Bloomery ironmaking during the Roman period in mid-Norway

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ABSTRACT: Finds of bloomery sites in the counties of South and North Trøndelag in Norway have indicated large-scale ironmaking, starting in the pre-Roman Iron Age and lasting until the Merovingian period. The industry was based on rich deposits of bog iron ore. Museum blooms from the period weigh around 18kg and are free from slag as well as sulphur and phosphorus. The carbon content is normally very low, but one bloom shows that steel could have been produced. The normal slag has an optimal character when fluidity and refining capacity are evaluated. The use of induced draught created by direct addition of wood is suggested, based on finds and experiments. Slag control of the carbon content of the iron was probably achieved by a cyclic operation. As the output calculated for Trøndelag exceeds local needs, export of iron is suggested. Iron metallurgy sheds light on a period of Norwegian history not well covered by other sources.

Introduction

Radiocarbon dating of charcoal from about 50 heaps of slag and roasted ore has created a new picture of early ironmaking in Norway. In 1982 the bloomery at the shieling of Heglesvollen in the county of North Trøndelag was found and was followed by research excavations at similar places over 15 years. The number of recorded sites, each with a row of a particular type of slag-pit furnace, has reached more than 300, indicating large-scale production and remarkable uniformity, beginning in the pre-Roman period and lasting to the Merovingian; the method disappeared around AD600. The finds, the process and the amount of iron are indicators of a well-developed society that began some 800–1000 years before the Viking period.

How the research began

In 1977 the author tried iron making as a school project. The smelting only produced slag, but aroused curiosity. In a second session smelting was based upon the book on contemporary ironmaking written by Ole Evenstad in 1782 (Evenstad 1790; Evenstad 1968), and was ably assisted by Ivar Berre and his pupils. Some iron was obtained.

During field recording in 1982 for a TV programme large heaps of slag pieces weighing 50kg and more were discovered near Heglesvollen. They were associated with a regular set of depressions along a scarp edge, giving rise to the expression ‘rosette furnace’; in the centre a ring of stones represented the top of a slag pit. This find led to excavations by archaeologists from the University of Trondheim. The type of site is different from those published by Pleiner (2000, 162–3). The standard Trøndelag site consists of four furnaces, 6m apart, regularly arranged along a scarp edge, each with a large slag dump in front, facing a creek, river or lake. As the slag heaps are of equal size, it is likely that the whole set of furnaces were operated as a unit.

The excavations took place during the years 1982–85. The archaeologist Lars F Stenvik has played a leading role at Heglesvollen and at six other sites, marked on Figure 1. He has given a comprehensive presentation of the finds in the first of three books on the history of

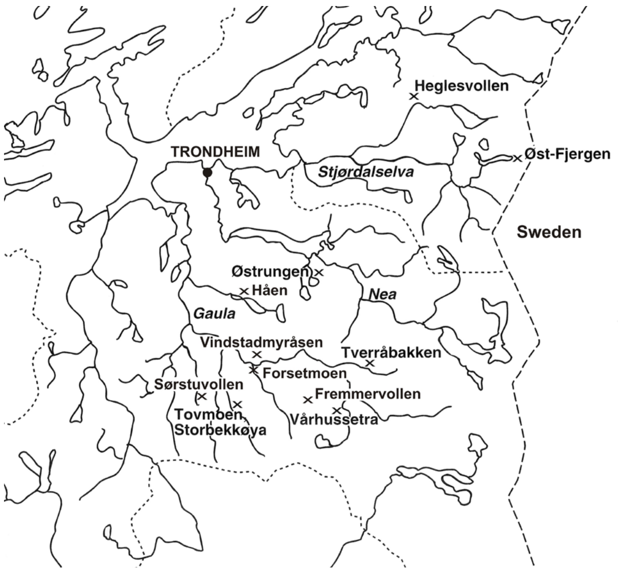

Figure 1: Mid-Norway showing bloomery sites of the Trøndelag type that have been excavated and studied by metallurgical analysis.

Trøndelag (Stenvik 2005a). The present author took part in the excavations, collected samples for analysis and evaluated the results. Ideas about the operation of the furnaces are set out below. New output calculations produce a ratio of iron to slag of about 1:1, *ie* a three-fold difference compared with a much-quoted ratio of 1:3 (Espelund 2004).

Bloomery furnaces in general

A bloomery furnace is a refractory cylinder, into which ore and a combustible (charcoal or wood) can be added. By reaction between in-blown oxygen in air and charcoal, a high temperature is created. The resulting CO-rich gas will by a counter-current process react with the iron oxide and create solid, metallic iron (the bloom). Air must be admitted for combustion of wood or charcoal. Means of retrieval of the solid bloom and separation of liquid slag are necessary. The slag was a waste product after tapping, but was functional in the furnace, controlling the quality of the bloom. Pleiner (2000) gives full coverage of European bloomery furnaces.

The Trøndelag furnace

The typical Trøndelag furnace is an underground pit with a dry stone wall measuring about 0.8m in diameter and also in depth. It has a vertical slot of permanent appearance in front, as shown in Figure 2. The very good state of preservation is due to slag in amounts up to 150kg, left *in situ* by the last smelters in order to prevent damage by frost. Figure 3 shows the excavated area around furnace C2a at Heglesvollen which includes the remains of C5, an older and exceptional furnace.

In these furnaces the blooms rested on top of the slag and were taken out hot through the slot. Solid slag was removed in the same way when the sequence of operations was over. At first this pit was regarded as the furnace proper (Farbregd *et al* 1984; Magnusson 1986). However, the stones in the pit were not affected by heat. In the slag heaps were many broken pieces of burnt clay with some grog added, about 20mm thick and black on one side, clearly representing a shaft placed on top of the pit. The shape of this shaft has not been clearly established but by analogy it is assumed to have been about one metre high. An updated presentation of the archaeology at such sites has been given by Stenvik (2005b), who also claims that the middle section of the furnace had a constriction, so that the inner diameter at this level was around 0.5m. If so, this may have been important for separation of the hot and the cold parts of the furnace.

Figure 2: Slag pit of furnace C2a at Heglesvollen after removal of topsoil and in situ slag. Notice the permanent, rugged opening and the inclined plane in front for removal of solid slag.

Figure 3: The excavated area around furnace C2a, looking west. Note the depressions around the central slag pit cut into the silty subsoil. The remains of C5, an older furnace, can be seen between the two trees to the left.

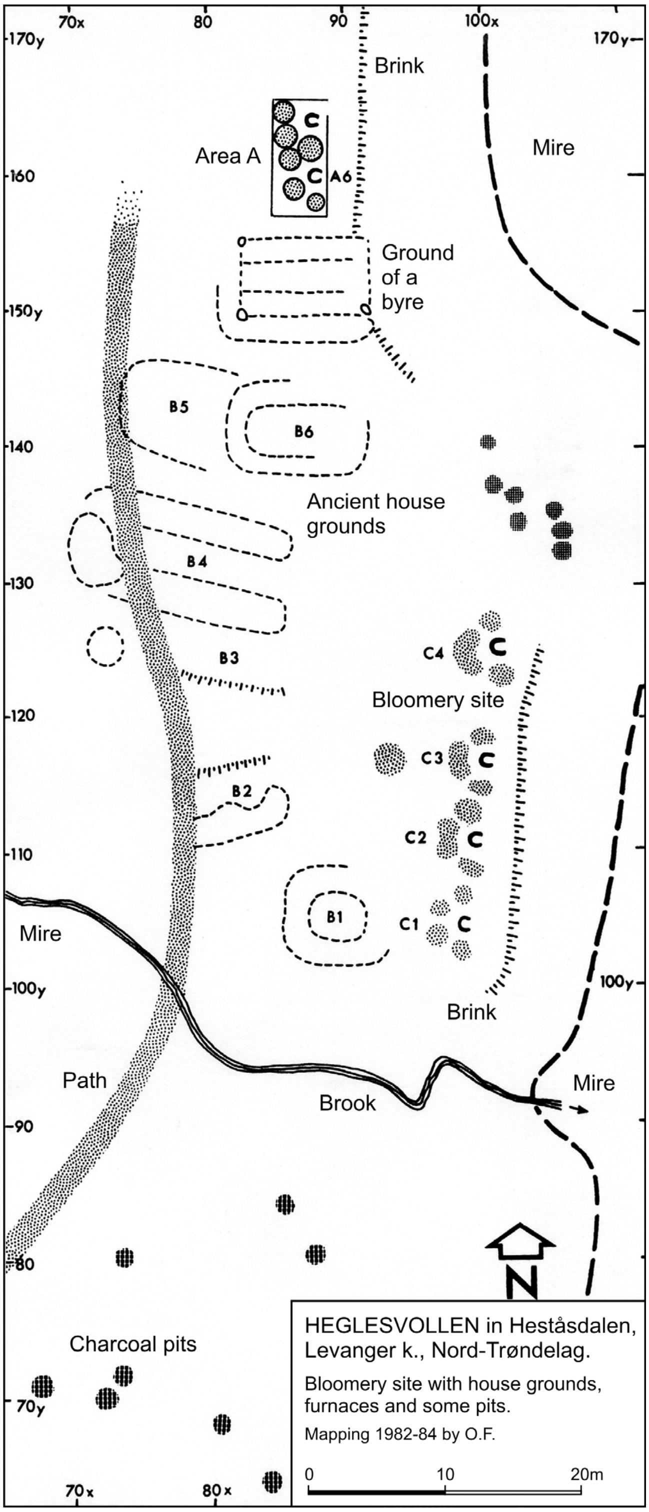

Figure 4: The area studied at Heglesvollen. The four furnaces are marked C1-C4 and another set of furnaces are marked A. B1-B6 are remains of houses. Other features are from recent centuries (after Farbregd et al 1984).

All the furnaces studied seem to be identical and give the impression of a very professional activity. Nowhere have traces of experiments leading into this type of iron-making been found in the area; it therefore appears that the process was imported from elsewhere – but where this was is still unknown.

The function of the houses at Heglesvollen (Fig 4) is uncertain, as no fireplace, objects nor accumulation of phosphate have been recorded. Nor has the role of water, indicated by a mire in front of the furnaces, been explained.

Several samples from different furnaces were radio-carbon dated. The values spread from about year 1 to AD450 (see data in Fig 7). Overall some 50 charcoal samples have been dated, giving a total range for the Trøndelag furnace of 300BC to AD600.

The character of the slag

The in situ slag and the slag in the slag dumps had the same character, with most pieces weighing up to 50kg, but some heavier. The largest pieces were simply rolled down the slope. The slag was non-magnetic, not showing any orientation. By sampling in 0.5m x 0.5m test pits in front of the set of four furnaces the total weight of slag at site C was found to be around 96 tonnes.

Most significant were numerous cavities in the slag showing wood grain, some elongated and parallel (Fig 5). The cavities may represent charcoal, which had burnt. but some were long, showing slight transverse ridges. They therefore represent wood that became embedded in liquid slag, which excluded air. Charring followed by shrinkage took place on the surface while the interior was not affected by heat. The larger part of this fuel has since decayed and disappeared.

Figure 5: Slag with cavities showing wood-grain and transverse ridges, corresponding to the surface of the half-burnt wood from a modern fireplace. The piece of slag shows that split wood had been placed in parallel. Scale bar 100mm.

Figure 6: Piece of slag from the cold, stone-lined slag pit. Note the ripples. Each ripple may represent c10kg of slag. Scale bar 100mm.

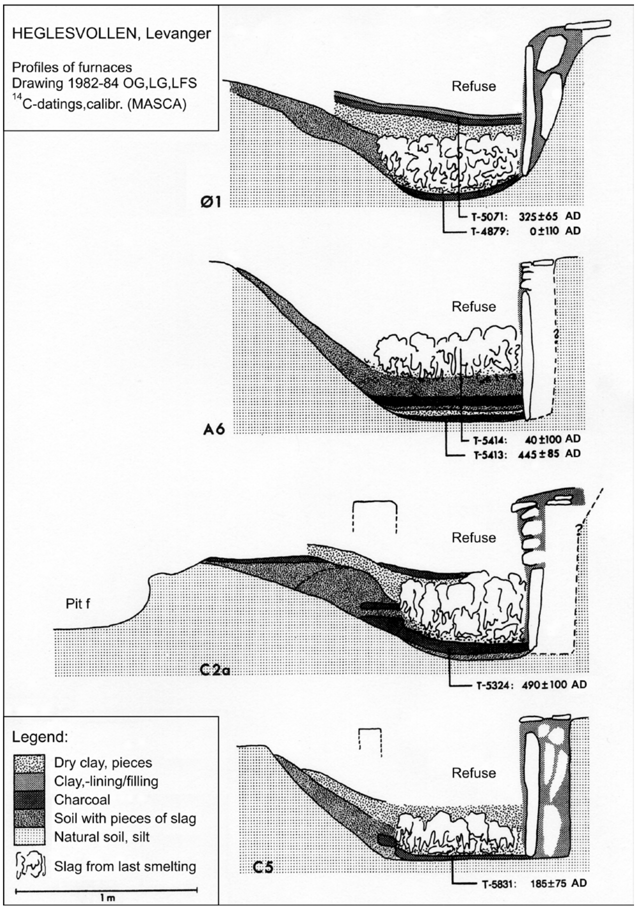

Figure 7: Cross-sections of furnaces Ø1, A6, C2a and C5 from the Heglesvollen site. A6 and C2a (with C5 adjacent) are shown on Figure 3; Ø1 is from a site further east. The irregular white areas are the remaining in situ slag in each furnace (after Farbregd et al 1984).

At the beginning of each run, pieces of wood were stacked criss-cross in the cold pit in order to create a platform for the charge, to fill the shaft above ground, and at the same time leave room for liquid slag. A few pieces of slag evidently solidified facing the cold stone-lined wall of the slag pit. They have parallel ripples, showing that slag in discrete amounts ran into the slag pit from above (Fig 6). The wood was gradually embedded in slag, which ran into the pit in portions of some 10kg up to a total weight of about 150kg. Each flow was the result of a temperature increase near the air inlets. As the slag did not adhere to the wall, it could be easily removed through the vertical slot at the end of each run. The pit and also the shaft could be used again. This is in contrast to the slag pit furnaces found in Poland and Denmark, and also large furnaces such as R 75 at Dokkfløy, north of Oslo (Larsen 1991).

The fuel and the firing

During the Roman Iron Age pine and birch were the dominant local tree species but pine was used exclusively for ironmaking. The traditional picture of a charcoal-fired furnace and the use of bellows therefore has been changed to a furnace fired with wood and operated by induced draught (Fig 7). A piece of burnt clay with the half of an opening measuring 80mm in diameter supports this view (Fig 8).

During smelting, a combustion of the gases from the resin and tar in the pinewood took place, creating flames several metres high. The wood was thereby transformed to charcoal, which followed the charge downwards to the level of the air inlets. When more wood was added, air was sucked into the furnace by means of a chimney fire, leading to a temperature rise at the hearth level, melting and probably also an adjustment of the composition

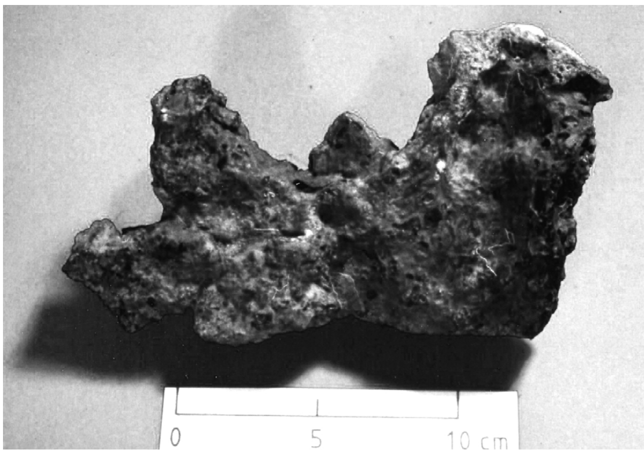

Figure 8: Half of a fired clay air inlet, found at the Vårhussetra site.

of the slag. This might take place as many as 15 times during a complete run. At the same time sintering of the primary particles of iron into a solid and compact bloom probably took place by grain growth.

Most of the sites from the Roman Iron Age lie some 100–200m below the tree line, far from present-day dwellings. Here the pine grows slowly, resulting in much heartwood. This direct use of wood corresponds with the lack of charcoal-burning pits in Norway older than *c* AD700. Such pits are connected with the second method for ironmaking, introduced around that time. This method will be discussed elsewhere.

The blooms

Iron blooms are rarely found at bloomery sites. However, some blooms from the period are in museums, as reported by Espelund (1998–99) and Stenvik (2006). One bloom (T-21 175) weighing 17.2kg was a stray find from Akset on the island of Hitra, some 80km west of Trondheim (Fig 9). The cut must have been made with a single blow of an axe in order to test the quality. As no secondary heating of blooms nor anvil stones and hammerscale have been documented, it shows that the bloom was retrieved in the red-hot state and no further smithing took place at the bloomery. Such blooms were transported elsewhere for smithing to finished objects (see below). This bloom is regarded as a standard primary product.

By immersion in water its density was found to be 4.9. Other blooms have densities in the range 5.5 to 6.5. The difference from 7.8 (the density of solid iron) is due to both large pores on the surface and micropores in the interior.

Figure 9: The bloom found at Akset, Hitra. Scale bar 100mm.

Table 1: Composition of the bloom from Akset (wt%).

C	Si	Mn	S	P	Fe
0.26	0.01	0.01	0.022	0.045	balance

A sample was taken from the most accessible part of the bloom, next to the cut and analysed in an industrial laboratory by Helen Langeng. Table 1 shows an excellent mild steel without significant amounts of detrimental sulphur and phosphorus. The very low values for Si and Mn, representing oxides, reflect an absence of entrained slag. A micrograph (Fig 10) shows a mixed structure of ferrite and pearlite. Hardness values were from 191 to 226 Hv, typical for annealed pearlite. Radiocarbon dating gave a date of 760–410BC (Tua-3591) but it is more likely that it was made somewhere in the eastern part of Trøndelag sometime after 300 BC.

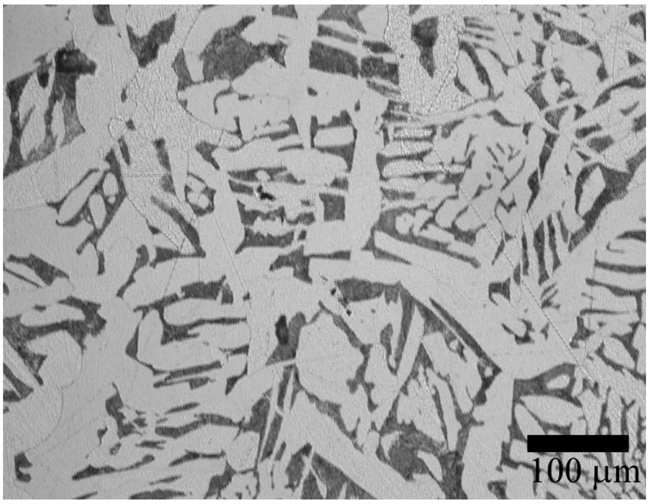

Figure 10: Micrograph of the bloom from Akset showing ferrite (light) and some pearlite (dark) with an average of 0.2% C. Note the texture inherited from the former large austenite grains.

Another bloom (T-22 057), a stray find from Namsskogan, 200km NE of Trondheim, is different (Espelund 1998–99). With one flat side and a weight of 9.3kg it is evidently half of a normal bloom, which had been cut in two. This half bloom was sectioned (Fig 11). A chemical analysis (Table 2) showed that the bloom is a good steel, suitable for edges of cutting tools after hardening by quenching. As expected, hardening took place when cut with a cutting wheel. The values for Si and Mn represent a slightly higher content of slag inclusions than for the bloom from Akset. This bloom was radiocarbon dated to AD390–545, which is as expected. It is not so compact as the Akset bloom so a density measurement would be meaningless. The adhering slag contained only 2.2% SiO_2 and 77.5% iron oxide (calculated as FeO). However, it was magnetic due to the presence of some Fe_3O_4, showing a high oxygen potential. A final slag after reduction should contain over 20% SiO_2. The

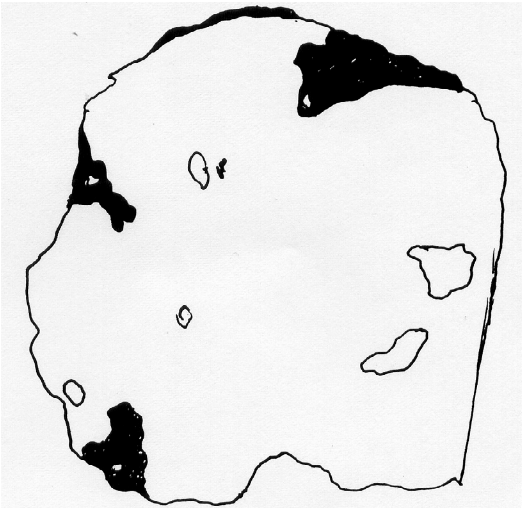

Figure 11: Cross-section of bloom from Namsskogan. Black areas are adhering slag, the open areas are cavities. Width c100mm.

Table 2: Composition of the bloom from Namsskogan (wt%).

C	Si	Mn	P	Fe
0.67	< 0.10	0.09	0.010	balance

bloom therefore seems to be the result of reduction to a carbon-rich primary iron, followed by refining by adding rich ore in the same furnace. With only 2.2% SiO_2 in the ore, one cannot expect formation of sufficient slag for a primary control of the carbon content of the metal. This half bloom is reminiscent of the Evenstad process, in use from about AD1400 to 1800. Espelund (2014) gives a full interpretation of this steel production.

That the blooms rested on top of the slag in the pit is shown by a large slag block, weighing 120kg, found at the site Øst-Fjergen (Fig 12). It must have been removed when a slag pit was to be repaired. The five shallow depressions seem to represent the positions of blooms of the kind shown in Figure 9.

Chemical analyses of slag and ore

The Trøndelag region was strongly affected by the last glaciation up to 10,000 years ago, leaving much moraine material. Such permeable deposits combined with a relatively high precipitation, moderate temperatures and a sloping landscape led to the creation of large areas with mires, providing good conditions for the formation of bog iron ore. During recent millennia the mires have grown in height, so that their character has changed from minerotrophic to ombrotrophic, now without ore formation.

Table 3 shows the composition of a representative smelting slag. A search for lumps of ore in the area was not successful but their likely composition can be calculated. An enrichment of 2.5–3 is normal for the elements Mn, Al and Si (Espelund 2004), so using the value 2.5 for enrichment and calculating backwards

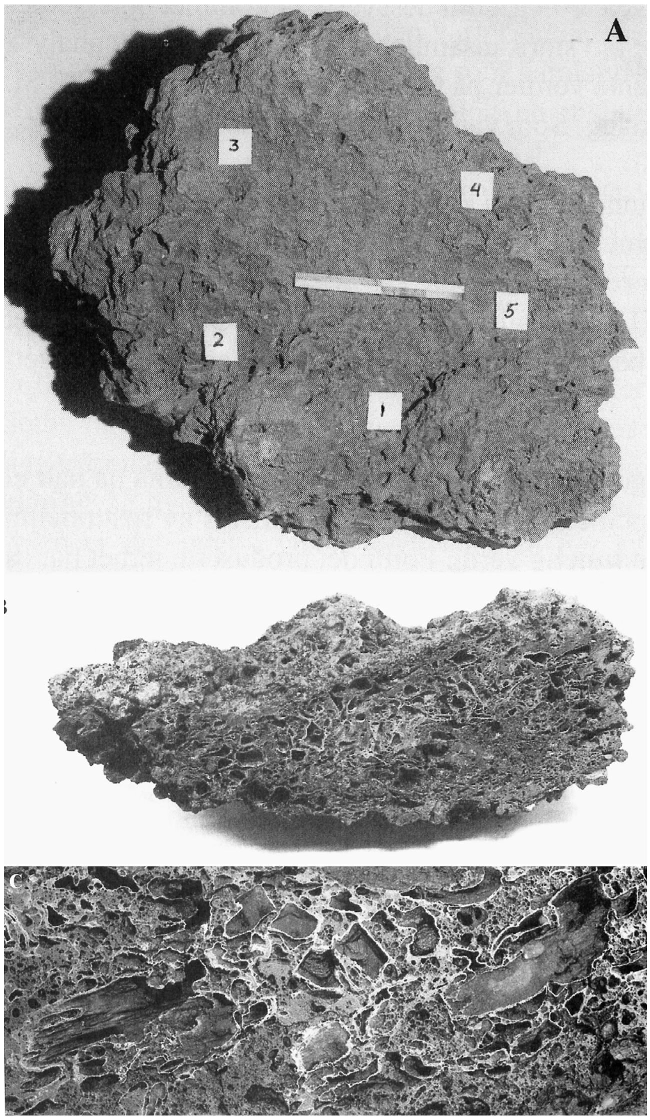

Figure 12: Slag block from Øst-Fjergen. A) top surface showing five shallow depressions, Scale bar 200mm; B) Section showing two of the depressions; C) Close-up of the section showing 'nutshells' of iron created around pieces of charcoal, image width c200mm.

Table 3: Composition of smelting slag from Heglesvollen and the hypothetical ore producing it (wt%)

	FeO	Fe_2O_3	MnO	SiO_2	Al_2O_3	CaO	MgO	BaO	K_2O	TiO_2	P_2O_5	Total	R
Slag	63.6		3.25	23.7	5.98	1.2	0.6	0.01	0.44	0.30	0.11	99.3	2.35
'Ore'		85.8	1.3	9.5	2.4	0.5	0.25	-	0.18	0.1	-		6.7

from the slag composition gives the hypothetical ore composition shown in Table 3. The symbol R for the fayalite ratio (FeO% + MnO%)/SiO_2% (molar values), is calculated in order to assess both ores and slags. The value R = 2.0 represents fayalite, with the general formula $(Fe,Mn)_2SiO_4$. Therefore one would expect a value near 2 for a fayalitic end slag, while good ores should have R well above 5. If this holds true, mass balance suggests that 25kg of ore produced 10kg of iron and 10kg of slag.

The operation of the Trøndelag furnace

Without doubt the use of wood (pine), creating a chimney fire and the necessary draught is effectively proven as an essential part of the operation after numerous experiments with full-scale furnaces by Ivar Berre (Berre 1998; 1999), well supported by finds of pine charcoal. During experimental runs some slag dripped into the slag pit, where pieces of carbon-rich iron could be found. The operation of the Trøndelag furnace is shown schematically in Figure 13.

The slag analysis (Table 3), with 3.25% MnO, 63.6% FeO and 23.7% SiO_2 (R=2.35) is very characteristic of successful bloomery smelting. The saying 'make your slag, and the metal looks after itself' is valid, as expressed by the chemical equilibrium

$$FeO + \underline{C} \leftrightarrow Fe + CO$$

Accordingly the remaining question is how a good slag could be created. In many experiments an over-reduction to carbon-rich metal without the required reaction between FeO and SiO_2 seems to take place. The ripples on the surface of certain pieces of slag (Fig 6) suggest a discontinuous operation, that has not yet been tested.

The required FeO-rich slag could have been created intermittently by an increased draught, as expressed by the cross-section at the hearth level shown in Figure 14. When idle, a hot zone with a heterogeneous mixture of slag and metal is expressed by the small 'beaver tail' zones, created at each air inlet. Between the air inlets there were dead zones in which a partial reduction to the lowest oxide had taken place. Whenever new wood

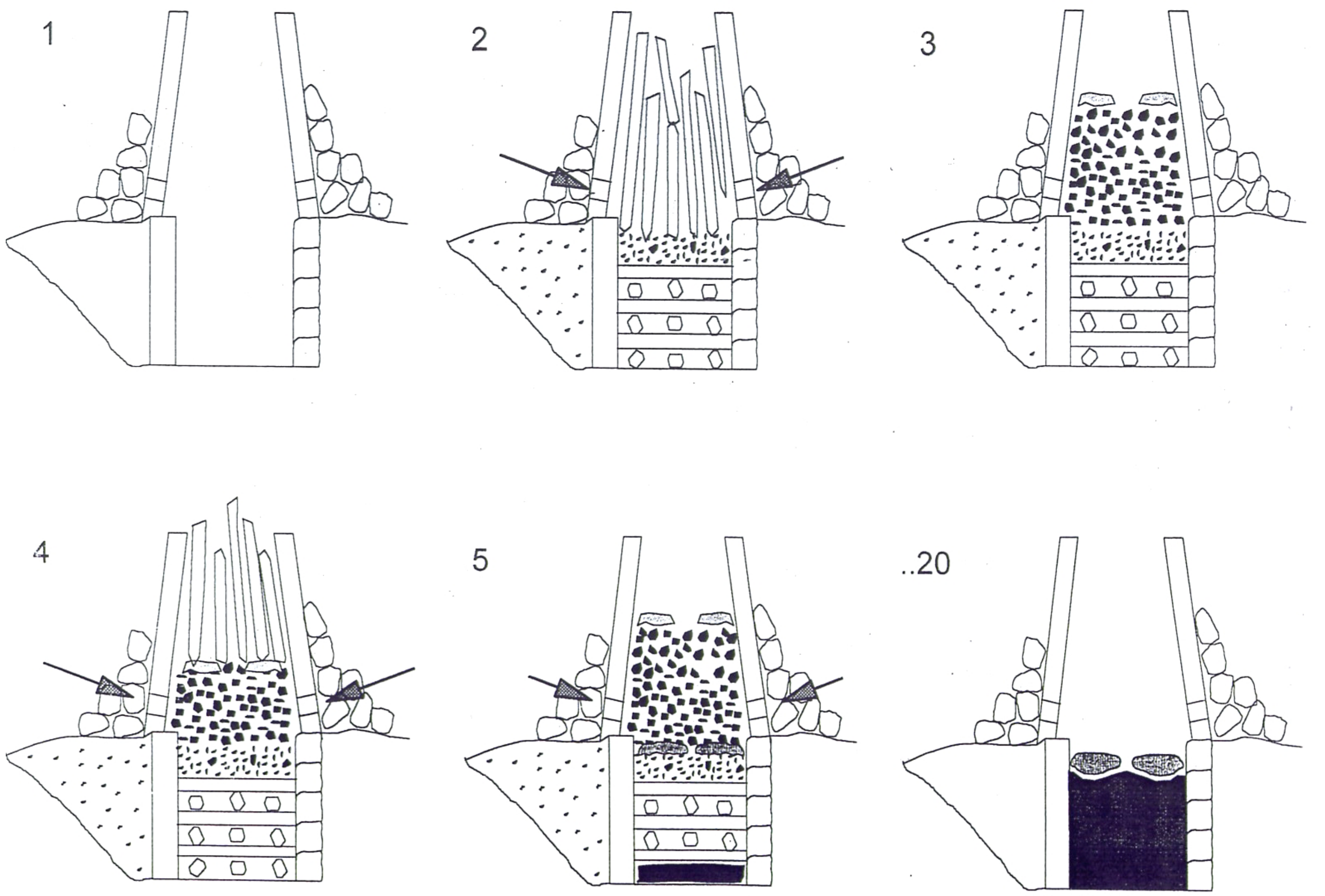

Figure 13: The suggested cyclic operation of the Trøndelag furnace. 1) The pit emptied after a previous run, 2) wood stacked criss-cross in the slag pit, with that added on top allowed to burn to charcoal, 3) the first ore added to the top of the burning charcoal, 4) more wood added, 5) due to increased temperature the first slag runs into the slag pit and blooms are beginning to form, 20) the above sequence of operations is repeated, here to a nominal step 20, ending with some 150kg of slag with the blooms resting on top.

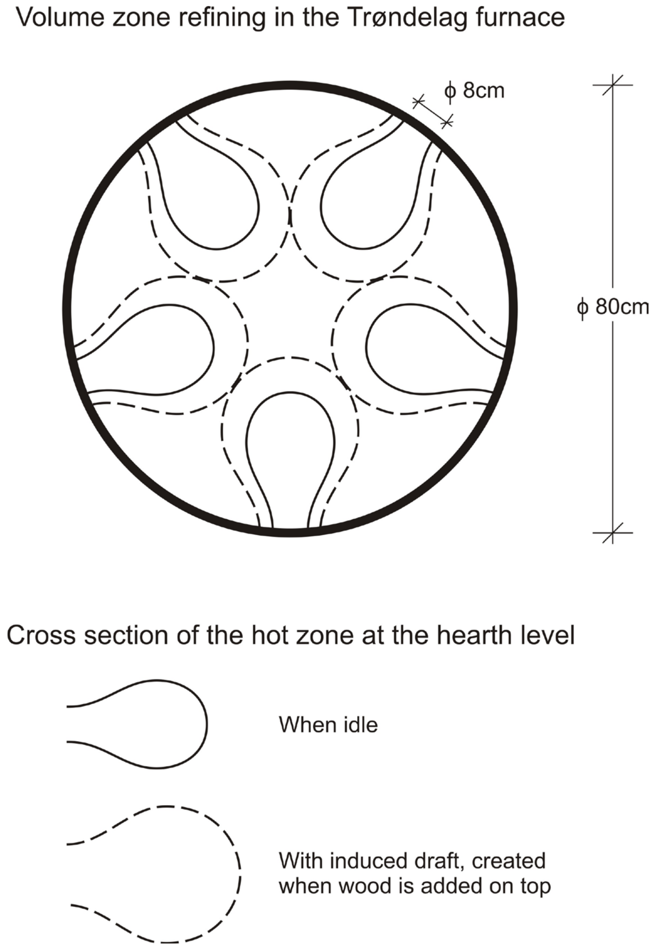

Figure 14: Diagram of the Trøndelag furnace. Air for combustion of charcoal enters at two rates, leading to alternating moderate and high temperatures.

was added on top, the increased draught enlarged the 'beaver tails', supplying FeO for the required refining of the primary iron or even prevention of an uptake of carbon. With only five 80mm-wide openings around a circumference measuring 2.5m it is likely that dead zones were created between the air inlets, and perhaps also in the middle.

If the proposed mechanism holds true, the operation of the Trøndelag furnace was simple. The refining resulted from the addition of wood from time to time. The secrets of this smelting were the size and the number of the air inlets, perhaps also the admission of air by closing and opening them. The discovery of just one air inlet (Fig 8), in spite of careful examination of the excavated material, suggests that the operators may have wanted to maintain a monopoly by destroying such pieces.

The proposed mechanism is not too different from the well-known Catalan process. With 94 tons of slag and an equal amount of metal produced at Heglesvollen alone it is evident that the process was easy to reproduce.

We assume that ironmaking at sites such as Heglesvollen was practised during the summer months by a group of about ten men over periods of 10 to 20 years. The group consisted of serfs, led by a chieftain, who controlled the art of ironmaking. The serfs were taken out of agriculture and worked during the rest of the year in woodcutting, seeking ore and transportation. No houses used as quarters for the workers have been found at the bloomery sites.

The region of the Trøndelag furnace

Intensive ironmaking took place in parts of the two counties North and South Trøndelag during the period about 300BC to AD600; the area is known for its early settlement and a varied landscape. Jewels and finds such as copper utensils and glass from the Roman Empire indicate trade (Stenvik 2005a). Recently an area at 200m above sea level at Forsetmoen (Fig 1) with a set of smithies from the same period has been excavated. The idea of transportation of iron from bloomery sites at about 500m altitude to a central place for smithing to finished objects now seems to be confirmed.

Trøndelag furnaces can be traced into neighbouring Swedish Jämtland, as shown by Gert Magnusson (1986); both the sites and the character of the slag show that the furnaces are identical. The conventional picture of a dug-in furnace operated by bellows suggested in 1986 has changed.

North of the Trøndelag area very few bloomery sites have been found and iron from the south was exchanged there for fish and sea mammals. The situation south of Trøndelag is not so clear.

After numerous radiocarbon dates it is clear that the technique of the Roman Iron Age disappeared around AD600. After AD700 a new, smaller type of furnace that was tapped at or above ground level, fired with charcoal and blown by bellows was introduced. The question remains as to why this happened.

A self-sufficient or a trading society?

We have assessed the annual production of iron in the Trøndelag area around AD200 at 40 tons, equivalent in weight to 40,000 axes. Much of this must have been exported and only transport by sea-going vessels would have been feasible. In recent years archaeologists have searched for ancient boat sheds. Because of the land-rise after the last ice age, which can reach a total of *c*180m, the boat sheds at altitudes 10–15 metres above the present coastline are of particular interest. Grønnesby (2007) mentions six such boat sheds, for which rediocarbon dating shows a good correlation with their elevation and which could accommodate ships up to 15m in length.

The destination of these exports is not yet clear, nor whether the iron went as blooms, tools or as weapons. Possibly relevant is the deposit at Illerup-Ådal in Denmark, where a large number of iron spears was sacrificed in a lake after a battle during the Roman Iron Age (Ilkjær 2000). Traces of cobalt but little phosphorus, detected by microprobe, indicate the metal was produced on the Scandinavian mainland.

We suggest a more complex society, with a greater population, in the early Iron Age than thought hitherto. Iron production during the Roman Iron Age had an industrial character, but was followed by a large number of small-scale production sites in later period. This contrasts with a concept of evolution of the iron industry.

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