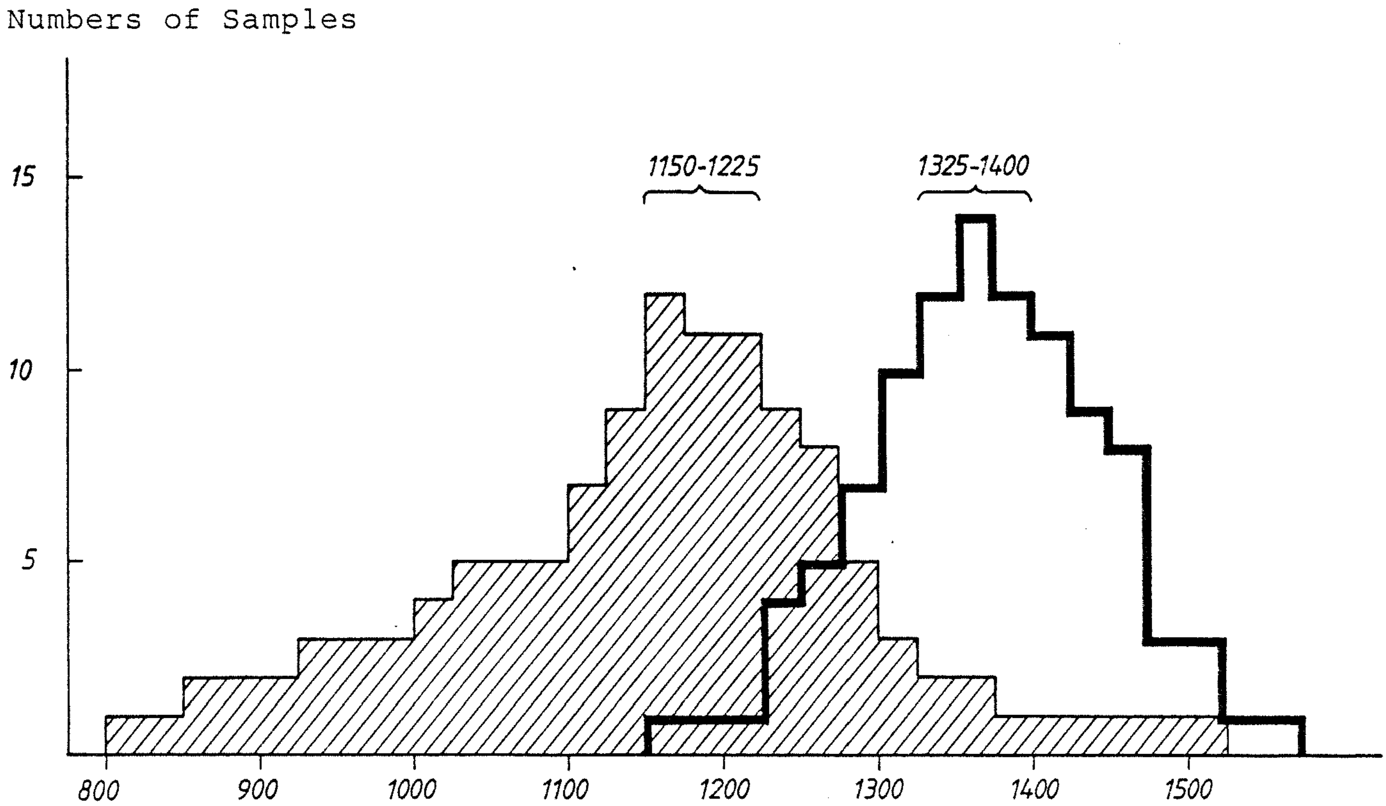
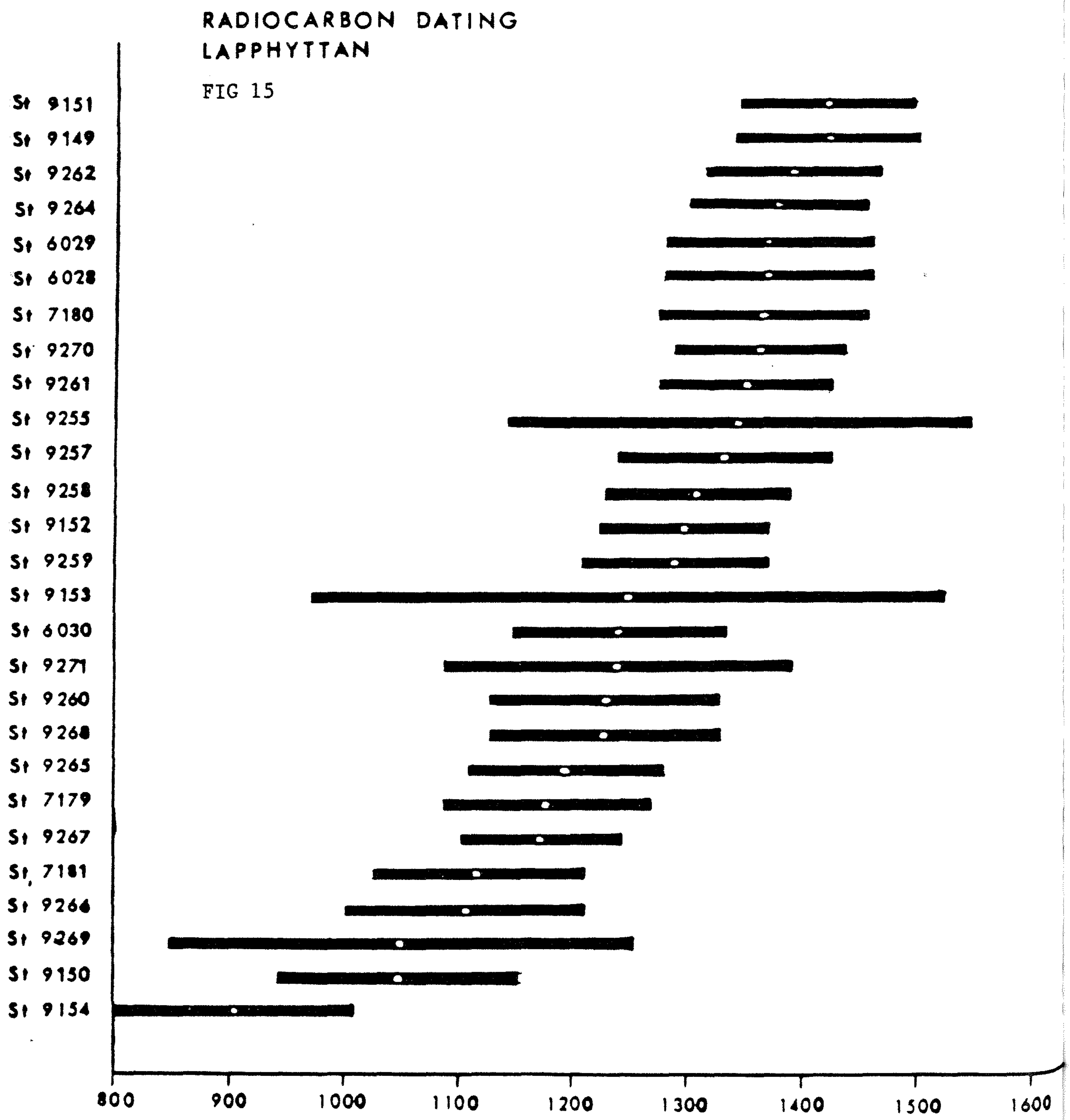


Fig Diagram showing the complete numbers of radiocarbondatings from Lapphyttan. The thin line shows the datings from the lower layers. The thick line shows the radiocarbondatings from the top layers.

Figure from Magnusson's paper "Lapphyttan - an example of medieval iron production" printed in "Medieval Iron in Society" (H 34).



Discussion of the paper by Inga Serning:

'Vinarhyttan and Juteboda - two medieval blast furnaces in Middle Sweden'

ERIK THOLANDER, Royal Institute of Technology, Stockholm

As the verbal discussion not will be recorded in this volume, I will repeat my question to Docent Serning and add a few points. I am asking:

> How can you claim the Juteboda furnace to be a blast furnace from the premises concerning the hearth bottom and the stack walls as described in your text ? Quoting from page 228 you are writing:

"The front part ... was ruined. The stack was preserved to a height of about 2 m, where the diameter was 1.8 m ... The bottom of the hearth consisted of one single, 70 mm thick slab with a diameter of 0.7 m ... not affected by heat except where some small iron droplets had stuck ... No walls remained in the much damaged hearth." Concerning the bottom slab you are suggesting: "... that it had been protected from heat by sand". No reasons are given in the paper for your above interpretations of the furnace matters.

The facts and observations displayed in the report are most interesting and valuable, but your conclusions don't seem much realistic to me. To begin with the last point quoted above, you apparently have not realized, that in a blast furnace producing liquid iron, you cannot protect the stone-slab bottom by means of a loose layer of sand only, because the sand will rise and float, while the iron immediately sticks to exposed spots of insufficient temperature, i.e. below the melting point of iron.

An old protection method was to use a four inch thick layer of coarse stones together with fine sand for filling all the space, then preheating by intensive firing until the sand partly fused, forming a glassy crust before any liquid iron arrived. Another possibility would be to mix sand and clay, ram the mass on the spot and dry it in order to get a firm slab cover.
In both cases, a protection crust would either remain to be found at the excavation, at least partly, or at a continuous production at proper temperature be removed to expose the hearth bottom completely to the liquid iron, causing widely spread heat effects. Nothing thereof has been reported. Instead of that, some iron droplets had stuck to the surface on a few spots only, which must mean three other things:

1:o the bottom slab had been reached by single droplets, not a liquid bath,

2:o the main product could not have been liquid and not have touched the bottom slab without leaving heat-attack signs on the stone surface,

3:o the produced iron must have been resting, in shape of a solid lump, on a bed of charcoal and thus been isolated from the slab surface.

In my opinion, therefore, Docent Serning's facts and observations give very strong reasons to consider the Jutebo furnace as a high bloomery or 'styckeugn'. When considering further that the stack or main wall was reported to be preserved to 2 m height, with exception of a ruined part of the front, and that no walls were found of an inner hearth, the character of high bloomery is confirmed. In a 'styckeugn' no inner hearth exists because the bottom part of the stack constitutes the hearth within a somewhat reduced diameter, 0.7 m here. Consequently, the problems of "damaged hearths" in Juteboda/Lapphyttan are easily solved: They have not existed!

In consequence with that, the front looks "ruined" because of the location there of a great opening necessary for the removal of the heavy iron-lump.

To Dr Fornander, who in the oral discussion tried to defend Serning's thesis of the furnace as a blast furnace by saying ... "that in Lapphyttan he had found many iron droplets sticking to slabs" ... I would like to add that:

1. This is new information, not mentioned in the two papers read previously, neither by Mr Magnusson nor by Mr Björkenstam and himself.
2. The existence in Lapphyttan of stone-slabs with the surface stuck by iron droplets does mean, together with certain design properties and observations, that my interpretation (displayed in the discussion of Mr Magnusson's paper) of Lapphyttan as a 'styckeugn' is supported and strengthened in the same way as above at Juteboda.

Summary and conclusion:

Because of the excavation reports and other information being discussed around the medieval furnace objects at Vinarhyttan, Juteboda and Lapphyttan, the following can be summarized as applicable to each of the three sites:

the lack of — any precise design character indicating a blast furnace in the modern sense of producing liquid pig iron only,

the presence of — certain indications relevant to a high bloomery (wide round hearth, moderate height, possibility of great front opening, signs of iron droplets stuck to bottom slabs),

the abundance of — pig iron prills on the ground, indicating the cast iron as useless and of no value (contradictory to the well known 17th century practice of collecting carefully the iron prills following the slag).

On the ground of the above statements I now claim, that none of the furnaces at Vinarhyttan, Juteboda and Lapphyttan can have been a blast furnace producing only liquid pig iron but, instead, all of them are qualified to belong to the medieval type of high bloomery, in Sweden called 'styckeugn'.

To the process of finding out the contextual matters necessary to create a true picture of the medieval development in the ferrous metallurgy and technology, Docent Serning's above paper is an essential contribution.

Discussion of the paper by Lennart Karlsson:

'Cistercian Iron Production'

ERIK THOLANDER, Royal Institute of Technology, Stockholm

In his very interesting paper Dr Karlsson gave some general information on the Cistercian monastic order in medieval Europe and some hits regarding activities of special importance at Nydala monastery in Småland, eventually extended to places outside its nearer surroundings. He also suggested the possibility of the Cistercians as the introducers of the blast furnace into Sweden and asked for opinions to that among the audience.

Myself, I have touched the problem of clerical influence upon the Swedish medieval iron industry at two or three occasions and especially that one from some Cistercian monasteries in Denmark and Sweden: Sorø, Åskloster, Nydala and Julita. Regarding these monasteries, it has been clear to me that there ought to have been some connections between the monks known to be experts in hydraulic engineering - the name of the order probably coming from 'cisterna' (Latin for 'dam','tank') - and some Swedish iron-making sites.

The situation on the Continent is better known (Sprandel, 1973) than the development in Sweden (Tholander, 1979), where little research work has been done hitherto. The probably oldest indication on clerical iron-making here, known to me, is a place with furnace remains, slag and heaps of rock ore at a small brook in the vicinity of Julita monastery, where I in 1973 discovered the possibility of its early use for iron-production under circumstances pointing at a technology in its very beginning. In spite of notice and presentations on site to representatives of the Riksantikvarieämbetet no measures, to my knowledge, have been taken for an investigation there.

Another site, where an excavation was made on private initiative and expense in 1974 and 1975, is Kåperyd near Taberg in north Småland under archaeologic leadership of Mrs Lena Thålin-Bergman. I took part as a metallurgic investigator. There, the investigation revealed the remains of a big furnace of at least 3 m height, situated in the very steep of the high bank of a little brook. Guided by a few fragments of the slag-clad back wall, still remaining in original positions, and a reconstruction of the hearth from a number of identifiable, partly slag-covered hearth-wall stones and a few parts (not slag-clad) of bottom slabs, I was able to draw some conclusions concerning the furnace design, construction and blowing practice, pointing at a high bloomery run on rock ore from Taberg during two different periods. From both periods, the slag indicated charge additions of lime, less in the earlier than in the latter, at which the iron loss to the slag had been depressed from a mean content of 7.5% FeO to 2.2% FeO (Tholander, 1978). The radiocarbon dating gave as mean values: end of 15th and middle of 16th century, respectively (Thålin-Bergman, 1978).

Nydala is located only about 40 km south of Taberg. The monastery was closed in 1527 by the king Gustaf I. From the dating figures it seems possible, that king Gustaf ordered a new blowing campaign in Kåperyd after the Crown's taking over of Nydala, if Kåperyd belonged to the monastery (only a guess).

Regarding the introduction of the blast furnace in Sweden, Dr Karlsson alluded on some influence from the Cistercians. I agree to that as possible as far as the high bloomery is concerned, e.g. in the 13th and 14th centuries. But considering the brutal activity executed by the rule of king Gustaf I against all Swedish monasteries, I think it rather more likely with an influence in the opposite direction, i.e. from Sweden to the Continent, in the case of the genesis of the modern blast furnace as a happening of the 16th century.

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