Iron and steel in ancient times

by Vagn Fabritius Buchwald

Historisk-filosofiske Skrifter **29**

Det Kongelige Danske Videnskabernes Selskab
The Royal Danish Academy of Sciences and Letters

DET KONGELIGE DANSKE VIDENSKABERNES SELSKAB

udgiver følgende publikationsrækker:

THE ROYAL DANISH ACADEMY OF SCIENCES AND LETTERS

issues the following series of publications:

	Authorized Abbreviations
Historisk-filosofiske Meddelelser, 8°	Hist.Fil.Medd.Dan.Vid.Selsk. (printed area 175x104 mm, 2700 units)
Historisk-filosofiske Skrifter, 4° (History, Philosophy, Philology, Archaeology, Art History)	Hist.Filos.Skr.Dan.Vid.Selsk. (printed area 2 columns, each 199x77 mm, 2100 units)
Matematisk-fysiske Meddelelser, 8° (Mathematics, Physics, Chemistry, Astronomy, Geology)	Mat.Fys.Medd.Dan.Vid.Selsk. (printed area 180x126 mm, 3360 units)
Biologiske Skrifter, 4° (Botany, Zoology, Palaeontology, General Biology)	Biol.Skr.Dan.Vid.Selsk. (printed area 2 columns, each 199x77 mm, 2100 units)
Oversigt, Annual Report, 8°	Overs.Dan.Vid.Selsk.

Correspondence
Manuscripts are to be sent to
The Editor
Det Kongelige Danske Videnskabernes Selskab
H.C. Andersens Boulevard 35
DK-1553 Copenhagen V, Denmark.
Tel: +45 33 43 53 00. Fax: +45 33 43 53 01.
E-mail: e-mail@royalacademy.dk.
www.royalacademy.dk

Questions concerning subscription to the series should be directed to the Academy.

Editor
Flemming Lundgreen-Nielsen

Iron and steel in ancient times

by Vagn Fabritius Buchwald

Historisk-filosofiske Skrifter **29**

Det Kongelige Danske Videnskabernes Selskab
The Royal Danish Academy of Sciences and Letters

Frontispice: Regin the Smith. Hylestad Church, Norway. Detail of Fig. 313.

Printed in Denmark by Special-Trykkeriet Viborg a-s
ISSN 0023-3307 ISBN 87-7304-308-7

Abstract

The history of iron and steel is presented from the earliest known examples until 1200 A.D., when new methods of production were introduced. In an introductory chapter the utility of meteoritic iron for tools and weapons is discussed, and it is shown how the three iron types, meteoritic, telluric and man-made iron may be distinguished. The competition between copper, bronze and iron in the Mediterranean area is followed, and the transition from Bronze Age to Iron Age explained. Early centres of iron production, such as Elba, are examined in some detail. In a chronological development, the Etruscan, Roman and Celtic handling of ores and metal is examined, and the success of Noric steel explained. The North European scene is explored, with emphasis on Norway, Sweden and Denmark, and it is shown that there were two steel-producing centres in Scandinavia, Valdres in the Iron Age and Viking Age, and Småland in early mediaeval times. The material has been examined from a metallurgical standpoint. The metal phases are analysed and tested for their hardness, and it is shown that ancient iron was usually a complex alloy of three elements, iron, carbon and phosphorus, the last one being an important component. The manufactured objects, whether nails, horseshoes or tools, were extremely heterogeneous, in the structure as well as in the hardness and the slag inclusions, but it is shown that there is a logical, metallurgical harmony between the heterogeneous zones. The furnace slags have been characterized by their morphology and composition, and the slag inclusions have been analysed in great detail and used to discriminate between artefacts of Danish origin and those of foreign origin. It turns out that a significant fraction of Danish Viking Age and early mediaeval artefacts have been imported from Norway, Scania and Halland. The special world of metallurgy is elucidated with discussions of furnace technology, forging, hardening, hammer-and pattern-welding. The war booty sacrifices, which are rich in pattern-welded swords, are treated with examples from Vimose, Nydam and Illerup Ådal.

Vagn Fabritius Buchwald, Docent (emeritus), Department of Metallurgy, Danish Technical University, DK-2800 Lyngby. Private address, Ingeborgvej 4, DK-2920 Charlottenlund.

Dedicated to the Danish conservators
who cunningly save and sustain our common past

Contents

Preface

In three decades of the 20th century I worked with iron meteorites and discussed their history and metallurgy. Among other things I confirmed that it was possible to forge tools and weapons from iron meteorites. This fact inspired me to visit some archaeological museums in order to identify ancient meteoritic artefacts. In this effort I have not been successful. Instead, however, I discovered the exciting world of ancient copper- and iron alloys. In due time I slowly phased the meteoritic studies down and turned my attention to, in particular, archaeological iron objects.The analytical methods I had applied on meteoritic material were now applied on man-made iron, steel and slags, in order to fully characterize the material.

The history of iron has been the object of many books and numerous papers. Common to most of these treatises is the emphasis placed on all sorts of furnaces, on production techniques, on forging and the associated machinery. With rather few exceptions little emphasis has been placed on the quality of the manufactured iron, its hardness, ductility, chemical composition, corrosion, and on its slag inclusions.

It will be shown here that objects of iron and steel – until about 1860 A.D. – were mainly iron-phosphorus-carbon alloys. They were heterogeneous and had significant slag inclusions, sometimes visible to the naked eye, but mostly only visible on a polished section under the loupe or the microscope.

The modern metallurgist comes to the archaeological metal with several prejudices. One is his staunch opinion that slag inclusions are utterly detrimental and should be kept to an absolute minimum. This is correct as long as we are dealing with modern machinery, with reciprocating movements, with wheels and rotating axles. Here slag inclusions may lead to disastrous failure by premature fatigue. Until the introduction of the steam engine in the 18th century slags were, however, a minor problem.

Another prejudice is that phosphorus cannot be tolerated in iron. In modern practice it is kept below 0.045% P, or even below 0.015% P in some prime qualities, mainly to escape brittle failure at sudden shocks, particularly at low temperatures. The ancient material was often rich in phosphorus, whether in Great Britain, Germany or France. Denmark, in particular, produced phosphorus-rich iron, with 0.2-1.0% P due to the extremely phosphorus-rich bog iron ores. Phosphorus, even in minute quantities, conferred a certain corrosion resistance to the iron, because the phosphorus in forging operations became concentrated in the immediate surface.

The archaeo-metallurgist thus faces a material world which is much different from the material world of 2004 A.D. In the following chapters we will follow the material from ore to finished – and finally to the corroded – product, with emphasis on the properties of the material, while somewhat neglecting the furnaces, on which so much has already been written. We will take a very close look at the slag inclusions, most of which prove to be smelting slags and thus should be able to tell us something about the original ore from which the object was made. It will be shown that the slag inclusions may serve to discriminate Danish-made objects from contemporaneous objects made in Sweden and Norway, a result which may prove to be of some significance when evaluating artefacts from Scandinavian excavations.

The book does not pretend to be a handbook of the prehistory and early history of iron metallurgy in Europe. But many well-studied examples have been included and presented on a historical background. Full analytical details of the metal and its slag inclusions are presented, in the hope that the archaeological researcher and excavator may find an answer to some of the problems that worry him, such as “what ore was used”, “did the blacksmith know his trade”, “how can the bulk slags be characterized and distinguished from each other”, “what fuel was used”, “was the furnace building material selected for maximum refractoriness", and "were hammer-welding, hardening, and coldworking applied?"

All analytical data have been obtained on the same Philips scanning electron microscope (SEM) in the years from 1984 to 2004 at the Department of Metallurgy at the Danish Technical University. Analyses from the literature older than 1960 are rarely quoted, because they often give a false impression of the quantity of silicon, manganese and phosphorus in the metallic phases. The old analyses were usually made on drillings and these could be an undetermined mixture of metal, slag inclusions and corrosion products. The analyses in this work are on uncorroded metal and on uncorroded slags, examined on polished sections, and they are separately presented and correlated in various diagrams.

It is a curious thought that only a hundred years ago it was still necessary to discuss whether iron or copper were the first metal to be used by man, see e.g. Daremberg & Saglio (1896), where the entry "Ferrum", written by L.de Launay at length weighs the arguments pro et con. Many archaeological researchers maintained that iron was in use before copper, otherwise it was difficult to explain the early occurrences of massive stone monuments which in their opinion must have been cut by tools of iron. That these ancient tools had never been found was, according to this view, due to their disappearance by corrosion. It is true that iron is more prone to corrosion than either copper or bronze. That is why the present work has little information on the early iron artefacts from, e.g., Anatolia and Palestine. We know that they existed, because imprints and scales have been preserved, but the metallurgist is lost, because the metal and the slag inclusions are too corroded for meaningful analyses.

In Chapter One iron meteorites are examined, and well-documented examples of forged meteorites are presented. Also a number of meteorites used as anvils are discussed. It is shown how meteoritic material can relatively easily be distinguished from native iron and from man-made objects. Even severely altered and almost decayed iron meteorites retain significant amounts of minerals unique to meteorites, thus discriminating them from artefacts.

In Chapter Two some early copper and bronze objects are presented, with photomicrographs and hardness determinations. The copper alloys, of course, remained with us after iron appeared on the scene, but they were restricted to special purposes and functions. Copper and copper alloys were in particular used for castings, where iron in the period under discussion was never cast. The superiority of copper alloys in certain respects even today may be exemplified by tinned copper household articles and electrical wires.

In Chapter Three iron is introduced as a most remarkable metal, which has almost nothing in common with man's first metals, copper, gold, silver, and lead. Ancient written sources have been examined and the history is taken up to about 500 B.C. with emphasis on Elba's iron ores and Etruscan iron production.

In Chapter Four the bloomery process is investigated. The direct iron production method is not so direct as usually implied, so it was felt necessary to distinguish four steps in the production line. The furnace slags from the various stages are discussed, and it is argued that the slag inclusions in the finished objects can almost exclusively be referred to step two.

In Chapter Five the emphasis is on the last five hundred years B.C., with a thorough examination of 24 Celtic swords, kindly put at the author's disposal by Dr.R.Pleiner, Prague. Noric iron is identified, and bipyramidal bars from Central Europe and currency bars from Britain are presented.

In Chapter Six chemical and metallurgical aspects are central issues. The diagnostic value of slag inclusions is discussed with examples from Halland, Scania, Jutland, Valdres and Småland. The mediaeval Scandinavian terms Kalmar iron, Blekinge iron, climp iron, klode iron, and Valdres iron are discussed.

In Chapter Seven the analytical method is presented. The analytical credibility is discussed with pertinent examples. The analytical harmony between the metallic iron phase and its slag inclusions is introduced and explained as an experimental and logical fact. The iron-phosphorus equilibrium diagram is introduced and various equilibrated and unequilibrated phosphorus-containing structures are illustrated and explained.

In Chapter Eight our history moves north to iron in Scandinavia in the last five hundred years B.C. Few iron objects were available for examination, but furnaces and bulk slags occur in profusion and could be subjected to a close study. The empirical quotients F and G are introduced.

In Chapter Nine iron objects and bulk slags from Denmark are examined. It was felt practical to limit this chapter to the period 0-600 A.D., a period when the iron-producing centres in Snorup, Drengsted and elsewhere in West Jutland were very active. In the last part of the chapter a general discussion of furnace construction material will be found.

In Chapter Ten the same period, 0-600 A.D., is examined, with examples from outside Denmark. First from Norway with numerous important steel examples. Then follows Sweden with spade-shaped bars, and Biskupice and Holy-Cross Mountains with slag-pit furnaces rather similar to the West Jutland furnaces. Great Britain is exemplified with bulk slags, while Spain is illustrated by an important excavation near Seville. Finally the author has allowed himself a digression to the contemporary iron pillar in New Delhi, India.

Chapter Eleven is devoted to the sacrificial weapon finds in Denmark, Vimose, Illerup, Thorsbjerg, Kragelund, Ejsbøl, and Nydam. A discussion of hammer-welding and pattern-welding with experimental work concludes the chapter. The importance of the sword in the ancient Edda literature and the sagas, and the naming, is briefly touched upon.

The final Chapter Twelve treats the period 600-1200 A.D. in Denmark, Norway, Sweden and Iceland. It is shown that a large number of iron objects found in Danish graves and fortifications were manufactured in Norway. In particular, nails and weapon axes came from Norway. Small phosphorus-rich iron bars, presumably meant for decorative inlay, have been identified as coming from workshops in Tommarp, Scania.

The book thus ends at about 1200 A.D., which is the period when an entirely new process, the indirect iron production method, was introduced in Northern Europe. Bog iron ores were replaced by hematite and magnetite ores, and the water mill was introduced to operate the bellows, but the fuel remained charcoal. For several hundred years the two processes, the direct bloomery method and the indirect blast iron method, lived alongside each other. But 90% or more of all iron was produced by the indirect method. In Carelia, Finland, and Dalarna, Sweden, the direct method lived into the 19th century, while blast iron furnaces were simultaneously in operation in adjacent counties.

Acknowledgements

A technological work of this sort has to be supported with illustrative material. Most photomicrographs were taken during 25 years of work at the microscope and on the scanning electron microscope at the Department of Metallurgy. Additional material has kindly been provided by FORCE Technology, Brøndby (Bo Mortensen and Hanne Hartig Jensen), and by Struers A/S, Ballerup (Mikael Rückert and Anne Guesnier), for which support I am very grateful. I am deeply indebted to my technician, Inger Søndergaard, who in all these years assisted in an unselfish and competent way on the scanning microprobe. I also thank many enthusiastic polytechnic students who made experimental work and prepared examination papers on copper- and iron alloys under my guidance: Claus Traulsen, Gert Mosdal, Arne Jouttijärvi, Kirsten Arndal, Lise Hobbs, Jens Ole Frandsen, Helene Madsen, Helle Wivel, Lene Høst-Madsen and many others. Edith Johannsen assisted with sample preparation, supported by a grant from Industriens Uddannelsesfond, and was an invaluable inspiration for the students.

I am much indebted to numerous museum curators and conservators, in Denmark and abroad, who have provided material, but have had to wait long to learn about the results. The reason lies in the nature of the task. Samples have continously been acquired and analysed, but it was necessary to develop a new method to evaluate and compare the results. This implied the acquisition of many samples from geographically widely separated areas and from the earliest period up to the 19th century. The construction of the database, now housing about 1200 different objects and perhaps 7000 separate analyses, took time. In lectures and minor publications in the 1990s my viewpoints were put forward.

From the following collections I have received material and support. In tables and text I have identified the samples examined with museum numbers etc., so that they are traceable.

Blicheregnens Museum, Thorning, Peder Hjorth Jensen
Nationalmuseets Bevaringsafdeling, Brede, Jørgen Nordqvist, Knud Holm, Birgit Sørensen, Birthe Gottlieb
Færgegården, Frederikssund, Søren A.Sørensen
Geologisk Museum, København, Minik Rosing, Erik Schou Jensen, Asger Ken Pedersen
Gilleleje Museum, Søren Frandsen
Djurslands Museum, Niels Axel Boas
Haderslev Museum, Orla Madsen
Herning Museum, Hans Rostholm
Holbæk Museum, Gunna Tranberg
Holstebro Museum, Torben Skov
Kunstakademiets Konservatorskole, Esplanaden, København, Jettie van Lanschot, Helge Brinch Madsen
Københavns Bymuseum, Lene Høst-Madsen
Nationalmuseet, København, Nils Engberg, Olfert Voss, Gerda Møller, Jette Arneborg, Helga Schütte
Køge Museum, Svend Aage Tornberg
Grønlands Nationalmuseum, Nuuk, Claus Andreasen
Museet Falsters Minder, Nykøbing Falster, Anna-Elisabeth Jensen
Næstved Museum, Palle Birk Hansen
Hollufgård, Odense, Jørgen Jacobsen
Bymuseet, Odense, Eskil Arentoft
Randers Museum, Ernst Stidsing
Ribe Museum, Stig Jensen, Helge Brinch Madsen
Ringkøbing Museum, Jens Aarup Jensen, Palle Eriksen
Roskilde Domkirkemuseum, Anette Kruse
Nationalmuseets Marinarkæologiske Undersøgelser, Roskilde, Flemming Rieck
Silkeborg Museum, Christian Fischer
Skanderborg Museum, Herbert Madsen, Mariann Hahn-Thomsen
Skjern-Egvad Museum, Torben Egeberg Hansen
Varde Staalværk, Robert Thomsen
Vejle Museum, Per Kristian Madsen
Viborg Stiftsmuseum, Jørgen Hjermind
Sydsjællands Museum, Vordingborg, Dorte Wille-Jørgensen
Værløse Museum, Benny Staal
Konserveringscentret, Ølgod, Elmer W.Fabech
Aalborg Historiske Museum, Lars Christian Nørbach
Forhistorisk Museum, Moesgaard, Aarhus, Jørgen Ilkjær, Hans Krongaard Christensen, Else Roesdahl, Jens Vellev, Helle Strehle, Morten Tvede

Oldsaksamlingen, Universitetet, Oslo, Irmelin Martens, Heid Gjøstein Resi, Hege Svane
Metallurgisk Institut, Norges Teknisk-Naturvidenskapelige Universitet, Trondhjem, Arne Espelund
Hallands Museum, Halmstad, Erik Rosengren, Per Wranning, Bo Strömberg
Hallands Länsmuseum, Varberg, Pablo Wiking-Faria
Kalmar Läns Museum, Kalmar, Gert Magnusson, Leif Rubensson
Historiska Museet, Lunds Universitet, Anders Ödman
Rigsantikvarieämbetet, Stockholm, Gert Magnusson, Lars-Erik Englund
Statens Historiska Museum, Stockholm, Lars Redin, Kerstin Engdahl
Tekniska Museet, Stockholm, Jan-Erik Pettersson, Rolf Österberg
Museovirasto, Helsinki, Jussi-Pekka Taavitsainen, Erkki Härö
National Museum of Iceland, Reykjavik, Thor Magnusson, Thorkell Grimsson

Náttúrufraedistofnum Íslands, Reykjavik, Sveinn Jakobsson
British Museum, Natural History, London, Robert Hutchison
Swiss Meteorite Laboratory, Glarus, Rolf Buehler
English Heritage, 23 Savile Row, London, David Starley
Arkæologisk Institut, Det Tjekkiske Akademi, Prag, Radomir Pleiner
Smithsonian Institution, Washington, D.C., Roy S. Clarke, Gene Jarosewich

A special acknowledgement is due to my colleagues in the old Department of Metallurgy, D.T.U., who have supported me in every way. I am also grateful to the staff of the Geological Museum, Copenhagen, who after my retirement in 1999 have provided me with office and all facilities. Professor Minna Skafte Jensen, Odense University, helped in the translation of relevant passages of Caesar's Gallic War. Dansk Metallurgisk Selskab, by its president, Professor Marcel Somers, supported the project on several occasions. Drs. Roy S. Clarke and Eugene Jarosewich, The Smithsonian Museum, Washington, D.C., assisted me in the meteoritical analytical work. Director Gunvor Skytte was most helpful during my studies September-October 2002 at the Accademia di Danimarca in Rome. My warmest thanks go to my wife, Kirsti, who helped me with the manuscript and often had a useful, critical remark. Finally, I wish to extend my gratitude to Professor Knud Sørensen, Aarhus, who read the manuscript and improved the language significantly.

V. F. Buchwald
Charlottenlund, 14. december 2004

Chapter 1
Meteorites and man

One Indian was Susap, a 70-year old Klickitat, who testified that he had seen the meteorite as a child and had been told by Wochimo, Chief of the Clackamas, that the Indians washed their faces in the water collected in the basins of the meteorite, and that their young warriors dipped their arrows in the water before engaging in battle with neighbouring tribes.

On the 14 ton iron meteorite from Willamette, Oregon. Buchwald 1975: 1313.

When our forefathers were slowly moving from a stone-age state to a more advanced stage they had a choice of several metals for the production of jewellery, tools and weapons. Gold, silver, copper and platinum metals occurred as native metals and were all used to a certain extent in the areas where they could be found. In addition, meteoritic iron was available, albeit in small, and usually rapidly exhausted, quantities. In the introductory chapter we will examine whether meteoritic iron is at all suited as a raw material for tool production, we will study the statistics of iron meteorites, and we will present a test sample of well-documented cases where meteorites have served a number of purposes. Finally, we will give some practical hints that will be of help in identifying meteoritic iron in ancient objects, and we will examine their deterioration and corrosion products.

The literary sources of the Middle East, Greece and Rome, are almost silent on the handling of iron meteorites, and we fare no better when we examine the lit-

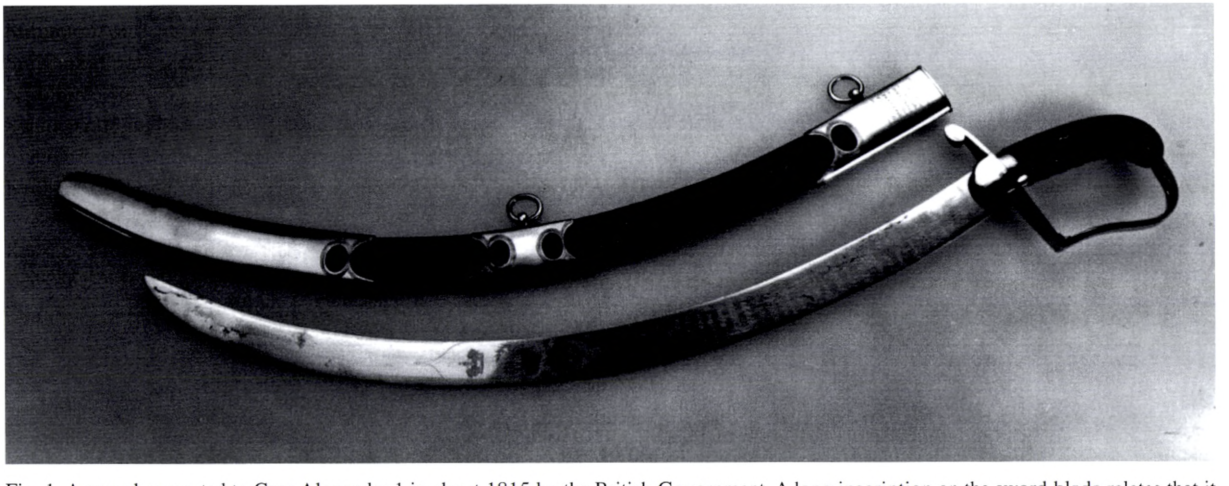


Fig. 1. A sword presented to Czar Alexander 1 in about 1815 by the British Government. A long inscription on the sword blade relates that it was forged from an iron metorite found near Cape of Good Hope, South Africa. Courtesy Rolf Buehler and Manfred Sachse.

erature of mediaeval Europe. Only as late as 1800 A.D. did meteorites become the subject of scientific interest. E.F.F.Chladni (1756-1827) devoted thirty years of his life to the study of meteoritic records. In 1819 he published a comprehensive work of meteoritic events known up to that date. Very few records concerned meteorites of iron. An iron mass in the shape of a horsehead and weighing 107 kg had been known since about 1400 AD at the Elbogen Castle in Bohemia, another mass of 135 kg had been found before 1793 near the Cape of Good Hope in the Dutch Cape Colony, and a 1000 kg mass had been found by the Spaniards in the 16th century when working the silver mines of Zacatecas, Mexico. Chladni provided other reports of high value, but it is characteristic that European examples were extreme scarce and mostly ill-founded.

The Cape of Good Hope meteorite presents a good example of the fate of iron meteorites among men. The finder had from time to time dislodged fragments from the mass and forged hoes and ploughshares for his farm work. A large fragment came to London where the metal proved to be malleable, so James Sowerby in 1814 was able to forge a slightly curved sword, 60 cm long and 3.5 cm wide, from it. The sword was provided with a long inscription and pre-

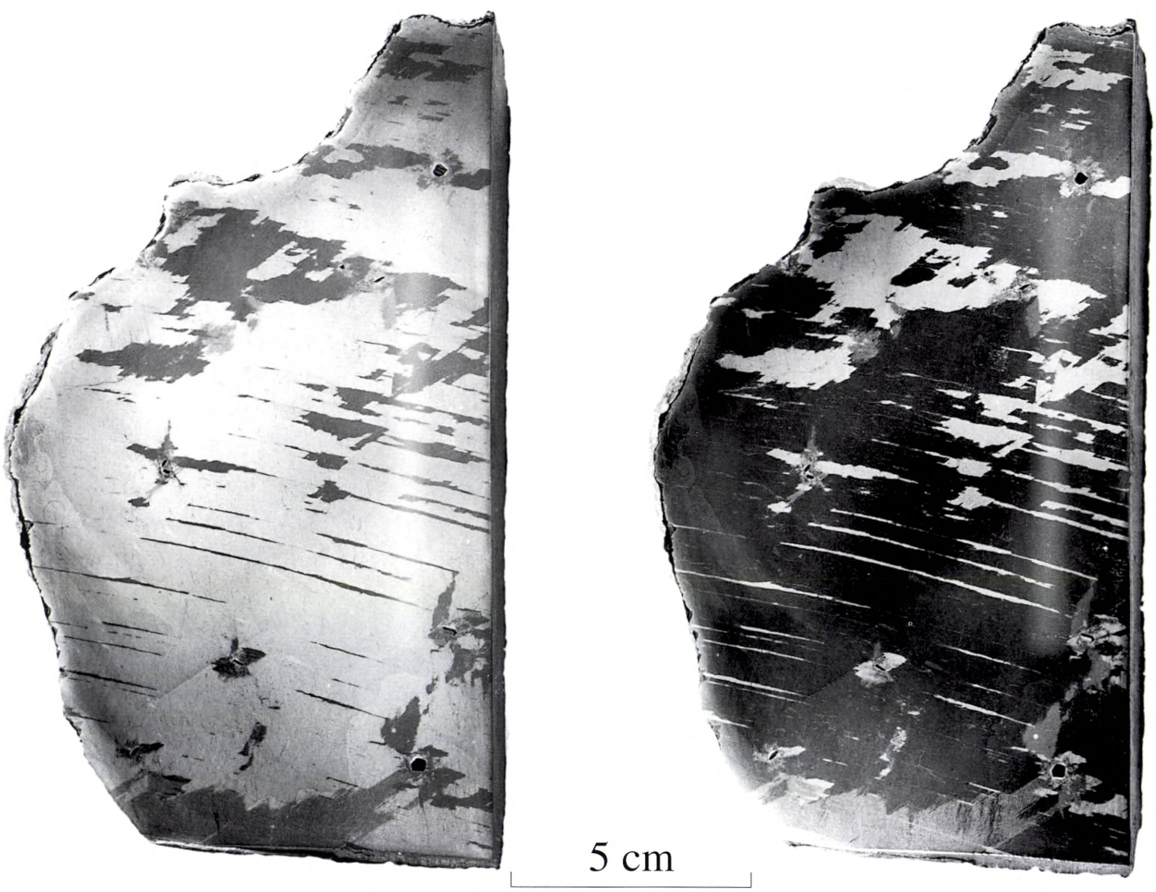


Fig. 2. Polished and etched section of the ataxite Hoba, Namibia. The extremely fine grained crystals reflect the light differently as the light source is moved. The structure of Cape of Good Hope is similar. Buchwald 1975: 647. See also fig. 14.

Fig. 3. Two large nails forged in the 1840'es from the hexahedrite Chesterville, South Carolina. Scale in cm. Buchwald 1975: 450.

sented to Czar Alexander in gratitude for Russia's stand against Napoleon. This sword has long been considered lost, but was recently relocated in the collections of the Hermitage, St. Petersburg (Rolf Buehler, pers.comm.).

The Cape of Good Hope meteorite belongs to a rare group of meteorites, the so-called ataxites, Table 1-1. It is fine-grained and displays no Widmanstätten structure. Its composition is 83% iron, 16% nickel, 0.8% cobalt and very little phosphorus (0.1%) and sulphur. This rather pure iron-nickel alloy, without phosphides and only few sulphides, is ductile and can be forged at a red heat as demonstrated by Sowerby. The spring was given it by hammering it when cold.

In Hraschina, Croatia, an iron meteorite was observed to fall on May 26, 1751. As is often the case, the meteorite split into several fragments as it entered the denser part of the atmosphere. The largest fragment of 40 kg was immediately excavated and forwarded to the bishop, from whom it passed to the Austrian emperor. Today it is the cornerstone of the eminent meteorite collection of the Museum of Natural History in Vienna. But what is of interest in the present context is that at least one other specimen, of 9 kg, which fell at some distance, was acquired by blacksmiths and forged into nails and distributed as curios – and of course now lost.

Since our European records are so meagre, we have to look elsewhere in order to form an opinion of what may have happened to ancient iron meteorites. Many illuminating reports are available from the pioneers as they spread over North and South America. For them to discover an iron meteorite was a stroke of luck since wrought iron was always scarce in the vast interior of the continents. Near Tucson, Arizona, two large iron meteorites of 635 kg (the Ring) and 287 kg (the Carleton mass) were discovered by the Spanish conquistadores in the 17th century. The masses were hauled from the mountains to the local settlements where for generations they served as anvils. Only as late as 1850 were they recognized as meteorites (ataxites) while embedded in the ground in Tucson, hence the naming. Two blacksmiths in the town had already used them for many years when in 1863 they were transported to San Francisco. Since 1941 they have been an attraction at the Smithsonian National Museum of Natural History in Washington, D.C.

At Cosby's Creek, Tennessee, a mass of about 350 kg was found in 1837 on an offset of an eminence about 30 m above the bed of the creek. It was easy to detach fragments from it because of penetrating terrestrial corrosion. The mass "was placed upon what is here called a log-heap, where after roasting for some time, it developed certain natural joints, of which advantage was taken with cold chisels and spikes, for its separation into fragments. These were put into a mountain wagon and transported 30 or 40 miles to Lary's Forge in Sevier County and Peter Brown's Forge in Greene County. The greater part was wrought into gun-scalps (that is the forged iron bar, before being bored for a gun barrel), horseshoes, nails and other articles of common use" (Buchwald 1975: 500). This meteorite, a coarse octahedrite with 6.7% nickel, was rather easy to split because long-term corrosion had attacked along the Widmanstätten lamellae and weakened the metallic cohesion.

At Chesterville, South Carolina, a mass of 16½ kg was ploughed up about 1849. The finder took it to the blacksmith, who proved it to be malleable. He cut several pieces from it, out of which he made horseshoes, nails and hinges for a gate. Some material survived and was acquired for the collections of Yale, London, Vienna and others. It is a rather pure hexahedrite with 5.8% nickel.

At Havana, Illinois, a group of Indian burial mounds was examined in 1945. In one grave of Hopewellian age, i.e.from about 300 B.C., a group of 22 rounded beads was found. Although severely corroded, the material could be identified as meteoritic iron. The Indians had coldhammered the meteoritic material into sheets and bent them into cylindrical shapes. They applied mild heat to anneal the coldworked metal and continued till they had shaped ovoid beads, provided with holes. The beads were put on a string, alternating with shell fragments.

In the state of Coahuila, Mexico, several iron meteorite fragments were found before 1850. They all belonged to the same shower. One mass of 114 kg served for many years as an anvil on the Sanchez Estate Farm. The blacksmith drilled a hole, 28 mm in diame-

Table 1.1. Iron meteorite structural classes (Buchwald 1975)

Structural class	Sym -bol	Ni% approx.	Bandwidth, mm	Meteorite example	Number of falls	Number of finds
Hexahedrite	H	5.5	-	Coahuila	5	65
Coarsest octahedrite	Ogg	6	>3.3	Jerslev	1	26
Coarse octahedrite	Og	7	1.3-3.3	Canyon Diablo	4	117
Medium octahedrite	Om	8	0.5-1.3	Cape York	12	273
Fine octahedrite	Of	9	0.2-0.5	Muonionalusta	6	72
Finest octahedrite	Off	9-18	<0.2, contin.	Föllinge	-	9
Plessitic octahedrite	Opl	10	<0.2, sparks	Ballinoo	2	26
Ataxite	A	16	-	Hoba	1	43
Anomalous	Anom	5-40	diverse	Morradal	3	52
Not classified	-			Sterlitamak	2	17
Total					36	700

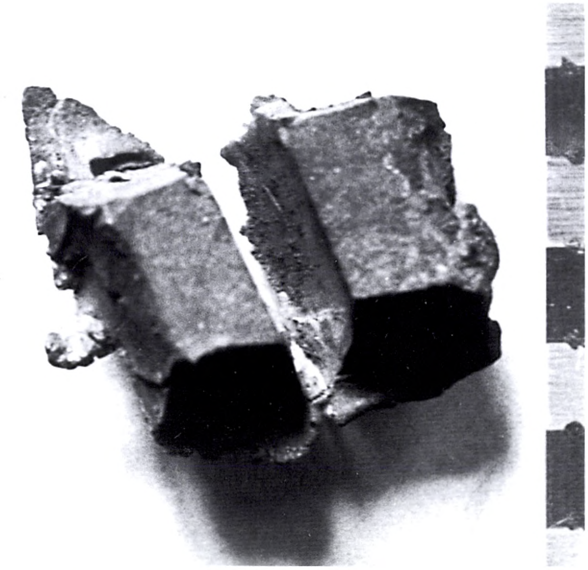


Fig. 4. Forged and hot-chiseled bar produced by a Malayan blacksmith from the Prambanan iron meteorite about 1800 A.D. Scale in cm. Buchwald 1975: 989.

ter and 4.5 mm deep, to support his swaging tool. A fragment of another Coahuila meteorite, which came to the Smithsonian Institution, Washington, was successfully forged into a beautiful and durable knife blade of great perfection. Coahuila is a hexahedrite with 5.6% nickel, very similar to the Chesterville meteorite above.

In the high valleys 25 km north of Toluca, Mexico, soil erosion from time to time uncovers fragments of a huge, ancient meteorite shower. The individual masses are mostly 0.5-25 kg heavy and thus very appropriate for handling in the local forges. The farmers have "from time immemorial" utilized the material and forged it into agricultural implements, such as hoes and machetes. A 4 kg crow bar, a so-called barretta, forged from Toluca iron, was secured in 1933 for the meteorite museum in Tempe, Arizona. Toluca is a coarse octahedrite with 8.1% nickel.

In the state of San Luis Potosi, Mexico, several iron meteorite fragments were found in the Descubridora mountain range north of Charcas in the 18th and 19th centuries. One fragment of 41.7 kg, called Descubridora, which already possessed a deep fissure from the atmospheric break up, was attacked with a copper chisel in order to split the mass completely. The attempt was unsuccessful, and the chisel is still to be seen wedged in the meteorite, now in Vienna's Museum of Natural History. Another, much larger fragment of 576 kg was hauled to the amalgamation works in San Miguel de Catorce to be used as a base for the ore crushing mills. According to the present label in the Mexican National Museum it was later used as an anvil during coin embossing in the city. The blacksmith at Poblizon had, however, on an early occasion under great difficulty succeeded in dislodging samples from the mass and forged highly estimated hoes and chisels from them.

From Asia there are reports of iron meteorites discovered in historic times. In 1891 a mass of 22 kg was found by a miner in the gold-bearing sands on the banks of the Toubil River in the Krasnojarsk region. The finder heated the entire mass to cut off a sample with a hot chisel. He examined the nature of the material by various heating and forging experiments, but disappointed to find that it was neither a gold nor a platinum nugget, he gave the meteorite to the Museum in Minussinsk, from where it was later transferred to the Mining Museum in St.Petersburg. The Toubil River meteorite is a medium octahedrite with Widmanstätten structure and 7.8% nickel.

In 1866, a meteoritic fragment reached the Netherlands from Soerakarta, Java. The fragment had allegedly been detached from a large block about one meter in diameter, which was preserved in the sultan's palace of Soesoehoenan in Soerakarta. The mass had originally been found in the 18th century near Prambanan. It had served as an iron source for the natives for a long time. When they wanted metal for particularly good weapons they heated the mass to a red heat and cut fragments from it. It appears that four beautifully finished daggers, krises, forged from the Prambanan meteorite have somehow found their way into the Ethnographical Collection in Vienna. Prambanan is a finest octahedrite with 9.4% Ni.

Many modern kris fanciers believe that most krises were formerly made of meteoritic iron. This hypothesis cannot be upheld. As shown by Bronson (1987), there are in fact very few nickel- containing krises, and most of those which do contain nickel have apparently been smelted from nickel-containing iron ores from Sulavesi (Celebes).

The Freer Gallery of Art, Washington D.C., owns two unique metal weapons from ancient China (Gettens et al. 1971). One is a broad axe (ch'i) with bronze tang (nei) and the rusted remains of an iron meteorite blade. The other is a dagger axe (ko) with a bronze blade and the remains of an iron meteorite point. They were found in the Honan province and may be dated to the early Chou dynasty, about 1000 B.C. The Chinese were at that time well acquainted with bronze metallurgy as proven by the skill with which the meteoritic blade has been joined to the bronze haft by the casting-on method. Although the meteoritic parts are now severely corroded, the presence of characteristic meteoritic minerals in the oxides unambiguously proves the meteoritic origin.

A similar, but still older artefact has been reported by Pleiner (2000: 8). At Boldyrevo, in the southern foothills of the Urals, Russia, a meteoritic iron adze was found mounted in a copper socket. The total length was 11 cm, and it was dated to the 18th century B.C.

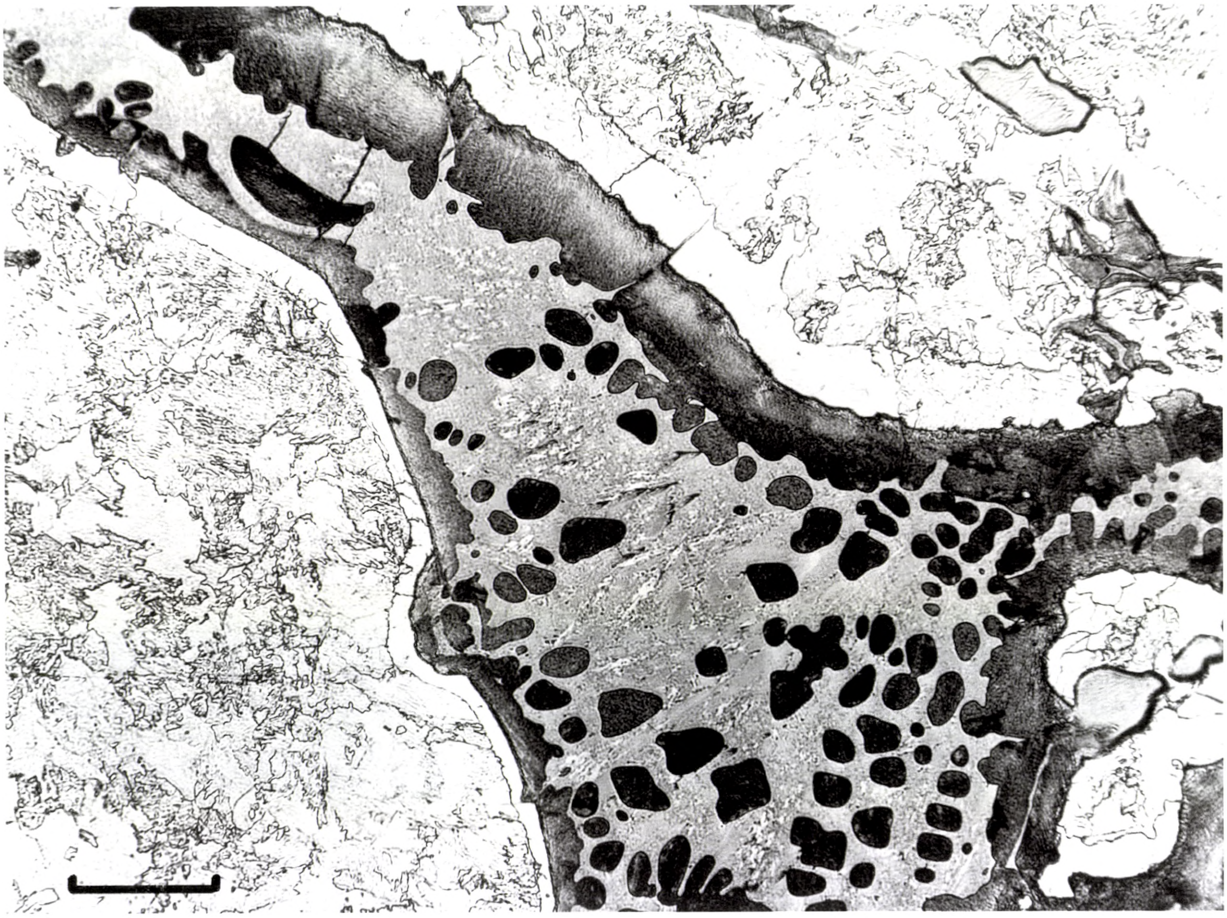


Fig. 5. A reheated and partially forged iron meteorite, from Netschaevo, Russia (Buchwald 1975: 891). The temperature was briefly above 1000°C, which caused the schreibersite crystal to melt and rapidly solidify again. Scale bar 0.2 mm.

Fig. 6. The huge 20 ton iron meteorite, Agpalilik, was found by the author in North Greenland in 1963. It was excavated and transported to Copenhagen's Geological Museum in 1967. It is the largest single crystal of iron which is known. Buchwald 1975: 410.

Coldhammered meteorites from Greenland

From Greenland we have interesting information as to the handling of iron meteorites. When in 1818 a British expedition searching for the Northwest Passage was stopped by heavy ice in the Melville Bay near Cape York, they met a hitherto unknown Polar tribe, "the Arctic Highlanders". To the surprise of the Scottish officers, the Inuit had knives with cutting edges of iron. Through the interpreter Zakæus, an Inuit whom John Ross had taken on board in Danish South Greenland, cautious contacts slowly developed. "Having now at length acquired confidence [the Inuit] advanced, offering in return for our knives, glasses, and beads, their knives, sea-unicorns [narwhale tusks], and sea-horse teeth [walrus ivory], which were accepted" (Ross 1819:116).

The Inuit reported that the knives were made from iron that was located in the mountains 10 or 15 miles to the north. The British expedition had, however, to continue and found no time for examining the story. For generations the romantic meeting and the tale of an Iron Mountain stirred the imagination of Polar explorers. Robert E.Peary was, in 1894, the one who solved the mystery. He was told by his Inuit guides where the iron was to be found, and in remarkable operations he secured three large blocks of 30.9 tons, 3 tons and 407 kg for the United States (Peary 1898).

Fig. 7. Basaltic boulders, used by the Inuit of North Greenland as hammers when coldworking small iron meteorite fragments. The large central one is 22 cm long and weighs 5.4 kg. Buchwald 1975: 410.

The blocks proved to be iron meteorites. They were sold for $ 40,000 and donated to the American Museum of Natural History in New York, where they are still on display.

In Peary's opinion the Inuit had chipped small flakes from the huge masses and hammered these into knives and arrowheads. This explanation has been repeated on numerous occasions (e.g.Craddock 1995:107), but as will be shown below there is a more plausible explanation.

In the 20th century other masses of 20.1 and 3.4 tons were discovered in the area east of Cape York, and many minor fragments from 0.5 to 250 kg were also found. The Cape York meteorite shower probably fell on glacial ice about 10,000 years ago, but later when the climate got milder the meteorites were deposited as stones among other stones, leaving no craters. It is the largest meteorite shower on Earth, extending over 125 km from NW to SE (Buchwald 1975:410). The two masses of 20.1 and 3.4 tons and many of the smaller fragments are on display at the Geological Museum in Copenhagen (Buchwald & Munch 1965; Buchwald & Graff-Petersen 1976).

What is here of major interest is the Inuits' comprehension of the material. They being nomadic hunters,

Fig. 8. A woman's knife, by the Inuit called an ulo, made from a coldworked Cape York meteorite fragment and inserted into a handle of walrus tusk. Width 6 cm. Buchwald 1975: 410.

Table 1.2. Iron meteorites that have served as anvils
A modern anvil may weigh about 80-140 kg.

Meteorite name	Type and Ni%	Location	Known since	Weight, kg
Arispe	Anom, 6.7	Sonora, Mexico	1896	122
Cacaria	Om, 7.7	Durango, Mexico	1876	41
Charcas	Om, 8.0	San Luis Potosi, Mexico	1783	576
Coahuila	H, 5.6	Coahuila, Mexico	1854	114
Rodeo	Om, 10.6	Durango, Mexico	1852	44
Santa Rosa	Anom, 6.7	Columbia	1823	460
Tucson, Ring	Anom, 9.5	Arizona, U.S.A.	(17th century) 1850	635
Tucson, Carleton	Anom, 9.5	Arizona, U.S.A.	(17th century) 1850	287
Yanhuitlan	Of, 7.5	Oaxaca, Mexico	1884	300

their tools had previously been based on bone, antler, tusk and stone, and their knives had cutting edges of slate or flint. But here, in a remote part of Greenland, the Inuit, entirely isolated from the rest of Greenland, learned to work meteoritic iron.

A meteorite shower may comprise a significant number of large as well as small fragments. At the present time we know, for example, that the Cape York shower was comprised of four huge fragments of 30.9, 20.1, 3.4, and 3.0 tons, of five fragments from 5 to 500 kg mass, and of numerous small fragments. Another iron meteorite shower, Gibeon in Namibia, comprised at least 81 large and small fragments (Buchwald 1975: 1385).

It appears that the Inuit meticulously searched the region for the small, nut-sized fragments and took them to two of the large meteorites that were conveniently located near their sledging routes. Since the local gneissic boulders were too fragile to serve as hammers, the Inuit brought basaltic boulders along from a dike 50 km distant and used them as hammer stones. Around one of the big meteorites, the 3-ton "Woman", a huge mound of at least 10,000 basaltic hammer stones has accumulated, suggesting that the interest in acquiring meteoritic blades continued for generations, probably from about 800 to 1800 A.D. The nut-sized meteoritic fragments were placed on the large meteorite anvil, and, being malleable were hammered into coin-sized flakes, which after additional grinding could be inserted into a bone or a walrus tusk to serve as a knife or a harpoon-head (Buchwald1964; 1992 b; 2001).

In the National Museum of Denmark, Copenhagen, there are a number of such tools. They were excavated by archaeologists in the 20th century at Inuit settlements dating back to about 1000 A.D. The author has

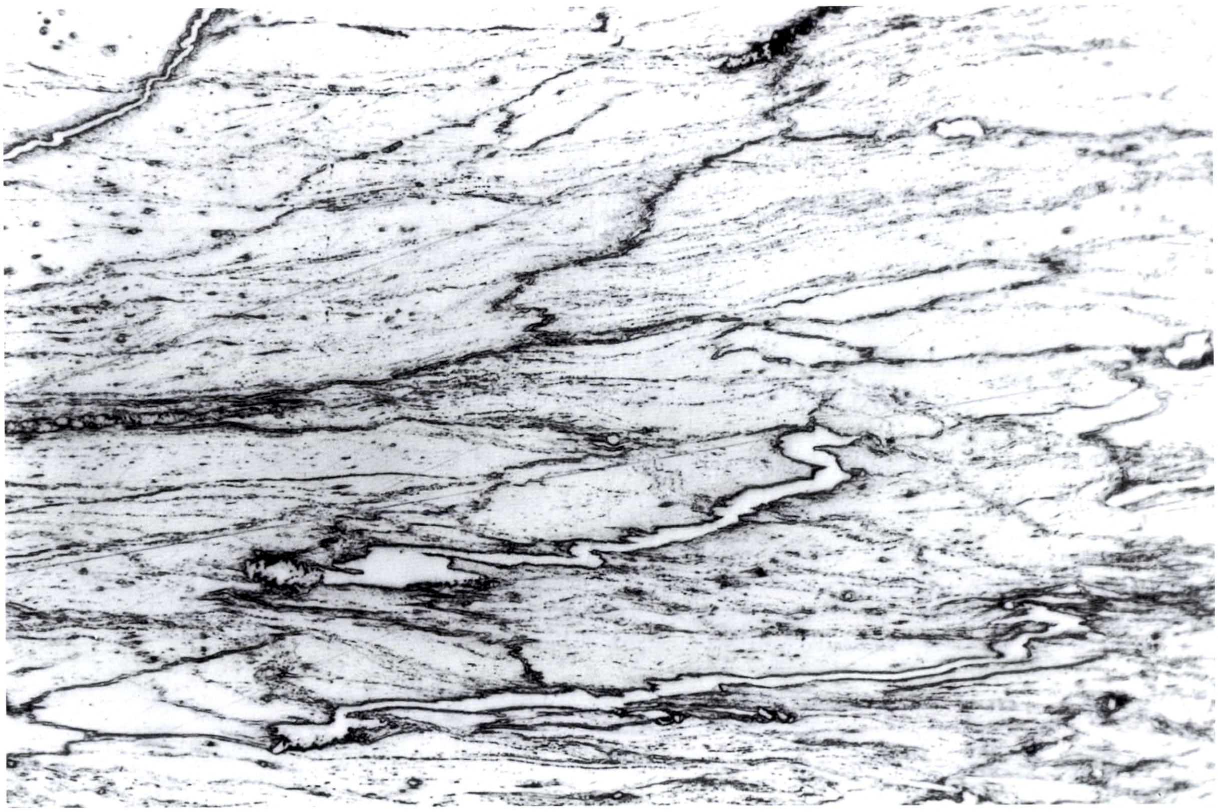


Fig. 9. Polished and etched section through the shock-hardened and distorted Cape York fragment L3-12686, found in an Inuit house ruin near Thule, North Greenland. Length 0.6 mm. Buchwald & Mosdal 1985.

Fig. 10. A lancehead of 16 g. Found in an Inuit settlement in Washington Land, but made by coldhammering a Cape York iron meteorite fragment, found 500 km further south. Length 50 mm. Buchwald 2001: 57.

examined 20 of these knives, blades and ulos (woman knives) and shown them to have a common origin as coming from the Cape York shower (Buchwald 1992a). Due to the coldhammering, the hardness of the metal is extraordinarily high, 245-339 (HV 200g). Other meteorite tools of Cape York origin have been found along the entire West Greenland coast, e.g. a 6.1 g knife blade at Sermermiut, Ilulissat (Lorenzen 1882), and a 6 g arrowhead from Nipaatsoq, one of the Norse settlements in southern Greenland (Buchwald 2001). Cape York material has been found as far away as among Canadian Inuit on Ellesmere Island, Somerset Island, and south of the Hudson Bay, 2400 km from the Cape York meteorite site, implying the existence of elaborate trade networks (McCartney& Mack 1973; McCartney 1991; Pringle 1997).

It is characteristic of the Inuit meteorite material that it was shaped only by cold deformation and grinding. Hot forging, welding, annealing or quenching were not applied, partly because the Inuit had no metallurgical background, and partly because wood for fuel was rather inaccessible, and if available, would primarily have been used as construction material or for cooking.

The newest example of an Inuit artefact is a 16 g lancehead, which in 1999 was excavated in Washington Land, about 500 km north of the Cape York district (Buchwald 2001). The lancehead had been shaped by coldhammering a meteoritic fragment of the Cape York shower. From the archaeological context the lancehead must be dated to the Thule culture 1200-1400 A.D. It is the northernmost piece of a meteorite ever found, and with its 16 g it is also the largest single piece which the Inuit succeeded in hammering into shape. The lancehead is very hard due both to its high nickel content, 7.8-8%, and to the extensive coldworking (HV 200 g: 237-244-246-255-280). It gave, no doubt, excellent service to the Inuit hunter.

Summary

The examples presented here have been selected among iron meteorites that have been identified and discussed by the author on earlier occasions (Buchwald 1975; 1990). The examples make it clear that i) iron meteorites may be forged at red heat to nails, horseshoes, hinges, swords, crowbars, ploughshares etc. to maximum weights of a few kilograms, ii) iron meteorites may be coldhammered to arrowheads, knives and other small objects with a maximum weight of a few tens of grams, iii) massive iron meteorites have served as anvils for generations. Many of these have survived to our days and may be studied in various museum collections, iv) iron meteorites do corrode in the terrestrial environment at approximately the same rate as wrought iron, so depending on size and burial they will eventually disin-

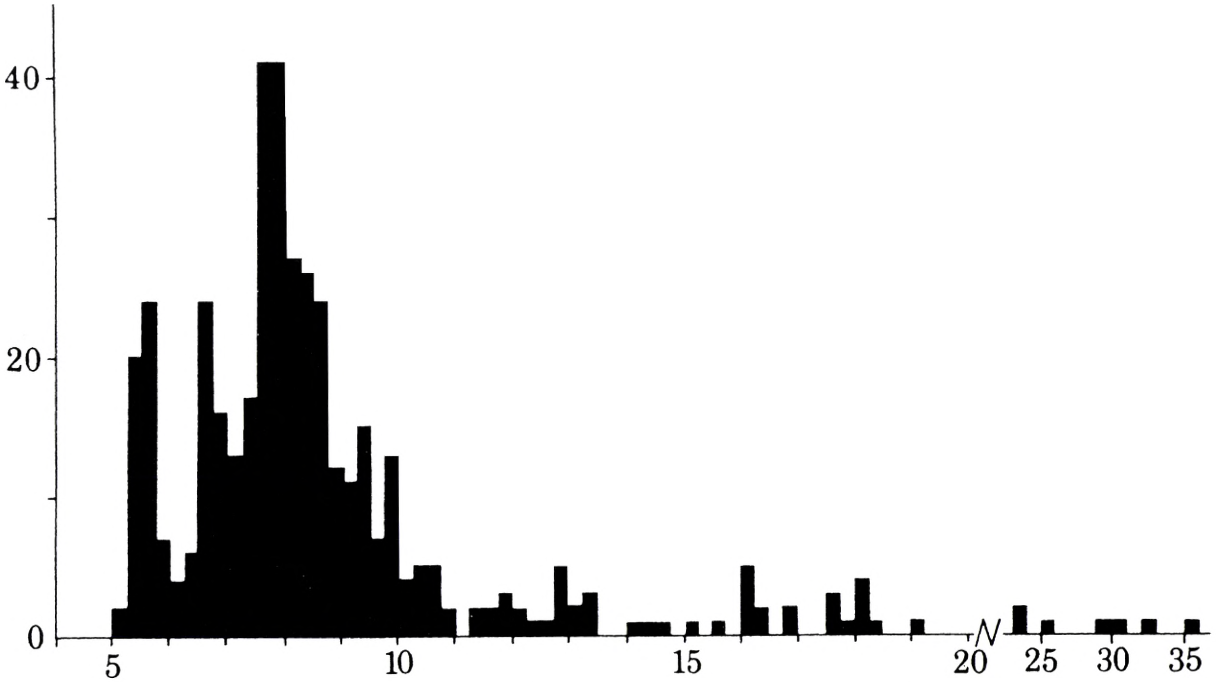


Fig. 11. An overview of the composition of iron meteorites. The bulk nickel content along the X-axis, and the number of each category (0.25% interval) along the Y-axis. No iron meteorite has less than 5% nickel. Buchwald 1992: 101.

Table 1.3. Statistics of falls and finds. Status 1990

	Falls	%	Finds	%	Total	%
Stone meteorites	855	95.0	3000	79.8	3855	82.7
Stone-iron meteorites	9	1.0	60	1.6	69	1.5
Iron meteorites	36	4.0	700	18.6	736	15.8
Total	900	100	3760	100	4660	100

Table 1.4. Statistics of meteorite masses, kilograms. Status 1990

	Falls	Finds	Total
Stone meteorites	15,200	8,300	23,500
Stone-iron meteorites	525	8,600	9,125
Iron meteorites	27,000	435,000	462,000
Total	42,725	451,900	494,625

tegrate and disappear. Even if the corrosion rate is about the same as for wrought iron, massive iron meteorites may survive for tens of thousands of years, particularly well when exposed on the surface of an arid region, e.g. in the deserts of Arizona, Mexico, Chile and Algeria, or in the cold and arid regions of Greenland and the Antarctic, on the so-called Blue Ice.

Archaeological evidence of meteorites

With this background we will now turn our attention to the results of archaeology. There are few, if any, examples from Europe, but a number of reports from the Middle East. In the following short summary I will lean heavily upon the works of Coghlan (1956), Waldbaum (1978; 1980), Merwe (1980) and Craddock (1995), who have critically examined the archaeological evidence.

In Table 1.5 are presented a number of objects which apparently are of meteoritic origin. The conclusions have been reached on the basis of nickel analyses, either qualitatively or quantitatively, and sometimes also on the basis of identification of remains of Widmanstätten structure. Considering the above referenced reports of meteorites in Asia and the Americas, it is surprisingly few and insignificant samples that have been identified in an archaeological context.

The famous 9 kg chunk of a meteorite which was found in the Minoan palace of Hagia Triada, Crete, and which was long assumed to be an iron meteorite (e.g.Waldbaum 1980) has recently been proven by Varoufakis to be a stony meteorite (see Craddock 1995: 107). The meteorite has a length of 29 cm, a width of 21 cm and a thickness of 10 cm, and has a recorded weight of about 20 lbs (9 kg). Already this discrepancy should have raised the suspicion that Hagia Triada could not be an iron meteorite (spec.gravity ab.7.8 g/cm^3), but must be a stony meteorite (spec.gravity 3.2-3.8 g/cm^3).

Table 1.5. Meteoritic iron in the Middle East (Coghlan 1956, Waldbaum 1978;1980)

Locality	B.C.	Type	Note
Tepe Sialk, North Iran	4600-4100	3 small balls	
El Gerzeh, Egypt	before 3000	9 beads	Widman. 7.5% Ni
Uruk-Warka, Mesopotamia	3000-2000	Fragment	+ nickel
Ur, Royal Cemetery, tomb PG/580	3000-2000	Flat tool	10.9% Ni
Alaca Hüyük, Anatolia	2400-2100	Pin with gold head	5.1% Ni
do.	2400-2100	Crescent shaped plaque	4.3% Ni
Troy, treasure L, Anatolia	2600-2400	Macehead	3-6% Ni
(Hagia Triada, Crete)	1600-1500	9 kg chunk, saw marks	(Ni?)
Tut Ankh Amon's grave, Egypt	1350	16 miniature chisels	+ nickel
do.	1350	Headrest	+ nickel
do.	1350	Dagger with gold haft	+ nickel
Deir el Bahari, Egypt	2000	Amulet with silver head	10% Ni
Ugarit, Ras Shamra,Syria	1450-1350	Battle axe,copper socket	3.3% NI

Another object discussed by Waldbaum (1980), but omitted from Table 1.5, is a rusted tool which was discovered fastened in a joint of the outer stones of the Pyramid of Cheops, 4th Dynasty. It has recently been shown (Craddock & Lang 1993) that the iron is neither meteoritic, nor ancient, but rather a tool left by an intruder in mediaeval or post-mediaeval times.

Also the last item of Table 1.5, the Ras Shamra battle axe, is somewhat suspect, until confirmed by modern metallography. The famous dagger from Tut Ankh Amon's grave should probably also be omitted from the list, according to new investigations, see Chapter 3.

During excavations of the Royal Cemetery of Ur, Chaldaea, Iraq, about eight fragments of a flat iron tool were found: C.H.Desch (Report Brit. Assoc.Adv.-Sci. 1929 96:440) reported 10.9% nickel and proved its meteoritic origin. One of these fragments (British Museum 1972:229) of 10x5x1 mm, which was examined in the present study, confirmed the earlier conclusion (Buchwald, in Graham et al. 1985). While all meteoritic structure had been lost, slender veins of metal up to 200x10 μm survived in the corroded goethite – maghemite oxide matrix. The veins were examined under the electron microprobe and found to have about 70% Fe, 30% Ni and 0.5% Cu, corresponding to normal meteoritic taenite. It is remarkable that even in so utterly destroyed material, 1-3% nickel has been retained in the oxides.

Physical, chemical and mechanical properties of iron meteorites

We have on record more than 700 different iron meteorites, Tables 1.3 and 1.4. The bulk nickel content ranges from 5 to 42%, but by far the most have nickel contents of 5.5 to 11%. The specific gravity is about 7.8 g/cm^3, dependent on the quantity of troilite (FeS) inclusions and the exact nickel content. They are all massive and attracted to a magnet. In Table 1.1 the meteorites have been classified according to their macroscopic structure as judged from a polished and etched section (Buchwald 1975).

The low-nickel meteorites, 5.0-6.5% Ni, are usually single-phased iron-nickel alloys, displaying only kamacite, i.e. body-centred cubic ferrite with 5-7% nickel in solid solution. In the kamacite Neumann bands are common. The Coahuila meteorite belongs here.

A large group with 6.5 to about 13% Ni typically has two-phased structures, displaying kamacite and taenite in various intergrowths. Taenite is face-centred cubic austenite with 40-50% Ni in solid solution. This group is, by common consent, the typical iron meteorite. It displays the beautiful Widmanstätten structure, the kamacite having precipitated octahedrally in the high-temperature parent taenite single crystal. Filling the angular interstices are fields called plessite, a fine mixture of kamacite and taenite, and often arranged in a micro-Widmanstätten pattern. The Cape York meteorite belongs here, it has all the virtues of being the typical iron meteorite.

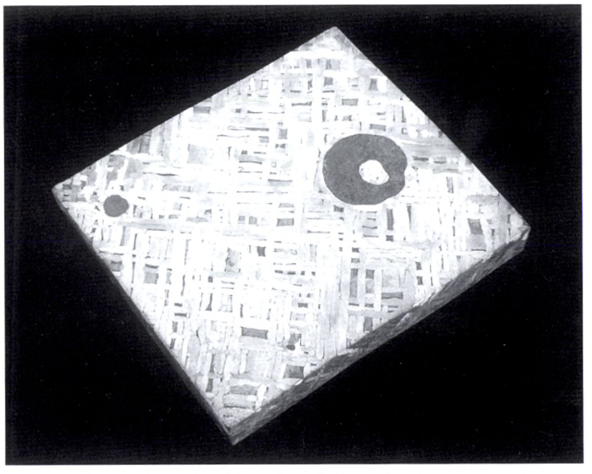


Fig. 12. Polished and deep-etched slice through the Agpalilik (Cape York) iron meteorite. In the dominating Widmanstätten structure are a large and a small inclusion of the iron sulfide mineral, troilite, FeS. Longest side of the slice 72 mm.

Fig. 13. Three knives forged from the Agpalilik (Cape York) medium iron meteorite (Om). The Widmanstätten structure becomes distorted on forging, and is developed by etching, after grinding and polishing. The tang is modern steel. Scale in cm.

The Widmanstätten structure is difficult to destroy. Even a blacksmith working for hours and repeatedly reheating his object to a red heat in order to forge it into objects will not be able to eliminate it entirely. Upon polishing and etching, the octahedral pattern, although distorted, will still be visible and give character to the sample.

A third group, rich in nickel, comprises various subgroups, of which the most important, with 16-18% Ni, is so fine-grained that it requires a good hand-lens or a microscope to distinguish the intimately intergrown kamacite and taenite phases. The Cape of Good Hope meteorite belongs here.

Some confusion has been caused by statements to the effect that iron meteorites are not malleable. As we have documented in the beginning of this chapter, such a general statement is unfounded. The situation is rather that the malleability is sometimes severely impaired by i) the presence of inclusions, such as troilite, chromite and silicates, and ii) corrosion.

Millimeter- to- centimeter-sized inclusions are particularly common in the coarse octahedrites such as Canyon Diablo and Toluca. The presence of large troilite nodules or silicate-graphite-nodules may lead to hot-shortness when forging, because the metallic coherence is entirely destroyed at red heat by molten sulphides in the grain boundaries. Since meteorites may be somewhat heterogeneous, the cunning blacksmith may, however, be able to select sound, inclusion-free material and end up with a forging of ac-

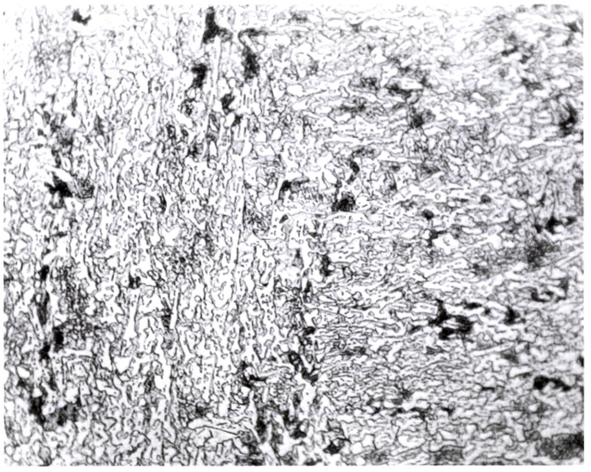


Fig. 14. The extremely fine grained structure, common to ataxites, like Fig. 2. A polished and etched section through Tlacotepec, Mexico. Length 0.2 mm. Buchwald 1975: 1205.

ceptable quality. In Cape York, for example, there are many inch-sized troilite inclusions. Nevertheless, with a bit of attention, forging experiments in Copenhagen succeeded in producing three daggers, the longest being 27 cm. During the forging, small fragments broke away and were lost due to local troilite and chromite inclusions, so one of the objects was smaller than originally planned. Polishing and etching with nitric acid in alcohol developed a beautiful, distorted Widmanstätten pattern of high decorative value.

Many iron meteorites are almost inclusion-free. This is true, in general, of the fine octahedrites and some ataxites. No wonder that these meteorites have served the finders well, e.g. the Cape of Good Hope meteorite discussed above and the Gibeon (Of) shower of Namibia, where many fragments in the 17th and

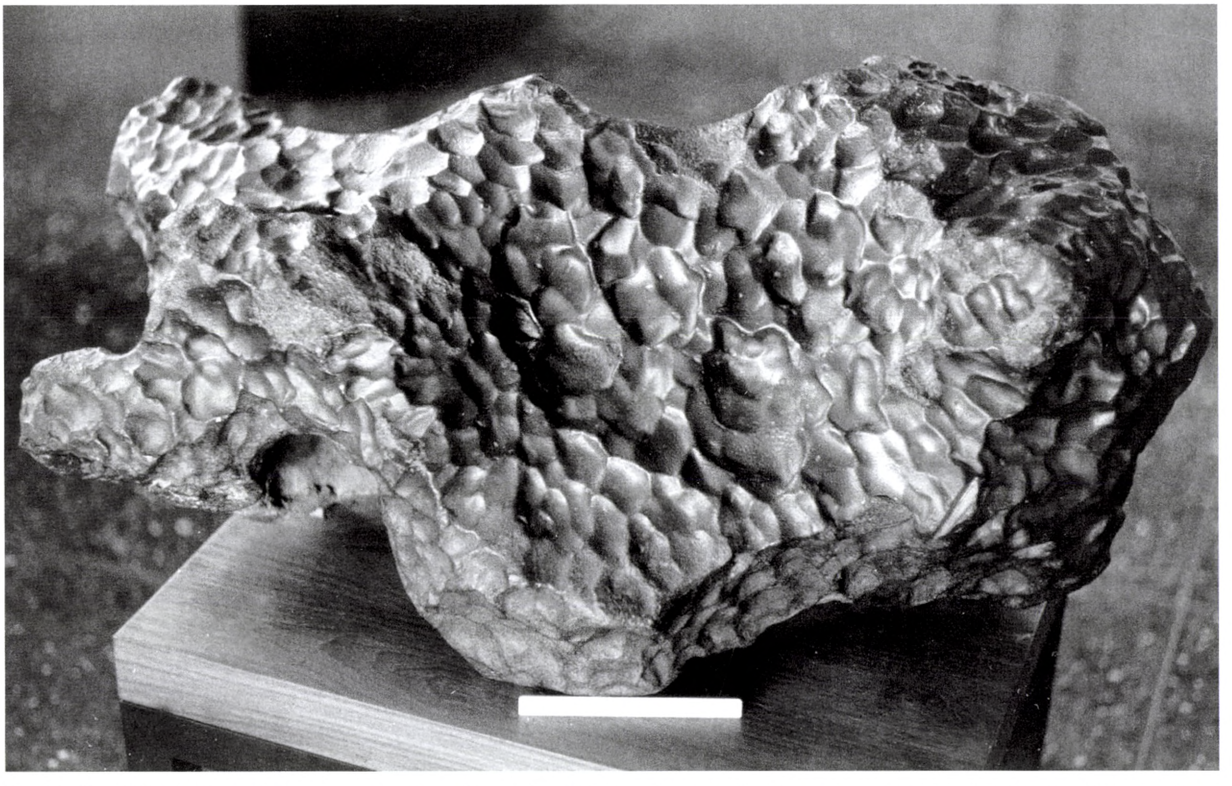


Fig. 15. The 350 kg Lichtenfels iron meteorite from Gibeon, Namibia, is a fine example of an uncorroded meteorite, showing the regmaglypts which were sculptured during the brief flight through the atmosphere. Length of ruler 15 cm. Buchwald 1975: 586.

18th century were forged into assagais and other weapons (Buchwald 1975:584). The quality of Gibeon was testified to by Krupp's laboratories, who in about 1900 found the material to be very ductile. It sustained a 180° bending test without fracturing, and had a tensile strength of about 410 N/mm^2.

The other limiting factor in hammering and forging iron meteorites is corrosion.

Corrosion of iron meteorites

Statistics of the last two hundred years indicate that a new iron meteorite fall is a very rare event. Once every fifth or sixth year a fall is observed and retrieved over the entire world. While we have recognized 36 <u>falls</u> from 1785 to 1985, about 700 iron meteorites have been found by ploughing, road construction or active searching, lately also applying electronic metal detectors. These finds are often very old. The Canyon Diablo iron

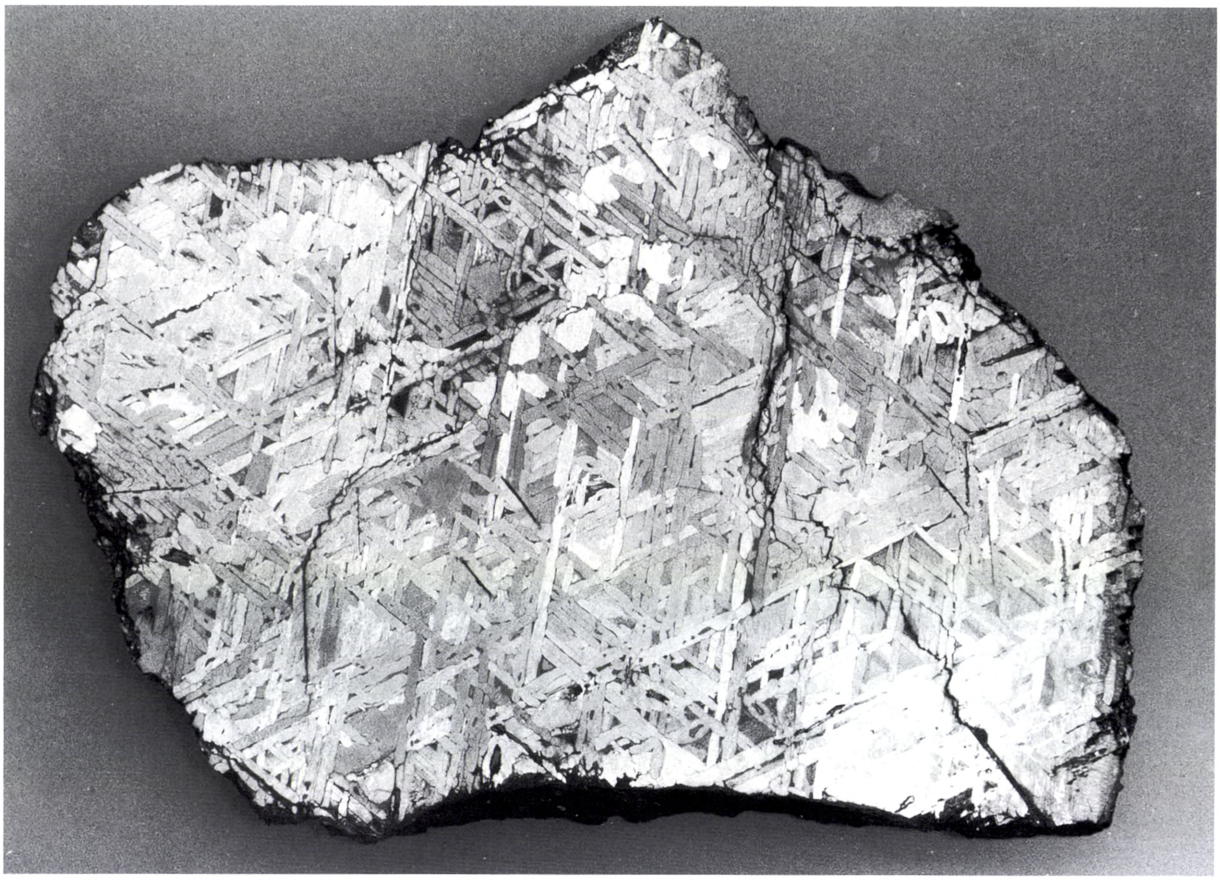


Fig. 16. Polished and etched cross section of the 13.5 kg Felsted medium octahedrite, found in Denmark 1978. Dark, branching lines of corrosion penetrate the entire meteorite. Length 15 cm.

Fig. 17. Corroded octahedral fragments of the medium octahedrite Santa Apolonia, Mexico. Scale bar in cm. Buchwald 1975: 1067.

meteorites discovered around Meteor Crater in Arizona are at least 20,000 years old, and the Cape York meteorites are estimated to be 4,000-10,000 years old. When these irons are exposed to terrestrial corrosion, an oxidic crust forms, consisting of magnetite, Fe_3O_4, maghemite, γ-Fe_2O_3, and goethite, α-FeOOH.

The corrosion also penetrates inside the meteorite, particularly easily if the meteorite has a coarse Widmanstätten structure, compare the Cosby Creek case above. Nickel does not confer any extra corrosion resistance to meteorites. On the contrary, the common two-phase structures of low-nickel kamacite and high-nickel taenite rather are a promotor of corrosion by providing numerous tiny galvanic cells. This leads to preferential attack on kamacite, thus significantly destroying the metallic cohesion.

Inside the meteorite where access to oxygen is limited, an unusual mineral, hibbingite, $Fe_2(OH)_3Cl$ with 18 weight% chlorine, may form. The chlorine atoms come exclusively from chloride ions of the terrestrial environment. Along the active corrosion front between goethite and unattacked iron, the mineral akaganeite, β-FeOOH with 2-6 weight% Cl will be present (Buchwald 1989; Buchwald & Clarke 1989).

If such a corroded iron meteorite is exposed to hammering and/or forging, the risk is high that the material will break either along the corroded Widmanstätten grain boundaries or along the ubiquitous schreibersite inclusions, where the corrosion attack is usually intensive.

In order to understand the weathering of iron meteorites and the nature of the oxidic end products, we will examine the corrosion process somewhat closer. Sometimes nature has been benevolent and initiated

Fig. 18. The largest meteorite on Earth is the 60 ton Hoba iron meteorite, an ataxite with a structure as Figs. 2 and 14. It has 16% nickel. It has never been moved, and has now been declared a protected national monument. It is located 20 km west of Grootfontein, Namibia. Buchwald 1975: 647.

its own, long-term corrosion experiment. When, e.g., a crater- or shower-producing meteorite falls, a large number of similar fragments start their terrestrial life under slightly different conditions. Some become deeply buried, others only slightly, and some come to rest exposed to sun and rain on a rocky surface.

Table 1.6. Bulk analysis of the Boxhole iron meteorite (Buchwald 1975)

Fe%	Ni%	Co%	P%	S%	Cu ppm	Ga ppm	Ge ppm	Ir ppm	Σ	Fe/Ni
91.68	7.67	0.49	0.11	0.05	133	18	37	8	100	11.95

Table 1.7. Bulk analysis of Boxhole shale ball (E.Jarosewich 1988, analyst). Weight %.

Fe_2O_3	FeO	NiO	CoO	P_2O_5	C	Cl	SiO_2	H_2O (+)	H_2O (–)	Σ
79.03	2.07	4.67	0.37	0.17	0.42	0.05	3.58	8.17	0.79	99.32

Table 1.8. Calculation of metal in the weathered oxides of the Boxhole meteorite. Weight %.

	as oxides	factors	as metal	as metal	recalculated to 100%
Fe_2O_3	79.03	x 0.699	55.32	56.93	93.50
FeO	2.07	x 0.777	1.61		
NiO	4.67	x 0.786	3.67	3.67	6.03
CoO	0.37	x 0.786	0.29	0.29	0.47
H_2O	8.96				
others	4.22				
total	99.32		60.89	60.89	100%

Nickel in metal, Table 1.6 : 7.67%.
Nickel in oxide, Table 1.8 : 6.03%.
Loss in nickel, absolute 1.64%.

Iron/nickel ratio in meteorite : 11.95
Iron/nickel ratio in oxidized meteorite : 15.51
Loss in nickel, relative : 21%.

The Boxhole iron meteorite, e.g., fell in Australia's Northern Territory about 5,500 years ago. It produced a crater, and meteoritic fragments happened to become exposed to different soil conditions. Some survived essentially unchanged on rocky surfaces, while others were entirely converted into oxidic shale balls (Buchwald 1975:338). For our purpose we will compare the bulk analysis of a well-preserved original Boxhole

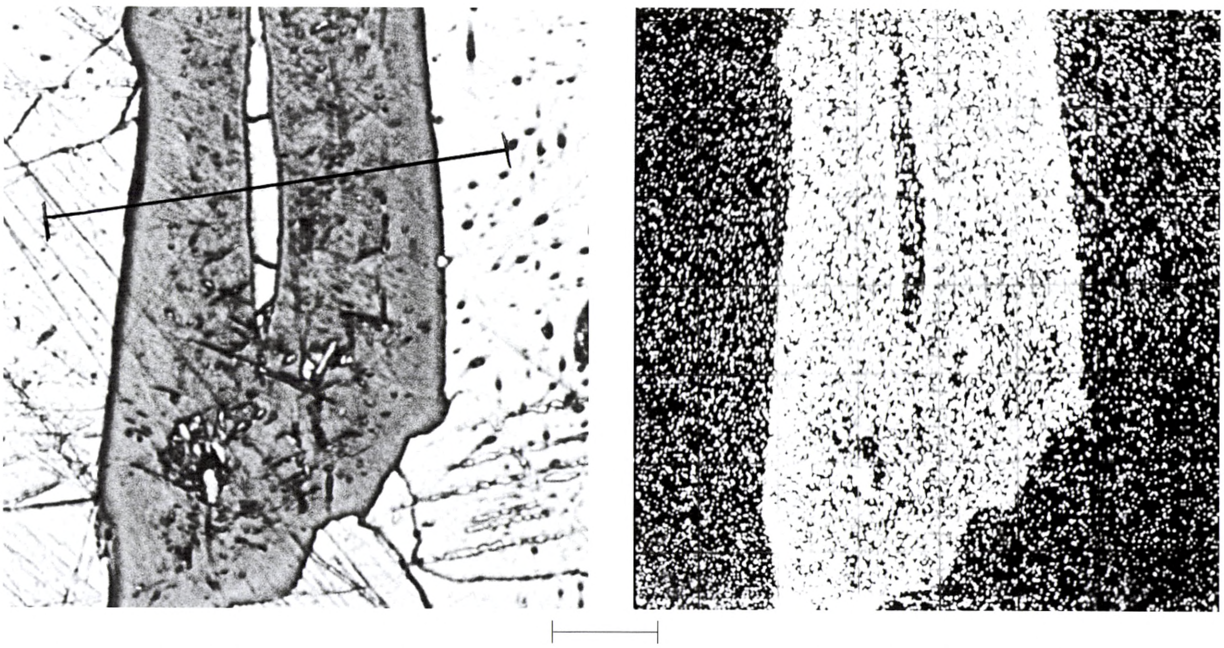


Fig. 19. Cross section through a Cape York meteorite fragment L3-12631. To the left, a plessite field in kamacite, as seen in the microscope. To the right an X-ray microprobe exposure showing high nickel concentration (white) in plessite, and low in kamacite. Scale bar 0.05 mm. Buchwald & Mosdal 1985.

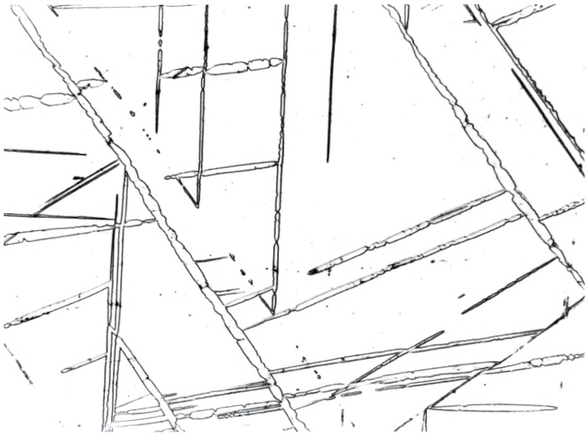


Fig. 20. Polished and etched section through the coarse octahedrite (Og) Silver Crown, Wyoming, U.S.A. Typical Neumann bands, produced at a cosmic collision eons ago. Seven directions are visible in the single crystal of kamacite. Side length 0.3 mm. Buchwald 1975: 90, 1132.

fragment with the bulk analysis of a 200 g shale ball, formed from the same meteorite by 5,500 years of corrosion, while buried in the North Australian gravelly soil.

By the kind cooperation of Dr.Eugene Jarosewich, The Smithsonian Institution, Washington, D.C., the above bulk analysis was performed on oxidized fragments of the shale ball. A sample of 20 g was crushed in WC- and agate mortars. A tiny fraction, 0.2 g or 1%, turned out to be surviving metal, and these flattened particles were removed from the analytical sample. The remainder was analysed by classical wet methods, Table 1.7.

The first five columns are oxides of the meteorite's main components, while the material of the last five columns has been introduced from the surrounding soil. H_2O (–) is hygroscopic moisture which can be driven off by moderate heating (110°C), while another part, H_2O (+), is held more strongly and requires igniting at 900°C. It is remarkable that the 5,500-year-old transformed meteorite still contains 1% of unaltered metal and 2.07% FeO, so the corrosion process has not yet run all the way to trivalent iron.

Since our main interest is to examine the behaviour of nickel (and cobalt), we will calculate the changes in nickel and cobalt due to corrosion, and use iron, the major metal, as a reference frame.

We see from Table 1.8 that the meteorite has lost 7.67 – 6.03 = 1.64%, or 21% of its nickel to the terrestrial surroundings, while the cobalt loss is insignificant. X-ray diffractograms of the oxidic powder reveal that it is composed of major goethite and maghemite, some lepidocrocite and a trifle of akaganeite. Electronmicroprobe analysis shows that nickel is present in both the goethite and maghemite minerals, and is about equally divided between the two, intergrown phases. Hematite, bunsenite and trevorite were looked for, but not found.

Table 1.9. Calculation of metal in the weathered Canyon Diablo (Og) meteorite. Weight %.

Original	meteorite	Oxidized	meteorite	as metal	as metal	as metal	to 100%
Fe	90.18	Fe_2O_3	77.10	Fe	53.89	61.85	92.61
Ni	7.10	FeO	10.25	Fe	7.96		
Co	0.46	NiO	5.92	Ni	4.65	4.65	6.96
P	0.26	CoO	0.37	Co	0.29	0.29	0.43
S	1.0	H_2O	6.36				
others	1.0						
	100%		100%		86.79	86.79	100%
Fe/Ni	12.7						13.3

Nickel in metal: 7.10%. Nickel in oxide: 6.96%. Loss in nickel: 0.14% (abs.), 2% (rel.)
Minerals in corroded material: Goethite, maghemite, lepidocrocite, akaganeite.

Table 1.10. Calculation of metal in the weathered Henbury (Om) meteorite. Weight %.

Original	meteorite	Oxidized	meteorite	as metal	as metal	as metal	to 100%
Fe	91.85	Fe_2O_3	78.45	Fe	54.84	61.30	93.31
Ni	7.51	FeO	8.32	Fe	6.46		
Co	0.45	NiO	5.28	Ni	4.15	4.15	6.31
P	0.09	CoO	0.32	Co	0.25	0.25	0.38
S	0.10	H_2O	7.63				
others	-						
Total	100%		100%		65.70	65.70	100%
Fe/Ni	12.2						14.8

Nickel in metal: 7.51%. Nickel in oxide: 6.31%. Loss in nickel 1.20% (abs.), 16% (rel.)
Minerals in corroded material: Goethite, maghemite, lepidocrocite.

Table 1.11. Calculation of metal in the weathered Hoba (A) meteorite. Weight %.

Original	meteorite	Oxidized	meteorite	as metal	as metal	as metal	to 100%
Fe	82.66	Fe_2O_3	49.68	Fe	34.73	53.53	82.88
Ni	16.41	FeO	24.19	Fe	18.80		
Co	0.76	NiO	13.54	Ni	10.64	10.64	16.47
P	0.07	CoO	0.53	Co	0.42	0.42	0.65
S	0.1	H_2O	12.06				
others	-						
total	100%		100%		64.59	64.59	100%
Fe/Ni	5.04						5.03

Nickel in metal: 16.41%. Nickel in oxide: 16.47%. Gain in nickel: 0.06% (abs.), 0.4%.(rel.)
Minerals in corroded material: Goethite, maghemite, calcite.

Table 1.12. Calculation of metal in the weathered Toluca (Og) meteorite. Weight %.

Original	meteorite	Oxidized	meteorite	as metal	as metal	as metal	to 100%
Fe	90.31	Fe_2O_3	79.00	Fe	55.22	62.63	93.58
Ni	8.14	FeO	9.54	Fe	7.41		
Co	0.49	NiO	5.47	Ni	4.30	4.30	6.42
P	0.16	CoO	n.d.	Co	n.d.		
S	0.70	H_2O	5.99				
others	0.20		-				
total	100%		100%		66.93	66.93	100%
Fe/Ni	11.1						14.6

Nickel in metal: 8.14%. Nickel in oxide: 6.42%. Loss in nickel: 1.72% (abs.), 21%(rel.)
Minerals in corroded material: Goethite, magnetite, akaganeite, hibbingite.

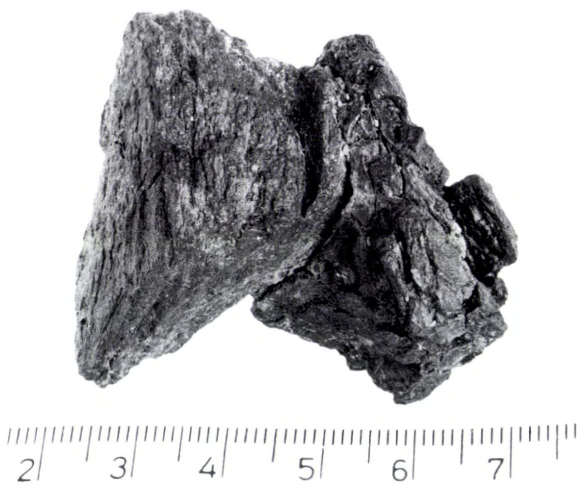


Fig. 21. Octahedral, rusty scales are all what is left of the crater-forming Monturaqui iron meteorite, Chile. Scale bar in cm. Buchwald 1975: 1407; 1989: 65.

In the above Tables four other iron meteorites have been examined in the same way. The analyses of the uncorroded meteorites have been taken from Buchwald (1975), while the analyses of the oxidic shales are from Buddhue (1957). All samples have in addition been examined for their oxide crystallography by Scintag X-ray analysis, and for their detailed chemical composition by studying polished sections by electron microscope analysis. The terrestrial age of the samples is not too well known. It appears that Canyon Diablo is more than 20,000 years old, while Hoba and Toluca are probably well over 10,000 years old. Henbury is the youngest with about 5,000 years, rather similar to the Boxhole meteorites, which were found only about 300 km to the northeast.

Further data to illustrate the corrosive break-down of iron meteorites are provided by the following two examples. In these cases we do not have any remnants of the original meteorite but only the severely transformed oxide shales. However, as noted before, the material is unambiguously meteoritic as evidenced by surviving tiny particles of taenite, schreibersite, $(Fe,Ni)_3P$, and cohenite $(Fe,Ni)_3C$, minerals which are unknown as terrestrial minerals.

The Monturaqui material is very old. Around a meteorite crater, 370 m across, in northern Chile's Atacama Desert, some hundred severely corroded, but magnetic fragments have been collected (Buchwald 1975: 1403). The morphology of the fragments suggests that the impacting body was an iron meteorite with coarse Widmanstätten structure and about 7% nickel. Thermoluminescence analysis points to an age of over 100,000 years. Even so the fragments, with a range in specific gravity from 3.57 to 4.03 g/cm^3, display numerous tiny remnants of taenite, cohenite and schreibersite. X-ray diffractograms and electronmicroprobe examination show the weathered bulk to consist of about equal parts of maghemite and goethite. Both phases contain 1.5-4.0 weight% nickel. Small amounts of the corrosion mineral reevesite, $Ni_6Fe_2(CO_3)(OH)_{16}$, 4 H_2O, were also noted.

Wolf Creek is a significant meteorite crater, 900 m across, in central western Australia. The crater is estimated to be of plio-pleistocene age, i.e. about ten times older than the Monturaqui crater. Numerous severely weathered fragments and kilogram-sized shaleballs have been recovered from outside the crater rim (White et al.1967). The 37 g magnetic oxidic fragment studied in the following had a specific gravity of 3.89 g/cm^3. Polished sections showed remnants of schreibersite, taenite and plessite with 20%, and even up to 40% nickel locally. The bulk oxides were goethite, maghemite and lepidocrocite with average nickel contents of 2-7%. The presence of the yellow-orange nickelcarbonate, reevesite, was evident, and in addition the green pecoraite, $Ni_6Si_4O_{10}(OH)_8$ was noted. Both were confirmed by X-ray diffractometry.

Canyon Diablo, Monturaqui and Wolf Creek prove that iron meteorites may survive for tens of thousands of years on the surface of the earth. Even if the metallic appearance is slowly lost, the oxidic fragments often retain a fossil Widmanstätten morphology, and the maghemite-goethite oxidic bulk material is strongly magnetic. The oxides retain an appreciable amount of the original nickel and cobalt content, and microscopic particles of taenite, plessite, cohenite, schreibersite and chromite survive very long and assist in proving the meteoritic origin.

Native or telluric iron

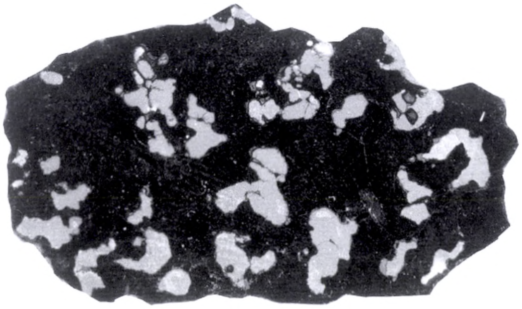


Fig. 22. Fragment of iron basalt with pea-sized iron inclusions (white). Eqaluit, Umanak, West Greenland. Longest dimension 32 mm. Buchwald & Mosdal 1985: 21. Type II material.

While meteoritic iron is rare, telluric iron is even more rare. Apart from tiny and now exhausted curiosities near Kassel, Germany, the only occurrence of interest is in central western Greenland (Buchwald & Mosdal 1985). When, in the 1840s and later, loose boulders of iron, ranging in size from 10.5 kg to 25 tons, were reported from Disko and the adjacent mainland, it was taken for granted that the material was of meteoritic origin. Geologic fieldwork by K.J.V.Steenstrup (1882) and very competent analytical work by Lorenzen (1882) served, however, to show that the iron belonged to the tertiary basaltic lava formation, which covers a large part of the Disko Bay area.

The telluric iron occurs in two forms. Type I is an

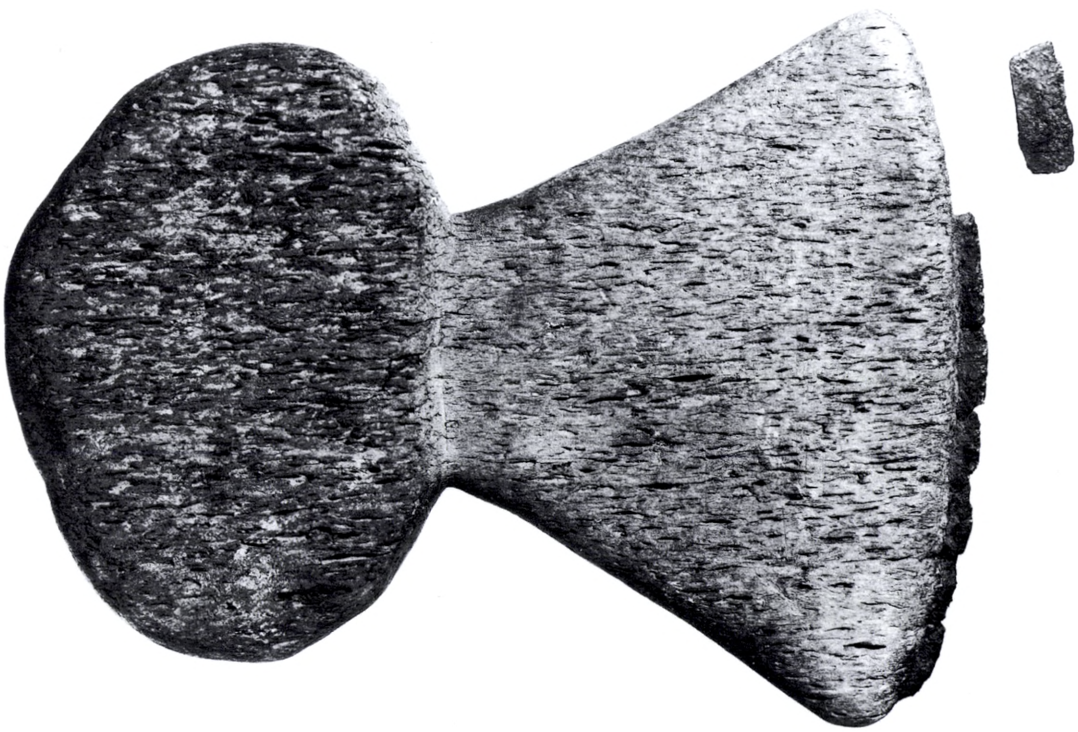


Fig. 23. Ulo, as Fig. 8, Geological Museum No. 1984: 864, found in a medieval grave at Qaersut, Nugssuaq, West Greenland. Small, cold-hammered fragments of telluric iron form the saw-like cutting edge. Longest dimension 7 cm. Buchwald & Mosdal 1985: 25.

Table 1.13. Tools produced from the pea-sized inclusions of telluric iron basalt (Buchwald 1992)

Object	Weight g	Ni%	Cu%	Si%	P%	S%	Mn%	As%	HV 100g
Ulo, L2855	0.1	1.90	0.05	0.01	0.018	0.014	0.02		186 ± 15
Harpoon, L 7210[C]	<0.1	3.7							198 ± 10
Knife, L7218	0.09	3.95	0.15	0.01	0.04		<0.02	<0.02	210 ± 20
Ulo, Lc 277	0.16	3.20	0.15	0.01	0.028		<0.02	<0.02	230 ± 25
Ulo, Lc 750	0.3	1.75	0.06		0.075	0.015			215 ± 15
Ulo, Lc 752	0.05	2.1	0.05		0.032	0.014			195 ± 8
Knife, Lc 755[C]	0.05	2							195 ± 10
Knife, Lc 800	0.05	2.00	0.10	0.005	0.065		<0.02	<0.02	210 ± 25
Knife, L2-621	0.08	2.15	0.15	0.013	0.045		<0.02	<0,02	230 ± 10
Knife, L2-959	0.08	2.15	0.10	0.10	0.030		<0.02	<0.02	225 ± 30
Ulo, Geol.Mus. [A]	0.1	3.90	0.06	0.010	0.018	0.015	0.02		225 ± 15

A Ulo 1984:864, see figure 23.
C these two samples were severely corroded and transformed into rust cakes with only little metal

unworkable nickel cast iron with more than 1.5%C, while type II is a malleable low-carbon nickel iron. Both types have between 0.05 and 4.0% nickel. Type I, which occurs in massive blocks, attracted the attention of Nordenskiöld, who believed them to be meteorites and in 1871 transported three masses to the Fenno-Scandinavian capitals (Nordenskiöld 1871). The huge 25-ton block is now outside the Riksmuseum in Frascati, Stockholm. The 6.6-ton block is outside the Geological Museum in Copenhagen, and the 3-ton block is in the Kaisaniemi Park in Helsinki. The type I boulders could not be worked by the Inuit, but they may sometimes have been used as hammerstones.

The type II material usually occurs as minute iron grains, disseminated in the basalt. They are 1-5 mm in size, but are sometimes sintered together into more massive aggregates with ilmenite, cohenite, troilite,

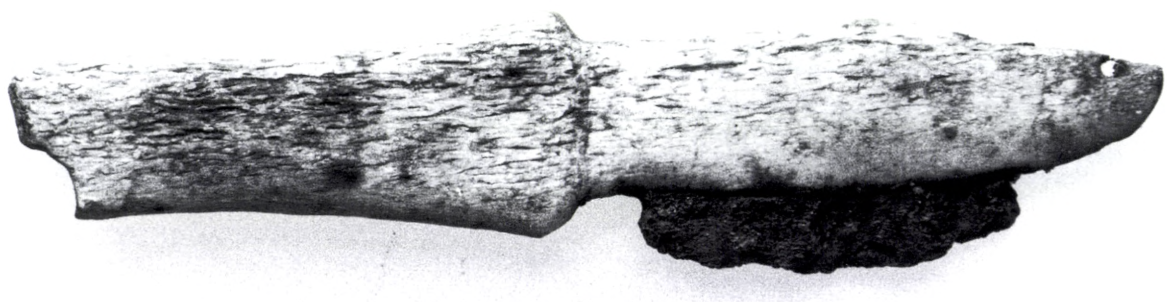


Fig. 24. Inuit knife, Lc 755, from Eqaluit, Umanak, West Greenland. Coldhammered fragments of telluric iron have been inserted into a bone shaft. 50 mm long. Buchwald & Mosdal 1985: 24.

and pearlite as accessory components. If this type of material, basalt with pea-sized inclusions, is crushed between other stones, the iron peas will be released and may be coldworked to flat, coin-sized fragments that may be inserted into the groove of a harpoonhead, an ulo or a knife. If several fragments of the same size are inserted into a groove, slightly overlapping each other, and the last one secured by a small rivet, one has an excellent tool with properties which are part-knife and part-saw.

Ten Inuit objects in the National Museum and one object from the Geological Museum, both Copenhagen, were examined in some detail, Table 1.13. They were all of type II and had been coldworked in much the same way as the Cape York meteorite samples discussed above. The hardness is high, but not so high as for the meteoritic samples, because there is much less nickel in the telluric iron, column 3. Other elements are also low. Carbon, as estimated from the structure, is in all cases below 0.2%.

All samples with known provenances are from either the Umanak District or the Disko Bay region, so the material has attracted far less attention by the Inuit than the meteoritic iron flakes, which have been found all over Greenland and on the Canadian side of Baffin's Bay.

It is remarkable that the Inuit are the only people that have utilized iron of three different categories: Meteoritic iron from Cape York, telluric iron from the Disko Bay area, and wrought iron, which was acquired by trading first with the Norsemen and later with the fleets of European whalers, who from about 1550 were common guests in the Greenland waters. In Table 1.14, the three iron categories are characterized on the basis of the archaeological finds in Greenland (Buchwald 2001).

Table 1.14. Characteristics of the three types of iron that were used in Greenland

	Nickel %	Cobalt %	Phosphorus %	Carbon %	Hardness HV 200 g	Phosphides	Taenite	Slags	Max. size, g
Meteoritic iron	>5	>0.4	0.1-0.3	<0.1	175-350	+	+	–	16
Telluric iron	1-4	0.1-0.4	<0.08	<0.5	125-250	–	–	–	1
Wrought iron	<0.2	<0.05	0-0.6	0-0.8	80-900	+	–	+	>1000

Conclusion

The study has revealed that meteoritic objects on a world-wide basis are extremely rare. The only people who had access to rather many meteoritic fragments and actually used them for no less than a thousand years, were the Polar Inuit who inhabited the northwestern part of Greenland, north of the Melville Bay. From the beginning they used the technique of coldhammering the nut-sized fragments of the Cape York meteorite shower. There was apparently over this long period no evolution in techniques or application of other methods (Buchwald 1992 b; 2001).

The Hopewellian Indians also coldhammered their meteoritic fragments, but in addition they applied reheating to anneal and soften the plates, so they could be folded into beads. In applying this method they may have resorted to methods known from copper technology, probably from contact with the tribes of Copper Indians and Copper Eskimos (Wayman et al.1992).

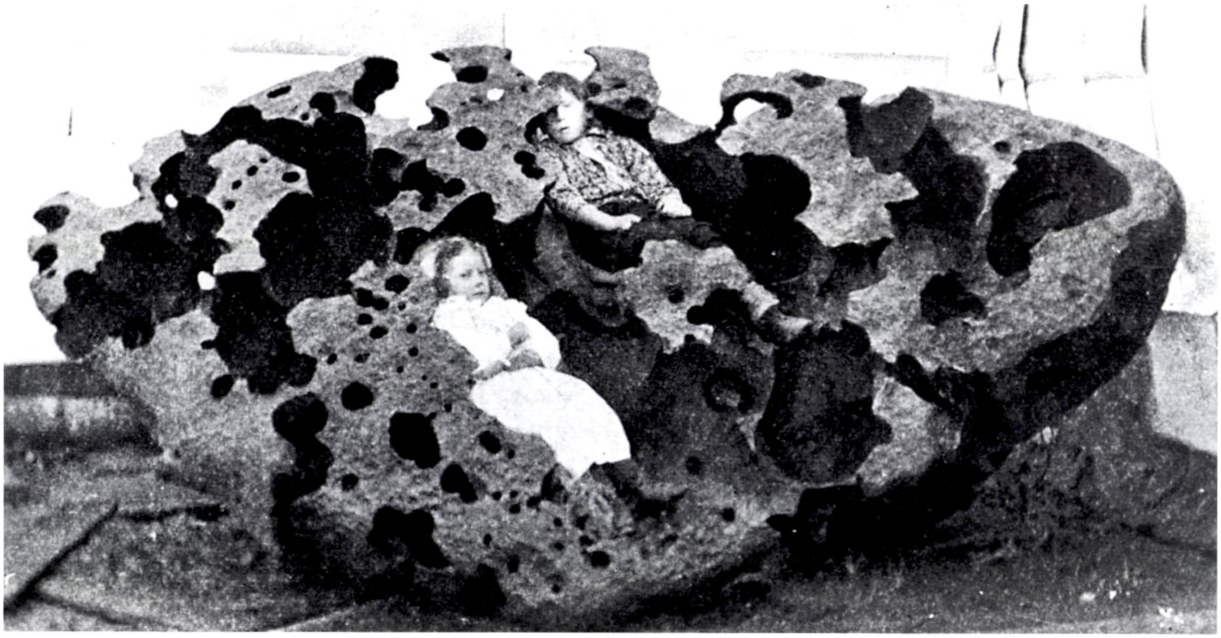


Fig. 25. The 14.1 ton iron meteorite from Willamette, Oregon, has lost perhaps 6 ton by terrestrial weathering. A boy and a girl are hiding in the corrosion grooves. Buchwald 1975: 1318.

The easily recovered iron meteorites of Europe were probably exploited in prehistoric times in much the same way as discussed above with examples from Asia and the Americas. Perhaps some forged ancient object in some museum collection will eventually turn out to be a meteoritic artefact. If suspected, a tiny polished section should be examined under the microscope for the characteristic meteoritic structures and minerals, supplemented by a nickel determination, best under the electronmicroprobe. Iron meteorites do not contain slags. Even in severely corroded meteorites some cohenite, taenite, plessite, chromite or schreibersite particles will suffice to prove the meteoritic origin.

The goethite-maghemite oxide shale, still magnetic, will display several percent nickel and roughly preserve the iron-nickel ratio of the fresh meteorite, even after more than 10,000 years' exposure to the terrestrial environment.

It appears that the knowledge and handling of meteoritic iron were too sporadic, both in time and space, to be of any importance for our ancestors, when they finally took up the challenge to extract iron from terrestrial ores and convert this iron into practical objects.

Chapter 2
Copper and bronze

So it is with the smith, sitting by his anvil, intent on his art-work.
The smoke of the fire shrivels his flesh,as he wrestles in the heat of the furnace.
The hammer rings again and again in his ears, and his eyes are on the pattern he is copying.
He concentrates on completing the task, and stays late to give it a perfect finish.

Ecclesiasticus, or The Wisdom of Jesus son of Sirach, 38: 28.

In the previous chapter it was argued that meteoritic iron was so rare and of such sporadic occurrence that it must have been of very limited utility to ancient people. Native iron, which for all practical purposes only occurs in northwest Greenland, was still less useful except for the Polar Inuit. Silver, gold and lead are outside our scope and will not be treated here. Copper and copper alloys are, however, of some interest, especially since research in the last decades has raised the question whether iron technology was indirectly born out of ancient copper technology.

While native iron was extremely rare, native copper was relatively common, both in Asia, Europe, and North America. It occurred in the lower part of the gossan, the secondary oxidized minerals, which then covered many sulphidic copper deposits. It is the general opinion that man's first experience with metals was based on native copper (Coghlan 1975; Tylecote 1987: 89; Wayman 1989). "Native copper is likely to have been the first metal used by man around the world. In the Middle East it appears on settlement sites in small quantities from the earliest Neolithic usually as an exotic luxury item alongside other exotics such as bitumen, obsidian and a variety of decorative and semiprecious stones and minerals, including malachite and azurite" (Craddock 1995:97).

"It is tempting to make the statement that the small and insignificant objects belonging to the earliest metal-using cultures of Egypt and Western Asia are made of native copper; but it would be more correct to say that they are almost certainly so made, for the majority of the objects referred to have not been analysed or scientifically examined and therefore there is as yet no scientific evidence in support of a definitive statement" (Coghlan 1951: 30). This opinion is still valid, the more so because a definitive distinction between native, melted copper and early smelted copper extracted from oxidic ores is difficult.

There have been many speculations about how early man first extracted copper metal from its ores, but this is not the place to review various viewpoints. It appears plausible that once he was able to use a charcoal fire and heat native copper in a clay crucible to the point of melting, 1083°C, it was not a long step to discover that pure copper could be produced from the attractive colourful oxycarbonates, malachite and azurite. It would result in pea-sized copper prills that just had to be separated from slags and ashes. On reheating they could be melted to larger units, poured into a clay or soapstone mould and thus acquire the desired shape. Apparently these early attempts occurred in Central Anatolia (Catal Hüyük), northern Mesopotamia and northwestern Iran, in the sixth millennium B.C.

From the fourth millennium B.C. comes the first firm evidence for smelting in the Middle East (Hauptmann 1985; Hauptmann et al. 1992; 1993; Flawn 1966). At Feinan in the Arabah Valley of southern Jor-

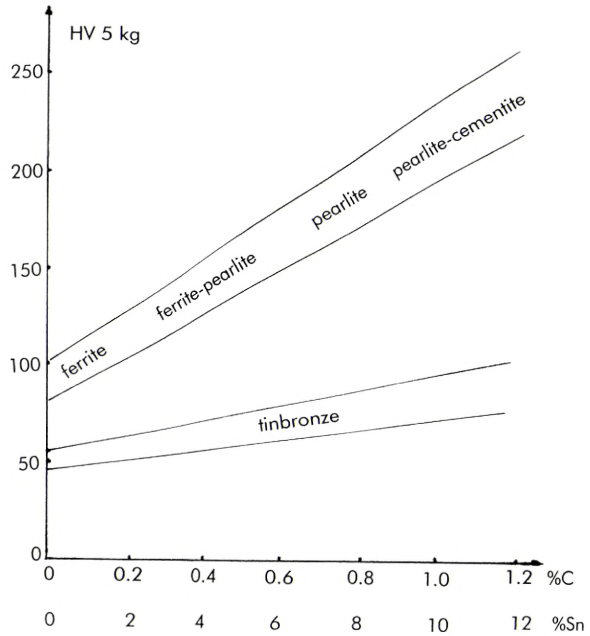


Fig. 26. Vickers hardness (5 kg load) of tinbronzes (0-12 weight percent tin), and ancient iron with carbon, but without silicon and manganese. Iron with 0-0.35% C is conveniently called wrought iron, or just iron, while iron with 0.4-1.4% C is called steel. The curves are for the annealed state.There is a natural spread in hardness, partly due to grain size variation, partly due to heterogeneities in the objects.

dan, excavations have shown that copper minerals were smelted more or less continuously from about 3500 B.C. to Roman times. The ores were in the beginning primarily malachite and chrysocolla, a copper silicate, and thus sulphide-free.

Other sites of high age are in southeastern Spain, southern Portugal, in the Balkans and in Ireland.

At Rudna Glava in Serbia, 140 km ESE of Belgrade and near the borders to Romania and Bulgaria, the remains of ancient copper mining were discovered in the 1960s. Pottery, left in the mine shafts was shown to belong to the Vinca culture, thus indicating that the mining activities took place about 4000 B.C. The ores were mainly malachite, azurite and cuprite, which here were the decomposition products of chalcopyrite and were easily recognized on the bare limestone massif (Jovanovic 1980). The miners followed the vein of ore downward, in some places to a depth of 15 m. Apparently no smelting took place at Rudna Glava; perhaps the ore was carried to settlements 80 km (!) west in the Morava river valley. Heavy copper chisels, socketed axes and rings of the same old age have been found at Plocnik somewhat south of Rudna Glava.

Apparently the development in copper technology took place independently in many places, since the early locations are so widely separated. Similarly, it is an archaeological fact that copper extraction and smelting developed independently in Central and South America as well as in China.

The discovery of smelting and extracting copper from its ores marks the true beginning of metallurgy. Starting with the simple, oxidized ores of the lower gossan which yielded rather pure copper objects, it later became necessary to use the more complex arsenic-rich ores and still later to dig deeper and work the difficult sulphidic ores that required roasting to remove some of the sulphur.

A few copper ore minerals contain some tin, e.g. stannite, Table 2.1 last line, but when tin later, about 2000 B.C., became an important alloying element, it is clear that by then it had become extracted from cassiterite, SnO_2, and become accessible as a pure metal, as bar merchandise, and was added in deliberate doses. Interesting are the west European razor knives which have been examined by Jockenhövel (1980). They were cast to shape in bronze in sand forms. After casting, the edge, 0.2-0.3 mm thick, was sharpened and hardened by grinding and gentle hammering.

Scandinavian museums are rich in copper and bronze objects (Vandkilde 1989; 1996; Jensen 1997). Only a small fraction of them have been examined with a view to studying their metallurgy and structure (Buchwald & Leisner 1990). While prehistoric copper and bronze finds from Britain (e.g.Coghlan 1967; Parker 1982), Wales (e.g.Savory 1980), Austria (e.g. Moosleitner & Moesta 1988), Switzerland (e.g. Rychner 1984), Sardinia (e.g. Tylecote et al. 1983; Demurtas 1999), Italy (e.g.Matteoli & Storti 1982; Giardino 1995; Benvenuti et al. 2000), Slovakia (e.g. Longauerova et al. 1999), Greece and Etruria (Craddock 1977) and Sweden (e.g.Oldeberg 1974; Hagberg

Table 2.1. Some important copper minerals

Name	Composition	% Copper	Structure	Spec.grav. g/cm^3	Colour of streak
Cuprite	Cu_2O	88.8	cubic	5.8-6.2	reddish brown
Tenorite	CuO	79.8	monoclinic	ab.6	black
Malachite	$CuCO_3$, $Cu(OH)_2$	57.3	monoclinic	ab.4	green
Azurite	2 $CuCO_3$, $Cu(OH)_2$	55.1	monoclinic	3.7-3.9	azure blue
Chrysocolla	$CuSiO_3$, 2 H_2O	ab. 36	amorphous	2.0-2.2	greenish
Antlerite	$CuSO_4$, 2 $Cu(OH)_2$	54.0	rhombic	3.9	green
Brochantite	$Cu_4(OH)_6SO_4$	56.2	monoclinic	3.9	green
Atacamite	$CuCl_2$, 3 $Cu(OH)_2$	59.4	ortorhombic	3.7	green
Chalcopyrite	$CuFeS_2$	34.5	tetragonal	4.1-4.3	green/black
Bornite	Cu_5FeS_4	63.3	cubic	4.9-5.3	metallic black
Chalcocite	Cu_2S	79.8	ortorhombic	5.7-5.8	lead grey
Covellite	CuS	66.4	hexagonal	4.7	black
Enargite	Cu_3AsS_4	48.3	pseudo-hexagonal	4.4	black
Tetrahedrite	Cu_3SbS_3	52.1	cubic	4.4-5.4	black
Tennantite	Cu_3AsS_3	57.0	cubic	4.4-5.4	black
Stannite	Cu_2FeSnS_4	29.5	tetragonal	4.3-4.5	black

1988) have been thoroughly discussed, much remains to be done on bronzes from Denmark.

There are no copper and tin ores in Denmark. The vast copper sulphide occurrences in Sweden and Norway were first exploited from about 1200 A.D. (Falun, Forshell 1992) and from about 1500 (Røros, Østensen 1999), so copper, tin and bronze had to be supplied from elsewhere, either in the form of finished items, or as scrap and bar material. The ancient "Danish" bronze age metallurgist demonstrated a fantastic cunning, when he produced such objects as the Skallerup wagon (ab.1600 B.C.), Solvognen from Trundholm (ab.1500 B.C.), the spiral-shaped lurs (1100-600 B.C.) and the Viksø helmets (ab.800 B.C.). He also fashioned, or decorated a number of beautiful gold goblets and cups, e.g. those found at Borgbjerg, Skelskør.

In the following we will study a range of copper and copper alloys from the early beginnings and until the present day. Thirty-three objects from the Scandinavian Bronze Age, Iron Age, Viking Age and the Middle Ages have been selected to represent tools and weapons as well as thin-walled cauldrons and personal decorative items. In addition, two Etruscan mirrors and a Roman copper nail, two cannon, a church bell and a modern spring-quality nickel silver alloy have been examined.

Analytical procedure

The procedure of cutting, polishing and analysing is the same as the procedures described in more detail in Chapter 3. On a SEM with energy dispersive X-ray analytical detector (EDAX), quantitative data for the following nine elements were obtained: Tin, sulphur, iron, nickel, zinc, arsenic, silver, antimony and lead.

The limit of detection with our method was 0.07-0.10 weight%. Sulphur occurs as the copper sulphide Cu_2S – or rather Cu_9S_5 – which may be identified on polished sections and measured by planimetry. The precision is estimated to be ±10%. The composition of the sulphides may be verified by EDAX. Sometimes small amounts of iron substitute for copper in the sulphides. Sulphur may also be determined by EDAX, but if lead is present, the S-value becomes erroneously high, and the only reliable method, apart from electron microprobe analysis, seems to be planimetry.

While iron is concentrated in the sulphides, nickel is partitioned between the bronze's α- and δ-phases, and concentrated by a factor of more than 3 in the δ-phase. The quantitative determination of lead in bronze is a problem that requires a careful procedure. Lead cannot be dissolved in copper, but occurs as discrete, interdendritic blebs, typically 2-20 μm across, which are rather uniformly distributed through the alloy. On routine polishing, the ductile copper phase tends to smear over the soft lead pockets, thereby masking the lead signal. It was found that the best method for a good lead analysis was to polish and etch, then polish and etch again. By the repeated operations the smeared copper was removed and the lead particles became exposed to their true extent. Tin, on the other hand, was determined on repolished sections, since it was found that it became enhanced upon etching, probably because some copper was selectively dissolved. Tin occurs in solid solution in the copper phase, in the as-cast alloy usually exhibiting severe segregation, or coring. Unequilibrated cast alloys with more than 5-6% bulk tin may exhibit the so-called δ-phase, an intermetallic, hard compound $Cu_{31}Sn_8$.

A technologically important characteristic of metal alloys is the hardness. The Vickers hardness number (at 5 kg load) is in the order of 45 for pure, unalloyed copper, but increases to above 300 for coldworked arsenic- and tin-containing bronzes, Fig. 40. A great deal is known about hardness and its variation, and it is safe to say that a hardness determination combined with a structural examination and a chemical analysis will usually fully characterize any object.

The samples 1-12 have in detail been treated before, with extensive background information on experimental alloy series, including many structural photomicrographs (Buchwald & Leisner 1990). The samples 13-36 are the results of current research at the Department of Metallurgy, The Technical University of Denmark, see Table 2.2.

Presentation of copper and bronze samples

Fig. 27. Tongue shaped axe, B 2926, 1335 g. Copper-arsenic alloy with 1.4% As, cast somewhere in central Europe and imported to Denmark about 2700 B.C. Scale in cm. Buchwald & Leisner 1990.

No. 1. B 2926. Tongue-shaped flat axe, 1335 g. Kirke Skensved sogn, Copenhagen amt. About 3000-2400 B.C. Apparently the axe-shaped bar was cast horizontally in an open mould somewhere in central or southeastern Europe. It arrived in Denmark as a semi manufacture for remelting and production of other objects. Analytically it is a copper-arsenic alloy with 1.4% As. After casting it has been only slightly worked and annealed, displaying equiaxial twinned α-grains. The hardness range is 66-97, due partly to some late coldwork and partly to arsenic segregation. No sulphides are present.

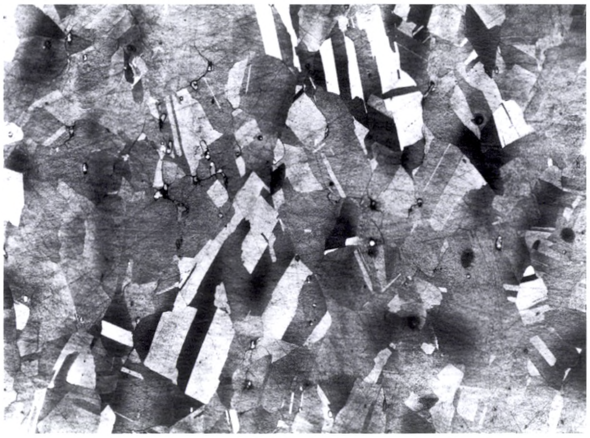


Fig. 28. Polished and etched section (PES) through the axe, Fig. 27. Slightly worked and recrystallized, twinned structure. Side 1.3 mm.

No. 2. B 5556. Thin-butted flat axe, 311 g. Stray find from Denmark. About 3000-2400 B.C. Analytically the axe is a copper-arsenic alloy with copper oxide inclusions. The microprobe reveals a number of unusual oxide inclusions, such as lead arsenate, lead-copper arsenate and lead antimonate. Sulphides are not present. The surface is irregularly covered by an inner red Cu_2O-layer and an outer green patina. While the Cu_2O is arsenic-free, the green carbonate corrosion product is enriched in arsenic. The axe has been cast vertically in a bivalve mould. Casting fins have been removed by hammering and the cutting edge significantly sharpened by hammering. On annealing the axe acquired its structure of equiaxial α-grains, without, however, entirely eliminating the initial coring. The hardness range is 57-81, the maximum values occurring at the cutting edge. It appears that the alloy was produced from ores derived from the oxidized (sulphide-free) arsenic-lead-antimony- enriched gossan of some sulphidic ore crop. Since the extraction slags are still present in the axe, it appears that the object has been in the molten condition only once, and thus probably cast and finished somewhere in central Europe. The origin of the objects no.1 and 2 may be very similar. – The axe, which was found with the famous Ice-man in the Ötztaler Alps and which is tentatively dated to about 3300 B.C., is similar in composition (Sperl 1992).

No. 3. B 1094. Low-flanged axe, 190 g. Pederstrup, Ballerup sogn, Copenhagen amt. About 1800 B.C. The axe was probably cast edge down, in a bivalve mould. Superficial hammering has sharpened the edge, removed casting flashes and enlarged the flanges by plastic deformation. The flanges are now up to 12 mm wide. Analytically the axe is a sulphide-containing copper-silver-arsenic-antimony alloy with a hardness range of 53-91 HV. It was probably made in Denmark and belongs to the Gallemose type. The polished sections show a yellowish alloy. Evidently the modest silver, arsenic and antimony content is sufficient to turn the red copper into yellowish shades. The alloy contains 0.4% sulphides, suggesting that the ores were of a sulphidic nature. Cu_2S occurs as minute, 2-10 μm bluish blebs. The structure displays equiaxed, twinned α-grains. Hammering and subsequent annealing have not entirely removed the coring. The axe probably served as the tool of a forest worker. A deep fissure that crosses the blade was apparently inflicted on the axe to make it useless before it was deposited.

No. 4. 11073. Low-flanged axe of type Hjadstrup, 480 g. Bygholm, Hatting sogn, Vejle amt. About 1800 B.C. The axe has the poorest finish of the Nos.1-10, and the general impression is that of a low-quality casting

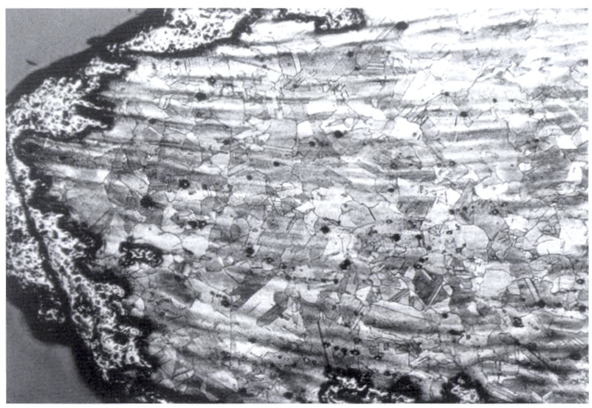


Fig. 29. Polished and etched section (PES) through a thin-butted flat axe, B 5556. Worked and recrystallized, twinned structure. Although of almost pure copper, the segregation from casting survives as diffuse striations after forging. Side 1.1 mm. Buchwald & Leisner 1990.

Fig. 30. PES through a low-flanged axe, No. 11 073. The segregation from casting survives, in a matrix of equiaxed alpha-grains. Side 2.6 mm. Buchwald & Leisner 1990.

technique. It is a very early example of tin bronzes made in Denmark.The alloy is complex, with 2.1% tin and significant contents of sulphur, nickel, arsenic, silver and antimony. The hardness range is from 69 to 151, and the structure is that of a cast coarsely crystalline α-texture in which coring has not been entirely eliminated by annealing. The flanges have acquired their basic shape by casting, but they have been locally improved by hammering. Here the α-grains are elongated and rich in slip lines, proving that some final cold-hammering occurred after annealing. Before deposition the blade was destroyed by a heavy blow.

No. 5. 26073. Flanged axe of type Virring, 250 g. Vicinity of Silkeborg, Skanderborg amt. About 1700-1600 B.C. The axe is of elegant design and well-preserved. It represents the important change to full tin bronze alloys, whereby other elements decreased in importance. The 8.8% tin is now systematically added. No doubt, the smith had access to imported tin bars, as well as to unalloyed copper. We agree with Liversage & Liversage (1989) who concluded from examination of Danish artefacts that "the consistency of the distribution suggests that the people who made the bronze knew exactly what tin content they wanted, even if they did not always hit it right". It is the general opinion that objects of this composition are not imports, but were cast in Denmark (Brøndsted 1939, Vol.2; Vandkilde 1989). Both the flanges and the edge have been worked after the casting, and thorough annealing has almost entirely removed coring. In places a little δ-phase, 3-15 μm across, remains as rounded blebs. Sulphides are common, elongated according to the forging directions and constituting about 1.6 volume percent. Repeated hammering and annealing have left the axe with a variety of structures, in general displaying recrystallized and twinned α-grains. Corrosion has attacked along slip-lines in coldworked, unannealed surface grains. The hardness range is from 85 in the central massive parts to 201 along the coldworked edges.

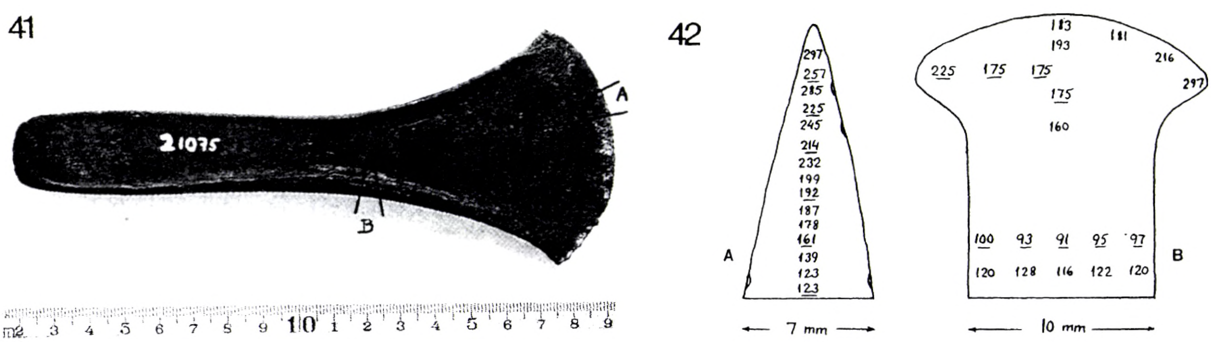


Fig. 31. Flanged axe of elegant shape, No. 21 075, of 354 g. The hardness measurements were taken as well on the edge, A, as on the flange, B. The Vickers hardness (5 kg) is underlined, the Microvickers hardness (0.1 kg) is also shown, without marking. Buchwald & Leisner 1990.

Archaeological timetable

	Scandinavian tradition			Continental tradition		
Climate	Ages	Periods		Ages	Periods	
	Mediaeval	Late mediaeval High mediaeval Early mediaeval	1050-1550	Mediaeval Age	Late mediaeval Crusades Carolingian Merovingian	1300-1500 1100-1300 750-1100 450-750
Subatlantic	Iron Age	Viking Age Germanic Iron Age# Roman Iron Age Pre-Roman Iron Age	800-1050 400-800 0-400 A.D. 500-0 B.C.	Roman Iron Age Celtic Iron Age	Late Roman Roman Empire La Tène Hallstatt	300-450 31B.C.-300 A.D. 250-31B.C. 500-250 675-500 800-675
Subatlantic	Bronze Age	Younger Bronze Age Older Bronze Age	1000-500 1700-1000	Bronze Age	Younger Bronze Age Older Bronze Age	2300-800
Subboreal	Neolithicum	Jættestue culture Enkeltgravs culture Tragtbæger culture	2400-1700 2800-2400 4000-2800	Neolithicum		4000-2300
Atlantic Boreal	Mesolithicum	Ertebølle culture Kongemose culture Maglemose culture	5400-4000 6800-5400 9000-6800	Mesolithicum		9000-4000
Late glacial	Palaeolithicum	Hamburg culture etc.	12000-9000	Palaeolithicum		12000-9000

often subdivided into Migration period 400-550 A.D and Vendel period 550-800 A.D.

No. 6. 21075. Flanged axe of type Virring, 354 g. Kragebæk, Holbæk amt. About 1700-1600 B.C. The axe has many similarities to the previous one, both in general shape and in composition. Polished sections through the massive bulk show a yellow alloy with 0.1-0.3 mm wide micropores from casting. In the cutting edge and on the flanges all pores have been closed by hammering. There are numerous sulphides, amounting to about 0.6 volume percent Cu_2S. They were sufficiently ductile to follow the displacement of the metallic matrix without breaking, during hot as well as coldworking. The axe has been cast, edge down, like the previous one, and while the flanges may already have had their general shape from the mould, they attained their final shape by hammering. Cold work brought the edges to the maximum hard-

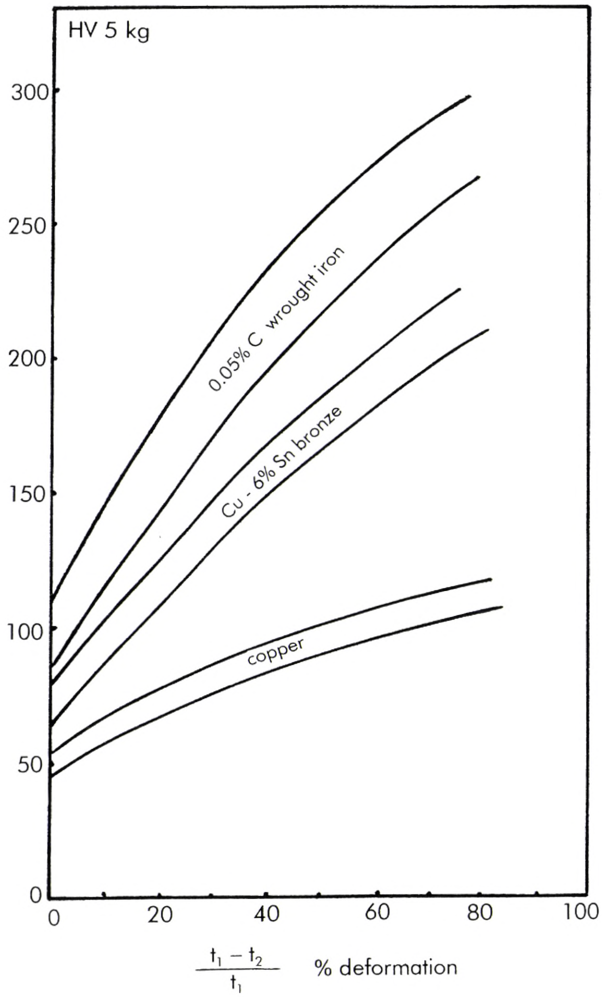


Fig. 32. Vickers hardness of cold-rolled copper, 6% tinbronze (no other additions), and 0,05% C wrought iron (<0.02% Si, <0.02% Mn); experimental results. The starting thicknesses of the bars were 6 mm (t_1), and the end thickness t_2. Reduction by rolling beyond 75% led to miserable, fractured material.

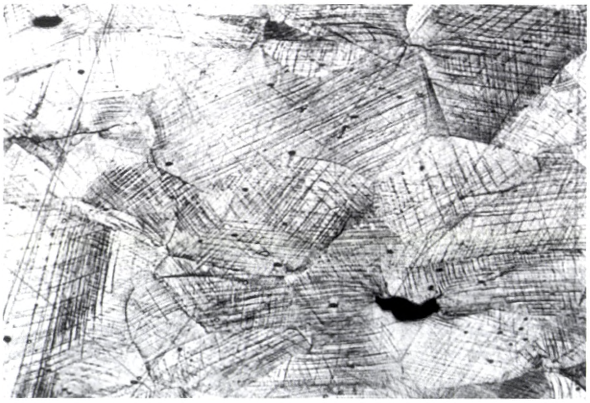


Fig. 33. PES through the flange, B, of Fig. 31. It is heavily cold-hammered and displays numerous sliplines and high hardnesses, corresponding to deformations beyond 60%. Side 0.7 mm.

No. 7. B 4077. Low-flanged axe of type Underåre, 132 g. Moskjær, Virring sogn, Randers amt. 1700-1500 B.C. The axe, which was found during turf-digging, is covered by an up to 3 mm thick corrosion layer. The exterior 2 mm consists of crystalline, pure Cu_2S, which must have grown under anaerobic conditions for 3500 years, deeply buried in the peat. The alloy is rich in tin (9.4%) and contains nickel, arsenic, antimony, 2 volume percent sulphides and – for the first time – substantial

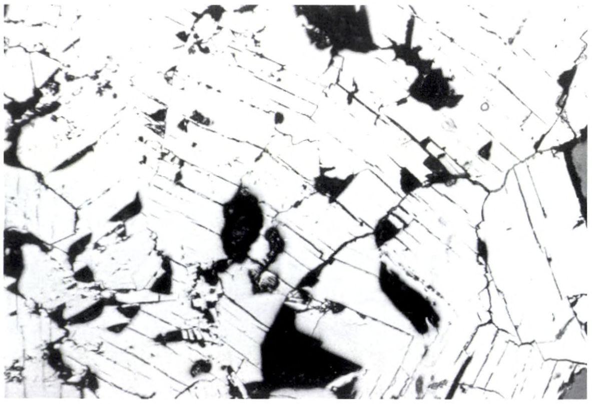


Fig. 34. Polished section (PS) through the exterior corrosion layer on axe B 4077. Under anaerobic conditions in a peat moor, an up to two mm thick layer of copper sulphide, Cu_2S, has formed. Side 2 mm. Buchwald & Leisner 1990.

ness for this alloy of 257 HV, and the flanges to a somewhat lower hardness. The edge acquired its final faceting by grinding. The axe is a fine example of the skill of the early Bronze Age smith, being of a very elegant shape and simultaneously displaying superior technological properties.

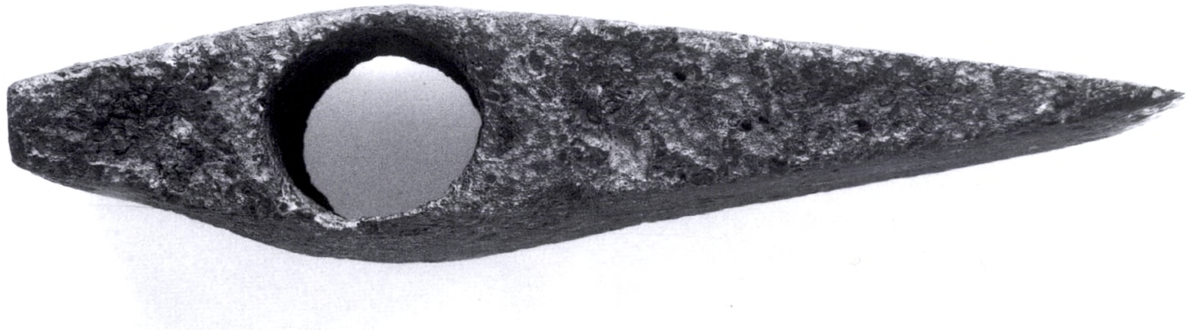


Fig. 35. The 1470 g heavy shaft hole axe, B 5564. Probably an unfinished object, pending grinding and decoration. Side 20.5 cm. Buchwald & Leisner 1990.

amounts of lead. Polished sections show a yellow alloy with distinct pin holes 0.1-0.3 mm across, resulting from solidification shrinking. The holes have been closed by forging on the cutting edge and to 3 mm depth on the flanges, the hardness having correspondingly increased up to 165. Elsewhere the alloy is almost as cast, with much coring and low hardnesses of about 85.

No. 8. B 5564. Shaft-hole axe of the Fårdrup type, 1470 g. Kragenæs, Birket sogn, Maribo amt. 1600-1500 B.C. This is a heavy-weighter, and the only shaft-hole axe in the selection. It is undecorated and slightly asymmetric. Analytically, it resembles the previous object, except that there are fewer sulphides. These are rich in iron, while the δ-phase is enriched in nickel. The cored, unequilibrated structure, full of microscopic pinholes and with prominent δ-phase, shows that the axe has been left as cast, except for some slight coldworking of the edge, where there is a hardness increase from bulk values of about 93 to a maximum value of 145. Considering the lop-sided shape of the object and the lack of finish by grinding and polishing, it is speculated whether it was meant as an axe at all, but rather was a bronze bar, providing metal for trading. Alternatively, it has been suggested (H.Vandkilde, pers.comm.), that the axe is an unfinished object, pending grinding and decoration in the geometric style, characteristic of the Fårdrup axes.

No. 9. B 3971. High-flanged axe of the Oldendorf type, 214 g. Denmark. About 1600-1500 B.C. This elegant axe has in the middle a moderate stop-ridge for shafting purposes, clearly a feature modelled into the mould. The edge has been sharpened for the outermost 13 mm by a combination of coldwork and grinding. Analytically the axe is little different from the previous two objects. It is a yellowish alloy with numerous small, blue sulphides, containing about 0.1% iron. The sulphides have participated in the strong deformation of edge and flanges and are now

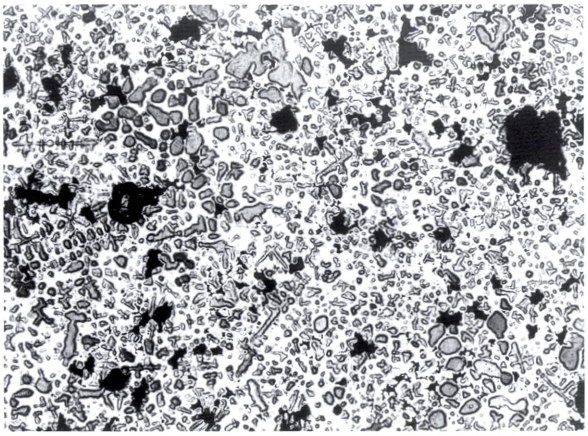


Fig. 36. PES through B 5564, Fig. 35. Segregated, unequilibrated structure with microporosities (black) from the casting. Side 5 mm.

in the shape of narrow, long filaments. This does not necessarily indicate hot-work, since it has been shown on experimental sulphidic alloys that the sulphides are sufficiently ductile to follow the metal even under heavy coldwork (Buchwald & Leisner 1990). Etched sections show a rather homogeneous, recrystallized tin bronze. Almost all δ-phase and coring have disappeared, due to repeated working and annealing operations. The bulk hardness is about 75, but due to final coldworking of edge and flanges the hardness here increases substantially, to maximum values just over 200 HV.

The axe provides a fine example of destannification, a phenomenon which otherwise has received little attention (Tylecote 1979). In a deep groove, no doubt a casting-fault, some sand particles from the mould have been impregnated by corrosion products. Tin has been selectively removed from the alloy to form tin-enriched corrosion layers, the ratio Cu-Sn having decreased to 3 instead of 11 in the alloy. The copper has reprecipated in the shape of a spongy, red mass, displaying particles 1-2 μm across. These copper grains are tin-free but contain 0.5-1% iron, derived from the sulphides or from the surrounding soil. Chlorine, calcium and phosphorus, which are present in the tin-enriched corrosion products, must come from the environment.

<ins>No. 10. 26106. High-flanged axe of the Oldendorf type, 225 g.</ins> Badstrup, Uggeløse sogn, Frederiksborg amt. About 1600-1500 B.C. This is a rather rough and clumsy-looking tool (Aner & Kersten 1973: 57). The cutting edge is badly notched, and the body is for unknown reasons heavily grooved parallel to the long axis of the tool. The alloy is low in tin and silver, lead is absent, but there is much sulphur, sulphides constituting about 5.5 volume percent. The sulphides are palmate-lobate, except in the heavily hammered edge and flanges, where they have been extended into slender 0.2 or 0.3 mm long strings. Etched sections display a cored structure with pinholes on which is superimposed a recrystallized, twinned α-structure. No δ-phase is present, due to the low tin content of 6%. The bulk hardness is only about 75, but in the edge and flanges it increases to 134. There are numerous slip lines in the coldworked, unannealed α-grains of the edge.

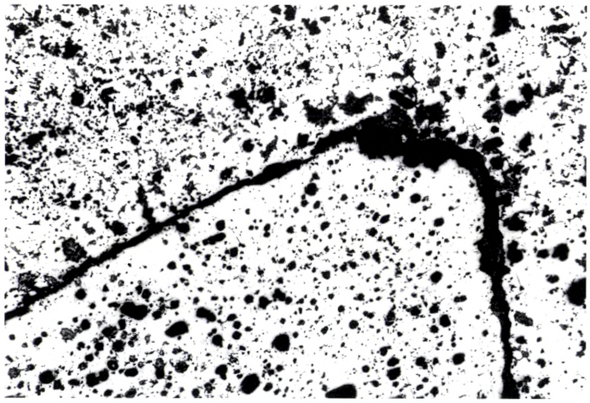


Fig. 37. PS through the joint between part A (bottom) and part B in the Hallenslev lur, No. 15 505. There was never established a metallic contact over the junction. Side 3 mm. Buchwald & Leisner 1990.

<ins>No. 11. B 15505. The Hallenslev lur.</ins> Hallenslev sogn, Holbæk amt. 1100-900 B.C. The Hallenslev lur was found in 1961 in several fragments (Broholm 1962). A 1.2-1.5 mm thick fragment, which comprised the soldered joint between two adjacent tubes, was examined. Analytically the tube is a low-tin bronze with significant impurities of arsenic, antimony and nickel. It is a reddish-yellowish alloy with interdendritic micropores from casting. Sulphides occur as 5-15 μm blue subangular blebs. Many interdendritic cavities are filled with copper oxides from corrosive attack, and many of these have segregated minute copper particles due to destannification. The etched sample shows a cored casting without δ-phase, in accordance with the low tin content. The hardness is only 62, in agreement with the annealed condition of a copper alloy low in alloying elements.

When the lur was originally assembled, the ends of two tubes, B and C, were cut to meander shape and positioned firmly about 20 mm apart. Then a mould was constructed à cire perdu so that an annular connecting link, A, could be cast. This reinforcement in thickness and the mechanical interlocking served well to fasten

Fig. 38. A pair of lurs from Brudevælte Mose, Fuglerup Gård, 2 km north of Lynge, Sjælland. Courtesy the National Museum, Copenhagen.

the tube parts securely. Contrary to general opinion, there has never been established a metal-to-metal contact. Instead a 2-3 μm thick Cu_2S layer covers the surfaces to be joined. Nevertheless, the joints were strong, and the later fragmentation took place away from the joints.

The annular link, A, differs from the alloy of the tube, B, in its significantly higher tin, arsenic, and sulphur content. It appears that the smith has purposefully added tin to the tube alloy in order to create a lower-melting, free-running alloy, which would be well suited for the assembly process. The solidus line of alloy A may have been about 75°C lower than that of B. No parts of the examined specimens have been worked after casting.

<u>No. 12. B 17482. The Ulvkær lur No. 2.</u>Tornby, Horne sogn, Hjørring amt. About 700 B.C. This is one of a pair of lurs found in 1988 by peat digging (Lysdahl 1990). The fragment here examined has suffered somewhat from the bulldozer which first brought the lurs to the light of day. The thickness of the cast plate is only 1.0 mm, proving the skill of the ancient smith. Analytically, this lur is very different from the older one, being a high-tin bronze, rich in lead and sulphur. Polished sections show a yellow, dendritic alloy with many microporosities. The blue sulphides are conspicuous as blebs and palmate inclusions, constituting about 5 volume percent. Etched sections display a beautiful cored casting with substantial amounts, about 20 volume percent, of bluish-grey δ-phase. Lead occurs as 20 µm rounded blebs associated with the δ-

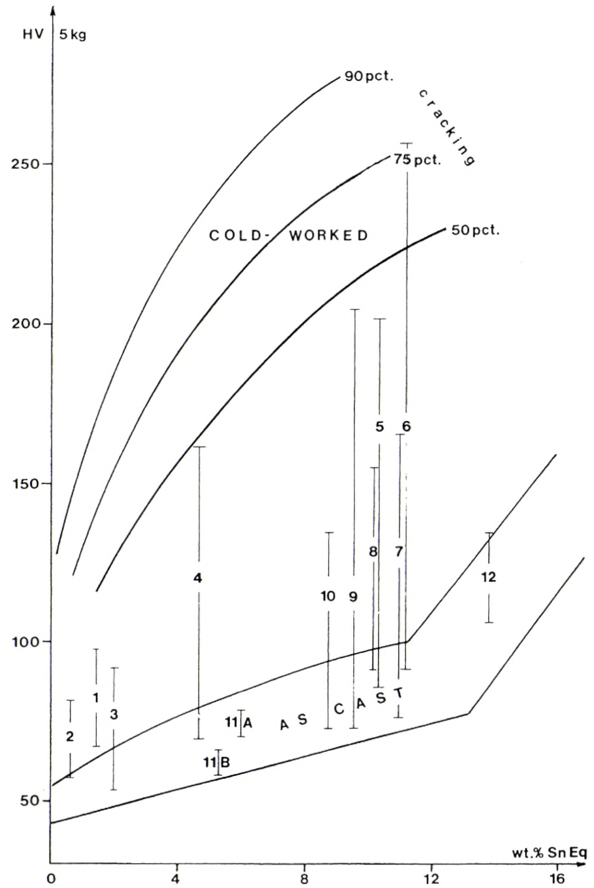


Fig. 40. Vickers hardness (5 kg) of 12 bronze objects superimposed on a diagram of hardness data for cast, coldworked and annealed tinbronzes. The lurs Nos.11 and 12, e.g., were only cast and have hardnesses in the lower band, while, e.g., the axe No. 4 in its coldworked parts show a hardness of 160, corresponding to about 50% coldwork, and in its annealed parts fall back to the lower band. Buchwald & Leisner 1990.

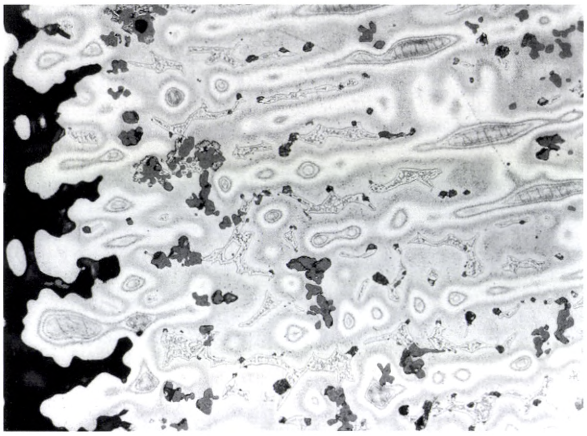


Fig. 39. PES through the Ulvkær lur, B 17482. Due to the high tin content (13%) the delta-phase is prominent as dotted, interdendritic islands. The dark inclusions are copper sulphide. Side 0.5 mm.

phase and the sulphides. The copper sulphide is as usual of the Cu_2S type with 1.2 to 3.6% iron in solid solution. The iron content of the adjacent metal phases is below the detection limit of 0.05%.

The Ulvkær lur represents a new alloy type which is rich in tin, lead, and sulphur, and poor in nickel and antimony. The casting succeeded very well, and no further hammering or annealing has taken place on this part of the lur, which is the circular end plate.

Fig. 41.A 69 g spiral-ornamented beltplate, B 3238. Corrosion has, in particular, attacked the coldworked ornaments. Scale in cm.

The following two objects are women's beltplates from about 1300-1200 B.C. They were found in Danish moors, but the exact localities are unknown, for which reason I was permitted to examine them and cut small samples for embedding and polishing. The beltplates are very similar, so what is said of No. 13 is equally valid for No. 14. The main reason for their examination was the argument whether the spiral ornamentation was engraved or already prepared in the mould, see Rønne (1988).

No. 13. B 3238. Spiral-ornamented beltplate, 69 g. Denmark, about 1300-1200 B.C. The beltplate is 114 mm in diameter, 1.6 mm thick in the centre and 0.8 mm thick along the periphery. Local corrosion has penetrated the plate, but when received all corrosion products had already been cleaned away. A section was cut radially right to the centre. The alloy is tin-rich, about 12% Sn, and had in the cast condition been cored with many inclusions of the tin-rich δ-phase (with 0.8% Ni and 0.1% Fe). Due to repeated hammering and annealing, the coring has disappeared, and the volume of the δ-phase has been reduced to equilibrium values. The matrix has recrystallized to 50-100 μm equiaxial α-grains and the ubiquitous sulphides ($(Cu,Fe)_2S$ with up to 8%Fe) have been rotated and elongated according to the hammer strokes. The hardness increases from 126 in the almost unworked centre to 215 in the peripheral parts where extensive working has stretched and thinned the plate. A close inspection shows that the plate material has been work-hardened under the spiral grooves. Here the matrix has recrystallized to a depth of 0.2 mm. Thus, after the beltplate had been cast and hammered to its final shape, engraving – applying a bronze chisel or a flint tool – induced local additional coldwork under the spiral grooves. The recrystallized α-grains are here very fine, about 25 μm, because of the heavy deformation. The corrosion attack is particularly intensive in the most heavily deformed zones. The conclusion is that the beltplate was cast as a rather massive plate. On the back, an eye was cast in for fastening. Then the exterior parts were hammered and annealed several times until the thin disk shape was reached. Finally, the engraving took place, followed by some slight annealing of the whole work. This explanation is in accordance with the opinion already expressed by Sophus Müller (1897: 257).

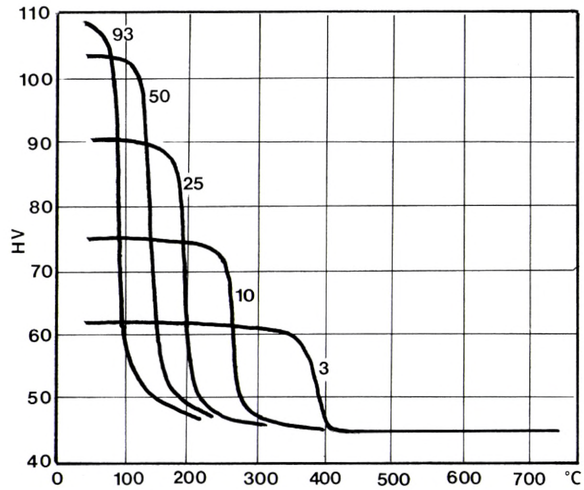


Fig. 43. The recrystallization temperature of deformed metals is dependent on the previous degree of deformation. Here shown for electrolyte copper, first deformed 93%, 50% etc. The recrystallization temperature after, e.g., 25% colddeformation, is 200°C. The recrystallization temperatures for tinbronzes lie higher.

Fig. 42. A spiral-ornamented beltplate of 334 g, B 1090. The artistic mastery is displayed in the beautiful and precise ornamentation, which was probably performed with a bronze or flint tool. Side length 75 mm.

Table 2.2. Analyses of copper alloys. Weight percent. Copper by subtraction.

No.	Mrk.	Sn	Zn	S	Fe	Ni	As	Ag	Sb	Pb	Cu	HV 100g	Date	Type
1	B 2926	<0.1	-	<0.1	<0.05	<0.05	1.4	<0.1	<0.1	<0.1	98.4	66-97	2700	axe
2	B 5556	<0.1	-	<0.1	<0.1	<0.05	0.47	<0.1	<0.1	<0.1	99.3	57-81	2700	axe
3	B 1094	<0.1	-	0.11	<0.05	0.08	0.50	0.9	0.4	<0.1	97.8	53-91	1800	axe
4	11073	2.1	-	0.15	<0.05	0.74	0.36	0.7	0.8	<0.1	95.0	69-161	1800	axe
5	26073	8.8	-	0.35	0.08	0.37	ab.1	0.09	0.22	<0.1	89.5	85-201	1700	axe
6	21075	8.8	-	0.15	<0.05	0.74	ab.1	0.22	0.5	<0.1	88.5	91-257	1700	axe
7	B 4077	9.4	-	0.40	<0.05	0.37	ab.1	<0.1	0.18	0.9	88.0	76-165	1600	axe
8	B 5564	8.4	-	0.23	0.12	0.46	ab.1	0.16	0.28	1.2	88.2	91-155	1600	axe
9	B 3971	8.0	-	0.25	0.05	0.49	ab.0.8	<0.1	0.28	0.5	89.5	72-204	1500	axe
10	26106	6.0	-	1.1	<0.05	0.15	ab.0.7	0.07	1.9	<0.1	90.0	72-134	1500	axe
11	15505B	2.4	-	0.1	<0.1	0.47	0.8	<0.1	1.5	<0.1	94.5	58-66	1000	lur
11	15505A	4.0	-	0.4	<0.1	0.70	1.2	<0.05	1.4	<0.1	92.2	70-78	1000	lur
12	B 17482	13.1	-	1.0	0.10	0.11	0.5	<0.1	<0.1	3.0	82.1	106-134	700	lur
13	B 3238	12.4	-	1.0	0.3	0.4	<0.1	<0.1	<0.1	<0.1	85.8	126-215	1200	plate
14	B 1090	10.3	-	0.6	0.1	0.7	0.3	<0.1	<0.1	<0.1	87.9	-	1200	plate
15	B 16101	13.2	-	0.6	0.1	0.9	<0.1	<0.1	<0.1	0.7	84.4	61-192	1100	palst.
16	B 8861	12.2	-	0.6	<0.1	0.6	<0.1	<0.1	0.4	0.6	85.5	76-150	1100	palst.
17	13917	11.7	-	0.8	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	87.2	108-169	900	sword
18	B 2349	4.7	-	1.0	<0.1	0.2	0.4	0.3	1.1	6.0	86.3	49-142	900	sword
19	8863	6.9	-	0.6	<0.1	0.2	<0.1	0.2	0.3	0.4	91.3	59-143	800	celt
20	16	8.7	-	0.8	0.1	0.1	<0.1	0.3	0.4	0.2	89.3	148-159	650	shield
21	H 2156	7.5	-	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	92.2	-	500	mirror
22	H 2170	10.3	-	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	89.4	-	400	mirror
23	114834	-	-	-	-	-	-	-	-	-	99.7	-	+40	nail
24	B 4877	<0.1	-	0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.2	99.5	61-62	500	westl.
25	SH24845	<0.1	-	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	99.8	86	500	eastl.
26	B 4386	10.0	1.4	0.2	0.1	<0.1	<0.1	0.1	<0.1	3.6	84.5	146	500	westl.
27	C 22608	12.7	-	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	2.1	84.9	202	500	westl.
28	C 28300	2.2	14.4	0.8	0.3	<0.1	<0.1	<0.1	<0.1	0.2	82.0	161	600	bowl
29	C 3607	4.1	16.9	0.2	0.5	<0.1	<0.1	<0.1	<0.1	0.5	77.7	169	600	bowl
30	C 148	2.8	25.0	<0.1	0.4	<0.1	0.3	<0.1	<0.1	ab.5	ab.66	-	900	bowl
31	C 10123	2.4	18.9	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	3.0	75.3	-	900	bowl
32	C 1961	5.4	11.4	0.1	0.2	<0.1	<0.1	<0.1	<0.1	1.8	81.0	-	900	bowl
33	C 1068	9.4	-	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	3.0	87.5	-	900	bowl
34	C 25596	10.8	0.3	0.1	0.1	<0.1	<0.1	<0.1	<0.1	2.8	85.8	-	960	bowl
35	C 24308	12.1	1.4	0.3	0.2	<0.1	<0.1	<0.1	<0.1	1.7	84.2	110-130	900	bowl
36	255	8.5	-	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	11.0	80.2	-	1300	kettle
37	Bell 462	22.8	-	n.d.	0.1	<0.1	0.1	0.1	<0.1	0.6	76.2	250	1350	bell
38	Gun 200	6.5	0.6	n.d.	0.5	0.2	0.4	0.1	0.6	2.8	88.3	65-70	1650	cannon
39	Gun 261	10.1	1.7	n.d.	<0.1	<0.1	0.2	<0.1	<0.1	0.3	87.4	75-80	1762	cannon
40	Spring	<0.1	22	<0.1	<0.1	18	<0.1	<0.1	<0.1	<0.1	59.9	100-225	1980	alloy

Fig. 44. A palstave, i.e. a bronze axe from about 1100 B.C. B 16 101, 264 g, 13 cm long.

No. 14. B 1090. Spiral-ornamented beltplate, 334 g. Denmark, 1300-1200 B.C. The beltplate is better preserved than No. 13. It is 1.8 mm thick near the centre, but has been thinned by hammering to 1.0-1.1 mm along the periphery. The alloy is similar to No. 13, but with less tin. The structure displays recrystallized α-grains, 50-100 μm across, in which there are numerous elongated $(Cu, Fe)_2S$ particles (1.6% Fe). The δ-phase has entirely disappeared due to the relatively low tin-content and the numerous annealing operations. Slip lines in the recrystallized α-grains under the spiral grooves bear witness to cold-deformation from the engraving operations.

An inner 10 μm thick, green corrosion layer is tin-rich and has the composition 22% Cu, 8% Si and 70% Sn, while an exterior 20 μm thick, brownish corrosion layer has the composition 11% Cu, 12% Fe, 6% Si, and 71% Sn. The microprobe could not determine O, OH, and CO_3, so the exact nature of the corrosion products is unknown, but silicon and most of the iron almost certainly have been introduced from the surroundings.

No. 15. B 16101. Palstave, 264 g. Denmark, about 1100 B.C. The total length is 130 mm and the width over the edge 40 mm. The edge is rather sharp with small bruises from intensive use. The palstave is covered by olive-brown corrosion products and there are numerous corrosion pits, 1-3 mm across.

No. 16. B 8861. Fragment of a palstave, 165 g. Denmark, about 1100 B.C. An ancient fracture has removed half of the palstave, leaving only the cutting part. It is now 70 mm long and 30 mm wide over the

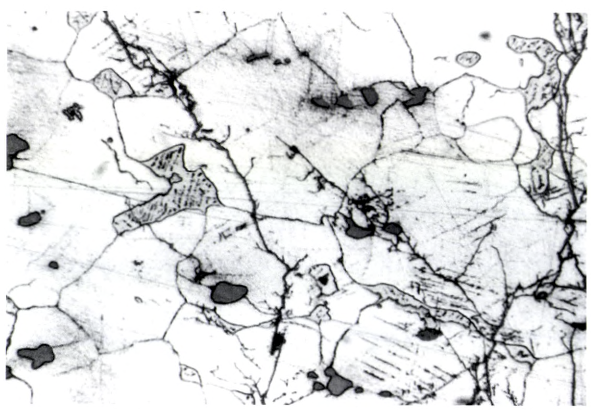


Fig. 45. PES through the palstave Fig. 44. Alpha-phase (white), delta-phase (dotted), and Cu_2S particles (dark). Stress corrosion (fine, branching lines) penetrate mainly along the sliplines. Side length 0.16 mm.

edge. The chemical composition, Table 2.2, is very similar to the previous sample and to two other palstaves, 30 B of 191 g, and 26098 of 259 g, which were also examined in this study. They are thus slightly richer in tin than eleven British palstaves which were metallographically described by Coghlan (1967).

No. 17. 13917. Sword fragment, 106 g. From the vicinity of Viborg, Denmark. About 1000-800 B.C. The fragment includes the tang and is only 195 mm long, but two thirds, including the point are now missing. Ancient scars have ruined the edges, and severe pitting corrosion has locally developed the dendritic coring from the casting operation.

No. 18. B 2349. Sword fragment, 169 g. Denmark, about 1000-800 B.C. The fragment is 134 mm long and includes a part of the hilt, all cast in one piece. The hilt has holes for nails which may have helped in fastening the non-metallic parts of the hilt (bone, wood, leather?).

No. 19. 8863. Celt, 121 g. Denmark, 900-700 B.C. The celt is of a simple, undecorated shape and has an eye for fastening to the shaft. It is 60 mm long and 41 mm wide over the cutting edge. The stereomicroscope

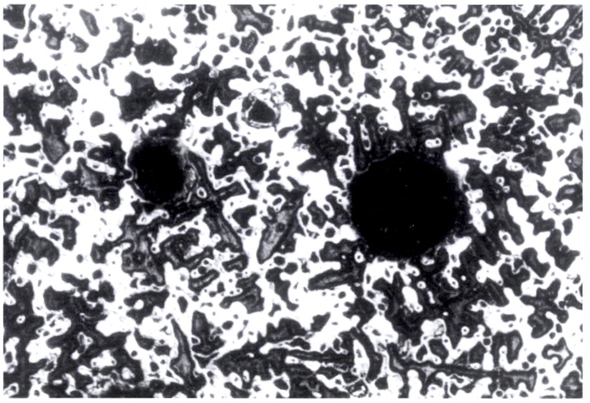


Fig. 47. PES through the broken sword, Fig. 46. The segregated structure and the many porosities suggest that the sword after casting was only subjected to a minimum of hammering and heat treatment. Side 2 mm.

reveals remains of a wooden shaft in the hole. This is provided with two inner ribs, formed in the original mould. The ribs are either casting fins, or, rather, meant to assist in securing the shaft.

No. 20. 16 II : 72. Bronze shield, fragment. Fröslunda, Skaraborg Län, Sweden, 700-600 B.C. A hoard of 16 unique shields was excavated in 1986 on the Kålland

Fig. 46. A broken bronze sword, B 2349, from about 900 B.C. It is low in tin (4.7%), but unusually high in lead (6%), which is not particularly good for a sword. Length 13 cm.

Fig. 48. A 6 cm long, simple bronze celt, No. 8863, about 800 B.C. Weight 121 g.

peninsula in Lake Vänern (Hagberg & Jacobzon 1986; Hagberg 1996). The shields are of the so-called Herzsprung type and supposedly a product of the Hallstatt culture. By the kind cooperation of Prof. Birgit Arrhenius, Lund, a fragment of shield No. 16 could be included in this survey. Also tiny, corroded fragments of shields Nos.3 and 5 were cursorily examined. The No. 16 fragment is 4 x 3 mm and max.0.2 mm thick. Apparently this is the original thickness, since little has been lost by corrosion. This shield has 8.7% tin, while the small fragments of shields 3 and 5 have respectively 10.6 and 7.5% tin. The other components are similar for the three shields. As is usually the case with Bronze Age objects, sulphur is present as conspicuous coppersulphide particles, which have been heavily stretched by the hammering operations, compare the beltplates Nos.13-14. The bronze has a springy character, and little annealing has taken place. The hardness is 148-159 (HV 100 g).

<u>No. 21. H 2156. Etruscan mirror, 412 g.</u> About 500 B.C. Now in Thorvaldsens Museum, Copenhagen. The circular part is 140 mm in diameter and 4 mm thick. The handle was lost in antiquity. One side is engraved with a winged Hermes with a cauldron in his hands.

<u>No. 22. H 2170. Etruscan mirror, 269 g.</u> About 400 B.C. Now in Thorvaldsens Museum, Copenhagen. The circular part is 147 mm in diameter, and the handle is preserved. The weight is, nevertheless, lower than that of H 2156, because the average thickness of the circular part is only 2 mm. One side is engraved with a scene displaying a hero attaching his leg mail while three other persons watch him. A rather substantial inner, active corrosion layer contains equal amounts of tin and copper (3.5 weight% each), and chlorine (0.5%). The exterior layer is tin- and chlorine-free and apparently a basic copper hydroxycarbonate. The composition of the two mirrors resembles analyses presented by Riederer (1987 : 116).

<u>No. 23. 114834. A copper nail from the Roman ship in Lake Nemi, southeast of Rome, 66 g.</u> About 40 A.D. A ship or a pram, built for Emperor Caligula's festivities, lost in Lake Nemi about 40 A.D. and recovered in the 1930s (Ucelli 1950). A large number of copper and iron nails have survived, and this 66 g nail is one of the surviving copper nails. It is forged square, 103 mm long and up to 10 mm thick. It is of 99.7% pure copper and consists of equiaxial twinned α-grains (Ucelli 1950). It is not quite certain whether this was the original structure, since the nail suffered from the cata-

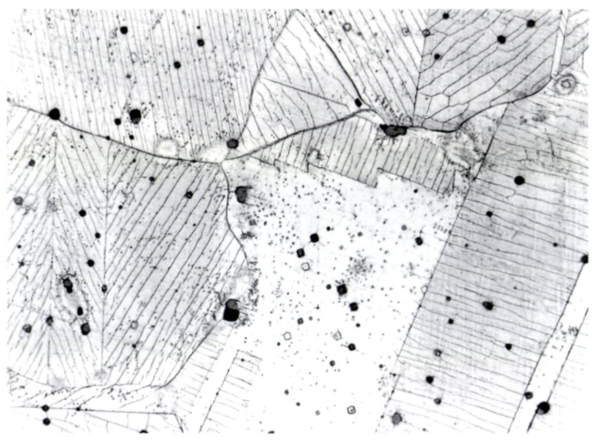


Fig. 49. PES from an Etruscan mirror, Thorvaldsens Museum H 2156, about 500 B.C. Numerous etch pits have shapes according to the orientation of the twinned alpha-grains. Side length 0.2 mm.

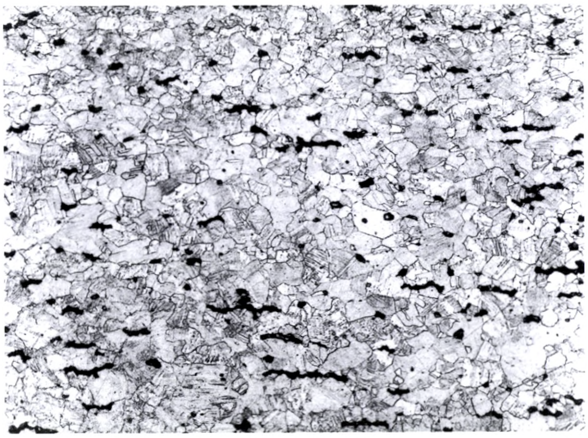


Fig. 50. PES through a bronze cauldron, a socalled Vestlandskedel, C 22 608, from about 500 A.D. The alpha-grains are finely recrystallized, and the lead inclusions have been extended along the forging directions. The delta-phase has been dissolved. Side 0.5 mm.

strophic fire that destroyed the ships in the museum in 1944. The nails were recovered from the ashes on the museum floor, Fig. 108.

The following numbers 24-29 are small fragments from cauldrons or vessels produced in the Germanic Iron Age and the early Viking Age (400-800 A.D.). These and several other cauldrons have been analysed for trace elements by Haldis Bollingberg (pers.comm.).

<u>No. 24. B 4877. Fragment of a vessel for mixing wine.</u> Bergen Museum, Norway, 400-800 A.D. The vessel is 0.45 mm thick and produced from virtually pure copper. The material is tough and could not be broken by repeated bending, i.e.corrosion has had little effect. The etched section displays 50-100 μm wide α-grains with well developed twinning. Lead is present as discrete 2-10 μm pearls and sausages. Small copper sulphide grains, 2-3 μm across, are also present. Repeated hammering and annealing has resulted in rather soft (61-62 HV) recrystallized metal.

<u>No. 25. SHM 24845. Fragment of a cauldron, a so-called Østlandskedel.</u> (Rygh 1885 Fig. 352; Broholm 1960:169; Trotzig 1991). Statens Historiska Museum, Stockholm, 400-800 A.D. The vessel is 0.27 mm thick and of a copper quality still more pure than No. 24. Lead inclusions and sulphides are rare, but they do apparently contain a little selenic (1-2 weight%). The metal displays recrystallized α-grains, 10-30 μm across, with well developed twinning. The vessel is only partially annealed after the last hammering, showing the rather high hardness of 86 HV.

<u>No. 26. B 4386. Fragment of a cauldron, a so-called Vestlandskedel</u>. (Rygh 1885 Fig. 353; Broholm 1960:169). Bergens Museum, 400-800 A.D. The Vestlands kettles are characterized by their peculiar shape. The type was produced from about 100 to 800 A.D. and was common in North and Western Europe. This vessel is 0.45 mm thick and strong, despite the severe corrosion attack. It is a 10% tinbronze with 3.6% lead and 1.4% zinc. The structure displays equiaxial α-grains, 25-50 μm across, with twinning. Near the surface some twinned grains are extra deformed due to late coldhammering. The hardness is 146 HV, suggesting incomplete annealing.

<u>No. 27. C 22608. Fragment of a cauldron, a so-called Vestlandskedel.</u> National Museum, Copenhagen, 400-600 A.D. The vessel is 0.4 mm thick. It is tin-and lead-rich, but zinc is absent, and sulphur is the lowest of all

Fig. 51. PES through a tombak cauldron for a footbath, C 28 300, about 600 A.D. Fine grained. twinned alpha grains.The surface corrosion mainly follows the slip lines. Side 0.7 mm.

the cauldrons. The metal is very fine-grained, displaying 8-20 μm slightly elongated α-grains with many twins. The repeated hammering and annealing operations have removed any trace of the tin-rich δ-phase. The last annealing operation was followed by coldworking, leaving the vessel very springy, in spite of the significant lead content. A greenish corrosion layer is significantly enriched in tin (68% Sn, 15% Cu, 2% Pb, 3.5% Fe etc.)

No. 28. C 28300. Cauldron for a footbath. National Museum, Copenhagen. 400-800 A.D. The plate thickness is 0.7 mm, but the plate is easily broken, because corrosion has penetrated along the sliplines, creating a corrosion grid. The metal is a brass with 2% tin, a tombak type. It is severely deformed, displaying 5-50 μm α-grains with dense twinning and sliplines. After a final annealing, additional cold deformation has given springiness and a hardness of 161 HV (100 g). Sulphides are very common as elongated, parallel and broken inclusions, typically 10x3 μm in size. The sulphides are zinc-rich, with more zinc than copper, of the type $(Cu,Zn)_2S$.

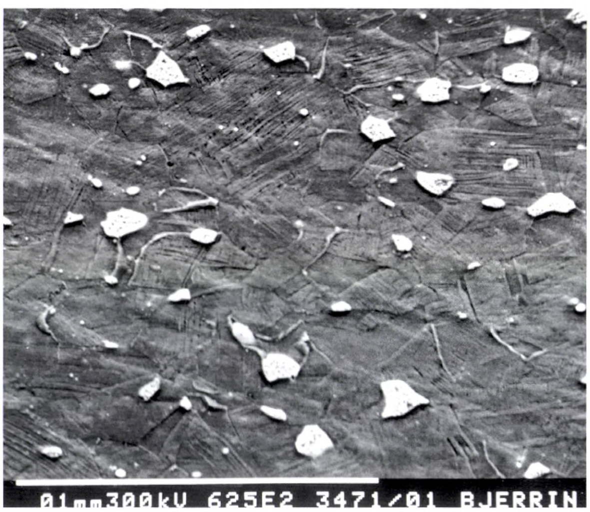


Fig. 52. Scanning electron micrograph of a brass vessel from Bjerringhøj, C 148, about 900 A.D. The lead inclusions (white) stand in contrast to the recrystallized alpha-grains with slip lines. Scale bar 0.1 mm.

No. 29. C 3607. Cauldron for wine-mixing. The National Museum, Copenhagen, 400-800 A.D. The plate thickness is 0.8 mm. The metal is a tin-containing tombak type like No. 28, but with more lead and less sulphur. Iron is rather high, present in the metallic α-phase as well as in the many zinc-copper sulphides. Late coldwork has left the 10-20 μm recrystallized α-grains somewhat distorted, displaying springiness and the relatively high hardness of 169 HV. The corrosive coating consists of distinctive blue layers of pure copperhydroxycarbonates and greenish zinc-lead-containing layers.

Fragments from the following six vessels, Nos.30-35, were kindly provided by Olfert Voss, The National Museum, Copenhagen.The vessels are of the same shape, with a horizontal top brim. Further vessel fragments from the Ladby boat grave, Møllemosegård, Skindbjerg and Trelleborg, were too corroded to be included in this analytical-metallographical study. The vessels are dated to the Viking Age, about 900-1000 A.D.

No. 30. C 148. Fragment of a vessel. Bjerringhøj, Denmark. 900 A.D. (Vellev 1991). The vessel has a plate thickness of 0.4 mm. The metal is a strong and dense brass quality with some lead, tin, iron and arsenic. The lead occurs as up to 15 μm blebs, and was by planimetry estimated to about 5 weight%, the most we have seen in the present study of the cauldrons. Evidently even this high lead content did not interfere with either coldworking or annealing in the production stage.

No. 31. C 10123. Fragment of a vessel. J.Br.55. Give, Denmark, 900 A.D. The plate thickness is about 0.5 mm. The metal is a tin-containing tombak with significant lead and some iron. The lead occurs as irregular rounded inclusions up to 40 x 7 μm. The lead leaves gaping holes in the corrosion layers. The small number of sulphides are associated with the lead globules – or vice versa. The metal displays recrystallized α-grains, 50-100 μm across, with numerous annealing twins. A corrosion grid is common in the object's surface layer.

Fig. 53. "Lion" head from the mounts of a harness-bow, about 900 A.D. National Museum No. 5254, unknown place of find. Compare Näsman 1991. Side length approximately 7 cm.

No. 32. C 1961. Fragment of a vessel. Chamber grave 14.10.06, Hørning, Denmark, 900 A.D. The plate thickness is about 0.5 mm. In composition it lies between Nos.30-31 and Nos.33-35, displaying 5.4% tin and 11.4% zinc. Some lead, iron and sulphur are also present. The metal is recrystallized with twinning, displaying 10-25 μm α-grains with severe corrosion.

No. 33. C 1068. Fragment of a vessel. Grave 13.07.09, Mammen, Denmark. 900 A.D. Severe corrosion leaves only limited metallic areas for inspection, so the data are not of good quality. The cauldron is apparently a 9% tinbronze with 3% lead and few other elements. The δ-phase has been dissolved due to repeated hammering and annealing.

No. 34. C 25596. Fragment of a vessel. Grave 8.02.17, J.Br. 79, Søllested, Denmark. 960 A.D. Also this cauldron is severely attacked by corrosion. Its composition and structure are similar to the previous one, No. 33. Chlorine is as usual present in the corrosion products on the level of 0.4-0.5 weight%, and the corrosion attack is still active.

No. 35. C 24308. Fragment of a vessel. Male grave with weapons, 13.01.04. Fly, Denmark. 900 A.D. The plate thickness is 0.5 mm. In composition it is similar to Nos.33-34, but has slightly more tin, zinc, sulphur and iron. The structure displays equiaxial α-grains 50-100 μm across with numerous twins. The δ-phase has been dissolved during the hammering and annealing operations. Elongated copper (zinc) sulphides are common as 10-15 μm inclusions.

The following general comments concern the belt-plates, Nos. 13-14, and the vessels, Nos. 24-35, covering a period of more than 2000 years. Tin-rich bronzes, with 10-12% tin, were used both in the older Bronze Age and in the Viking Age, but in the Bronze age alloys zinc was never present and lead was rare. From about the birth of Jesus Christ, zinc became a common alloying element. It was, e.g., also introduced in the Roman coins, first in Anatolia about 50 B.C. Zinc was added to the copper smelt as galmeje (= calamine), which is a mineralogical cover name for indefinite mixtures of hemimorphite, $H_2Zn_2SiO_5$, hydrozincite, $Zn_5 [(OH)_3CO_3]_2$, smithsonite, $ZnCO_3$, and willemite, $(Zn,Mn)_2SiO_4$. In reducing smelting, the zinc was extracted from the minerals and transferred to the copper smelt. Zinc as a free metal was, in Europe, first isolated in the 18th century (Weeks 1968).

The alternative to tin bronzes was a tombak, with 10-20% zinc, or a brass, with 20-35% zinc, and these alloys became common in the Roman Iron Age and later. As may be seen from the data, some tin and lead were usually present also, while sulphur and iron occurred on a low, but significant level. The objects were cast as billets or plates and were shaped by repeated hammering and annealing. Where lead was present on a high level, hot forging was hardly applied, because lead is liquid at forging temperatures and quite a risk in α-copper-zinc and α-copper-tin alloys. Hammering and annealing removed all porosities (almost), coring and segregation, and the tin-rich δ-phase was dissolved. The sulphides became stretched and now reveal the "forging" directions. The metal itself, on the other hand, after final annealing developed equiaxial α-grains of uniform size, telling nothing of former smithing work. The craftsman may by some final coldwork have added hardness and springiness to the plate or vessel. The hardness is the best way of evaluating the degree of final coldwork. When lead is well distributed as small particles it does not detract from the springiness or ductility of the metal.

Decorations could not be applied to the mould, but had to be added after the desired shape had been attained. It must have been quite a job to coldwork the 10-12% tin bronzes. In modern practice it is unusual to cold-roll alloys with more than 10% tin, and even this requires heavy machinery.

<u>No. 36. Kettle, "malmgryde" for cooking purposes.</u> Møntergården, Odense, about 1300 A.D. A section was removed from the heavy, cast cauldron. It is a straight tin-lead-copper bronze, with more lead than tin, and a little sulphur. The cast, unworked structure is coarsely dendritic, with a significant δ-phase in the interstices. The lead is present as a large number of conspicuous, dark inclusions, often associated with the δ-phase. The presence of lead as an alloying element secures that the cast object has a minimum of porosities. On the other hand, the presence of lead in kitchenware was a rather risky affair, but most objects were anyhow tinned on the food-side.

The casting of mediaeval bronze kettles in Denmark and northern Germany has been studied by Vellev (1988).

The last four items of Table 2.2 are included from the literature in order to carry typical copper alloys up to our own time with appropriate examples. Nos. 37-39 are from Forshell (1984; 1992), while data for No. 40 have been extracted from catalogues from the Nordiske Kabel- og Trådfabrikker, Copenhagen.

<u>No. 37. Church bell 462.</u> Vätö Church, Uppland, Sweden, about 1350 A.D. Now in Statens Historiska Museum, Stockholm (Forshell 1992). The bell is 72 cm wide at its opening and of Roman-Gothic type. The purity of the metal suggests the use of virgin copper, tin and lead, or thoroughly refined bronze scrap. The bell composition, with 22-24% tin and about one percent lead, was typical of large church bells. Today the amount of lead is smaller. The high tin content results in a structure with major proportions of the hard, intermetallic δ-phase, $Cu_{31}Sn_8$. The texture secures a low damping capacity and gives the bell a pleasant sound. Whether the presence of 0.1% silver (a donation from the church congregation?) contributes to a pleasing timbre is an unsolved question.

Fig. 54. Copper oxhide ingot from Enkomi, Cyprus, about 1200 B.C. Weight 39.3 kg, length 72 cm. Cyprus Museum, Nicosia. No. 1939/VI.204/4.

No. 38. Bronze cannon, no.200, 12-pounder. Founder Franz Roen, Glückstadt, Denmark, 1650 A.D. The heavy, 1475 kg gun was taken as war booty and is now in the Armémuseum, Stockholm (Forshell 1984). The analysis is the average of three analyses (bore-chips) taken from the muzzle, the central part and from the button. Franz Roen cast 25 cannon between 1645 and 1654, mainly 12-, 18- and 24-pounders, and they have tin contents between 5 and 8%, lead between 2 and 4%, and zinc between 0.1 and 0.4% (Forshell 1992). The structure of No. 38 is estimated to be a coarse-grained cored α-tin bronze with a little δ-phase and numerous pockets of lead. The hardness is estimated at 65-70 HV.

No. 39. Bronze cannon, no.261, 6-pounder. Cast in Frederiksværk, Denmark, 1762 A.D. The analysis is the average of three samples, as above, from a 184 cm long gun, weight about 400 kg, and cast on the occasion of an impending war with Russia (Eriksen 1956). The analysis which is typical of a series of Danish guns from the late 18th century (Forshell 1992) is significantly richer in tin than No. 38, and the alloy is much purer with respect to iron, nickel, arsenic, silver, antimony and lead. It appears that Classen, the proprietor of Frederiksværk, used pure copper and tin for his cannon factory and abstained from using scrap metal. This may be corroborated by a note, to the effect that the factory in 1757 acquired a party of 20 skippund (ab.3,200 kg) copper and 5 centner (ab.250 kg) tin (Eriksen 1956). The structure of No. 39 is estimated to be a coarse-grained, cored, pure tin bronze with significant δ-phase and a hardness of 75-80 HV.

An interesting point is the relationship between cannon and church bells. While bells usually contain 18-24% tin, cannon contained 6-12% tin. We have often heard that the kings in emergency situations ordered the churches to give up one or more of their bells for the king's arm factories. King Frederik I thus called in more than a thousand bells for the Danish civil wars in the 1530'es (Vellev 1978). But what is rarely mentioned is that the government would have to add at least equal weight of copper or rather pure copper alloys, in order to arrive at the proper alloy composition for a gun. That is, the Royal Mint would have had to add a lot of copper coins to the molten bell bronze.

<u>No. 40. Modern nickel silver.</u> The Nordiske Kabel- og Traadfabrikker A/S, Copenhagen, 1980 A.D. The historic examples Nos.1-39 are concluded with a modern high-grade alloy, nickel silver (or Nysølv), which is a rather hard, corrosion-resistant alloy with an attractive silver-white colour. It is used for clinical and optical instruments and, since it can be rolled to acquire superior spring-qualities, it is much appreciated for relay contact springs in telecommunication. Here it is also essential that it is easy to solder and resistant to tarnishing. Present-day alloy control can keep unwanted elements well below 0.1%, and sulphur is not present in modern copper alloys. Incidentally, ancient copper and bronze artefacts of indefinite provenience should be tested for sulphur. If present, the object is hardly a modern imitation.

Chapter 3
Iron – a very special metal

O, Jupiter, let the entire Chalybean people perish, because they were the first to open the veins of the Earth and apply the hardened iron.

Quintus Lutatius Catulus, about 100 B.C. Beck 1891:543.

Iron is a common metal, constituting on the average 5 weight percent of the Earth's surface deposits, and overtaken only by aluminium, which is good for 8%. The two metals have a high affinity to oxygen and sulphur, so they always occur bound in various compounds as, e.g., hematite, siderite, pyrite, kaolininite, cryolite, and feldspars. In bauxite and laterite they occur together. The only exception is iron's rare occurrence as a native metal in a few basaltic rocks, as discussed in Chapter 1.

Iron is a very peculiar element and very different from the elements copper, silver, gold, lead, and tin,

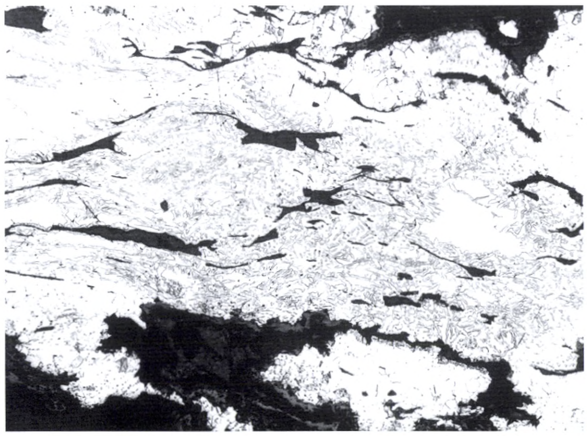


Fig. 56. Phosphorferritic, unequilibrated structure in a small, tongue shaped bar, 774-2, from Tommarp, Skåne, Chapter 12. PES. The black inclusions are production slags. Side length 2.5 mm.

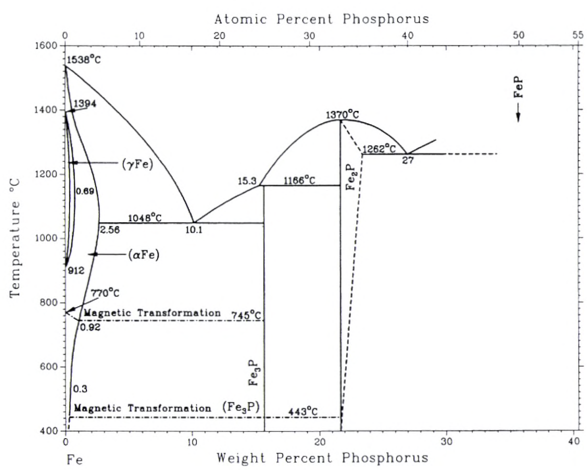


Fig. 55. The iron-phosphorus equilibrium diagram (Metals Handbook). Of interest to archaeology is only the left portion up to 3 weight percent phosphorus, see Fig. 171.

which were the first to be known among ancient people.

1. The melting point of iron is so high, about 1538°C, that it could not be melted until modern time, in the 19th century. Copper, silver, gold, lead, and tin were all known in molten form, and alloys could be prepared by mixing them in various proportions.

2. When heated, iron undergoes a phase transformation at 912°C. Here the low-temperature, body-centred cubic alpha-phase, called ferrite, transforms in an instant into the face-centred cubic gamma-phase, called austenite, which is the stable form up to about 1400°C. It is important to note that these two phases are ex-

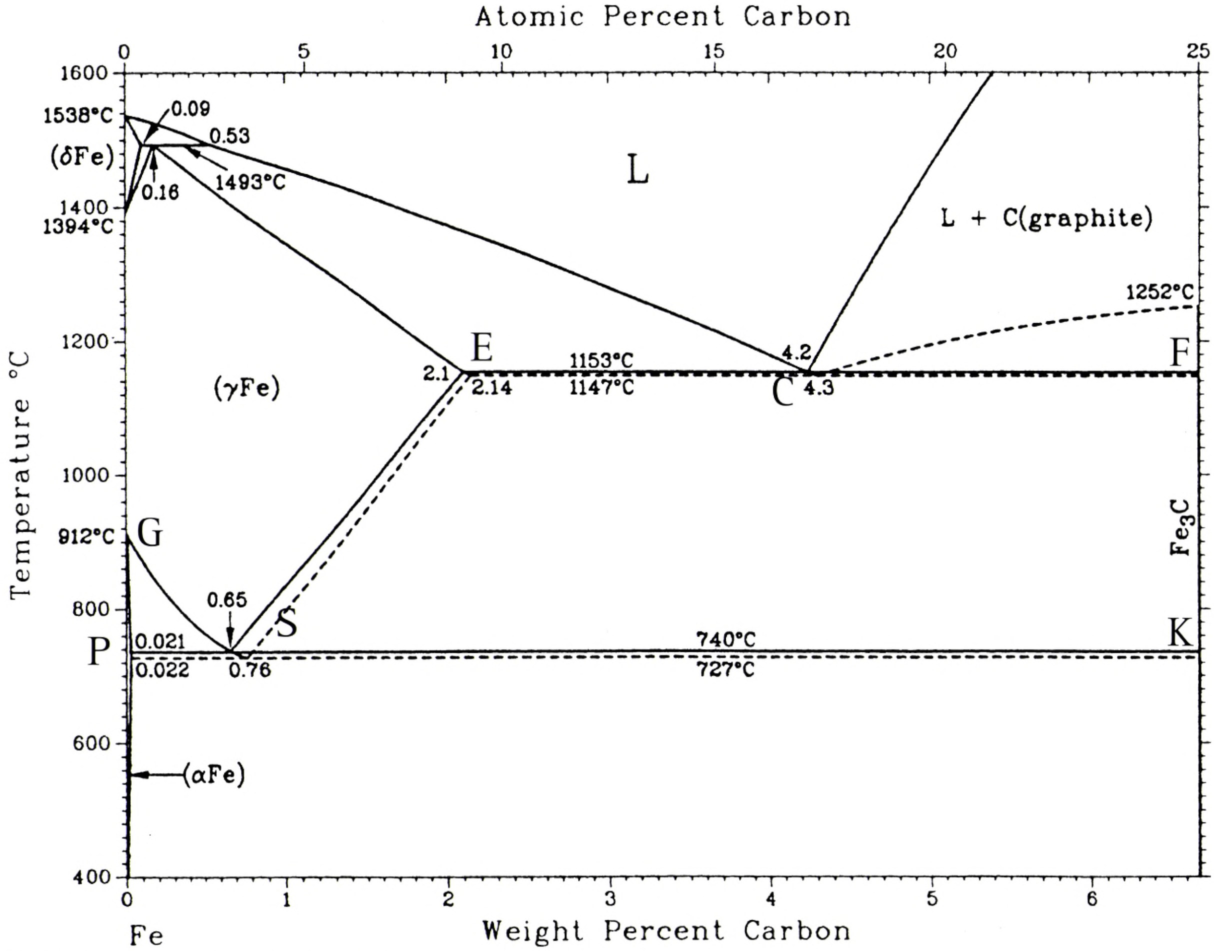


Fig. 57. The iron-cementite equilibrium diagram. American Society of Metals. 1992.

tremely different in physical as well as in chemical (alloying) respects. The ferritic phase is <u>the</u> iron which we all are familiar with. It is hard and somewhat related to other hard metals as chromium and molybdenum. The austenitic phase is on the other hand physically related to copper and silver. The austenite is malleable and ductile, and can, like copper and silver, with a minimum of effort be given bar, plate, tube or wire shape.

3. When cooled to room temperature, the austenite transforms back into ferrite, which is hard and stiff and difficult to work. With ancient methods, little could be done with cold iron, except in small dimensions like a nail or a knife. The blacksmith must have discovered these facts at the very beginning, more than 3000 years ago, so he knew that any shaping had to take place above red heat, best at 1000-1100°C, when, as we know now, iron was in its malleable, austenitic phase. He would continue his work until the material had lost its heat by radiation, i.e. had transformed back into ferrite, and if not finished, he would put the object back into the fire in order to recreate the malleable austenite. The Danish proverb "The Devil snatches seven coldsmiths every New Year's Eve"

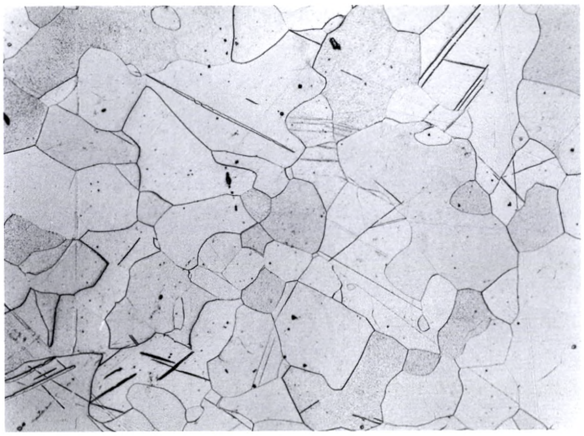


Fig. 58. Ferritic wrought iron with a few Neumannbands. Dokkfløy-vann 37 462 a. PES. Side 1 mm.

goes back to the knowledge and pride of the ancient blacksmith who detested any colleague who didn't understand how to "forge when the iron was glowing hot" (Publilius Syrus, Maxim 262, about 42 B.C.).

4. While white-hot in the austenitic phase, iron is rather easily joined to another piece of hot iron. Forge-welding can be done without flux, but quite often the blacksmith adds sand to facilitate the joining operation. The sand may be rather pure quartz sand, SiO_2, or crushed flint, or impure beachsand, but the active component is SiO_2. Under the reducing conditions on the hearth, this will react with the thin oxide films on the surface of the objects and combine to form fayalite: $2\ FeO + SiO_2 \rightarrow Fe_2SiO_4$. Above 1200°C fayalite is fluid and will be squeezed away under the hammer-strokes, leaving pure iron surfaces to be welded. As an example, consider an iron plate which must be transformed into a tube. It is heated and bent into tube form, and the overlapping edges are hammer-welded to a close fit, applying some sand to ease the joining.

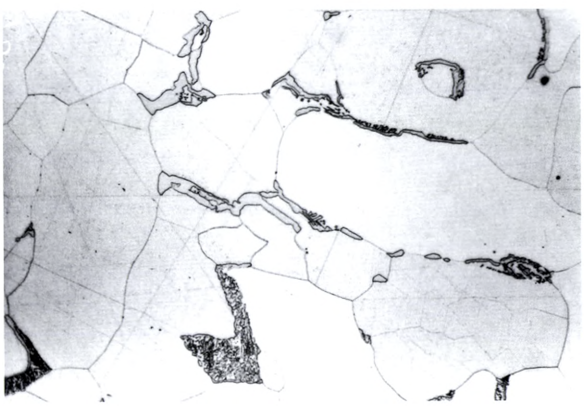


Fig. 59. Ferritic wrought iron with a little more carbon, 0.1%, with grain boundary cementite and a little pearlite. The development is typical for ancient irons that always had less than 0.04% Si and 0.04 Mn. PES. Oil immersion. Sønder Onsild axe. Side length 0.12 mm. Buchwald 1976.

5. Iron is attracted to a permanent magnet, but only while it is in the ferritic phase. At the so-called Curie Point, 770°C, ferrite loses its magnetic properties and soon after transforms into austenite, which is not magnetic. It is, however, not known whether this peculiar behaviour was of any significance in the early history of iron.

Fig. 60. Ferritic-pearlitic iron with about 0.35% C. A rather rapid cooling from about1000°C has resulted in the characteristic Widmanstätten structure. PES. Sønder Onsild axe. Side 1.1 mm.

6. The behaviour of one of iron's isotopes, Fe^{57}, is another of iron's peculiarities. In 1957, R.L.Mössbauer discovered a method to produce and measure gamma-rays with a very precise frequency, based on this iron isotope. This peculiarity was, of course, of no consequence for the blacksmith.

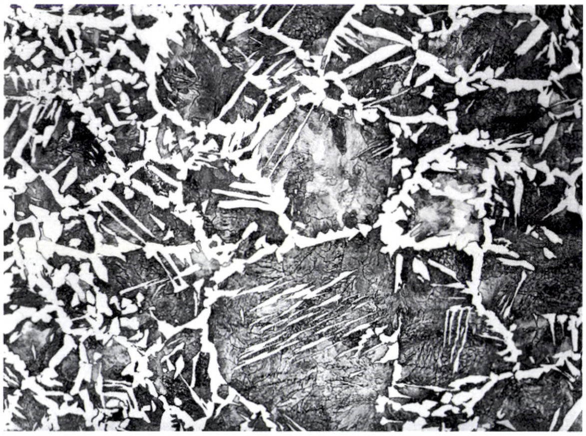


Fig. 61. Ferritic-pearlitic steel with about 0.45% C. A rather rapid cooling from about 1000°C has resulted in the Widmanstätten structure. PES. Sønder Onsild axe. Side 1.1 mm.

7. Due to the two allotropic forms of iron, its alloying behaviour is also peculiar. Of central importance to this work is ferritic iron's ability to dissolve up to 2.5 weight% phosphorus, while austenitic iron only dissolves up to 0.3% P. When an Fe-P alloy after forging, at say 1000°C, is cooled, new unequilibrated hard structures are formed, the so-called ghost structures. The exact appearance of the ghost structure under the microscope depends on the forging temperature, the bulk phosphorus content, and the cooling rate. Basically the ghost structure consists of unequilibrated ferrite with overlapping distinct and indistinct grain boundaries, and with significant variations in the phosphorus content from grain to grain.

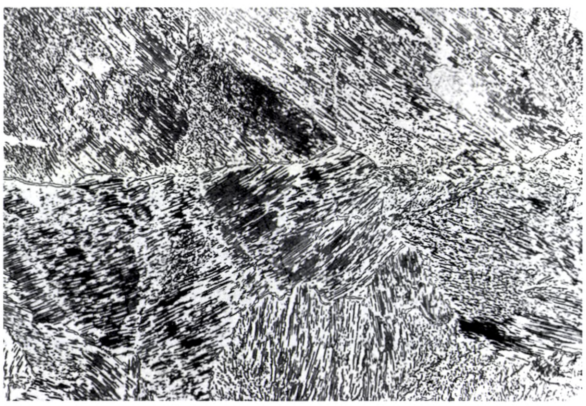


Fig. 62. Pearlitic structure in a steel with about 0.7% C and no silicon, manganese or phosphorus. The cementite lamellae form colonies inside the original 0.1 mm large austenite grains. PES. Oil immersion. Sønder Onsild axe. Side 0.15 mm.

8. The other important element, carbon, is almost insoluble in ferrite, which displays a maximum of 0.02% C at 730°C. But carbon is easily dissolved in austenite, even up to 2.1% at 1150°C. When an iron-carbon alloy is cooled from forging temperature, say 1000°C, it is transformed either into two-phased equilibrated structures (ferrite-pearlite) or into unequilibrated structures (martensite). The exact appearance depends on the forging temperature, the amount of carbon and the cooling rate. Iron-carbon alloys with more than 0.4%C (and less than 1.7%) are called steel. They may be ferritic-pearlitic, pearlitic or martensitic. In this work it will be emphasized that iron alloys were, up to about 1870, of a very heterogeneous nature, both with respect to carbon, to phosphorus, and to the amount and composition of the slag inclusions. The iron phase was always low in silicon, <0.02%, and manganese, <0.04%.

Fig. 63. Hypereutectoid structure in a steel with about 1.2% C. Incipient corrosion has attacked the pearlitic grains, while the cementite network and lamellae so far have remained unattacked. PES. Sønder Onsild axe. Side 0.5 mm.

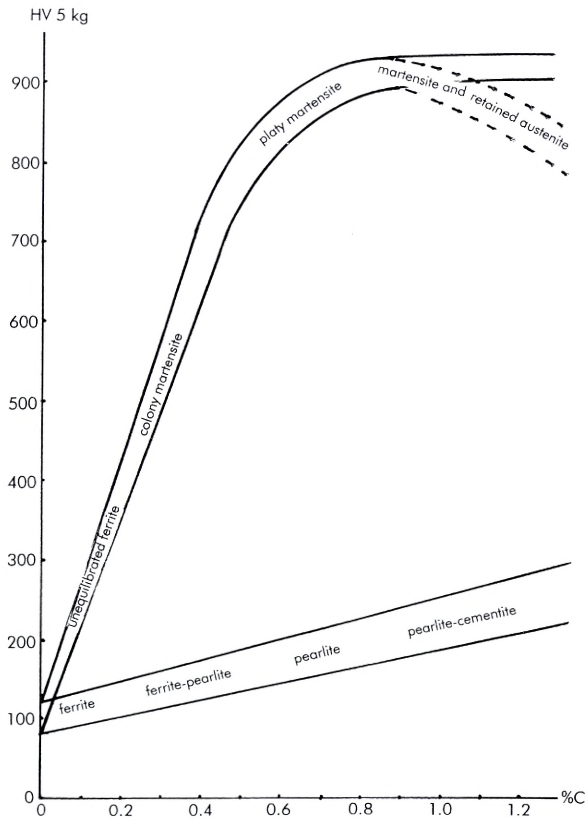


Fig. 64. The Vickers hardness (5 kg) of iron and steel as a function of the carbon content. The lower set of curves are for equilibrium structures, the upper show the surface hardness of water-quenched material. Unless special precautions are taken the hardness of quenched, high carbon material will follow the stippled lines.

9. Iron-carbon alloys can be quench-hardened. When an Fe-C alloy, after having been equilibrated in the austenitic region (see the iron-cementite equilibrium diagram), is abruptly cooled, e.g. in cold water, it transforms into unequilibrated martensitic structures. These are much harder than the equilibrated ferritic-pearlitic structures. The high carbon martensitic structures are very brittle, and useless, unless they are tempered, that is, immediately after quenching reheated to 100-600°C for some short time. The exact procedures and quality of the finished object depend on carbon content, austenitizing temperature, cooling rate, tempering temperature, and dimensions. An inch-thick bar will, e.g., after quenching only be martensitic in an exterior 1 mm thick ring zone.

10. The alloying behaviour of binary iron-carbon alloys is usually described with reference to the equilibrium diagram, where the melting points and stable alloy phases are shown, see e.g. Fig. 57. Iron is very peculiar in its behaviour towards carbon. The ultimate equilibria are displayed in the iron-carbon diagram (not shown here) which is of particular interest when cast irons are discussed (Vogel et al. 1998, chapter 19). Wrought iron and steel are better treated on the background of the metastable iron-cementite diagram, Fig.

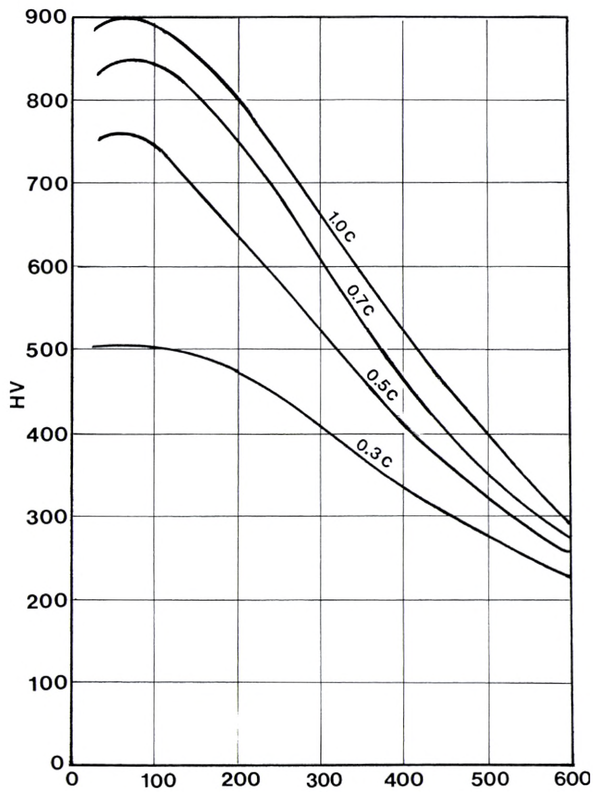


Fig. 65. The Vickers hardness of water-quenched steel after annealing (tempering) for half an hour at the indicated temperatures. Annealing treatment above 721° C has no meaning, since part, or all, of the material will then transform to austenite, according to the iron-cementite diagram, Fig. 57.

Fig. 66. Colony martensite in a quenched iron with 0.25% C. Vickers hardness 407. PES. Side length 0.14 mm.

57, where the metastable compound Fe_3C, cementite, forms the right border of the diagram. Even if cementite is metastable, it remains as a structural component of iron and steel as long as they are not extensively heated for a long time above 720°C. Cementite is thus present unaltered in 3000-years-old artefacts.

11. The addition of carbon to iron lowers the melting point of the alloy, until at 4.2%C a minimum is reached, the so-called eutectic point at about 1150°C, Fig. 57. That is, the refractory metal iron can be melted "easily", if an alloy with carbon can be made. Pig iron from the blast furnace and cast iron for modern diesel engine cylinders are basically eutectic Fe-C alloys which will be in the molten condition above 1150-1200°C. These iron-carbon alloys are occasionally met with in archaeological situations, but were hardly of any importance before 1150-1200 A.D., see the Epilogue.

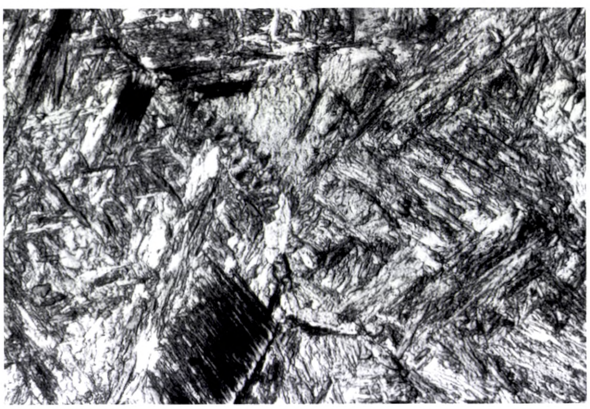


Fig. 67. Colony martensite in a quenched iron with 0.30% C. Vickers hardness 501. PES. Side 0.14 mm.

12. The two-phase ferritic-pearlitic structure is quite wear-resistant, and can be ground to a hard edge-cutting tool, of much better quality than a bronze tool of the same hardness. Hardness alone is not enough. The edge-quality of iron depends on the presence of finely disseminated, ultrahard and ductile cementite particles in ferrite. Still better for a cutting edge is the tempered martensitic structure (§ 9) with hardnesses above 450HV. The high quality of a pearlitic or martensitic knife edge may be compared to the disappointingly dull edge of a modern stainless steel knife when made of a carbon-free 18% chromium-8% nickel alloy, which is austenitic.

Fig. 68. Colony martensite in a quenched steel with 0.40% C. Vickers hardness 633.. PES. Side 0.14 mm.

The assertion, commonly met with and tacitly underlying many archaeological opinions, that "Figures for the relative hardness of soft, wrought iron, and bronze of around 10% tin, clearly show that a good bronze when fully work-hardened is considerably superior in hardness to the primitive iron" (Coghlan

Fig. 69. Martensite in a quenched steel with 0.50% C. Vickers hardness 753. PES. Side 0.14 mm.

1956: 69) is not tenable. First, it would have been more appropriate to compare work-hardened bronze with work-hardened iron. In that case, the two materials are comparable, attaining hardnesses of maximum 200-280 HV (200 g) (e.g. Buchwald & Leisner 1990). Secondly, the body-centred cubic ferrite retains its cutting edge better than any ancient bronze alloy. Thirdly, pure iron is an academic abstraction. The bloomery product was from the very beginning heterogeneous, being a binary iron-carbon alloy, a binary iron-phosphorus alloy or a ternary iron-carbon-phosphorus alloy, or a combination of these. Each of these had superior qualities relative to pure iron and to normal tin bronzes. Even given the omnipresence of slag inclusions in iron objects, this was no worse than the presence of voids in cast bronze objects. A knife made of iron is much better than one made of bronze, which was immediately realized in the Middle East, where knives are among the earliest iron objects, e.g. from 1100 B.C.graves in Cyprus.

13. Iron has a high affinity to oxygen and water and is easily attacked, especially if chloride-containing solutions are present. Chloride destabilizes the thin protecting iron oxide films which naturally cover any iron surface. Small amounts of chloride are enough to initiate, and under humid conditions, maintain a corrosive attack under the formation of metastable hydroxychlorides, such as hibbingite, $Fe_2(OH)_3Cl$, and akaganeite, FeOOH, Cl (Buchwald 1989). Under normal care, a tool or a polished iron surface will preserve its shiny appearance equally well as a bronze object will preserve its golden or reddish lustre. Iron-phosphorus alloys with 0.1-0.3% P are somewhat more corrosion-resistant than iron-carbon alloys. This fact can, e.g., be observed in the laboratory when a metallographic sample is prepared by polishing and etching with Nital (a solution of 2% nitric acid in ethanol): The phosphorus-rich parts are slowly attacked and stand out bright, with indistinct grain boundaries, while the carbon-rich parts are rapidly attacked and become dull and dark.

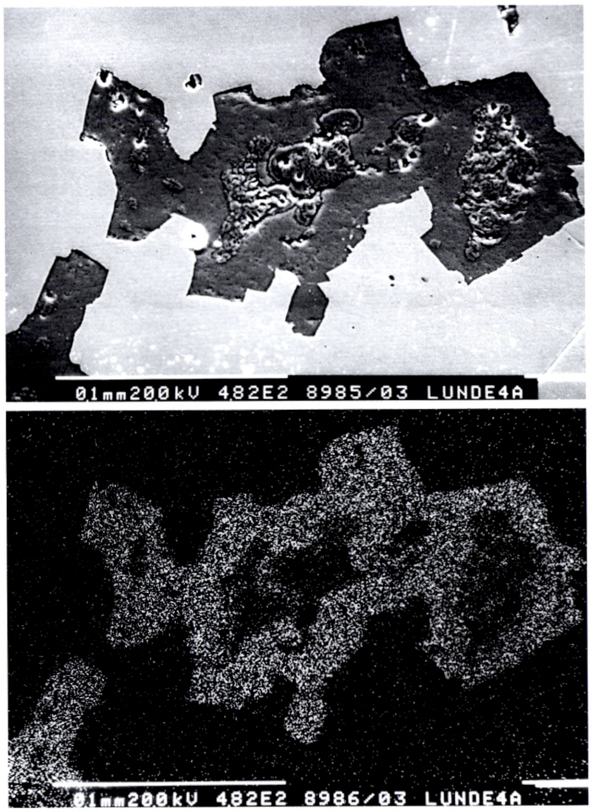


Fig. 70.Corrosive attack on a nail, No. 4, from Lundeborg (Chapter 9). Above, a SEM photo showing unattacked iron (white) and a central slag surrounded by hibbingite. Below, the same in a chlorine-analyzing mode. Chlorine is only present in the mineral hibbingite, $Fe_2(OH)_3Cl$. PS. Scale bar 0.1 mm.

From this brief presentation of the element iron it has become evident that it was "a big step for mankind" to move from the well-known world of the face-centred cubic, rather noble metals, gold, silver and copper, which could easily be alloyed, melted and cast, to the new world of refractory iron with its little understood phase transformations, many metastable phases, and the annoying rust formation. The blacksmith did, of course, not know the physical-chemical background, and he did not know the elements phosphorus and carbon. Phosphorus and carbon were first identified as alloying elements of iron in the late 18th century, and the alpha-gamma transformations were first examined and explained with the advent of X-ray analytical equipment in the first quarter of the 20th century. But the ancient blacksmith learned his business by trial and error and very rapidly made good progress. His major problem may have been to separate the solid iron from the furnace bloom and slags, and consolidate the iron into a handy bar. When he had mastered this step, subsequent shaping and welding were relatively easy.

Iron in ancient written sources

It is surprising how little has been written and preserved to our time on ancient mining, technology and metallurgy. When metals are occasionally mentioned, it is gold, silver, copper and bronze that the ancient authors have in mind. When it comes to iron, there are only a few independent sources. As to origin, the classical authors apparently follow two traditions, one referring the discovery to the Chalybes, while another tradition only remembers the Idaean Dactylae. For a thorough presentation and discussion of ancient sources the reader should consult Beck (1891).

Strabo (65 B.C.-25 A.D.) tells us about the Chalybes, who lived on the Black Sea Coast east of Trapezunt (Trabzon), in Colchis. "The Chaldaei of today were in ancient times named Chalybes. And it is just opposite their territory that Pharnacia is situated, which on the sea, has the natural advantage of pelamydes (tunny) fishing and, on the land, has the mines, only iron mines at the present time, though in earlier times it also had silver mines. Upon the whole, the seaboard in this region is extremely narrow, for the mountains (a 3000-m-high mountain range), full of mines and forests, are situated directly above it, and not much of the land is tilled" (Geography, Book 12). Thence is derived the Greek word chalyps (χαλυψ) for steel, while the Greek word for iron is sideros (σιδηροσ).

Diodorus Siculus, who like Strabo lived in the time of Emperor Augustus (63 B.C.-14 A.D.), had a somewhat different version: "The Idaean Dactyli were in fact born on Mount Ida in Phrygia and passed over to Europe (Crete) together with Mygdon. And since they were wizards, they practised charms and initiatory rites and mysteries ... The Idaean Dactyli of Crete, so tradition tells us, discovered both the use of fire and what the metals copper and iron are, as well as the means of working them" (History, Book 5: 64).

Pliny the Elder (23-79 A.D.) was quite interested in ores and minerals, unfortunately however, mainly in connection with their application as pigments and as medicinal drugs. Iron was noted when it was used in a gold mine: "The rock is broken to pieces with crushing machines carrying 150 lbs of iron ... the Asturia, Callaecia and Lusitania (Portugal) mines produce in this way 20,000 lbs weight of gold a year ..." (Natural History, Book 33: 71). With respect to the early history of metals, Pliny only had a note "Manufacture of bronze some ascribe to the Chalybes and others to the Cyclopes. The forging of iron Hesiod ascribes to the people called the Dactyli of Ida in Crete" (Book 7: 197).

Herodotus (490-420 B.C.) had no recollection of the early manufacture of iron, but presented several observations on its contemporary application, e.g., in detail describing the armament of Xerxes' Persian army, about to invade Greece in 480 B.C. (History, Book 7: 60ff). Iron was far from conspicuous in the army, leather cuirasses and bronze weapons were apparently by far the more common, and lances and javelins were of wood that had their ends burnt to sharp points. But the Indian troops had arrowheads of iron, the Assyrian contingent had ironclad wooden clubs, and the Persian army had leather cuirasses covered by small iron plates like fish-scales. In another place Herodotus interpreted an answer from the oracle in Delphi in a most interesting way, implying that already in his time the iron blacksmith used double bellows to kindle the fire. In addition, we learn that the city of Tegea, 35 km SW of Tiryns, was well known for its blacksmiths, who among other things produced foot-chains for the slaves (Book 1: 66-68).

On a more poetic note Virgil (70-19 B.C.) in his Aeneid (Book 10: 173) compared the rich iron ores of Elba with the famous Chalybian iron ores, while Aeschylus (525-456 B.C.) in "Prometheus bound" (verse 707) warned the traveller against the iron-producing Chalybs who live in the vicinity of the Caucasus and are considered a ruthless and unfriendly people.

From Rome and Greece let us turn to the Near East for ancient texts on iron. In a very early inventory text from Sumerian Uruk III, about 2000 B.C., iron objects are listed among weapons and vessels of gold, electrum, silver and what must probably be understood as bronze (Vaiman 1982: 33).

In documents of the old Hittite kingdom, about 1700 B.C., the Anitta text mentions iron, in the Sumerian form AN BAR. It is here apparently used in the description of a throne, but it is unknown whether iron was used as a construction material, or as decorative inlays. Most probably the last, because iron was at that time more than eight times the value of gold (Waldbaum 1980: 75).

The ancient records of Assyria and Babylonia have been published by Luckenbill (1926-27). The early status and supply of iron are well illustrated by the often quoted Kizzuwatna Letter from the Hittite King Hattusilis III (about 1289-1265 B.C.) to an Assyrian king (Kempinski & Kosek 1977). In it the Hittite king apologises for his inability to provide the Assyrians with iron for the present time. Instead he sent the Assyrian king an exceptional gift, an iron dagger of high value. It was probably rather similar to the famous dagger presently on display in the Tut Ankh Amon section of the Egyptian Museum in Cairo.

The Hattusilis Letter suggests that iron about 1275 B.C. was still a commodity, with a place in luxury trade and exchange more valuable than gold, eagerly sought and not readily available. 150 years later, Tiglath-Pileser I (about 1114-1076 B.C.) obtained iron or iron ore from Nairi, a province around the upper streams of the Euphrates and the Tigris (Maxwell-Hyslop 1974). In the tenth to seventh centuries iron became more abundant and was often mentioned in Assyrian lists of booty and tribute (Jankowska 1969: 263). Hoards of 150 tons were thus present in Damascus, of three tons in Hattina, of three tons in Carchemish, and of nine tons in Bit-Zamani (the precise weights are uncertain).

From about the same time we have the Biblical references to iron: "No blacksmith was to be found in the whole of Israel, for the Philistines were determined to prevent the Hebrews from making swords and spears. The Israelites had to go down to the Philistines for their ploughshares, mattocks, axes, and sickles to be sharpened (1.Samuel 13: 19-20, Oxford University Press 1970). Not long afterwards the fight between David and Goliath took place: "Goliath said to David "Am I a dog that you come out against me with sticks?" ... David answered, "You have come against me with sword and spear and dagger, but I have come against you in the name of the Lord of Hosts" (1.Samuel 17: 43-45). We here have the conflict, not between a mythical giant and a normal human being, but between a heavily armed Philistine warrior and a Hebrew herdsman, only equipped with his sling. Iron was not yet common, and whatever there was, was under strict control by the Philistine traders and blacksmiths along the coast. Their iron had probably been supplied from Anatolian producers.

David's victory over the Philistines, coupled with triumphs in Edom, at last enabled his people to have access to iron for everyday use and for building the new Temple. No longer did they need to dread their enemy's iron-tyred chariots as in the days of the judges (Joshua 17: 16; 2.Samuel 8: 14; 1.Chronicle 22:3). The iron ore and the furnaces of David and Solomon were probably located in the Arabah Valley. The "industrial" centre of the blacksmiths may have been Ezion Geber (present-day Eilat) as proposed by Nelson Glueck after having conducted a number of excavations in the 1930s. The excavation of an iron smithy in the northern Negev desert, Israel, was recently described by Rothenberg & Tylecote (1991). The smithy had been part of an Assyrian citadel that was destroyed around 600 B.C. Otherwise archaeology has not identified many blacksmithing hearths.

In the Homeric epic the Odyssey we have an exceptional hint at the blacksmith's cunning treatment of steel, when Odysseus with his men blinded the one-eyed Cyclops Polyphemus. "And as when a smith dips a great adze in cold water amid loud hissing to temper it – for therefrom comes the strength of iron – even so did his eye hiss around the stake of olive-wood" (Odyssey, 9. song: 391, translated by A.T. Murray, Loeb Classical Library).

The archaic period described in the Odyssean narrative is difficult to fix in time, since the Odyssey is a conglomerate of tales, first edited and issued as a total of 24 songs in the 4^{th} century B.C. However, the general scarcity of iron and the common references to weapons and armory of bronze point to the 8^{th} or 7^{th} centuries. No doubt, quench-hardening of steel as described in the epic had been well known for centuries before the poem was conceived. Hardening was, however, restricted to tools, particularly to knives, files and chisels, only occasionally including a dagger, a sword or an axe.

The archaeological evidence of early iron, until about 500 B.C.

In the following some important <u>iron objects</u> will be brought into focus. Several authors have summarized the evidence for very ancient objects of man-made iron, e.g. Wainwright (1936), Coghlan (1956), Forbes (1964-1972), Waldbaum (1978) and Pleiner (2000). The following is a small selection of the best documented and analysed cases, beginning with objects which can be dated to between 3000 and 2000 B.C. (Waldbaum 1980). Objects thought to be of meteoritic origin were treated in Chapter One.

In Mesopotamia archaeologists found the corroded fragments of a dagger blade with a copper handle, lying among a hoard of copper objects from Tell Asman, about 2400 B.C. From Tell Chagar Bazar, also Mesopotamia and the same time, are reported a number of corroded, shapeless iron fragments.

In the Royal Tomb K at Alaca Hüyük in Anatolia, 2400-2100 B.C., a low-nickel iron dagger blade with a gold-covered crescent hilt was found together with pins of meteoritic iron. The dagger was clearly a ceremonial weapon (Wertime 1973), Fig. 71[1].

A number of beautiful swords, maces and axeheads were part of the Royal Treasury at Dorak in northwestern Anatolia, near the Sea of Marmara, 2400-2300 B.C. (Yadin 1963). While most swords had bronze-, or even silver-blades, one was of iron. It had a hilt inlaid with gold and amber, and an obsidian pommel carved in the form of two leopards. The sword had a total length of 75 cm.

For a rusted tool found in a joint of the Cheop's Pyramid, see Chapter One.

The next period, 2000-1600 B.C., is very poor in iron finds. From Cyprus, the Lapithos tomb 313, about 1800 B.C., was reported a rusted lump which had undoubtedly been produced from man-made iron. But a 30 cm long spearhead from Buhen, Nubia, presumably from the 12^{th} dynasty, may be of questionable origin (Waldbaum 1980: 74).

In the next 400 years, 1600-1200 B.C., iron finds are becoming somewhat more common, and the finds are distributed over a wider geographical area, covering Mesopotamia, Syria, Palestine, Egypt, Anatolia,

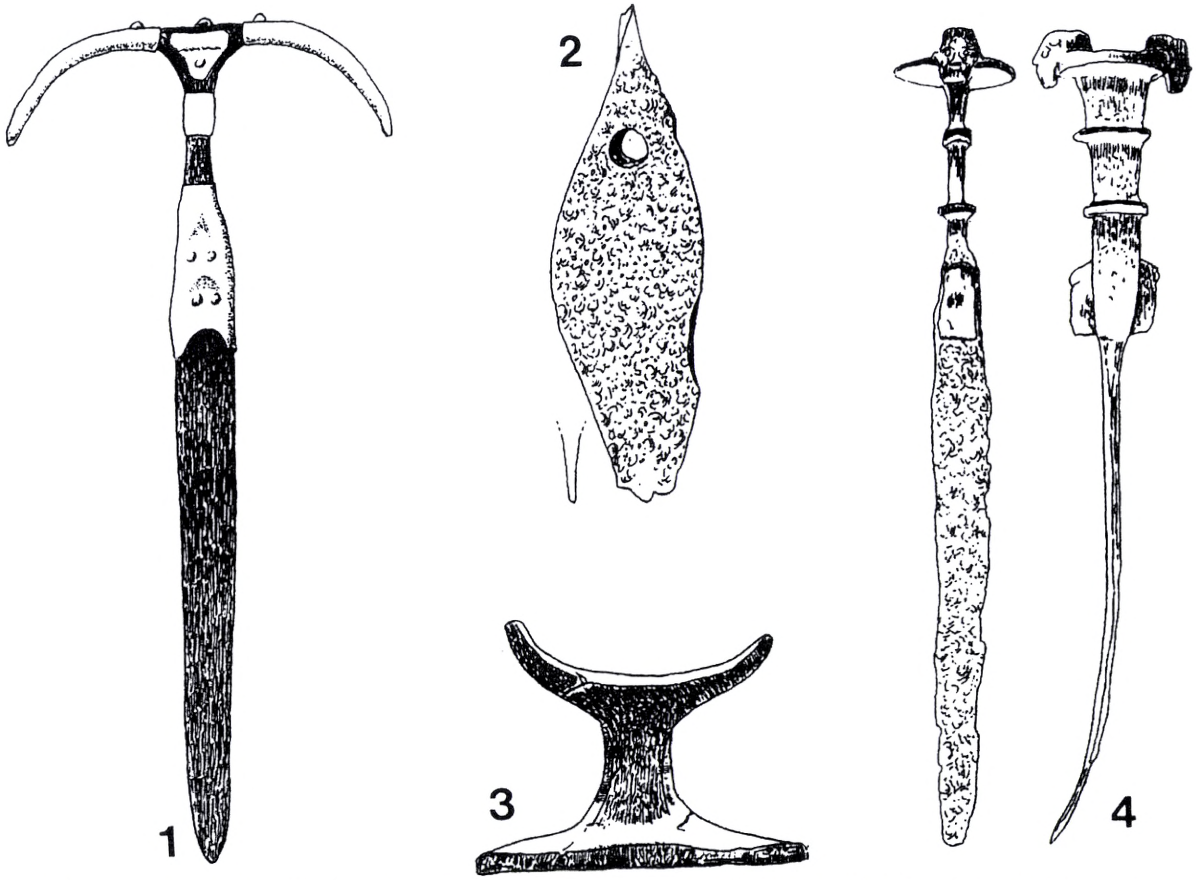


Fig. 71. Four examples of early ancient iron objects. **1**, Alaca Höyük, Turkey, an iron dagger with gilded hilt and pommel, from a royal tomb about 2300 B.C. **2**, Khorsabad, Iraq, a bipyramidal iron bar from the store of the Sargon II palace, 8th century B.C. **3**, Thebes, Egypt, a miniature headrest from the Tut Ankh Amon tomb, 1323 B.C. **4**, a bent short sword from Luristan with human heads on the pommel, length 38 cm, 8th century B.C. From Pleiner 2000: 8.

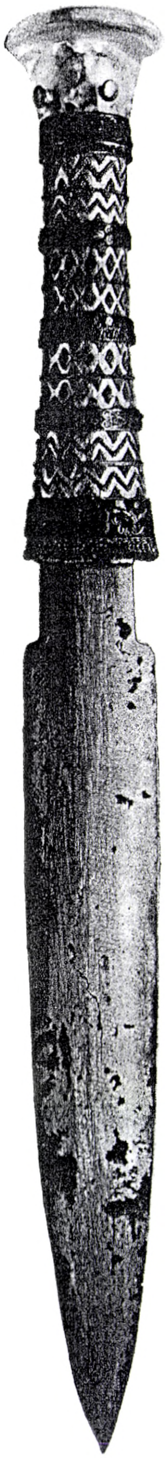
Greece, Cyprus, Rhodes, Lesbos and Crete. The majority of finds continue to be of a precious or cultic nature, and the objects are often studded with gold or provided with elaborate handles. Unfortunately, a significant number of the finds have never been subjected to chemical or metallographical analyses.

From the 15th century's Hurritic Nuzi in Mesopotamia comes a copper dagger with a hilt made of two iron plates, fastened to the blade with an iron rivet.

From Syrian Ras Shamra, Ugarit, comes the famous battle ax, with an iron blade and a cast-on copper socket, inlaid with silver and gold (about 1400 B.C.). The presence of 3.5% nickel in the iron is enigmatic and invites a metallographic examination in order to decide whether it is meteoritic or man-made. Nickel in ancient objects is not necessarily of meteoritic origin but may stem from rare iron ore types, enriched in nickel (Blomgren 1980; Bronson 1987).

In Megiddo, Palestine, an iron ring was found in tomb 912 B, 1400-1200 B.C., and in Telles-Zuweid two iron arrowheads and a handle were reported, also dated to 1400-1200 B.C.

During the extensive examination of the Hittite Bogazköy ruins east of Ankara, Anatolia, a number of



iron objects and rusty lumps were found. Among those that could be identified there were a chisel, two axe blades and two spearbutts, dated to 1400-1200 B.C.

In a royal tholos tomb at Vaphio, Greece, an iron ring was discovered. In another tomb, at Kakovatos, the Peloponnese, a ring with a bezel and part of a hoop in iron was found, the whole overlaid with gold. In a third tholos tomb, at Volo, a small square iron plaque was discovered, and in a chamber grave in Asine, fragments of an iron ring were found. Two iron rings were found in chamber tombs Nos.10 and 28 in Mycenae. All these finds may be dated to 1500-1200 B.C.

On Crete an iron nail with a flat head ornamented with a gold rosette was found in the late Minoan Knossos palace, 1600-1400 B.C. In Phaistos, of about the same age, two iron rings were found. One was plain, the other had a large bezel engraved with figure-eight shields and spiral laminations of gold and bronze.

On the island of Lesbos, a tanged knife was found at Thermi, with an uncertain dating, but probably 1400-1200 B.C.

The famous dagger with a gold hilt and a pommel of rock crystal, which was found together with magnificent treasures in the tomb of Tut Ankh Amon, was apparently made of meteoritic iron (Carter 1923-26; Coghlan 1956: 32; Waldbaum 1980; Pleiner 2000), but the documentation for its composition is rather vague. Aitchison (1960:94) was convinced that it was a bloomery product.

In Palestine, a significant amount of metalwork comes from both stratified tells and from tomb sites. From Tell es-Zuweid we have a leaf-shaped, tanged arrowhead and a fragment of a tool (chisel?). From an early Philistine tomb at Tell el-Farah South several iron bracelets were excavated. An iron dagger with a cast-on bronze handle and three small iron rings were

Fig. 72. The finest weapons buried with Tut Ankh Amon in about 1323 B.C. were two daggers found wrapped in with the royal mummy. One had a blade of gold. The one here pictured had a 21 cm long blade of iron, and the grip was finished with a sparkling rock crystal. The blade probably is a very early example of well-preserved man made iron. From Aitchison 1960.

also found. At Beth-Shan there were several pieces of iron, a fragmentary dagger, rusty fragments adhering to a heavy mass of bronze, and three iron nails. At Megiddo, an iron ring and a hook were found, and at Tell Qasile the remains of a knife blade with three bronze rivets attaching it to an ivory handle were discovered. All the Palestinian material quoted here may be dated to 1200-1100 B.C. (Waldbaum 1978).

In the following century, 1100-1000 B.C., at least 78 examples of iron objects from thirteen different sites came from Palestine. And in the next period, 1000-900 B.C., more than 192 examples from seventeen sites in Palestine were examined (Waldbaum 1978). The excavated material gradually shifted from rings, ornamented daggers and bracelets, to utilitarian objects, such as knives, hoes, arrowheads, ploughshares, sickles, axeheads and various tools. It appears that most of the Palestinian objects were manufactured from iron bars imported from Anatolia.

In similar studies of Syrian, Cypriotic, Cretan, Anatolian and Egyptian objects, Waldbaum was able to present the same picture. In general, finds of iron objects nearly tripled in the 11th century over those from the 12th, and more than doubled in the 10th over those from the 11th century.

In the last period to be covered in this chapter, 900-500 B.C., iron becomes quite common all over the Mediterranean and even beyond. Iron technology is also practised in Etruria and by the Celtic peoples of central Europe. There are now so many archaeological finds of weapons, tools, nails, bars, and scrap metal that it has been found justifiable to cut some of them for metallographical studies. Although upon closer inspection many objects turn out to be severely corroded, sufficient metal sometimes survives to allow for structural and chemical examinations and for hardness testing.

It was in the course of the 9th century that iron became common enough in Assyria to be used for tools and weapons, for which it was so well suited. Under Assurnasirpal II (ab.883-859 B.C.) and Shalmaneser (ab.858-824) iron as war booty and tribute came predominantly from regions adjacent to the upper Euphrates (Moorey 1985). At Khorsabad, in the palace of Sargon II, the storehouse, room 84, excavated by Place (1867) and described as a huge wall, held 160 tons (ab.5,600 talents) of iron, and that was only part of the iron found at this site. The iron was mostly in the form of bipyramidal "Spitzbarren" of 4-20 kg mass, quite clearly semiproducts of wrought iron for trading purposes. They could be dated to the last quarter of the 8th century (Beck 1891:112, 134, 166; Pleiner & Bjorkman 1974; Tylecote 1976: 43). Metallography on some of the bars revealed that they were of a heterogeneous ferritic-pearlitic nature, while some tools found together with the bars surprisingly were of soft, wrought iron (Pleiner 2000: 16, 297).

Some early metallographic descriptions are due to Carpenter & Robertson (1930). An Egyptian hoe from about 800 B.C. displayed a heterogeneous ferritic-pearlitic structure with a hardness range of 116-187. An Egyptian chisel from about 700 B.C. had similarly a very heterogeneous structure, with 0-0.4%C and corresponding ferritic to ferritic-pearlitic structures. The hardness was quoted to range from 137 to 302 Brinell, but the hardness was surprisingly low at the chisel tip, where it should have been maximal.

Additional examinations were performed for the Pitt Rivers Museum, the University of Oxford, and quoted by Coghlan (1956). A severely corroded spear from Deve Hüyük, Syria, and dated to 600-500 B.C., had a heterogeneous structure as if it had been forged from several surficially carburized layers of iron. Carbon ranged from 0 to 0.6%, and there was a nickel content of 0.32%, while phosphorus was as low as 0.02%. The hardness ranged from 108 to 153 HV, and no attempt of quench-hardening had taken place.

A spearhead from Vace, Yugoslavia, dated to about 500 B.C., had varying carbon content, from less than 0.1 to above 0.6% locally, and the hardness was rather low, 103 to 134 HV. The spear socket was made by rolling over a faggot of wrought iron to form a forge-welded tubular section.

An iron pick from Lachish, Palestine, from before 588 B.C. displayed a hardness range from 136 to 183 Vickers. The average carbon content was 0.20% and phosphorus, manganese, and silicon were all below 0.015%.The author interpreted this and several other tools as being purposely carburized and piled (Coghlan 1956: 134, 139). The descriptions and the photomicrographs are in the present author's opinion better interpreted as unintended, heterogeneous structures, being the natural outcome of the ancient bloomery process.

The first ironmasters and blacksmiths

Ancient literary sources like Strabo and Diodorus Siculus agree that the origin of iron technology was to be found somewhere in Anatolia, be it among the Chalybian or the Dactylian peoples. It is important to note that neither of them mentions Greece, Egypt or Mesopotamia, countries that otherwise were known for their pioneering contributions. Iron ores are abundant in the mountain regions of Anatolia, not least in the basin of the river Halys. The Hittite confederacy controlled these provinces from about 1800 to 1200 B.C., and it seems that some of the confederate tribes, like the Chalybi and the Dactyli, were the active metallurgists responsible for the early iron and steel production.

The same provinces are also known for silver, copper and tin ores (see, e.g., Zwicker 1980). It has been suggested (Sperl 1977; Charles 1980; 1985) that the first knowledge of iron must have been associated with the production of copper and bronze by people long acquainted with copper metallurgy. When the easily accessible oxidized copper ores, such as malachite and azurite, had been exhausted, the coppersmiths had to exploit the much more difficult sulphidic ores, such as chalcopyrite, covellite, enargite and bornite, Table 2.1. The presence of copper in these hitherto neglected ores might have been surmised from the strong green colour displayed by the flame when heating the ores. This flame colour must have been well known to all copper smelters (Charles 1985).

During reduction in the copper furnace some of the iron in the new ore types would inevitably become reduced and then dissolved in the liquid copper, which at 1100°C can dissolve up to 2 weight% iron. On remelting, and cooling under reducing conditions, most of the iron will precipitate and can be observed as discrete rims or particles. The introduction of hematite as a flux during the copper production could have contributed to the formation of free iron.

This theory serves to explain the presence of iron through the later Bronze Age, though as a very rare commodity that was valued higher than gold. For many hundred years, perhaps even more than one thousand years, there was no change in these conditions. Iron was a royal metal, reserved for status symbols, precious gifts and cultic applications.

It is not long ago that a similar development occurred for another new metal. Aluminium was discovered by H.C.Ørsted (1777-1851), who presented a bean of the shiny, new metal at a meeting of the Royal Danish Academy of Sciences and Letters in April 1825 (Bergsøe 1975). For two generations aluminium remained a very rare metal, because it was difficult to manufacture. Emperor Napoleon III had aluminium plates for his dinner sets, while the ordinary courtiers had to be content with gold settings. The 4.5 kg pyramidal top of the Washington Monument in Washington, D.C., was finished in 1881 and was an aluminium casting (Roy S.Clarke, pers.comm.). And in Denmark, King Frederik 7 in 1856, had the goldsmith Jørgen Dalhoff produce fantastic parade helmets for himself and the princes of cast and hammered aluminium (Dalhoff 1915: 327). A surprising metallurgical first!

When, in 1855, the first small aluminium factory had been built in accordance with Sainte-Claire Deville's method, the metal gradually became better known, but it was only with the introduction of electricity that aluminium could be produced in quantity. In the Hall-Héroult electrolysis of bauxite-cryolite melts, aluminium has since the 1890s been produced in huge amounts. At the time of the first world war,

Fig. 73. A parade helmet of aluminium, forged by Jørgen Balthasar Dalhoff in 1856 for king Frederik 7. No. 8765 in the Chronological Collection of the Danish Kings. Rosenborg Castle, Copenhagen.

aluminium and aluminium alloys were applied in light metal constructions, such as aeroplane frames. Today the metal has surpassed copper as the industrially most important metal after iron and steel. While it took iron more than 2000 years to advance from a precious metal of high status value to a common metal for tools and construction, it took aluminium less than a hundred years to cover the same development.

While the discovery of iron probably took place in Anatolia, one is not impressed by the amount available as long as the Hittite rulers governed the empire. It appears as if the blacksmiths did not understand the promises of the new metal and were satisfied with producing very limited amounts, reserved for the upper strata of society. When, however, the Hittite empire was dissolved about 1200 B.C., a new epoch dawned. Perhaps skilled artisans now were free to travel, and perhaps the bloomery method for producing wrought iron on the basis of hematite and limonite which abounded along the upper streams of the Halys, Euphrates and Tigris, and along the western and southwestern slopes of the Caucasus, now became widely known.

Fuel was hardly a problem, since forests were common in the same area as the ores. Potential customers would soon discover the value of iron in tools and weapons. After 1100 B.C. iron was suddenly everywhere, as knives on Cyprus, as arrowheads in Palestine, as hoards of tribute in Damascus and as swords in Hama, Syria (Riis 1961-62).

It appears that iron was extracted from its ores in Anatolia-Nuria, and was here converted into bars for trading. Most of the manufacture took place in Syria, Palestine, Cyprus, Assyria and Greece. None of the

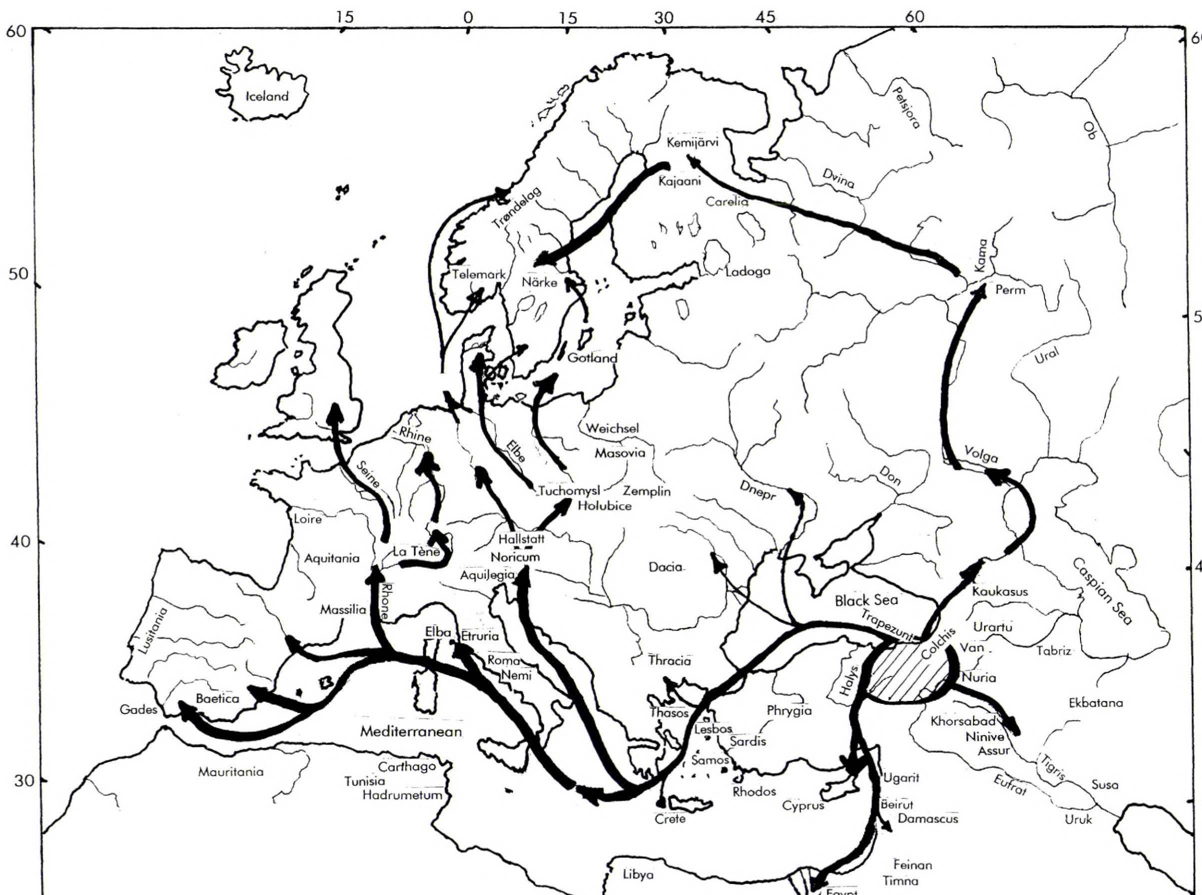


Fig. 74. Map showing a few important locations relating to early iron handling. The arrows suggest the spreading of iron handling in the period 1200-300 B.C.

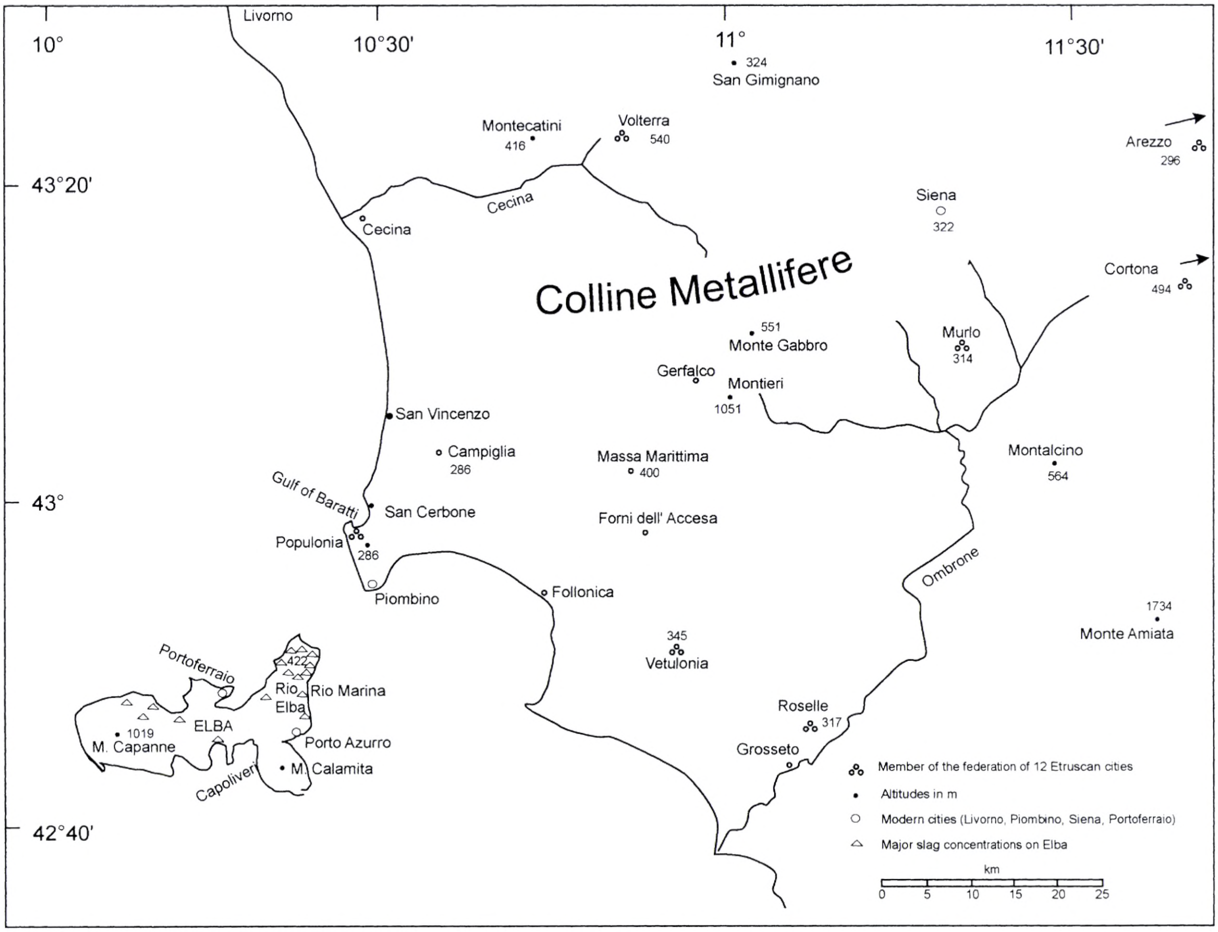


Fig. 75. Map of Elba and part of Etruria, now Tuscany.

ancient historians probably ever saw a bloomery, i.e. a furnace for the extraction of iron from the ores. But many had observed a blacksmith at work, in the city or at the fortress. And we know how Herodotus described the blacksmith at work (Book 1:66).

Ancient bloomery sites are little known, but according to Pleiner (2000: 58) this situation is improving. A number of small-scale bloomery ironworks with one or two furnaces have been investigated south of modern Tbilisi in Georgia. Other furnaces have been identified on the Black Sea Coast at the foot of the Caucasus Mountains, slightly northeast of the assumed Chalybian provinces. Each bloomery site consists of one or two bowl furnaces, often paired like twins. They are dated with considerable uncertainty to about 1000 B.C. (Pleiner 2000: 38,58).

Elba

The island of Elba, or Ilva, was in ancient times inhabited by a tribe of Ligurians, the Ilvaites, who gave the name to the island. About 800 or 750 B.C.it was invaded by people from the Etrurian mainland, and from this time, the Elban iron ore became an important source of iron for all the Mediterranean countries.

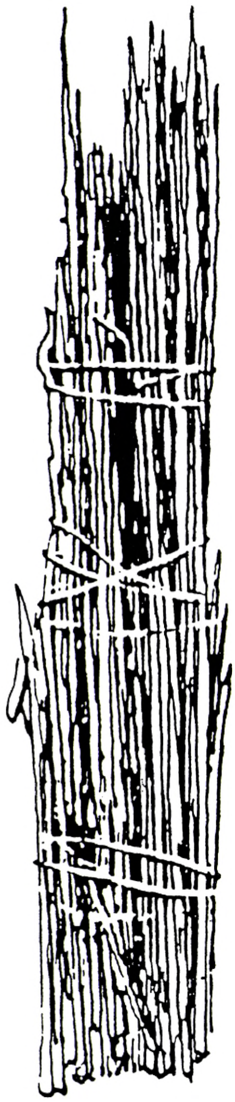


Fig. 76. A fascicle of about 180 iron spits, spieti or obeloi. Six of these constituted a drachme, Greek for handful. They are usually forged 5x5 mm square and have lengths of 60-120 cm. They were apparently used as currency bars before coins became common. From Pleiner 2000: 15.

The ores were, of course, known to the ancient authors: "Off the city of Tyrrhenia known as Poplonium (Populonia) there is an island which men call Aethaleia (Elba, Ilva). It is about one hundred stades (18 km) from the coast and received the name it bears from the smoke and soot (aithalea) which lies so thick about it. For the island possesses a great amount of iron rock which they quarry in order to melt and cast (misunderstanding) and thus to secure the iron, and they possess a great abundance of this ore ... " (Diodorus Siculus, Book 5: 13). According to Pliny (Book 7. 147), Populonia was the only Etruscan city along the coast. We know today that its location was due to the Elban ores. Ores and/or semiproducts were shipped from Elba to Populonia, where large-scale industry converted ores and semiproducts into bars and finished products.

For centuries Phoenicians, Syracusans, Carthaginians and Romans were fighting for control over Elba and Populonia, which were parts of the Etruscan confederacy, governed from Caere. "The Syracusans chose Phayllus as admiral and sent him to Tyrrhenia (Greek for Etruria). He sailed at first to the island of Aethaleia (Elba) and ravaged it ... another general, Apelles, sailed with sixty triremes against the Tyrrhenians ... After sacking many places on the Tyrrhenian coast and in Cyrnus (Corsica) he subdued Aethaleia" (about 453 B.C.) (Diodorus Siculus, Book 11:88). "As for (the castle of) Populonia it is situated on a high promontory that makes an abrupt descent into the sea and forms a peninsula. It too sustained a siege at about the same time as Volaterra" (Strabo, Geography Book 5: 2,6.). According to Diodorus (Book 20), the Roman consul Fabius went north, even to the northern part of Etruria which had previously been outside the operations of the Roman army. He made peace with the cities of Arretium and Crotona and laid siege to Casto-

Fig. 77. The famous bronze chimera, cast about 450 B.C., was found in Arezzo, one of the Etruscan confoederate cities. The lion is a symbol on fire, the goat on the mountains, and the snake, that hides itself in the bowels of the earth, symbolizes the mineral ores. Museo Archeologico di Firenze.

la (probably the castle that protected the iron industry of Populonia) and finally conquered it.

Etruria was subdued and became part of the Roman republic, so when Scipio Africanus in 205 B.C. needed ships and equipment for his devastating attack on Carthage, he received support from Etruria: "The Etruscan communities promised that they would aid the consul, each according to its own resources. The men of Caere promised grain for the crews and supplies of every kind. The men of Populonium iron, Tarquinia linen for sails ... Arretium three thousand shields ... a total of fifty thousand javelins (pilae), short spears and lances (hastas longas). Also axes, sickles, baskets and hand mills ... Scipio so pushed the work that on the 45th day after the timber had been brought from the forests, the ships, rigged and equipped, were launched ... embarking some 7000 volunteers in 30 warships" (Livy, Book 28: 45) (Livy, 59 B.C.-17 A.D.).

The iron ores of Elba have thus been of principal interest from ancient times to the present day. No other iron mines have a similar long history. Archaeological examinations show that the ores for several centuries were smelted in small furnaces all over the island, strategically placed where fuel was available. At least 100 furnaces and large slag heaps have been identified. The local population took good care of the forests and apparently "harvested" the necessary fuel by coppicing, coming back to the same area every 20 or 30 years (G.Brambilla, pers.comm.). As the demand for iron increased, additional furnaces were, from about 450 B.C., built on mainland Italy.

The site chosen on the mainland was the Gulf of Baratti (Zecchini 1983), protected against pirates by the fortress on top of the promontory Populonia. Here was an easy landing beach for the ores, clay for furnace construction, and forests where chestnut, oak, pine and ash could be charred. Archaeological studies have revealed that the site already before the major iron industry appeared, for several hundred years had housed activities associated with copper and bronze, coming from Massa Marittima in the Colline Metallifere about 30 km to the east (Minto 1954; Santi 1969; Warden 1984). In Iron Age Etruria, Populonia, in fact, was the main producing centre of plentiful and highly specialised bronze objects (Bartoloni 1991). Populonia was the Pittsburgh of antiquity.

The early Etruscan tombs near the Gulf of Baratti, e.g. in the San Cerbone cemetery, in due time became entirely covered by furnace debris and slags!

Some slags were in the 19[th] century removed and reused for macadam. However, in the years 1915-1943 the modern steelworks Societa Breda di Milano, Societa Populonia Italica di Genova and Societa Ilva organized slag recovery on the grand scale. The ancient slags contained 50-60% FeO and constituted a magnificent and easily accessible iron ore for the blast furnaces in Portoferraio, Piombino and Follonica, and even as far away as Naples and Trieste (Minto 1943). The slags along the coast from San Vincenzo to Follonica and, in particular, in the Gulf of Baratti were removed by large machinery, down to the cretaceous subsoil, and freighted away. It is estimated that two million tons of slags were removed in those campaigns.

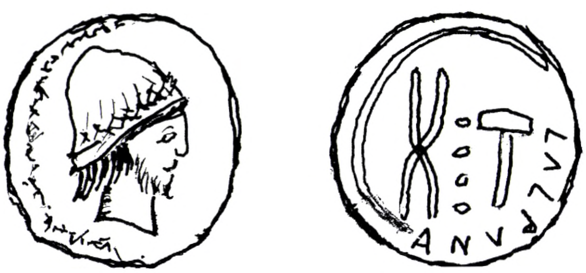


Fig. 78. A coin from Populonia, Etruria, with early smithing symbols, hammer and tongs. About 600 B.C.

Under the 2-8 m thick slag deposits a number of well-preserved Etruscan circular tombs were detected. The oldest were found in the grounds of San Cerbone and were of Villa Novan Age, about 900 B.C. The youngest were from about 420 B.C. In one tomb "Dei flabelli di bronzo" on Poggio della Porcareccia, fluid iron slag had penetrated the roof of the tomb and partly covered a gold earring. While the older tombs were rich in bronze objects, the younger ones, e.g.Tomba No. 2, 7 m in diameter at the same site, contained bronze objects as well as a lancehead, a fire dog, a tripod and fragments of a sword, all of iron. It appears that maximum iron smelting activities occurred after 450 B.C., and that little veneration for the tombs of the ancestors was shown.

The archaeologists were happy with the well-preserved and unplundered Etruscan graves, that emerged from under the slag deposits. They had little interest in furnaces and slags, and therefore we today know next to nothing about the ancient metallurgical activities concerning copper, and especially the iron production on the Etruscan coast.

Among the few metallographical studies of iron from Etruscan graves the work of Leoni & Panseri (1961) must be mentioned. In a grave from Vetulonia, dated 700-600 B.C., they found a lancehead and a bark-spade, made of heterogeneous iron. The spade-edge displayed low-carbon martensite, hardened to about 550 HV. From a 400 B.C. grave at Montefiascone they examined a composite lancehead with two mm-thick iron layers with 11-12% nickel, Vickers hardness 250, squeezed between soft ferrite of Vickers hardness 133. Apparently a small iron meteorite had been forge-welded to ordinary wrought iron.

In Villa Giulia, the magnificent Museum of Etruscan Art in Rome, the newly arranged exhibition (2002) presents a large number of iron objects from ancient graves, before 500 B.C. But few, if any, have been metallurgically described. There are hand-cuffs and horse trappings from 725 B.C. Visentium (Bisenza), and a three-forked fibula from 850 B.C. Cerveteri (Caere). There are axes, lanceheads, knives, fibulae wound with gold wire, iron-clad wheels for a two-wheeled chariot (biga) from 700 B.C. Narce, and swords, lanceheads and fire dogs from 700 B.C. Faleri, just to give an idea of the wealth of well-preserved and relatively uncorroded iron objects.

Some peculiar objects in Etruscan graves are the so-called spieti (Italian) or obeliskoi (Greek), thin spits of rectangular cross section and 40-80 cm long (Pauly-Wissowa Realenzyclopädie, sections Drachme and Oboli). They may be of bronze, but are mostly of iron. "Probably all the ancient money was of this sort, some peoples using iron spits for coins and some bronze, whence it comes that even to this day many small pieces of money retain the name of oboli (Greek obeliskos) or spits, and six oboli make a drachme (Greek, a handful), since that was so many as the hand could grasp" (Plutarch 45-120 A.D., Lysander, Loeb Vol.4, Chapter 17). In a tomb from San Raffaele, Todi, 450-400 B.C., a group of six spits were found together. They were forged as four-edged blunt staves, ending in an eye or a small hook (Bendinelli 1916). Many of the rich grave goods from Todi are presently exhibited in Villa Giulia, Rome.

Iron spits have also been found in other ancient Etruscan graves, e.g., in Caere (Cerveteri) 650 B.C., and Banditaccia, Camera degli Alari, 630 B.C. Iron spits were also reported from a number of graves by Brizio (1899), but here they did not occur in bundles of six, but of five or eight. They were very long, 80-106 cm, and they were secured to each other by iron wires and ring-shaped handles.

Since the spits were somewhat enigmatic, for example with respect to their pecuniary relationship, it was decided to find out, at least what they were made of. Steel perhaps?

In the Etruscan collection of the Ny Carlsberg Glyptotek, Copenhagen, there is a magnificent display of a princely tomb (No. 11) with two wagons (a biga and a cart) from Colle del Forno, Commune di Fara Sabina, the Rieti Province, NE of Rome. It has been dated to 625-600 B.C. Among the grave goods were fragments of about ten spits, the longest 60x0.5x0.5 cm square. A 29 g fragment (HIN 641), 18.5x0.5x0.5 cm, was cut in three different places, and longitudinal and transverse sections were prepared. Fragments of a thin iron band, probably a decorative fitting, 2-5 mm thick, were also examined (HIN X).

The spit is composed of carbon-free ferritic iron with 1% copper in solid solution. The copper has added a few points to the otherwise low hardness of ferrite, Table 3.1. The copper may also have increased the long-term corrosion resistance. The slag inclusions are 0.01 to 0.1 mm wide and composed of fine-grained, crushed calcic fayalite (17% CaO, 3% MgO, 2% MnO) in a glass matrix.

The fitting, Table 3.1, line 3, is different. The metal is ferritic-pearlitic with about 0.2%C. Copper and phosphorus were not detected, but one surface had inadvertently become slightly carburized, to a hardness of 198 HV. Otherwise the hardness was low, 121-138. The slag inclusions were still richer in CaO than the

Table 3.1. SEM-EDAX analysis of slag inclusions, Colle del Forno, Etruria.

Mrk.	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Σ	F
641	36.8	34.0	1.9	0.6	14.6	5.2	2.9	2.5	0.3	1.2	100	7.1
641	38.2	32.8	1.8	0.6	14.7	5.0	3.0	2.5	0.2	1.2	100	7.7
X	52.3	10.7	0.5	0	25.1	5.7	3.5	1.2	1.0	0	100	9.2

Lines 1-2. Two analyses of a 29 g fragment of iron spit HIN 641. HV 200 g: 105-114-116-121-133.
Line 3. A 3 g fitting, HIN, 2-5 mm thick. HV 200 g: 121-127-130-138- (198)

previous one, and all were glassy and rather small, less than 0.05 mm thick.

The slag composition suggests that the iron ores were extracted from the Colline Metallifere, known to be rich in limestone and chalcopyrite (Tanelli 1983). This would explain the high copper and sulphur content of the iron spit. In Chapter 4, Tables 4.1 and 4.2 we shall see that the ores of Elba will give rise to very different and somewhat purer slag inclusions.

Judging from this single analysis of a typical spieti it appears that they were soft, ferritic wrought iron bars, and definitely not steel, as one might have suspected from their small and regular shape, and from the notes in the literature. Perhaps then, the spits are just what the name implies, tools for food-preparation over the open fire. This is, by the way, also the opinion of modern research, e.g. Kohler & Naso (1991). It would be interesting to learn whether other spieti and oboli have the same very characteristic and unusual composition, copper-rich ferrite with calcium-sulphur-enriched slag inclusions.

The archaeological results and the literary sources thus agree that iron production in this ancient time occurred on the island of Elba, and on the mainland in the Campania and the Colline Metallifere. Populonia was an important manufacturing centre, but much of the manufacturing took place elsewhere. Bars and unfinished blooms were traded over land to other Etruscan cities, particularly to Arezzo, or by sea to Dicearchia (=Puteoli, Pozzuoli), the harbour of Naples. Our knowledge about this trade is limited. Perhaps, however, we have a glimpse of the semiproduct, an iron bar lost underway, in a description by Fossa-Mancini (1922): It was a rectangular bloom, weighing about 2.5 kg and measuring 20x4.5x4 cm.

In a female grave at Osteria Nuova, 20 km NW of

Fig. 79. An Etruscan tomb, Tomba dei Carri, 7th century B.C., at San Cerbone, Baratti. For more than 2000 years the tomb lay well protected against graverobbers, because it was totally embedded in iron slags. The rich tomb, which among other things contained two bigas, was excavated in the 1980'es.

Rome and dated to 800-700 B.C., there was a purse with a bear tooth, a boar tooth, and fragments of iron rings. The objects are exhibited in the Museo Nazionale Romano delle Terme Diocleziane, Rome. Do we here have a hint of the ancient times when "they were wizards, and practised charms and initiatory rites and mysteries" in order to run a successful iron furnace? (Diodorus).

Elba

Ancient name Ilva, Aethalia

223 km^2, distance from the north coast of Elba to Populonia 15 km. Highest point, Monte Capanne 1019 m (western Elba)

Some copper ores (native copper, chalcopyrite, atacamite) and silver-bearing galenite, and pyrite.

Main ore hematite, locally better than 60% Fe. Beautiful hematite crystals.

The ore had 5-10% SiO_2 and few impurities. Phosphorus was below 0.01%.

Mining since about 800 B.C. Mining for hematite concentrated in the eastern part of the island.

Open-pit mining around Rio Marina.

Some mining for magnetite near Capoliveri, Vallona, Mons Calamita, and Ginevro.

Many ancient slag heaps, concentrated along the north coast.

Production 200 B.C. about 10,000 tons of ore annually.

Production 1870 A.D. 100,000 tons of ore. 1914: 300,000 tons of ore. 1931: 400,000 tons of ore.

Blast furnaces in Portoferraio and, on the mainland, in Piombino and Follonica.

Italsider, the most important producer, had in Rio Marina 1951 550 workers, in 1961 546, in 1971 477, and in 1981 298 workers. Today there is no activity.

Through its history the island has been controlled by 1) the Ilvaites, a Ligurian tribe, 2) Etruscans 3) Phoenicians, 4) Phocaeans from Marseille, about 600 B.C., 5) Syracuse about 400 B.C., 6) Rome 300 B.C.-500 A.D., 7) Longobards, 8) Pisa, 9) Genova, 10) Firenze, The Medici family, who founded Portoferraio, Elba, 11) Spain's Philip II, 12) French occupation of Tuscany and Elba 1809, Napoleon in exile 1814-1815, 13) from 1815 part of the Grand Duchy of Tuscany, 14) from 1860 part of the new Italy.

Good collections of the minerals and ores of Tuscany and Elba are on display in the Mineralogical Museum, University of Firenze; The Mineralogical Museum, Viale di Scienze, Citta Universitaria, Rome, and in Portoferraio, Elba.

Chapter 4
Early iron in the Mediterranean area, and the bloomery process (I)

He works and blows the coals
and has plenty of other irons in the fire.

The Acharnians, Aristophanes (446-380 B.C.)

In the previous chapter, the history of iron was followed from the humble beginnings until about 500 B.C. The development was illustrated by a few examples from the literature. The sketch was based upon the general opinion that the discovery of iron as a promising metal occurred in central or northeastern Anatolia and that the knowledge from there spread in all directions, according to a scheme like Figure 74 (Pleiner 1980: 382; 2000: 19,31; Serneels 1993: 9). Iron took over where it was best suited, particularly for knives, files, chisels, hammers, axes, arrowheads, daggers, swords, lanceheads and javelins; as agricultural tools like ploughshares, sickles and horse-trappings; and as fire-resistant material in the household and smithy for spits, fire dogs, vessels and tongs. Important early applications were also handcuffs, chains and myriads of nails, large and small, as well as wire. Bronze maintained its position for decorative, for ritual, and for jewellery purposes, as well as for vases, drinking cups, buckets, cauldrons, candelabra, defensive weapons (shields, leg protection, helmets), statues and monuments.

A driving force for the development of early iron technology was, no doubt, the demand for weapons. The 12th century B.C. was a time of trouble throughout the ancient world. Nebuchadressar I brought about a brief Babylonian renaissance, but was stopped by the expanding Assyria. Tiglath Pileser I (1116-1078 B.C.) brought the Middle Assyrian empire to its highest level of ascendancy. He was a fierce and clever warrior, and an insatiable huntsman. His ruthlessness in warfare made him, and Assyria after him, hated and feared. The kingdom of Van, centred around the iron-rich Urartu, was repeatedly attacked by him and his successors, which is a major reason for his treasure vaults' abundance of iron objects.

In Egypt, Rameses III (1188-1156) rallied his forces to face the deadly menace of the Sea Peoples, a loose confederation of Pelast (Philistines), Tjikar (Sicilians?), Danuna (Greek Danaoi), Shardina (Sardinians) and undetermined tribes. Some of the Sea Peoples, notably the Philistines and Tjikar, settled the Palestinian coast. The weakened Hittite empire in greater Anatolia finally succumbed in the general chaos, but some Hittitic tribes moved south into Syria and Palestine, occupying among other sites Carchemish and Aleppo. From another direction came the Aramean tribes. The Israelites came on the scene as described in the Biblical Book of Judges. Israel's full control of the land was not established until the time of David, after 1000 B.C.

In Greece, Pylos was sacked and burned about 1200, and later during the 12th century the Mycenaean civilization was destroyed, Mycenae itself falling about 1100 B.C. The invading people, the Dorians, reduced the population to a barbarian state, and the Greeks became illiterate for generations to come.

It has been maintained that the success and upsurge of iron depended entirely on its ability to become car-

Fig. 80. Greek vase painting from about 500 B.C., on an Oinochoe. British Museum, No. 1846.6-29, 45. The master is reheating a copper or a bronze bar to recrystallize and soften it before further hammering, assisted by a younger helper. The cauldron on top of the furnace may contain molten wax for cire-perdu work in the bronze shop. Oddy & Swaddling 1985.

burized and converted into steel. I am not convinced that this is necessary for its successful application. Even today only a small proportion by weight is used as hardened steel, e.g. for drills, chisels, tools in general, knives, springs, rifles and guns. 90, or rather 95%, is used as mild steel ("wrought iron") for construction, tubes, wires, nails, cars, cans, ship-, bridge- and harbour building. Hardened steel has, of course, from the beginning had a high value, but it was hardly an important driving force. The normal heterogeneous ferritic-pearlitic material was in itself superior to bronze, as argued in Chapter 3.

It has also been suggested that the change to iron was due to shortcomings in the supplies of copper and, especially, tin. It may be part of the story, but on the other hand, copper and bronze did not disappear from the scene. They were only restricted to objects for which they were better suited than iron, for example a hammered helmet for the warrior, a vessel for the home, or statuary, whether of small size for the household, or of large size for monuments in the temples.

It has further been suggested that there was a fuel-saving incentive to change from bronze to iron. It is hardly the case, the amount of fuel and labour, from ore to finished objects, is about the same, whether bronze or iron is concerned. When the blacksmith first had learned his business and produced the first iron hammers and tongs to grip the glowing iron, the success of iron was guaranteed. And, importantly, the iron ores were widespread, not of the size of modern-day iron mines, but more than sufficient for the needs of the ancient societies.

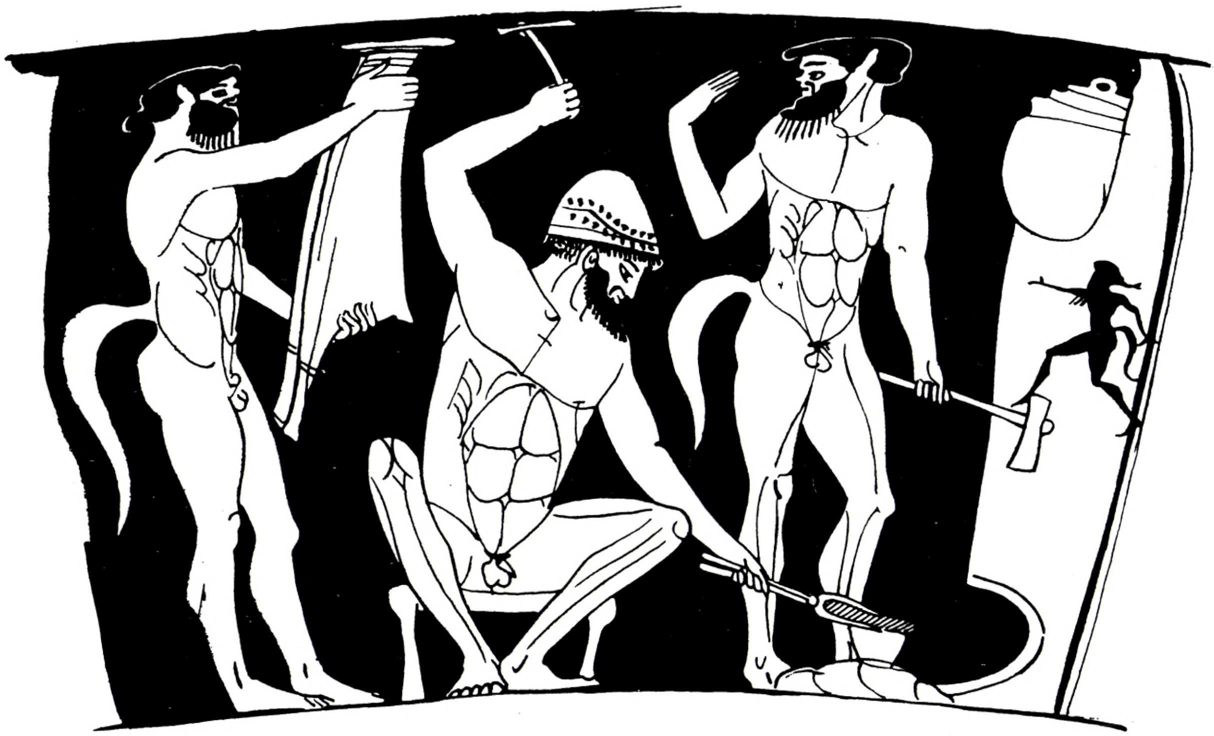


Fig. 81. Greek vase painting from about 470 B.C. on a column-crater in the Museum in Caltanisetta, Sicily, No. 20 371. The master has withdrawn the softened copper or bronze bar from the fire and is now forming it on the low anvil. Hammer, tongs and anvil are probably of iron. Figs. 80 and 81 illustrate two phases of the same process in the bronze shop. Oddy & Swaddling 1985.

The Stone Age did not end because of the lack of stones, and the Bronze Age did not end because of the lack of bronze. It was much more a question of innovation and discovery of a material, iron, which was better and more easily accessible than bronze.

Greece had no reputation for iron production in ancient times. Although there are reports of slag accumulations on the island of Sephiros, 120 km SE of Athens, and of iron production in eastern Macedonia and on the island of Thasos outside the Macedonian coast (Photos et al. 1984), it is apparent that the Greek mainland was dependent on import, either of bars or of manufactured objects. Greek vase paintings have often been taken as evidence for iron smelting and working (e.g. Livadefs 1956), but it has later been convincingly argued (Oddy & Swaddling 1985) that the vase paintings depict processes associated with the casting of bronze, the forging of bronze, and with the working of wax models for cire perdu casting.

Homer refers to iron 22 times in the Iliad and 29 times in the Odyssey, but bronze is the major metal in the epic. Iron was in that period rare and it had a high value, as may be seen from the athletic competition in honour of the fallen Patroclus (Ilias, 23.Song: 826-835). Achilleus chose prizes for the winner, and exhibited an iron bloom (perhaps a bipyramidal bar, see later), which in former days the hero Eëtion was wont to hurl. The bloom was praised as representing sufficient iron for the winner, so in five years' time he had no need to send his shepherds or ploughmen to the city for iron supplies.

The Parthenon was built on the initiative of Pericles. Pentelic marble was used for its erection, which lasted ten years (447-438 B.C.). The marble blocks

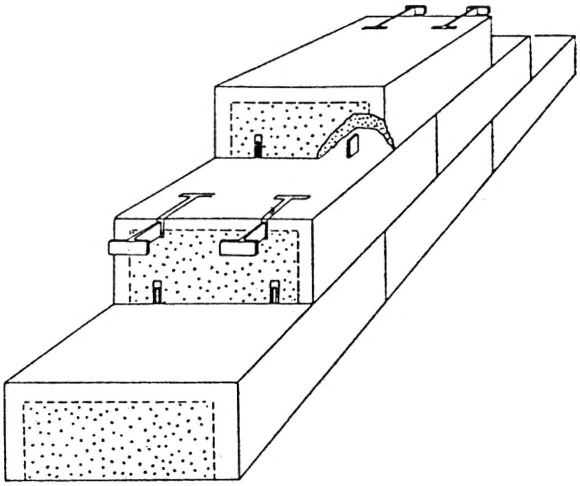


Fig. 82. The dowel and the double-T-shaped iron clamp were used to fasten (marble) building blocks together. Here a reconstruction of the Parthenon foundation, 447 B.C. Livadefs 1956.

were chiseled to form, but they were not joined by lime-mortar. Instead they were – like numerous other important buildings in Greece – secured by iron clamps and dowels, Figure 82. Some of these have been meticulously examined by Livadefs (1956), who presented metallography, analyses and technical facts. In Table 4.1 are quoted some of his results from a dowel and two clamps. These have survived for 2400 years due to their being inserted in melted lead, which has provided an effective seal against corrosion.

The analytical values reveal an iron produced from rich, pure and well-roasted iron ores, probably of a hematite nature. Phosphorus, sulphur and manganese are practically absent, while silicon is a little high, probably because the drillings for the analytical determination were polluted by some silicate slag inclusions. Carbon is variable, between objects and inside the same objects, as is usual for bloomery iron. The dowels and the clamps display a heterogeneous structure, where ferritic streaks alternate with ferritic-pearlitic zones, which is further documented by Livadefs, who also measured the Brinell hardness, HB in Table 4.1. The paper ends with several pages of interpretation which, however, must now be considered obsolete, in particular where the author discusses an iron production furnace giving liquid iron.

The iron ore occurrence on Elba was something special. Discovered about 800 B.C., the ores became intensively mined from about 500 B.C., and have been exploited more or less energetically since then. In particular, there was much activity in the Etruscan-Ro-

Table 4.1. Chemical composition of a dowel and two clamps from the Parthenon (Livadefs 1956)

	% C	% S	% Si	% P	% Mn
Dowel N	0.395	0.008	0.043	0.024	nil
Clamp B					
Flange	0.419	0.016	0.055	0.032	nil
Web	0.117	0.006	0.056	0.008	nil
Clamp E					
Flange	0.104	0.006	0.061	0.012	nil
Web	0.350	0.007	0.065	0.006	nil

N Dowel, 7x0.7x0.6 cm. Ferritic-pearlitic. HB: 88-92-134-156-166.
BF Clamp, flange, about 25x0.8 cm. Ferritic-pearlitic. HB: 85-89-98-131-140.
BW Clamp, web, about 25x0.8 cm. Ferritic. HB: 87-98-99-101-114.
EF Clamp, flange, about 25x0.8 cm. Ferritic. HB: 91-96-97-100-130.
EW Clamp, web, about 25x0.8 cm. Ferritic-pearlitic. HB: 91-97-107-122-124.

man period and in mediaeval times under the protection of the Pisan and Florentine navies (Biringuccio 1540). Presently they are considered uneconomical to mine in competition with the cheap iron ores which are shipped from Australia or South America to the blast furnaces of northern Italy.

While the Elban population never became rich from their ores, tradesmen and manufacturers on the mainland apparently enjoyed the benefits of the excellent ore. In centres like Volterra, Tarquinia, Caere and Aretium (Arezzo) the tombs display the wealth of the upper strata of the Etruscan population. Many bronze objects of high artistic value were finished in the centres, for example the bronze she-wolf which later became a symbol of Rome, and now is on display in the Capitoline Museum. Another fantastic expression of Etruscan art is the bronze chimera, found in Arezzo and cast about 450 B.C., Fig. 77.

The bloomery process

The bloomery process, or the method of producing wrought iron in a direct way, has been treated by numerous authors through the years (e.g. Gilels 1936; 1958, Tylecote et al. 1971, Thomsen 1975, Espelund 1992-1993, Serneels 1993, Pleiner 2000, Lyngstrøm 2002). It is, however, necessary here to recapitulate some essential traits about iron and slag formation in order to better appreciate the analyses which will fill much of the coming pages.

We have seen that iron is a common metal, but that it is bound in various chemical compounds. If a miner-

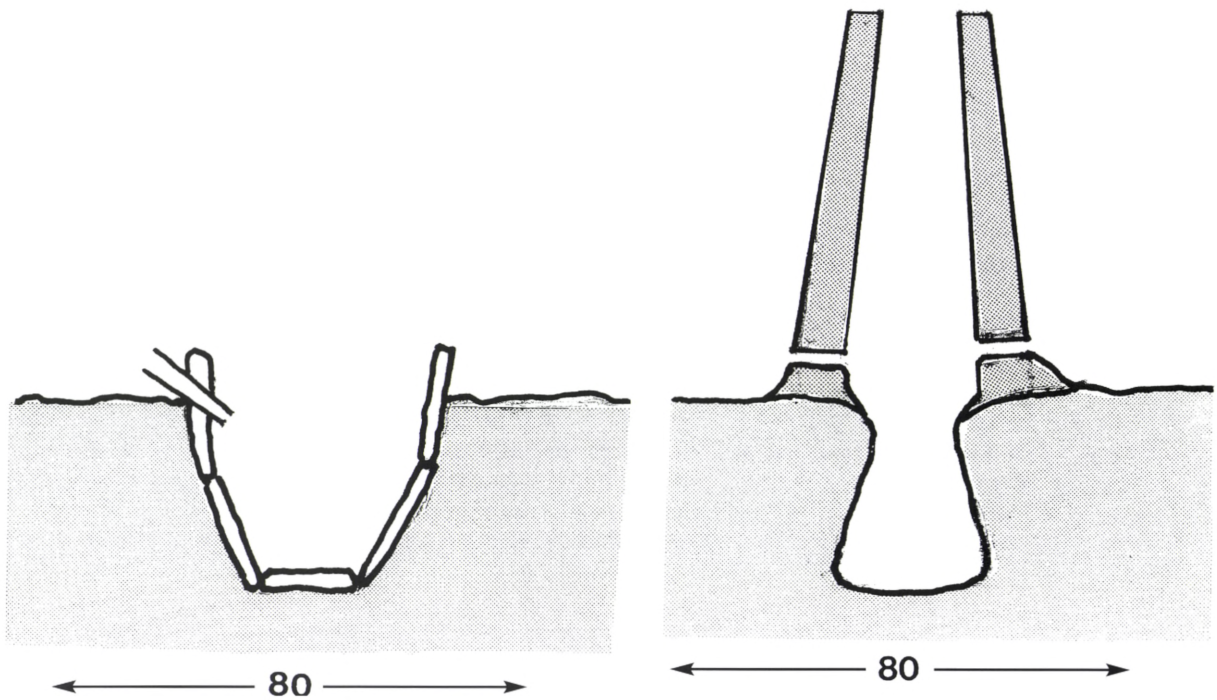


Fig. 83. A sketch of two important iron furnace types. **1**, bowl furnace (Norwegian "hellegryte"), lined with flagstones. The furnace is blown from the left. **2**, clay-built shaft furnace with slag pit and two air-holes for blowing. Measures in cm.

Table 4.2. Important iron minerals

	Formula	max.% Fe	Examples
Magnetite	Fe_3O_4	72.4	Dannemora, Kirunavaara
Hematite	α-Fe_2O_3	70.0	Elba, Cumberland, Southern Spain
Goethite	α-FeOOH	62.9	Common precipitate from solutions
Siderite	$FeCO_3$	48.2	Durham, Siegerland, Hüttenberg
Ankerite	Ca (Fe,Mg,Mn) $(CO_3)_2$	45	Erzberg

Table 4.3. Important ore types

Ore type	Typical iron content,% Fe	Examples
Magnetite	59-62	Grängesberg, Norberg
Hematite	52-55	Elba, Bilbao, Mesabi Range
Clay ironstone	30-40	South Wales, Staffordshire
Limonite, Brauneisenstein	35-37	Northamptonshire
Siderite	35-45	Siegerland, Schmalkalden, Erzberg
Bog iron ore	45-55	Snorup, Tvååker
Lake ore	40-50	Vidöstern, Småland, Eastern Finland
Minette	26-35	Luxemburg, Lorraine

al, a deposit, or a rock can be excavated and with contemporary requisites and economic gain can be converted into wrought iron, the mineral, deposit or rock is called an iron ore. Tables 4.2 and 4.3 list some important iron minerals and a number of iron ore types that have been utilized since ancient times.

Table 4.4 gives an overview of the four steps of the bloomery operations (Buchwald 2001).

The first step is roasting, the name suggesting the timber framework upon which coarse fragments of the dried ore were fired. The temperature of the ore was typically raised to 400-550°C for several hours, and the purpose was to remove water and to weaken the cohesion, so the ore could more easily be crushed to nut-size. If we let the typical ore be represented by the formula FeOOH, corresponding to goethite in Table 4.2, the principal roasting reaction runs

1) $2\ FeOOH \rightarrow Fe_2O_3 + H_2O$.

Water evaporates, and α-Fe_2O_3, hematite, mixed with γ-Fe_2O_3, maghemite, are formed, of a very characteristic purplish red colour. The roasted material is magnetic due to the presence of maghemite as opposed to the unmagnetic charge on the roast. The roasted ore is an eminent red pigment and rather easily recognized if present near ancient furnace sites.

Since iron ores are often contaminated by sulphides – the Elban hematite contained appreciable pyrite and sometimes chalcopyrite – the roasting has the additional effect of burning significant quantities of sulphur to sulphur dioxide, poisonous fumes which can be detected by their sticking odour.

2) $4\ FeS_2 + 11\ O_2 \rightarrow 2\ Fe_2O_3 + 8\ SO_2$.

The roasting was usually carried out near the production furnaces, and the roasted ores were normally not stored, but used "immediately".

In the roasting operation no slag was formed. Biringuccio (1540, Book 1, Ch.6), who stressed that it is important to sort the ore carefully and handpick the

Table 4.4. The four steps of the bloomery process

Step	Process	Primary purpose	Equip-ment	Atmos-phere	Compo-nents	A Product	B Waste	Relative quantity of slags	Ease of identifi-cation
1	Roasting	Removal of water and sulphur, loosen coherence of the ore	Roast, wooden logs	Oxidizing	Iron ore, wood	Roasted iron ore	Ashes, unreacted ore	No slags	Difficult in the field
2	Production	Reduction	"Closed" furnace	Reducing	Roasted iron ore, wood, charcoal	Slag-rich bloom	Production slag	1000	Easy
3	Purification	Consoli-dation, slag removal	Cleaning hearth	Oxidizing	Slag-rich bloom, charcoal, sand etc.	Slag-depleted iron bar or plate	Puri-fication slag	20-50	Not too difficult
4	Manu-facturing	Shaping, forge welding	Smithing hearth	Oxidizing or reducing	Slag-depleted iron bar, charcoal, sand etc.	Nails, horseshoes locks, agricul-tural tools	Manufac-turing slags, sinder	1-2	Easy

material for the furnaces, also made a point of sorting after the roasting had taken place: "Thus roasted, he will put (the ore pieces) in an open place so that the rain will wet and the sun will dry them out. Having left them thus for some time, he must look them over again piece by piece before they are brought to the furnace in order to see whether some trace of another metal has appeared". I suspect that Biringuccio here in particular addressed the copper-contaminated ores, which he was familiar with from the Colline Metallifere in Tuscany. Copper is unwanted in iron, because it makes it red-short, and copper would be disclosed by its greenish spots on the roasted and weathered ore pieces.

The next operation, step 2, is the production, or reduction stage. The preheated furnace, a bowl or a

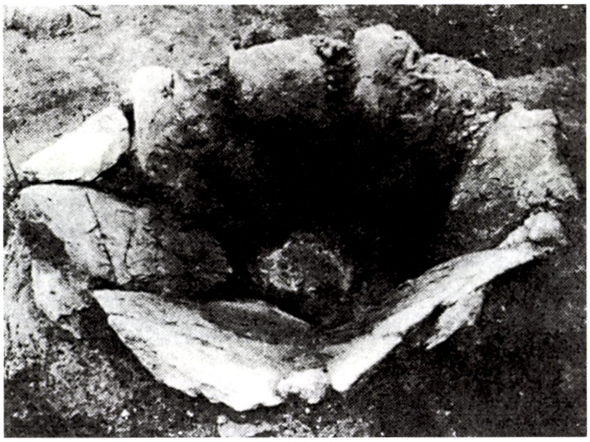


Fig. 84. Flagstone lined furnace (hellegryte) from Erlandsgård 6, Møsvatn, Telemarken. 400-700 A.D. Martens 1988: 70. Diameter at the top side 95 cm.

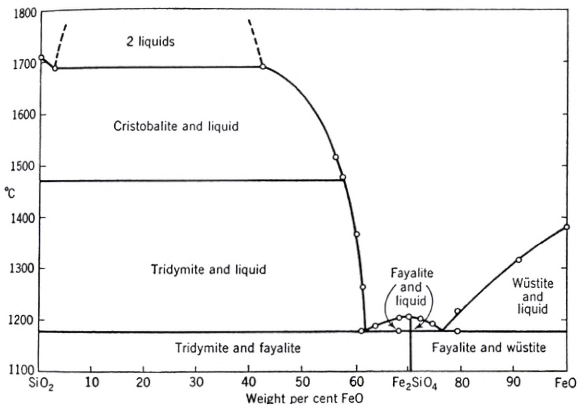


Fig. 85. The FeO-SiO_2 equilibrium diagram. Darken & Gurry 1953.

shaft, was charged with alternating batches of iron ore and charcoal, generally with about equal weights of ore and coal. The reduction to iron can be expressed with the following principal reactions. In these the active reducing agent is not solid coal, but gaseous carbonmonoxide, formed from burning coal (equation 5):

3) $Fe_2O_3 + CO \rightarrow 2\ FeO + CO_2$

4) $2\ FeO + 2\ CO \rightarrow 2\ Fe + 2\ CO_2$

5) $2\ C + O_2 \rightarrow 2\ CO$

where eq.5 occurs in the hot zone (1200°C) near the tuyere, the blowing hole. Reaction 4 occurs somewhat higher in the furnace, and reaction 3 may be perceived as the first reduction step, taking place in the medium-upper part of the furnace.

In practice these equations are far too simple, because some SiO_2 is always present, either as sand (e.g.introduced with the charcoal when shuffled from the stack pit or the pit), as quartz from the ore, or as amorphous silica present in the bog iron ore. We shall consider five examples, A-E, which involve different ore qualities.

A. A roasted, inadequate “ore” with 56% Fe and 20%SiO_2

6) $3\ Fe_2O_3 + 2\ SiO_2 + 3\ CO \rightarrow 2\ (FeO + Fe_2SiO_4) + 3\ CO_2$

The balance shows that the composition of the charge is inexpedient, since all iron in the end is being bound in the slag and lost. The yield of free iron is nil. The composition of the slag on the right side of the equation corresponds rather well with the eutectic minimum temperature of 1150°C in the FeO-SiO_2 equilibrium diagram, Fig. 85.

B. In the second example, a roasted ore, slightly richer in iron (57.0%) and poorer in SiO_2 (17.6%) is selected:

7) $7\ Fe_2O_3 + 4\ SiO_2 + 9\ CO \rightarrow 2\ Fe + 4\ (FeO + Fe_2SiO_4) + 9\ CO_2$

Theoretically the situation has improved, since two out of 14 iron atoms have been reduced to free iron, i.e. a yield of 14.3% (basis iron atoms) or 112/1360 = 8.2% (basis roasted ore).

C. In the third scenario, a roasted ore with 58.9% Fe and 15.8% SiO_2 is presented, a realistic and probably rather common case.

8) $2\ Fe_2O_3 + SiO_2 + 3\ CO \rightarrow Fe + (FeO + Fe_2SiO_4) + 3\ CO_2$.

The situation has improved significantly. The yield of iron is now 25% (basis iron atoms) or 56/380 = 14.7% (basis roasted ore).

D. In the fourth example, the roasted ore contains 60.3% Fe and 13.8% SiO_2, a very fine combination:

9) $7\ Fe_2O_3 + 3\ SiO_2 + 12\ CO \rightarrow 5\ Fe + 3\ (FeO + Fe_2SiO_4) + 12\ CO_2$.

The yield in iron is 5/14 = 35.7% (basis iron atoms) or 21.5% (basis roasted ore).

E. In the final example a very rich, roasted iron ore with 64% Fe and only 8.6% SiO_2 is presented:

10) $4\ Fe_2O_3 + SiO_2 + 9\ CO \rightarrow 5\ Fe + (FeO + Fe_2SiO_4) + 9\ CO_2$.

The yield is very high, 5/8 = 62.5% (basis iron atoms) or 280/700 = 40% (basis roasted iron ore). It is a question whether a favourable situation like this has ever been realized in a practical bloomery process.

It is to be noted that the slag composition ($FeO + Fe_2SiO_4$) in all five examples is the same, corresponding to the lowest melting point in the FeO-SiO_2 system, and also corresponding rather well to the composition of a majority of real slags found on ancient production sites. From the equations 6-10, it is evident that the archaeologist will be unable to calculate the yield, or the ore composition, from a slag analysis alone. In the present examples five different ore mixtures have resulted in the same slags, but with different yields. We thus need more information in order to calculate the yield of ancient furnaces, primarily an identification of slag and ore composition from the same furnace run.

The five equations also serve to bring home another point: Only a fraction of the carbon charge is needed for the iron reduction proper. In equation 8 for example, 3 mol CO was required for the reduction of the charge of 380 g (320 g iron oxide and 60 g SiO_2). The 3 mol of CO were formed from 3 C, or 36 g charcoal (if we consider the charcoal to be 100% carbon, which is not quite correct). But all experience shows that to an ore charge of 100 kg it was customary to add 100 kg of charcoal. That is, less than 10% of the coal was needed for the reduction. The remainder was used in heating the furnace and the charge and keeping the reaction going.

Examining the relative quantities of iron and slag in the bloomery process, it will be realized that there are large variations. Taking again reaction 8 as an example, 1 Fe = 56 g = 56/7.8 = 7.2 cm^3 iron is formed together with the slag ($FeO+Fe_2SiO_4$) = 72 + 194 g = 266/3.3 = 80.6 cm^3. The volume of the slag is thus in a typical reduction furnace more than ten times the volume of the metal. If the composition of both the applied ore and the slags is known, it is possible approximately to calculate the yield of iron from the measured amount of slags on the site.

Charcoal and ashes

Fuel for the reduction furnaces was wood and charcoal and, in rare cases, peat. In general, wood was utilized in funnel or bowl-shaped furnaces, while charcoal would be best suited for the cone-shaped shaft furnaces. In the first type the dried wood might be stapled in and on top of the furnace, and the ore would be charged as the wood sank together and became converted into a charcoal charge. This open fire was probably not very economical with respect to the consumption of fuel.

Charcoal could be made of any wood available. In Sweden and Norway, pine and birch, and in later periods spruce, were commonly used. In Denmark oak, hazel and alder. In Tuscany chestnut, pine, oak and ash, and in Crete olivetrees and their stumps. In Timna, Israel, charcoal was produced from acacia and date palms. In Tuscany logs of Tree heather, Erica arborea, were charred and were particularly appreciated as coal for the smithing hearth (G.Brambilla, pers.comm.)

In ancient times the wood to be charred was cut to the proper thickness and length, and was filled into a pit and covered by ferns, leaves, and soil to prevent open fires from developing. From late mediaeval times, the charring usually took place in large stacks above ground. The stacks were likewise covered by whatever was available to prevent the stack from catching fire. Evidently the resulting charcoal was not just coal, but was contaminated by "soil", part of which ended up in the furnace.

Biringuccio (1540, Book 1, Ch.6) was of the opinion that charcoal of soft wood (pine, fir, poplar, willow, elm, walnut, lime and alder) made a soft and tough wrought iron, while charcoal of hard wood (Quercus ilex, Quercus cervis, beech and ash) made it strong, hard and less tough. "But you cannot and should not be too particular, for you are forced to use whatever you can have, even though there should be a great waste" (ibid. Book 3, Ch.10). As a general rule five tons of air-dried wood will give one ton of charcoal, using the old technology and not applying closed retorts (Bergström 1947). The charcoal should be stored under protection, best in a shed or a large house, as was common in the mediaeval Swedish Bergslagen.

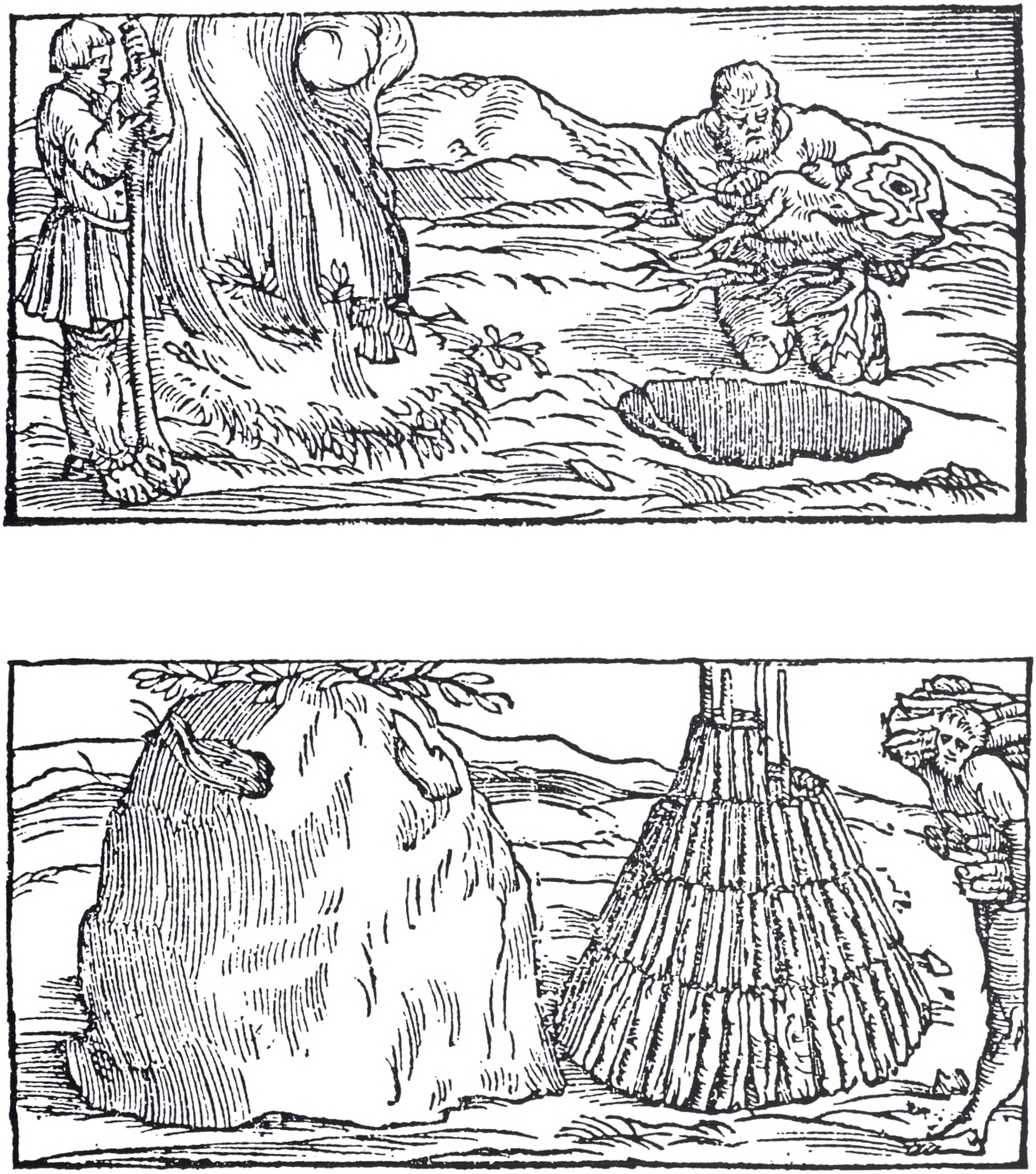


Fig. 86. Charcoal burning. Above, the ancient method. Wood and tree stumps are placed in a pit (right part of the wood cut) and burned (left part). Below, the mediaeval method, after about 1400 A.D. The wood is chopped into pieces of similar size and raised in a pile (right part), covered, and burned (left part). Biringuccio 1540.

Table 4.5. Chemical composition of ashes from various trees

	Ashes %	K_2O	CaO	MgO	MnO_2	Fe_2O_3	Al_2O_3	SiO_2	SO_3	P_2O_5	CO_2	Σ
1	0.14	13.0	39.3	10.8	5.4	3.0	-	1.8	-	0.4	21.9	95.8
2	0.18	16.9	34.6	6.8	4.8	2.8	2.7	2.4	5.0	3.9	19.5	99.2
3	1.16	9.5	49.8	6.8	2.8	1.0	10.7	1.9	2.8	6.0	7.5	98.7
4	0.24	13.9	39.6	7.5	3.5	1.6	1.4	2.2	3.2	0.4	25.3	98.6
5	0.22	18.6	30.8	10.3	3.5	0.9	3.4	2.0	3.9	5.1	21.3	99.7

1, Pine, heartwood 2, Pine, sapwood 3, Pine, bark 4, Spruce, heartwood 5, Birch, average

The chemical composition of ashes from various Swedish trees has been thoroughly examined by Åkerman & Sundström (1898). A few typical analyses are presented in Table 4.5. First, the amount of ash from wood dried at 20% relative humidity, and ignited and burned to equilibrium at above 900°C, ranges from 0.14 to 0.24% by weight. Pine bark alone leaves about 1.2%, and still more does bark from spruce (not shown in the table). The composition of the ashes is different between different parts of the tree, heartwood, sapwood and bark, but rather similar between tree sorts. The ashes of sapwood and, in particular, bark are enriched in phosphorus, and bark is also consistently enriched in calcium and aluminium. Manganese is surprisingly high, but the authors showed that trees from other locations, e.g. Söderfors, had much more normal values of only 20% of what is presented in Table 4.5. Important are the rather high proportions of K_2O, CaO and MgO, often occurring in the ratios about 2 : 4 : 1, and adding up to about 80% of the solid part of the ashes.

Ashes from deciduous trees contain about 4 times the phosphorus of coniferous trees (Bergström 1947). Young trees and twigs of both deciduous and coniferous trees are enriched in phosphorus relative to older tree mass. Finally, the composition of ashes from one and the same tree sort may vary significantly with the locality and composition of the soil on which it grows.

Although described as the direct process, it becomes evident from studying Table 4.4 that four steps are involved in the bloomery process. In the first step no slag is formed, and in the fourth step the quantity of slags is rather insignificant. But the slags of steps 2 and 3 are plentiful and important. They are, however, often confused and difficult to tell apart.

Fig. 87. Production slag from a slag pit furnace, about 300 A.D. A 192.5 kg slag of the socalled elephant's foot type, from Snorup, West Jutland. Scale bar 20 cm.

Step 2 B, the production slags, or reduction slags, occurs in and around the primary ancient furnaces. They are highly reduced and have no magnetite, and they are usually not attracted to a magnet. They may contain networks and laces of free, reduced iron which, entrapped, never coalesced with the bloom and thus diminished the practical yield of the furnace process. The specific gravity of production slags is about 2.9-3.7 g/cm^3. The viscosity is low when FeO is high (60-70%), but high with lower FeO-content. The included gases more easily escape the FeO-rich slags,

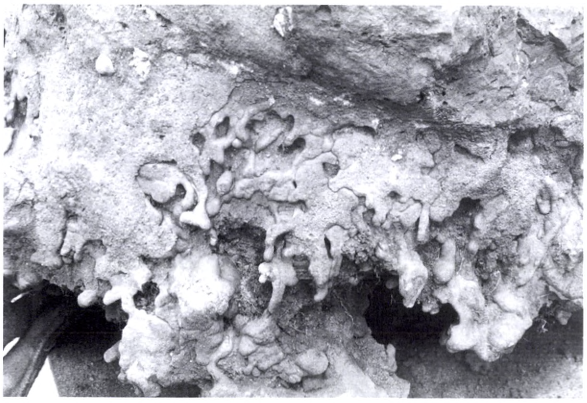


Fig. 88. Close up of the right side of the slag block in Fig. 87. The slag bears the imprint of the claey sand of the pit wall. Side length 20 cm.

which thus for two reasons have relatively high densities: High FeO-content and low porosity.

Production slags may coalesce to form enormous lumps of 100-200 kg, or even more, as in the north European shaft furnaces with underlying pits ("the slag-pit furnace", Tylecote 1987; Voss 1993). Or they may be individual chunks of 100-500 g from shaft furnaces with side- tapping. Or even as small as 10-50 g when they escape as tapslag in small portions. Tapslags may, incidentally, be recognized on their undersides showing impressions and inclusions of the soil, and topsides which have been partially oxidized (magnetite!) when coming into contact with the air. Cross sections through tapslags reveal internal borderlines, separating consecutive runs. Occasionally, tiny iron grains, 5-30 μm across, may be identified inside the tapslags.

I have looked for, but not found evidence for iron masters having added any flux to bloomery furnaces in ancient times. The slag compositions can be explained as the result only of reactions between charcoal ashes and the local ores. Above the tuyere, part of the intensively heated furnace wall has often reacted with slag and been consumed, but such slag constitutes a very minor portion, is easily recognized, and should always be excluded from the average slag analyses.

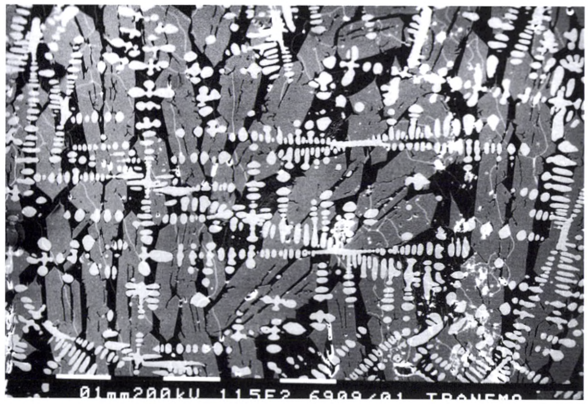


Fig. 90. Tap slag from a small, medieval furnace at Tranemo, Väster Götland. Fayalite laths (grey), wüstite dendrites (white) and glass (black). Sample 3, Chapter 12. PS. SEM photo. Scale bar 0.1 mm.

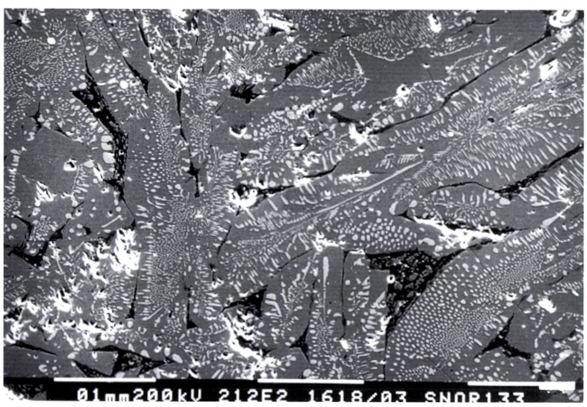


Fig. 89. Section through a bottom slag, No. 133, Snorup. SEM-photo. PS. Fayalite laths with exsolved wüstite in intricate patterns. A little glass (black). Scale bar 0.1 mm.

<u>Step 3 B</u>, the purification slags, plano-convex slags, or Kalotschlacken, occurs in and around the purification hearth. This was a shallow, charcoal-filled bowl into which the (two) bellows protruded from the side. The bellows were protected by a fire-resistant shield, for example a soapstone or a plate of baked clay with a hole for the bellows. The blacksmith apparently applied significant quantities of sand, in the widest sense, for the operation. The raw, spongy bloom from

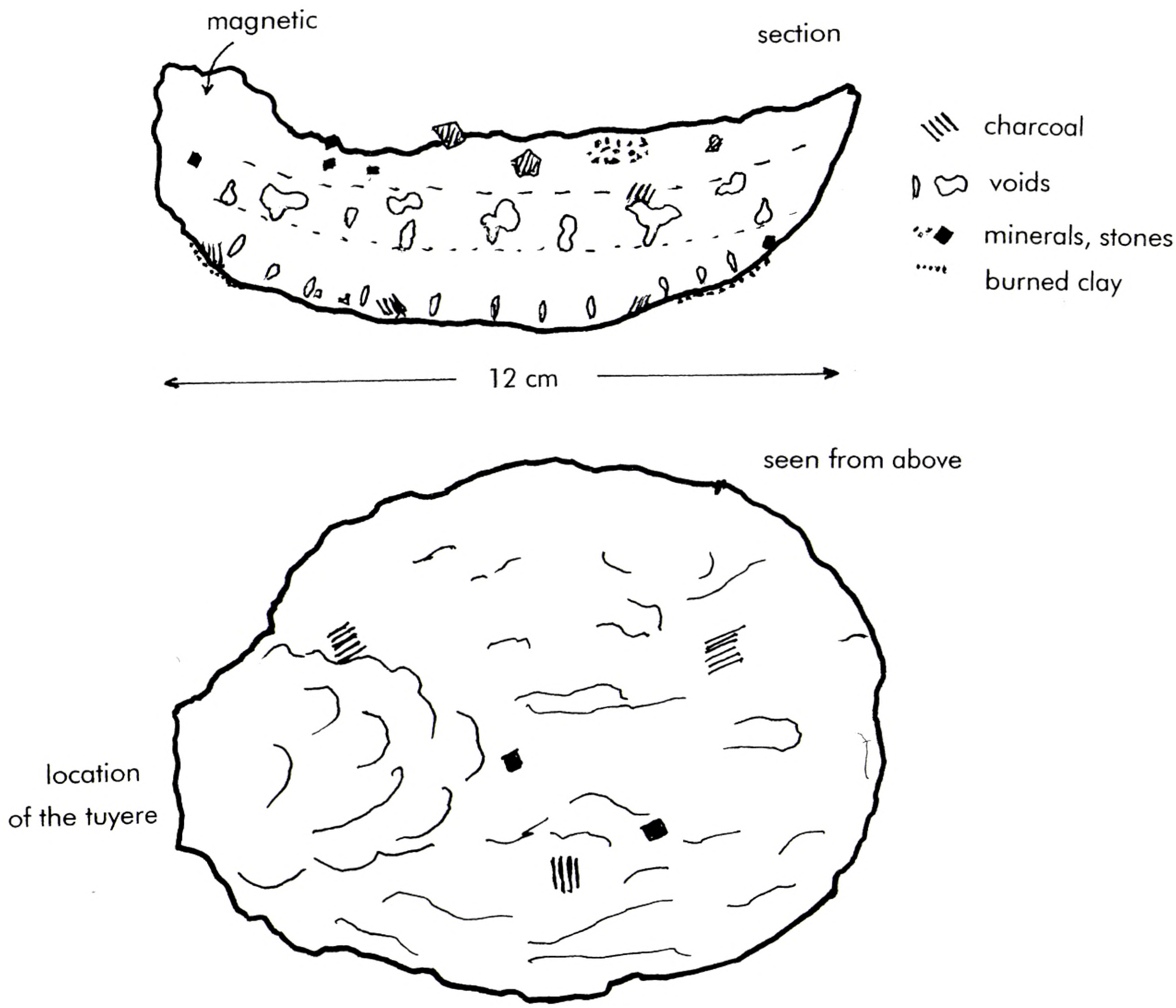


Fig. 91. Section and top view of a purification slag of the kalot type. The air blast produces ripples on the surface, and some magnetite may form in this part of the slag. Inclusions of charcoal, unburned iron, and various "stony" particles are common.

the production furnace was reheated to above 1100°C in the purification hearth. The heat was generated by the vigorous burning of charcoal and by oxidation of iron:

11) $C + O_2 \rightarrow CO_2 + 94$ kcal

12) $2\ Fe + O_2 \rightarrow 2\ FeO + 129$ kcal,

two exothermous reactions, the last one giving rise to a significant loss of iron. The generated iron oxide reacted with the sand added by the blacksmith, to give fayalite, the iron-rich end member of the olivine mineral series. This took place under further strong heat production:

13) $2\ FeO + SiO_2 \rightarrow Fe_2SiO_4 + 217$ kcal.

That these are not insignificant heat productions may be seen by comparison with an example from daily life, the heating of water. If we take an equal amount of water (2 Fe = 112 g), and heat it from 0°C to 100°C and let it evaporate, it requires

Fig. 92. Layered purification slag, or kalot slag, 753 g, side length 11.5 cm. From section 800, Snorup.

112 x 1 x 100 = 11.2 kcal plus 112 x 540 = 60.5 kcal, or a total of 71.7 kcal for 112 g of water to evaporate. The reaction heat released on the hearth in reactions 12 and 13 is about five times as large!

The new slag mixed itself with slag exuding from the bloom and flowed to the bottom of the hearth. Here it solidified, making a "cast" of the bottom. As the hearth was filled up, the blacksmith would remove the plano-convex slag with a pair of tongs and throw it away, making the hearth ready for a new operation. Sometimes the marks of tongs may be identified on the slags.

The typical plano-convex slag is 10-16 cm in diameter and slightly oblong, with a weight of 100-1500 g and a specific gravity of 2.5-3.0 g/cm^3. It may be irregular or stratified if the hearth was in discontinuous use and/or was not regularly cleaned. When cleaning the hearth and removing the slag, the ideal bun shape was easily destroyed, the result being numerous irregular fragments. Penetrating studies of the plano-convex slags have been published by, among others, Thomsen (1971 c), Westfalen (1989), Espelund et al. (1987) and Madsen (2004).

The plano-convex purification slag is heterogeneous, displaying undissolved sand grains, feldspar particles, white-burned small stones (perhaps from calcined flint added as "sand"), as well as bone and charcoal fragments, or even an occasional nail (from a board used as fuel?). The top side of the kalot often displays glazed parts, shining in mother-of-pearl colours, and the surface may exhibit ridges or corrugations from the violent wind passing from the bellows over the hot, viscous mass.

Very often sections through the slag display 10-50 μm iron particles, angular or rounded, but never forming lace work as in the production slags. I assume that these iron particles were formed by the violent reactions on the hearth when part of the iron bloom burnt away to form iron oxides (Equation 12). Small portions became trapped inside the slag before being entirely consumed by burning. Few of the operations in ancient iron technology led to chemical equilibrium. So, surprisingly, we find free iron inside an otherwise well oxidized mass of slag.

The common presence of minute iron inclusions in purification slags makes them vulnerable to the weather. Under humid conditions iron is converted into hydrous iron oxides which stain the plano-convex slags and in the long run make them fall apart. On the other hand, iron-free purification slags may survive very well and retain their shape for a thousand years.

Since purification hearths were located near the production furnaces as well as in distant cloisters and manors and in the towns, we find today large numbers

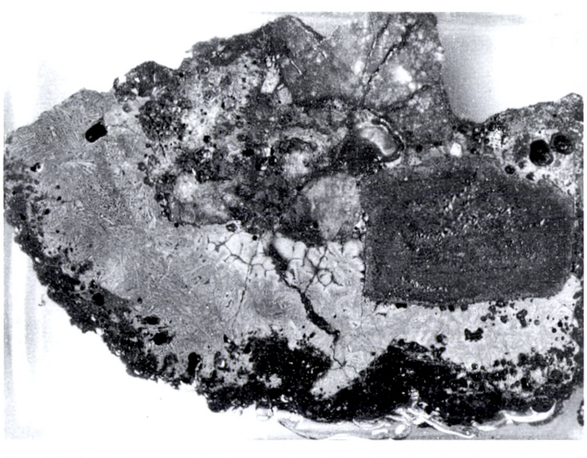


Fig. 93. An extremely dirty kalot slag, D 180 of 728 g from Krogdal Vang, north Sjælland, about 1500 A.D. The bottom part is mostly slag, while a large stone is mixed in to the right, and the top is an irregular mixture of slag, charcoal and "stones". Side length 8 cm.

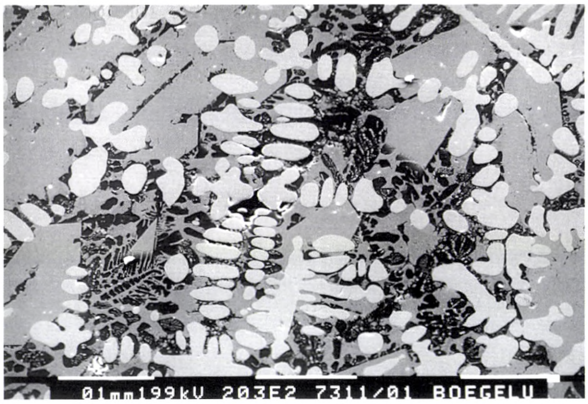


Fig. 94. Purification slag of the kalot type from the Viking age village Bøgelund, Stevns, Chapter 12. Fayalite laths (grey), wüstite dendrites (white) and leucite-rich matrix. PS. Scale bar 0.1 mm.

of Kalotschlacken in thrifty trading centres such as Trondheim, Hedeby, Ribe, Viborg, Laholm, Visby and Helgö, localities which may be miles away from the nearest production furnaces. We see from this that the primary bloom was itself a merchandise that might be moved for long distances. The bloom was perhaps only rarely finished to bar or plate on the production site. Bars and plates do not give rise to purification slags.

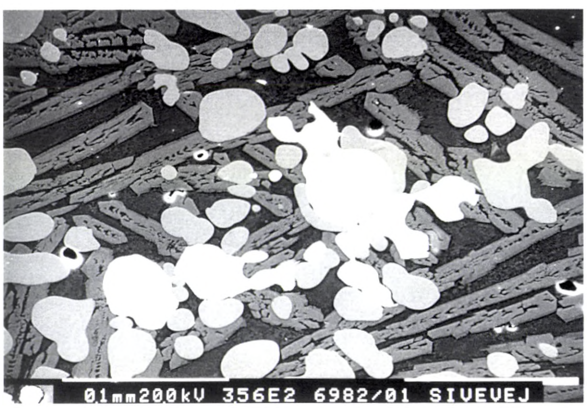


Fig. 95. Purification slag of the kalot type from about 1100 A.D. Sivevej, Grenå, DJM 2353x34, A8. Globular iron particles (bright white), wüstite dendrites (off-white), slender fayalite laths (grey), and glassy matrix. PS. Scale bar 0.1 mm.

The sinder, or manufacturing slag from Step 4 D, occurs in only small quantities and is of little significance. It forms when the blacksmith shapes, and builds up his work piece by piece by forge-welding. Since his starting point, the purified bar from step 3, is already notably depleted of slag inclusions, any new slag must form from iron lost from the work-piece by burning, this FeO then reacting with the sand as explained above. The new slag is basically Fe_2SiO_4, with surplus of SiO_2, and with very limited contents of K, Al, Ca, and Mg from the charcoal ashes. In this slag type elements such as manganese, phosphorus and

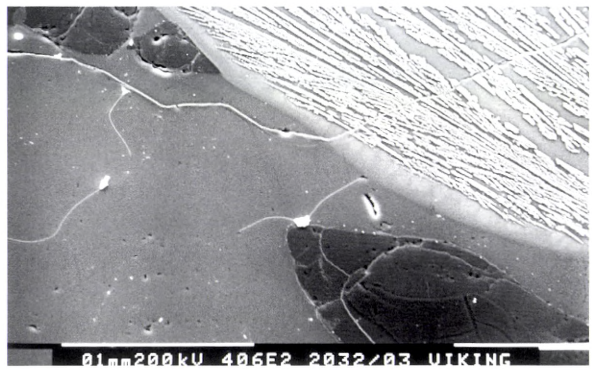


Fig. 96. Heterogeneous production slag from a Viking age furnace, RAÄ 266, in Tranemo, Väster Götland. Probably scrap, containing iron (not in the picture), glass with feathery fayalite (right), glass with 66% SiO_2 (grey), and undissolved quartz grains (black, with cracks). PS. SEM. Scale bar 0.1 mm.

barium will be very low. On a modern forge hearth where the blacksmith does not use charcoal, but pit coal (Steinkohle), and where he works with modern silicon- and manganese-containing steels, the sinder attains a different composition, for example becoming significantly enriched in titanium and aluminium.

The texture of the sinder is loose, pumice-like and glassy, sometimes with imperfect, feathery olivine crystallites in the glass. The specific gravity is less than 2.5 g/cm^3, both because FeO is low and because the porosity is high.

In the manufacturing stage the bar or plate of step 3

Fig. 97. Iron age bloom of 1 kg from Sønderbygaard, Grindsted sogn. The bloom has not been hammered and probably represent scrapped material. Sections reveal irregular networks ("lace works") of iron with 0.5% phosphorus and slag, consisting of fayalite, calciumphosphate, leucite, and a little hercynite. Side 12 cm.

is transformed into its final shape. The common blacksmith, present in every small town and village up to a hundred years ago, would handle all the general business of a utilitarian nature, like fittings, agricultural tools and repair work. The nailmaker would, aided by his special nailmaking apparatus, the oliver, produce large and small nails by the thousands (Bodey 1983).

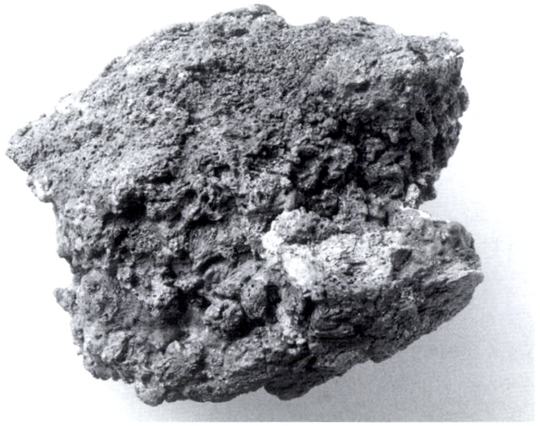


Fig. 98. The opposite side of the bloom, Fig. 97.

The locksmith would be responsible for locks and keys, the farrier, or shoeing smith, would make and fit horseshoes and horse trappings, the needlemaker would make needles, usually of steel (Rollins 1981). The cutler would manufacture any kind of knife, from coarse dagger types, via table-setting knives to complicated folding knives, the majority being made from carbon-rich steel (0.4-0.7% C), water-quenched and tempered at about 300°C. A rather special smith was the filecutter, who also worked in steel (Termansen 1960), while the armourer and the spurrier would provide the army with weapons, harnesses and equipment for the mounted warriors.

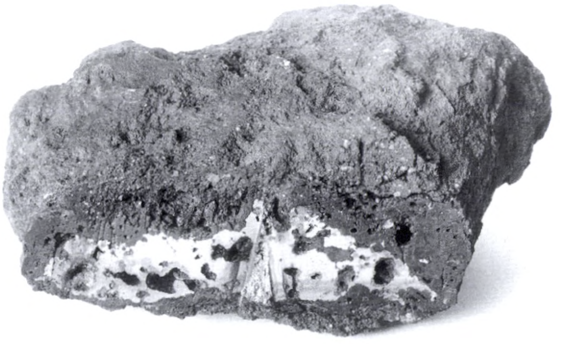


Fig. 99. Section through a slightly forged, medieval bloom from Hinge, central Jutland, showing the metallic parts (white). Side length 7 cm.

In late mediaeval times it was common for smiths in the major cities to form guilds, many of which lived well into the 19^{th} century (Robins 1953). The protector of the smiths was Saint Eligius or St.Loy, and their feast day was December 1^{st}, on which all work, shoeing horses as well as wagon wheels, was laid down. St.Eligius (588-659 A.D.) became bishop in Noyon, France, but he was originally a goldsmith and manufactured beautiful shrines for relics for the Catholic churches. Somehow various legends grew up around him, the most impressive one concerning shoeing of horses. In order to facilitate the shoeing, he dismembered the leg from the horse, did the work inside the

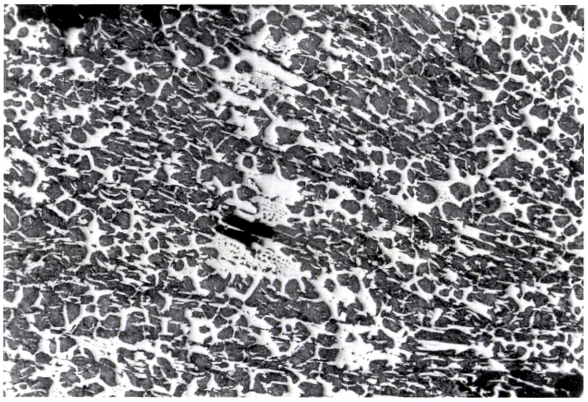


Fig. 100. Section through the bloom Fig. 99. The material is an ultra hard iron-carbon-phosphorus eutectic, socalled steadite, with slag inclusions. PES. Side 5 mm.

Fig. 101. Another section through the same bloom, Fig. 99. This area is hypereutectoid, about 1.5% C, with well-developed cementite lamellae (white). Figs.100-101 make it plausible that the ironmaster scrapped the bloom as a failure because of its extreme hardness. PES. Side length 5 mm.

smithy and miraculously put the finished leg back on the animal. St.Eligius became popular all over Europe. In Florence the guild of the farriers had the saint sculpted by Nanni di Banco (1415) and put into a niche at Orsanmichele, where it still decorates the building together with representations of other major guilds (Florenz Kunstführer 1955).

From early on it may be assumed that the blacksmith of all these occupations was a different man from the blacksmith, or iron master, who produced the iron, and purified the iron to merchandise, in bar and plate form. The bars might be traded over long distances before they reached their final destination, where they were manufactured into finished items. Therefore it was of some signficance that the manufacturing blacksmith could recognize the material

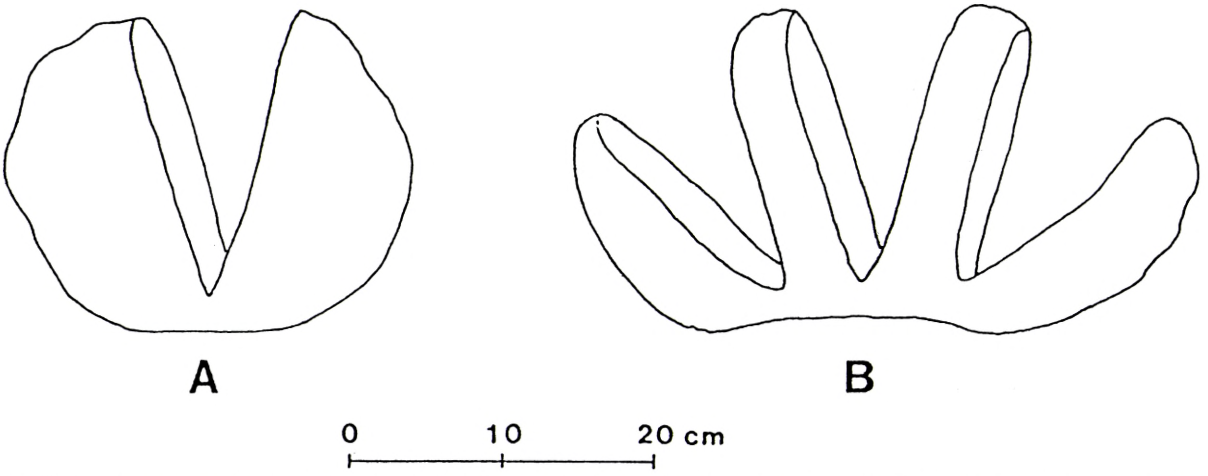
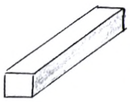


Fig. 102. The Scandinavian intermediate product and trading object in the mediaval age. Left, a Norwegian fellujern, of 3-15 kg, with one deep cut. Right, a Danish klode, of 6-10 kg, with three deep cuts, see Chapter 12.

Table 4.6. Iron bars, 0.0-0.3% carbon, for trading

Name, Synonym	Shape	Dimensions, cm Weight	Period	Examples where found	Figure
Double pyramid, bipyramidal bar, Spitzbarre		45 x 7 x 5 3-10 kg	Assyria Hallstatt La Tène	Khorsabad Switzerland Rhineland-Pfalz	71, 131
Oboli, obeliskoi 6 obeliskoi = 1 drakme. Spieti		50 x 0.5 x 0.5 0.1 kg	700-400 B.C	Greece, Etruria, Rome	76
Rectangular bar, Roman bar		30 x 5 x 5 5-7 kg	700 B.C.-400 A.D.	Etruria, Rome, Yugoslavia, ship wrecks	112
Currency bars, sword-shaped		75 x 3 x 0.5 0.5-0.6 kg	300 B.C.-0	Beckford, Danbury, England	135
Fellujern, Two-fingered blæsterjern		30 (diam.) x (12-16) cm thick 5-16 kg	800-1400 A.D.	Møsstrond, Hardingbukti, Sweden, Ireland	102, 345
Mästermyr bar		40 x 3 x 0.5 cm 0.4-0.8 kg	900-1100 A.D.	Haithabu, Trelleborg, Gotland	–
Klode, four-fingered blæsterjern		30 (diam.) x (8-10) cm thick, 4-12 kg	800-1600 A.D.	Denmark, Halland, Scania, Iceland	102, 163-166
Spade-shaped blæsterjern		30 x 10 x 1 0.6-1.6 kg	800-1100 A.D.	Jämtland, Hälsingland	250
Loaf-shaped bar		12 (diam.) x (4-5) cm thick, 1-3 kg	900-1100 A.D.	Hungary	228
Phosphor tongues		8 x 2 x 0,3 10-20 g	1000-1200 A.D.	Scania	176

he received. Perhaps this is why we find ancient iron for the trade in rather many shapes. The shapes of Table 4.6 are characteristic of different times and different countries. The material of all is heterogeneous wrought iron, generally with 0-0.3% carbon, some phosphorus, 0-0.5%, and some slag inclusions. The

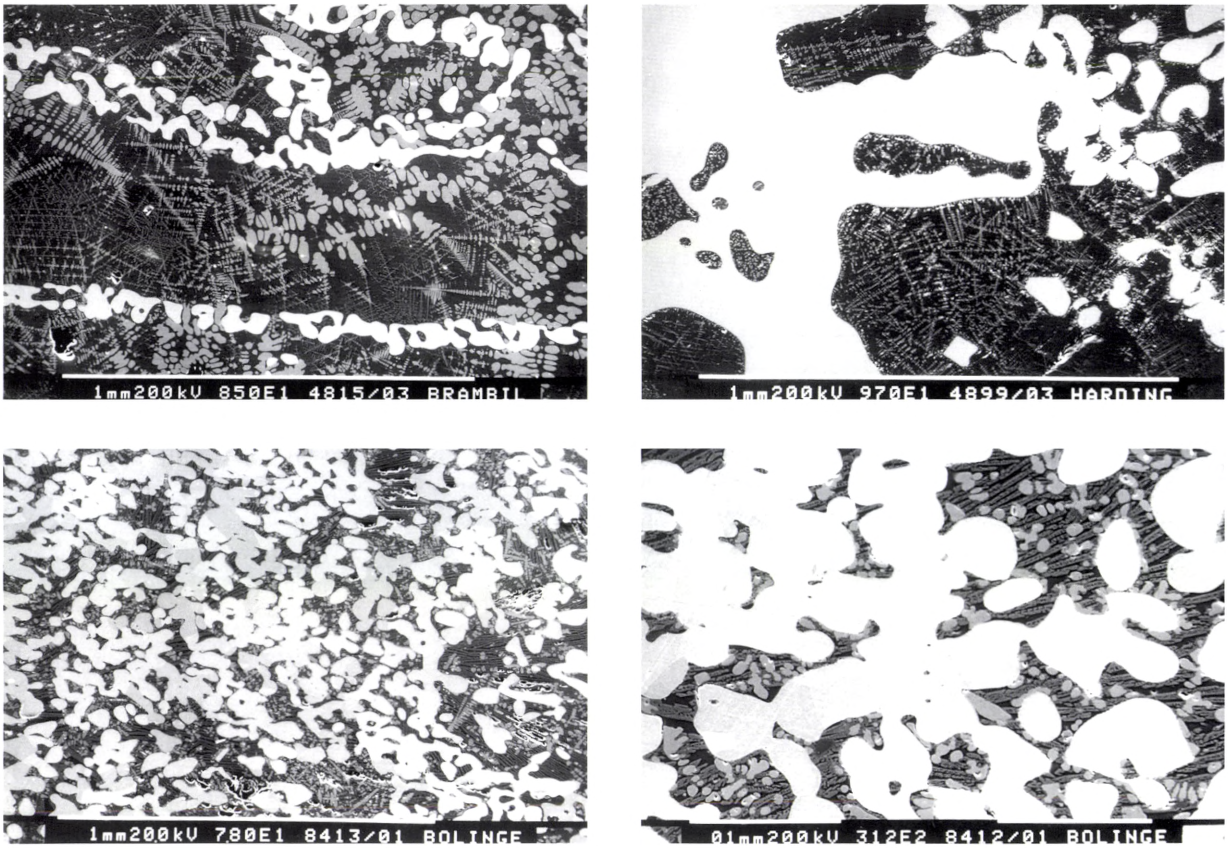


Fig. 103. Four views of the development of a bloom. In Brambilla (Elban experiment) the new iron is segregated in strings and carpets, separated by wüstite rich slag. In Hardingbukti and Bölinge the iron particles have already coalesced over larger volumes, but still include major slag, consisting of wüstite, fayalite and glass. Further consolidation requires hammering. PS. Scale bars 1 and 0.1 mm.

steel bars of Table 4.7 were generally smaller, contained 0.3-0.8% carbon, no phosphorus and few slag inclusions, but also these were heterogeneous and might contain zones with as little as 0.2% carbon. Steel bars were often traded in the hardened condition, so the blacksmith in an instant could verify the quality of the bar with a stroke of his file. The hardening would, of course, disappear as soon he put his material into the forge in order to work it.

It is characteristic that the objects figured in Tables 4.6 and 4.7 are often found in hoards. It is believed that they were traders' merchandise, which was buried in a critical situation, and was never retrieved by the owner. Many of the types shown were provided with an eye or a hook for easy transportation. For example the axe-shaped bars, or wedges, of southern Norway had a hole through the neck, and twelve such bars could be carried on a pole of spruce, put through the holes.

In order to illuminate the bloomery process a number of ancient slags from the Mediterranean area will be examined. The first, Table 4.8, is a 150 g fragment of a production slag from Portoferraio, Elba. A 5 mm thick part of the glazed furnace wall is still adhering, but the analysis is taken on the slag. This is composed of 70 volume% fayalite with some magnesium substituting for iron, 15% wüstite with 0.3% TiO_2, and 15% matrix

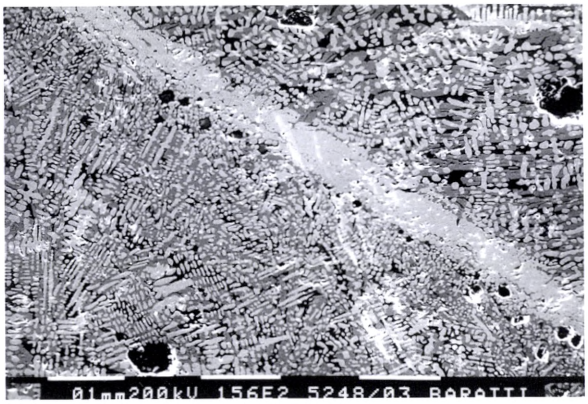


Fig. 104. Etruscan tap slag, 343 g, from Baratti, 500 B.C. The oblique, grey, wüstite rich line separates two tappings. Wüstite dendrites, 0.02 mm wide fayalite laths and glass matrix are present. PS. Scale bar 0.1 mm.

with feathery dendrites. The fayalite crystals are angular, blocky and about 0.1 mm across typical of a production slag, which has solidified and cooled rather slowly inside the furnace.

The second, Table 4.8, line 2, is a 343 g tapslag from the 2 m high slag deposit, eroded free along the beach in the Gulf of Baratti. The slag is composed of 40 volume% fayalite with some magnesium and calcium, 30% wüstite with 0.3% TiO_2, and 30% very fine-grained matrix. The grain size of both fayalite and wüstite is significantly smaller than the previous one, because the slag is a tapslag that cooled and solidified rather rapidly.

The third example is an experimental production slag, made during an International Seminar in May 1989 under the auspices of Centro Universitario Europeo per i Beni Culturali, and with Gino Brambilla as the responsible iron master. Analysis 3 is a surprisingly true copy of Nos.1-2, slags which are about 2500 years older. All were based on hematite from Elba and local charcoal. It is noteworthy that phosphorus could not be detected, evidently being very low in both ores and charcoal. Also manganese is very low, and sulphur is low in the two ancient slags – but very high in the modern experiment. The explanation seems to be that the ores for the modern experiment had not been roasted, while the ancient ores had been, in order to eliminate the pyritic sulphur.

The three examples agree in their high FeO-content. It is clear that the modern Italian steel industry here had a veritable iron mine. In the course of a generation, 1920-1950, about two million tons of slags

Table 4.7. Steel bars (0.4-0.7% C), for trading

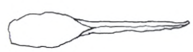
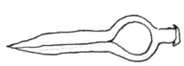
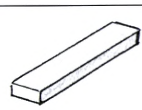
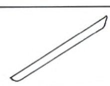
Name, Synonym	Shape	Dimensions, cm Weight, g	Period	Examples where found	Figure
Valdres Iron, spoon-shaped bar		(20-35) cm long, 0.5-1 cm thick 15-400 g	300-1300 A.D.	Valdres, Southern Norway	154
Wedge-shaped bar		(20-35) cm long, 1-4 cm thick 400-2000 g	500-1300 A.D.	Valdres, Southern Norway	243, 246
Teint iron, Blekinge Iron		30 x 2 x 1 cm? 200-400 g?	800-1300 A.D.	Norway, Sweden, Iceland	–
Kalmar Iron		70 x 3 x 0.3 cm 400-500 g	1000-1400A.D.	Småland	155

Table 4.8. SEM-EDAX analyses of ancient Mediterranean slags

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Σ	F
1	26.1	63.4	0.1	0	1.0	7.4	1.0	0.5	0.1	0.3	99.9	3.52
2	20.6	68.5	0.2	0	2.6	5.5	1.5	0.6	0.2	0.2	99.9	3.75
3	20.5	67.2	0.1	0	2.1	6.0	1.2	0.7	0.2	1.9	99.9	3.42
4	23.1	70.1	0.3	0	1.3	3.7	0.6	0.3	0.2	0.3	99.9	6.24
5	32.9	56.5	0.3	0	1.0	7.1	1.1	0.4	0.4	0.3	100	4.63

1 Portoferraio, 150 g fragment of production slag. Fayalite with 1.8% MgO. 500 B.C.
2 Baratti, 343 g tapslag from production furnace, 500 B.C.
3 Experimental production slag, Gino Brambilla, Portoferraio, Elba. 26th May 1989
4 Trastejon, Huelva, Spain. 20 g tapslag from production furnace. 300 B.C.
5 Trastejon, Huelva, Spain, 30 g tapslag from production furnace. 300 B.C.

were removed from the deposits behind the Gulf of Baratti and converted into pig iron in the blast furnaces of Piombino, Folonica and others (Minto 1954).

In southern Spain, in the province of Huelva, there is a modern iron mine, Cala, which has been operated for its magnetite and hematite deposits. Archaeologists have identified ancient iron slags at the settlement of Trastejon, only a few kilometers to the south. By the kind cooperation of Dr. Mark Hunt Ortiz, Sevilla, I have examined ore and slags from this site, which has provisionally been dated to 700-500 B.C.

Fig. 105. Hematite ore from Trastejon, Huelva, Spain. 100% Fe_2O_3, as scaly microcrystals in a void. PS. Scale bar 0.1 mm.

Fig. 106. Hematite ore from Trastejon, Huelva, Spain. 100% Fe_2O_3, as cauliform crystal aggregates in a void. PS. Scale bar 0.1 mm.

The hematite is pure, except for a few inclusions of quartz, estimated at max.4% SiO_2, and scattered inclusions of 0.3-1 mm grains of pyrite and chalcopyrite. Apparently an ore which has much in common with the Elban hematite ore. Figures 105-106 show typical growth forms of hematite, as hexagonal blades and as cauliform knots. The two slags, Nos.4-5, are tapslags. They are very fine-grained, with minute wüstite dendrites and fayalite laths. Cross sections show how individual runs have deposited new layers on top of already solidified and somewhat cooled slags. The composition of the slags is rather similar to

Fig. 107. Spanish tap slag, 20 g, from Trastejon, Huelva. The first layer, above in the picture, had time to cool before the next layer (below) ran out. The cooling effect resulted in fine grained wüstite and fayalite in the second layer. PS. SEM. Scale bar 0.1 mm.

Nos. 1-3, because they are derived from similar pure hematite ores.

No iron objects have survived from the furnace sites discussed above. We are reduced to examining irons from, in particular graves, and occasionally from old buildings. A specially favourable case is the two Roman ships, or rather Emperor Caligula's festive barges, which sank about 50 A.D. in Lake Nemi, 25 km SE of Rome, and were recovered in the early 1930s. Tacitus (Annals XV: 35) has vividly described the function of these ships and the orgies on board and in the brothels on the borders of the lake during Caligula's and Nero's times. The story of the ingenious recovery, the museum building in the early 1930s and the tragic loss by German barbarism in 1944, is of major interest and has been told by Ucelli (1950). The ships were burned by a retreating German company, and only little was saved, among other things three anchors, some bronze objects and thousands of copper and iron nails which were lying in the ashes. By the kind permission of the present director of Museo delle Navi Romane Nemi, Dr.Giuseppina Ghini, six iron nails have been cut and metallographically examined, Table 4.9.

Five of the six nails are ancient. They are ferritic with very low carbon content, less than 0.07%, and correspondingly low hardness, ranging from 81 to 152. The relatively few high values above 130 are due to some coldwork associated with bending and hammering. One nail, No. 33, is entirely different. It is homogeneous and displays numerous, small (about 0.03 mm) sulphidic slags in a ferritic-pearlitic hard matrix. In the microprobe the particles were identified as minute (Mn,Fe)S slags, suggesting a modern nail

Table 4.9. SEM-EDAX analysis of slag inclusions in nails from the Nemi shipwrecks

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Σ	F
29	31.7	49.3	1.9	0.4	2.7	10.4	2.3	0.4	0.5	0.4	100	3.05
30	19.7	63.9	0	7.0	3.6	0.8	2.3	0.6	0	1.9	100	24.3
31	0.2	99.3	0.6	0	0	0	0	0	0.1	0.1	100	-
32	44.1	47.7	0.4	0.3	2.5	3.4	0.9	0.2	0.2	0.3	100	13.1
33	0.1	18.5	45.7	0	0.1	0.1	0	0	0	(35.5)	100	-
35	10.2	84.0	0.1	1.4	1.1	1.8	0.4	0.3	0.1	0.6	100	5.67

29 Nail. 167 g. 21.5 cm long. 1.2 cm square. Ferritic. HV 200 g: 113-126-132-137-152.
30 Nail. 84 g. 16.9 cm long. 0.7 cm square. Ferritic. HV 200 g: 111-113-113-114-131.
31 Nail. 112 g. 16.1 cm long. 1.1 cm square. Ferritic. HV 200 g: 95-97-98-103-108.
32 Nail. 62 g. 11.3 cm long. 1.0 cm square. Ferritic. HV 200 g: 81-87-88-89-97.
33 Modern nail. 60 g. 10.3 cm long. 0.9 cm square. Ferritic-pearlitic. HV 200 g: 140-143-144-160-163.
35 Nail. 69 g. 19.5 cm long. 0.9 cm square. Ferritic. HV 200 g: 82-84-86-91-91.

Fig. 108. Nails from Lake Nemi, Rome. 40 A.D. Six are iron nails, Nos. 29-33, 35. The second from the right, No. 34, is a copper nail. All have square cross sections. Scale bar 5 cm.

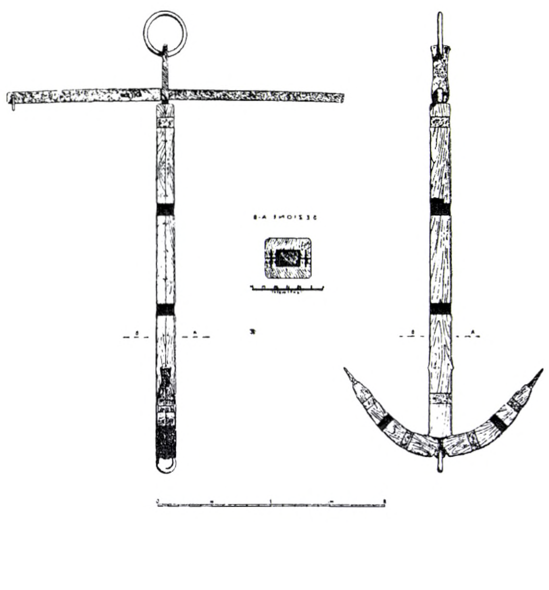


Fig. 109. One of the three anchors from the barge in Lake Nemi. The anchor was huge, 4 m long, and weighed 417 kg. It must have been one of the biggest iron objects of antiquity. The iron shaft was protected by a wooden casing. Ucelli 1950: 268. Scale bar 2 m.

from a Bessemer or Siemens-Martin furnace. The nail was evidently a modern product, having been placed in the ship when it was restored in the Museum in the 1930s!

Three of the nails, Nos.31,32, and 35, are very similar to the somewhat larger nails examined and published by Ucelli (1950: 268) and Table 4.10. The nails A, B and C, are heterogeneous in their composition and structure, but generally of a ferritic, soft nature

Table 4. 10. Chemical analysis of nails and an anchor from Lake Nemi (Minto: 268)

	% C	% Mn	% Si	% P	% S	% Cu	% Ni
A	0.019	0.002	0.01	0.09	0.011	0.063	0.040
B	0.21	tr.	0.004	0.04	0.006	0.016	-
C	0.04	0.003	0.009	0.063	0.011	0.33	0.008
D	0.07	0.039	(0.162)	0.061	0.001	0.15	-

A Nail. 233 x 12 x 12 mm. Ferritic.
B Nail. 233 x 16 x 16 mm. Ferritic, some pearlite.
C Nail. 264 x 16 x 16 mm. Ferritic.
D Anchor. 4 m long. Stamped 1275 (Roman) pounds, about 417 kg.

with very little contamination. The presence of copper is interesting and may suggest that these objects were made in the Colline Metallifere district of Tuscany, see the map Figure 75.

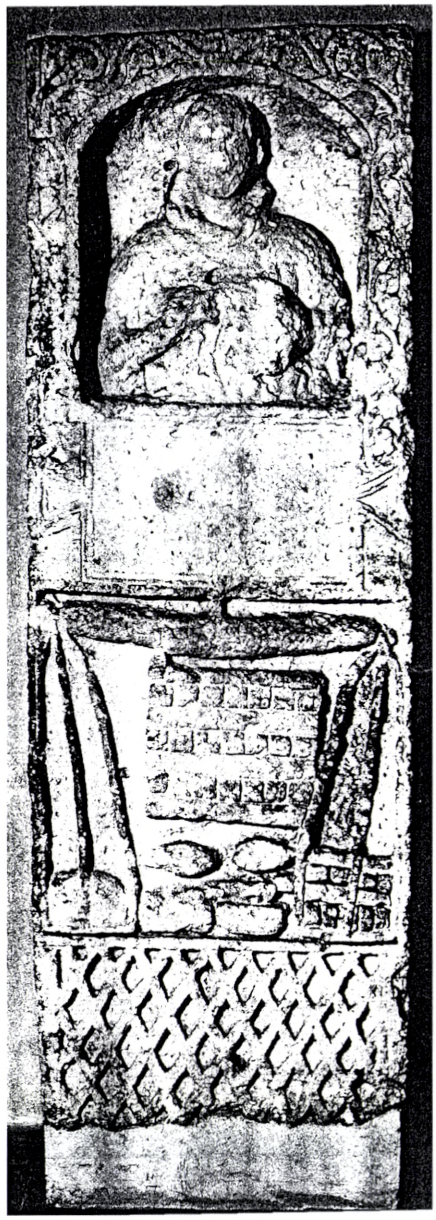
Analysis D in Table 4.10 is of one of the three anchors rescued from the barges in Lake Nemi. This one, 4 m long, had a rectangular iron stem, 10 x 6 cm, enveloped in a wooden case. An ancient stamp OC-CLXXV may be interpreted as the total weight of the anchor, 1275 Roman pounds, equal to about 417 kg. The iron had survived very well under the anaerobic conditions in the freshwater lake's bottom mud. Its composition is similar to the nails, in particular to nail C. The high silicon content reported for the anchor is an error, caused by the presence of significant slag inclusions in the drillings taken for analysis. The long shank of the anchor has been forge-welded from a number of Roman iron bars, some of the more easily identified weldings suggesting that the individual parts were about 30 cm long, corresponding to weights of 5-7 kg. Even these parts must have been forge-welded from smaller bars of 2-4 kg weight.

The Roman bars

In the Augst Roman Museum, at the Rhinepassage, 20 km east of Basle, Switzerland, there is a tombstone for a Roman merchant, displaying his main interest, trading in iron, Fig. 110. A number of iron bars are shown, all of quadratic cross section, but apparently of two lengths. On the right scale is a pile of 20 bars, each measuring A x A x 5A cm, and in the middle is a pile ready to be weighed of 42 bars, each measuring A x A x 7A cm. If we assume A to be 2 Roman inches, about 5.2 cm, the small bar is 5.2 x 5.2 x 26 cm and must weigh about 4.9 kg, assuming the specific gravity to be 7.0 g/cm^3 for this slag-rich and somewhat porous semiproduct. Correspondingly the larger bar is presumably 5.2 x 5.2 x 36.4 cm with a weight of approximately 6.9 kg. On the left scale is seen a large weight, which in order to counterbalance the 20 iron bars (about 98 kg), can hardly be stone or iron, but must be of lead, specific gravity 11.3 g/cm^3. If we assume the mass on the left scale to be lead and weighing about 98 kg (a common Roman packing unit of 300 libra (pounds)), its volume would be 8.7 l, or 8673 cm^3, corresponding to the approximate dimensions of, e.g., 22 x 22 x 18 cm. This estimate comes close to the dimensions shown on the tombstone.

Not too many Roman bars have been found during archaeological excavations. The semiproduct was

Fig. 110. Tombstone for a Roman merchant, buried in Augst, east of Basle, Switzerland. The scale with the iron bars is shown enlarged to the left. The tombstone is 2 m high.



meant to be used and would only survive under special circumstances. In Croatia, near Mount Majdan, no less than 97 bars from the first centuries A.D. were found in 1880. Only 28 have been saved for our time (Durman 1997). They are of several sizes, each weighing from 11 to 15 Roman libras (1 libra equal to 337-340 g), and have quadratic to rectangular cross sections of 4.5-5.0 cm. The bars were produced in Pannonia at Majdanpek in the vicinity of Mount Majdan, where enormous slag accumulations have been documented. Over 6 ha are 2-7 m high slag heaps, amounting to about 3 million tons! The iron production took place

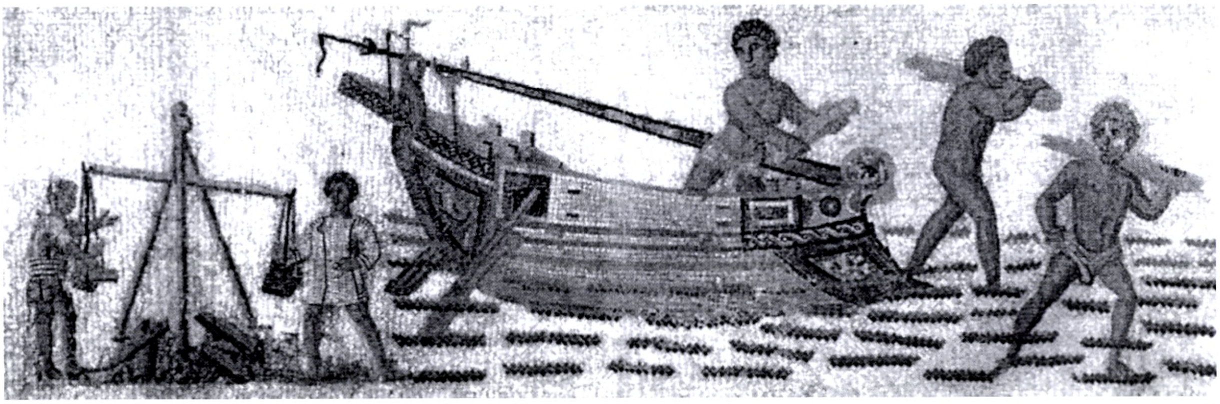


Fig. 111. Mosaic from Hadrumetum, Sousse, Tunisia. About 250 A.D. Iron bars, probably from the region of Tuscany-Elba, and made from Elban hematite ores, are carried ashore from a Roman ship and weighed. Feugère & Serneels 1998.

between 100 and 450 A.D. and, in particular, provided the four Roman legions in Pannonia with iron.

Fortunately a number of subaquatic discoveries have in the last decades dramatically increased our knowledge of the Roman bar. Shipwrecks from at least 16 locations in the western Mediterranean have yielded several hundred bars (Parker 1992; Feugere & Serneels 1998). They may be dated to a period of more than 500 years, from about 150 B.C. to 400 A.D., and they occur in a number of shapes, of which the two discussed above from the tombstone are quite numerous. But longer bars, e.g.100 x 5 x 2.5 cm (appr.8.8 kg) were also common. Perhaps these meter-long bars are what are shown being unloaded from a ship on a Tunisian beach and pictured in the third century mosaic of Sousse, Hadrumetum in Tunis, Fig. 111.

On many of the Roman bars there are stamps, like CRVTIL and HAEDVI, which may contain clues to production sites and dating. Unfortunately the state of corrosion makes many stamps illegible. In one shipwreck corrosion had cemented a large number of bars together to a compact mass of 18.2 x 6 m!

The location of the shipwrecks, see the map in Feugère & Serneels (1998), suggests that a majority of the bars may have been produced from Elban ores on the Italian coast near Populonia. No less than seven shipwrecks with iron bars were found at the mouth of the Rhone, near Saintes-Marie de la Mer, showing the importance of the trade route into Gaul/France. Perhaps the merchant at Augst (Augusta Raurica) received his iron bars via this route?

As the technology of iron products spread to the west and became known in Greece, the Balkans, Italy and Spain, it also spread southwards through Egypt and Nu-

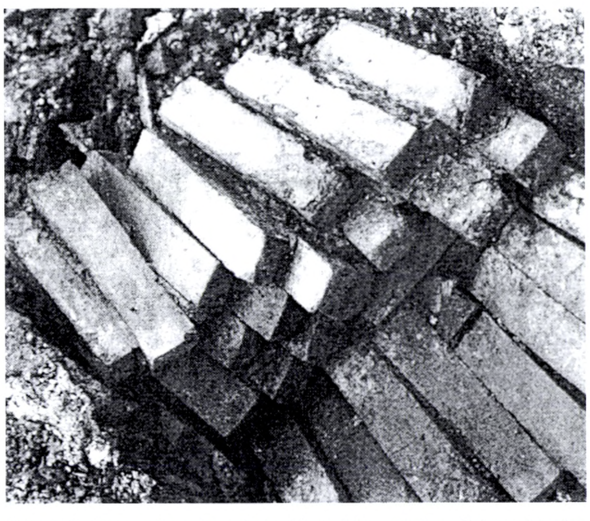


Fig. 112. Roman iron bars found in a ship wreck at Saintes-Maries de la-Mer in the Rhone delta. They are probably from the beginning of our era. Individual bars measure about 105 x 5 x 2.2 cm and weigh about 9 kg. Feugère & Serneels 1998.

bia to Sudan and the rest of Africa (Percy 1864; Beck 1891; Aitchison 1960; Tylecote 1975). European soldiers, missionaries and colonial officials coming to Africa in the 18th and the 19th centuries were surprised by the scale of ironmaking they found there. Visitors to Bambuk (now Bamako) in Senegal (now Mali) about 1800 noted how the many ironsmiths were able to produce chains, rings, hoes, spears, scissors, swords and other items and evidently knew well how also to produce cast iron from available iron ores and how to reduce this to malleable iron, and perhaps even steel. Four goldmines which had been worked since about 1100 A.D. formed the economic backbone of Bambuk's trade. Copper and gold were worked into various items and into delicate ornaments and jewellery (Buchwald 1975: 1134). The Africans continued to improve their iron technology, but never transformed it as did the Europeans in the Middle Ages. They remained remarkably successful, prospering until cheap imported iron finally drove them out of business in the 20th century.

Presently, there is considerable interest in the iron technology of ancient Africa (see,e.g., Tylecote 1975; Kirknæs 1981; Bernus & Echard 1985; Schmidt 1995; Ige & Rehren 2003), but this is not the place to discuss the development. Instead we will in the next chapter move north, cross the Alps into central Europe and examine the technological achievements of the Celtic tribes.

Carbon-14 dating

The carbon-14 dating method is a scientific-and rather costly-procedure for dating carbon-containing objects. It covers a period up to about 50,000 years before the present. The method was invented and implemented by Willard F.Libby between 1947 and 1951 (Libby 1954; Levi & Tauber 1976; Rasmussen 1994). In 1960 Libby was awarded the Nobel prize in chemistry for his invention.

All living organisms contain a little of the radioactive isotope C-14. During their lifetime, they are in equilibrium with the surrounding atmosphere due to photosynthesis. They have the same ratio between C-14 and the stable isotope C-12 as the atmosphere. When the organism dies, no new C-14 atoms are incorporated, and the original ones disappear, in accordance with the radioactive half-life, which has been calculated to 5730 years.

Furnace sites are particularly well-suited for C-14 dating, since charcoal is usually found on the sites, either free or included in the slags. About 1 gramme of charcoal is needed for dating. The fewer C-14 atoms, the older the sample. The newest method, AMS, accelerator mass spectroscopy (Gillespie et al.1984), only requires a few milligrammes of carbon and can, in principle, date, e.g., a 0.4% carbon steel object (Cresswell 1992; Possnert & Wetterholm 1995; Rasmussen et al. 1998).

Unfortunately, in Scandinavia the most widely used wood for iron-making was pine. This tree was often used long after it was a living organism, thus introducing some uncertainty. In general, material selected for dating should be charcoal from twigs or young trees.

The C-14 method requires calibrations that take into account that the atmospheric C-14/C-12 ratio has not remained constant through time. Presently the calibrated curves, worked out by comparison with dendrochronological results, cover the period back to 10,000 years B.C. This suffices for the archaeometric studies of archaeological artefacts.

Chapter 5
Celtic Europe and Noric Steel

You should hammer your iron when it is glowing hot.

Maxim 262, Publilius Syrus, about 42 B.C.

The Celtic tribes of central Europe are first mentioned briefly by Hekataios from Miletus and shortly after by Herodotus (Book 2: 33; Book 4: 49). Herodotus only reports that such a people exists around the upper streams of the river Ister (the Danube) and has as neighbours the Cynesians. The more distant parts of Europe, such as most of France, England, Ireland and Scotland, and the area between Rhine and Weser, were also inhabited by Celtic tribes at the time of Herodotus, but they were beyond the knowledge of the Mediterranean writers. The Celts were the bearers of the westernmost of the Indo-European language families, which had a close affinity with the Italic languages. The Germans, their northern neighbours, called them Walah, from which were derived walloons, Wales, and Scandinavian vælsk. The Greeks called them Galates, and the Romans called them Galli, but they themselves used the name Keltoi. The fact that the Celts became masters of iron technology centuries before their nearest neighbours was an important reason why they were able to form a strong military confederacy in central Europe, from where they raided and/or conquered other provinces.

Celtic Sennones invaded Etruria and pushed forward to Rome, where the Roman army was conquered and the city itself was sacked, only Capitol resisting the siege (390 B.C.). Celtic tribes settled in northern Italy, and others penetrated Pannonia and went along the Danube into the Balkans and Macedonia. Delphi was sacked in 279 B.C. From Thracia they conquered Bysantium, passed the Hellespont and fought against Phrygians and Lydians. About 240 B.C. they were conquered by King Attalos of Pergamon, after which this Celtic group finally settled in the same area that 1000 years earlier had been the nucleus of the Hittite empire, now called Galatia after the newcomers (Broholm 1960).

The Celts in France and west of the Rhine, e.g. the Belgae, moved or were pushed to the extreme western parts of Europe and settled in Bretagne, Brittany. Other groups crossed the Channel and settled in Wales, Scotland and Ireland, where a characteristic Celtic art developed, well known from the mediaeval illuminated manuscripts, the stone crosses and the rich Irish literature.

The ancient time in central Europe which is treated in this chapter is traditionally divided into the Hallstatt period, 800-500 B.C., and the Celtic period, 500-31 B.C., also called the Pre-Roman Iron Age, or the Celtic Iron Age.

The Hallstatt period is named for the cemetery near the Hallstätter Lake, 50 km SE of Salzburg, where about 1270 graves were excavated between 1824 and 1939. The graves contained bronze as well as iron objects and bore witness to trading connections with the Adriatic Sea. In kilometer-long tunnels in the vicinity rock salt was mined from at least 800 B.C. and up to Roman times. Salt was, no doubt, a backbone of their economy.

The late phase of the Hallstatt period is characterized by rich graves, in which princes and princesses are surrounded by iron daggers and lances, gold, jewellery, and four-wheeled wagons with iron tyres (Pare 1992). Iron tyres were an innovation in Europe and

Fig. 113. Antenna sword with midrib from the Celtic Hallstatt period. The motive on the hilt is apparently a man with uplifted arms. The iron blade is severely corroded.

were first used in the Hallstatt period. The wagons, the wheels and the fittings have survived in many of the princely graves. Each wheel was provided with a tyre which was made from a single piece of forged iron. The numerous tyre nails display a variety of different heads and are from 27 to 92 mm long. The naves were provided with iron- or bronze fittings, and there were horse bits of bronze or iron. Imported goods from Greece and Etruria were common in the princely graves.

Characteristic of the Hallstatt culture are the richly decorated iron swords with bronze or ivory hilts and large bell-shaped pommels. In the younger part of the period the swords were supplemented by iron daggers with bronze hilts, often ending in figures that resembled a man with lifted arms, the so-called antenna hilt.

Examinations of iron objects from the Hallstatt period have been published by, e.g., Pleiner (1958: Chapter III), Emmerling (1971) and Lang (1984). By the kind cooperation of Professor Hasso Moesta, Saarbrücken, it was possible to analyse a fragment of a Hallstatt sword from 700-600 B.C. (grave 2029, Saarländisches Landesmuseum), Table 5.1. Metallographic sections revealed that the sword was heterogeneous with several mm-wide parallel zones of shifting composition, but generally with 0.2-0.3% carbon. Zones with 0.30-0.45% phosphorus in solid solution displayed ghost structures and 0.1-0.2 mm phosphorferrite grains. The slag inclusions were highly unusual, consisting of broken, angular fragments suggesting heavy cold work. A very common slag was the magnesian variant of hercynite, pleonast $MgAl_2O_4$. Chromium and vanadium are present on the 0.5-1.5% level in the pleonast molecule. The bulk Al-Ca-Cr-V-rich slag, without fayalite and very little glass, is unique and may eventually be helpful in tracing the production site. The sword has, after forging, suffered considerable cold work. No attempt at water-quenching has taken place. The sword appears to be an example of an inexperienced blacksmith, groping his way and experimenting with an ore type which was not a success and resulted in a mediocre sword of rather poor coherence. The ore type was apparently not used later?

A Celtic sword from about 500 B.C. was described by Oldeberg (1952) and reviewed by Coghlan (1956: 140). The assembly of tang and hilt was of an advanced design, displaying a tubular hand grip surrounding the tang. The longitudinal seam of the hand grip had been brazed with a copper-tin alloy. The structure and hardness of the blade were unfortunately not reported, but the carbon content was variable, about 0.5%.

In the Hallstatt period objects of iron were rather rare and reserved for the upper strata of society, but about 500 B.C. there occurred a radical change with the appearance of thousands of swords as well as spearheads, horse equipment and other objects of iron. As the cultural habits among the Celts demanded inhumation graves in most of the following centuries, few iron objects were heated on the funeral pyre.

The La Tène settlement was situated on a bay at the eastern end of Lake Neuchatel, just north of the present city of Neuchatel. The site was discovered when the water level of the lake receded in the 1880s. It is

Table 5.1.A. SEM-EDAX analyses of slag inclusions in 24 Celtic swords

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Σ	F
2029	27.8	18.2	0.3	3.9	25.0	21.0	0.9	1.0	1.5	0.3	-	100	1.32
586	23.4	61.0	1.3	7.4	1.5	3.4	1.1	0.4	0.1	-	0.4	100	6.88
599	23.6	51.5	0.8	12.7	5.8	3.0	1.6	0.7	0.2	-	0.1	100	7.87
601	54.2	14.0	1.4	0	6.2	17.2	5.1	1.2	0.7	-	-	100	3.15
602	30.6	58.9	1.1	0.1	3.3	3.5	1.8	0.3	0.4	-	-	100	8.74
604	32.0	46.2	1.2	3.1	5.4	8.4	2.1	1.0	0.3	-	0.3	100	3.81
606	53.1	9.2	3.1	0.5	23.6	6.2	2.2	1.6	0.4	-	0.1	100	8.56
588	23.7	69.1	0.2	0.6	1.9	3.5	0.6	0.1	0.2	-	0.1	100	6.77
596	46.6	20.5	1.2	0.1	6.8	17.6	4.5	1.8	0.8	-	0.1	100	2.65
595,N	46.5	22.5	7.0	0.9	5.7	11.7	3.6	1.4	0.5	-	0.2	100	3.97
603,N	50.8	20.6	6.1	0	1.8	15.1	3.2	1.8	0.6	-	-	100	3.36
605	57.2	8.0	1.1	0	8.5	16.7	6.0	1.6	0.9	-	-	100	3.43
598	45.1	26.4	2.2	0.2	4.9	15.7	3.5	1.0	0.7	-	0.3	100	2.87
199	39.5	26.1	15.0	0.7	3.9	10.7	2.7	0.6	0.6	-	0.2	100	3.69
587	31.1	48.4	1.6	3.5	5.2	7.4	1.4	0.4	0.5	-	0.5	100	4.20
592	53.3	25.0	0.6	0.5	6.1	9.4	3.7	0.8	0.5	-	0.1	100	5.67
593	21.2	56.1	2.6	11.2	4.6	2.2	1.3	0.3	0.2	-	0.3	100	9.64
594	46.3	35.8	0.2	1.6	3.8	8.5	2.1	0.9	0.8	-	-	100	5.45
510,N	53.8	6.2	11.5	0	10.1	9.6	5.1	2.4	1.0	-	-	100	5.60
597	61.6	16.3	0.8	0	5.6	11.2	2.7	0.9	0.7	0.2	-	100	5.50
600	21.3	66.9	0.1	3.6	2.9	4.1	0.4	0.4	0.3	-	-	100	5.19
613	56.7	12.7	1.8	0	4.4	19.5	3.7	0.4	0.8	-	-	100	2.91
614	44.5	20.1	5.7	0.9	8.8	11.2	4.0	3.2	1.4	-	0.2	100	3.97
615	28.0	47.9	2.4	4.8	8.4	5.6	0.8	1.4	0.6	-	0.1	100	5.00

assumed that the site was a military post, probably occupied by Helvetians, a prominent Celtic tribe, from about 300 to100 B.C. The last 500 years before Christ are in central Europe named for this well-studied site. A modern museum opened on the site in 2000 and displays the Celtic culture and how this mobile and warring people spread the knowledge of iron over northern and western Europe.

Rich burials of the early period, 500-300 B.C., occur in the upper Rhine valley in the vicinity of Koblenz, and in the Champagne district of northeastern France. During the middle period, 300-150 B.C., the Celtic area had its greatest extent, stretching across central Europe from the Carpathians to the Atlantic Ocean and comprising parts of Britain, Spain and northern Italy. In the last period the Celts were under pressure, both from Teutonic tribes of the northeast and from the Roman legions from the south. Caught, pincer-like, between the disciplined forces of Rome and the unschooled, but equally effective Teutons, the Celtic civilization was squeezed out and ultimately vanished from European history,

Celtic iron objects are richly preserved and well-studied, e.g. by Pleiner (1958: chapter IV), Emmerling (1971), Lang (1984), and Serneels & Maulvilly (2001). A penetrating study of the Celtic sword was published by Pleiner in 1993. By the kind cooperation of Dr.Pleiner it has been possible to reexamine 23 of

Table 5.1.B. Structure and hardness of 24 Celtic swords

work	% C	% Mn	% P	% Cu	% Ni	Structure	HV 200 g	Cold
2029	0.2-0.3	-	0.4	-	-	Phosphorferrite	-	++
586	<0.1	0.014	0.76	0	0.051	Ferrite, P-ghost	120-178-183-194-201	+
599	0-0.2	0.019	0.34	tr.	0.011	Phosphorferrite	205-217-226-244-250	+
601	0.1-0.3	0.016	0.06	tr	0.051	Ferrite-pearlite	182-186-186-188-195	+
602	0.1-0.3	0.008	0.11	0.04	0.024	Ferrite	132-142-148-150-182	++
604	<0.1	0.031	0.09	0.05	0.048	Phosphorferrite	160-178-190-201-203	+
606	0.3-0.7	0.016	0.02	tr.	0.090	Pearlite-ferrite	148-156-199-211-217	+
588	0.2-0.6	tr.	0.15	0	0.032	Phosphorferrite, pearlite	177-185-189-198-201	+
596	0.1-0.3	0.017	0.07	0.05	0.034	Ferrite-pearlite	166-182-186-206-206	++
595 N	0.4-0.7	0.030	0.03	tr.	0.065	Pearlite-ferrite	181-191-202-258-260	+
603 N	0.5-0.6	0.017	0.11	0.03	0.078	Pearlite-ferrite	194-199-224-226-233	+
605	0.5-0.7	0.023	0.04	0.11	0.191	Spheroidized pearlite	199-218-218-222-228	+
598	0.1-0.3	0.013	0.04	0.08	0.097	Ferrite-pearlite	153-157-168-182-213	+
199	0-0.3	tr.	0.21	0	0.055	Phosphorferrite, pearlite	146-151-166-187-202	+
587	<0.1	tr.	0.16	0	0.031	Phosphorferrite (pearlite)	154-156-158-164-190	+
592	0.1-0.4	0.016	0.09	0.07	0.171	Phosphorferrite (pearlite)	177-194-207-220-226	+
593	<0.05	0.017	0.45	tr.	0.015	Phosphorferrite	146-158-185-204-206	+
594	<0.05	tr.	0.10	tr.	0.028	Phosphorferrite	145-168-170-195-206	+
510 N	0.3-0.4	0.055	0.04	0.06	0.012	Spheroidized pearlite	115-115-118-124-128	+
597	0.1-0.2	tr.	0.01	tr.	0.040	Ferrite (pearlite)	127-133-134-146-168	+
600	0.1-0.2	tr.	0.15	0.07	0.065	Phosphorferrite, pearlite	147-148-155-167-212	+
613	0.3-0.6	0.012	0.28	0.13	0.018	Pearlite-ferrite	188-190-197-238-261	+
614	0-0.2	tr.	0.11	0.73	tr.	Ferrite-pearlite	148-148-150-169-195	++
615	0.2-0.5	tr.	0.24	0.35	0.032	Ternary Fe-C-P	175-176-188-203-209	+

The manganese, phosphorus, copper and nickel analyses are from Pleiner (1993), the other data are new. Hardness values are Vickers at 200 g load. Slag analyses are by SEM-EDAX in weight percent. N, i.e. Noric steel.

his specimens in order to present additional analytical work on, in particular, the slag inclusions in the swords, Table 5.1.

The first entry of Table 5.1, the Hallstatt sword No. 2029, has already been discussed. The following 18 swords are arranged according to their age, No. 586 being dated to about 350 B.C., No. 510 to about 100 B.C. The last five entries are only approximately dated to between 350 and 100 B.C. All are from graves in Bohemia, Moravia and Slovakia, and except for one, No. 510, they are from inhumation graves. All are double-edged, pointed swords of rather similar appearance. Many details are to be found in Pleiner (1993) and will not be repeated here.

No. 586 (Pleiner 1993: 82) is from Jenisuv Ujezd, Bohemia, about 350 B.C. The sword blade has midrib and is broken into two pieces and has a preserved length of 490 mm. The section near the point shows ferritic structures with less than 0.1% carbon, but much phosphorus in solid solution, up to 0.7%, and correspondingly high hardness values, up to 201 HV. The slag inclusions are broken, due to severe coldwork. Some coarse phosphorferrite grains display Neumann bands for the same reason. The slags have on the average 7.4% P_2O_5, which is very high, and point to a particularly phosphorus-rich iron ore.

No. 599 (Pl.1993: 92) is from Holubice, Moravia, about 350 B.C. The sword blade has midrib and a preserved length of 685 mm. Two sections were taken from opposite sides in order to simulate a full cross section without destroying the coherence of the sword. The sections near the middle of the sword show laminated textures where phosphorus-rich zones up to 0.34% P, alternate with ferritic-pearlitic zones, about 0.2% C, and even ternary Fe-C-P networks. Heavy coldwork has fragmented the slag inclusions and hardened the metal, up to 250 HV. The slag inclusions have on the average 12.7% P_2O_5, the most of all the swords in this investigation.

No. 601 (Pl.1993: 93) is from Holubice, Moravia, about 350 B.C. The blade has midrib and is 724 mm long. Sections near the middle of the sword display a laminated texture of ferritic-pearlitic material, very low in phosphorus, but with 0.1-0.3% carbon. For this carbon content the hardness is high, up to 195 HV, due to coldwork. The slag inclusions are fragmented for the same reason. The slags are very poor in phosphorus, and are generally of an entirely different composition from Nos.586 and 599, suggesting a different ore. The slags are similar within all zones of the ferritic-pearlitic lamination, suggesting that the texture is due to the natural variation of the bloomery process and not to any deliberate carburizing or piling.

No. 602 (Pl.1993: 93) is from Holubice, Moravia, about 350 B.C. The blade is flat and 636 mm long. Several incisions along the sword show basically ferritic structures, <0.05%C. Locally along the edge there are coarse ferritic grains, up to 0.5 mm across. These grains have phosphorus in solid solution (0.1-0.4% P). Locally there occur ferritic-pearlitic patches with up to 0.2% C. There is much cold deformation, and the irregularly distributed slag inclusions are severely fragmented. The composition of the slags is everywhere in the sections sufficiently similar to suggest production from the same bloomery furnace and thus no piling from different sources.

No. 604 (Pl.1993: 95) is from Holubice, Moravia, about 350 B.C. The sword blade has midrib and is 735 mm long. There are adhering parts of an iron sheet scabbard. Incisions near the middle of the blade display mostly ferritic structures, but ternary Fe-C-P structures occur locally. The hardness is high for the low carbon and phosphorus level. This is due to much coldwork. The slags are similar in the different parts of the texture, suggesting that the sword was forged from material from only one furnace.

No. 606 (Pl.1993: 95) is from Holubice, Moravia, about 350 B.C.The blade has midrib and a preserved length of 607 mm. The blade is carbon-rich, 0.3-0.7%C, and displays the normal heterogeneous structure where low carbon Widmanstätten structures alternate with almost fully pearlitic structures. Phosphorus is absent. The slags are all glassy, and many are fragmented due to coldwork. The slags are unusually rich in CaO, but all are in harmony and suggest a sword made of iron from the same bloomery and without additional carburizing.

No. 588 (Pl.1993: 86) is from Makotrasy, Bohemia, about 350 B.C. The flat blade is 700 mm long, and incisions for metallographical studies have been taken near the middle and the point. It is very heterogeneous, displaying phosphorferrite (HV 172-201) alternating with ferritic-pearlitic parts. Locally fully pearlitic parts attain hardnesses of about 300 HV. Carbon thus goes from less than 0.1% to 0.8%. The slags are of two sorts, one sort being wüstite-fayalite-glass and occurring in the ferritic parts, another which is glassy in the pearlitic-ferritic parts. The sword was probably forged from two bars of different origin. The average slag quoted in the table is from the phosphorferritic part.

No. 596 (Pl.1993: 90) is from Krenovice, Moravia, about 300 B.C. The blade has midrib and a length of 765 mm. Four incisions along both edges show an almost phosphorus-free ferritic-pearlitic structure with the normal variations for a heterogeneous bloom. Carbon varies between 0.1 and 0.3%, and Widmanstätten structures are common within the higher carbon ranges. The slags are in harmony with all material coming from the same bar. Titanium is rather high:

Fig. 114. Slag inclusion in the phosphorferritic part of the Celtic sword, Makotrasy 588. Cracked and slightly corroded wüstite-fayalite-glass composite. PS. Scale bar 0.01 mm.

The average slag composition is very similar to that of the slightly older sword No. 601.

No. 595 (Pl. 1993: 89) is from Krenovice; Moravia, about 300 B.C. The blade has midrib and is 665 mm long. Incisions along both edges midway show carbon steel, with alternating pearlitic-ferritic and fully pearlitic zones. Locally there are a few phosphorus-enriched patches, but generally the blade is a fine carbon steel with more than 0.4% C and with hardnesses from 181 to 260 HV. The slags have been fragmented due to coldwork. The fayalite of the slag is enriched in manganese and magnesium, displaying up to 6% MnO and 1.7% MgO in the $(Fe, Mn, Mg)_2SiO_4$ – molecule. The bulk manganese and magnesium content of the slag points to a special ore type, similar to the Erzberg ore in the Austrian Alps. If this can be proven by other independent evidence, we here have an early example of the famous steel from Noricum.

No. 603 (Pl.1993: 94) is from Holubice, Moravia, about 300 B.C. The blade has midrib and is 685 mm long. Samples from the middle of the sword show a rather homogeneous pearlitic-ferritic structure with 0.5-0.6% C and virtually no phosphorus, either in the metal, or in the slag inclusions. The slags are small and glassy, and many are broken due to coldwork. All slags are in harmony with the sword having been forged from material from only one furnace. The significant manganese and magnesium content suggests a spathic ore like the one occurring in Noricum. The sword is a rather close duplicate of the preceding one, in terms of slag composition.

No. 605 (Pl.1993: 95) is from Holubice, Moravia, about 300 B.C. The blade has midrib and is 702 mm long. Incisions near the middle part of the sword show a rather homogeneous pearlitic-ferritic steel with 0.5-0.7% C and virtually no phosphorus, either in the metal, or in the glassy slag inclusions. Much of the pearlite has upon prolonged heating around 600-700°C become somewhat spheroidized. Later the slags have been fragmented by coldwork. Many glass slags display minute, 1µm iron globules, indicating a high degree of reduction during the furnace operation. The composition of the slags is similar to that of the swords Nos. 601, 596 and 598, suggesting the use of similar phosphorus-poor, low manganese ores, and thus possibly made on the same site. The homogeneous metal and slag inclusions suggest that the sword was manufactured from a single, much reduced pearlitic bloom.

No. 598 (Pl.1993: 91) is from Holubice, Moravia, about 250 B.C. The sword has a flat blade, which is 700 mm long. Incisions near the middle show a ferritic-pearlitic material with a carbon range from 0.1 to 0.3%. The hardness is high for this carbon level due to

Fig. 115. Slag inclusion in the Celtic sword, Krenovice 595. Distorted slag with broken fayalite crystals. Pearlitic metal. PS. Scale bar 0.01 mm.

Fig. 116. Slag inclusions in a pearlitic-ferritic matrix. Krenovice 595, as Fig. 115. PES. Side length 1.2 mm. Courtesy FORCE Technology.

significant coldwork, which also has broken a great deal of the glassy slag inclusions. Phosphorus is absent in the metal as well as in the slags. There are welding seams that show the various steps in the forging operations, as material from the same heterogeneous bar is bent and folded back on itself to become hammer-welded. The structure may easily be mistaken for a "composite sword" produced from a number of different bars, but the slag compositions prove that all material must come from the same stock.

No. 199 (Pl.1993: 108) is from the type locality La Tène, the Zihl deposit, at Lake Neuchatel, Switzerland, about 250 B.C. The sword fragment is only 316 mm long and has an unobtrusive midrib. Sections, which were taken across the fractured end, show a heterogeneous texture where ferritic-pearlitic parts with 0.1-0.3% C merge into a phosphorferritic part with less than 0.05% C and 0.1-0.2% P. The slag inclusions in the two parts are widely different in composition, the one entered in Table 5.1 belonging to the ferritic-pearlitic part. The sword must have been forge-welded from two bars of different origin, one being made from a manganese-rich ore, the other from a "normal" ore, much less enriched in manganese. The fragmented slags, and the fragmented fayalite laths inside the slags bear witness to much forging at rather low temperatures, 800-700°C.

No. 587 (Pl.1993: 86) is from Makotrasy, Bohemia, about 200 B.C. The sword which has a flat blade is 720 mm long. Incisions near the middle show phosphorferritic structures with up to 0.3% P and less than 0.05% C. The ferrite grains are 15-75 μm across, and many are rich in Neumann bands. Along the edge the grains show cold deformation. The relatively high hardnesses are due to a contribution of phosphorus in solid solution and coldwork. Also the slag inclusions are broken by coldwork. The slags are all of one sort, suggesting forge-welding from only one bar.

No. 592 (Pl.1993: 88) is from Malomerice, Moravia, about 200 B.C. The sword is long, 755 mm, and has midrib. Incisions near the middle show two major textures. One is ferritic-pearlitic with 0.1-0.5% C and glassy slags. The other is phosphorferritic with up to 0.4% P in solid solution and wüstite-fayalite-glass slags. The average slag analysis entered in Table 5.1 belongs to the slags in the ferritic-pearlitic zones. The sword has apparently been forge-welded from several, possibly three, different iron bars.

No. 593 (Pl.1993: 88) is from Malomerice, Moravia, about 200 B.C. The sword, of which 570 mm has been preserved, has midrib. Incisions near the middle show various linear textures, but all are basically built up of phosphorferrite. Phosphor-ghost structures appear where there is 0.4-0.6% P in solid

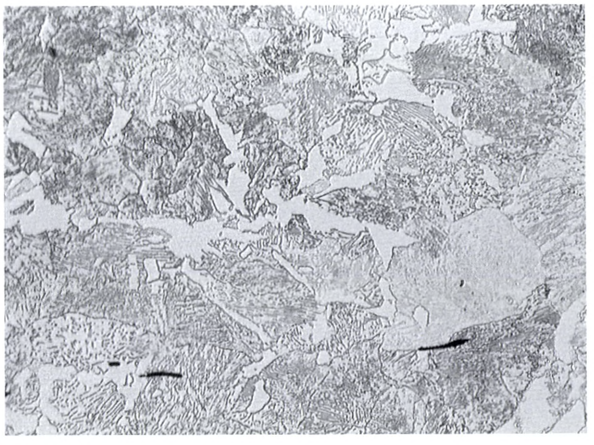


Fig. 117. Detail of Fig. 116. Phosphorus-free pearlite-ferrite with about 0.5% C. PES. Size 0.15 mm. Courtesy FORCE Technology.

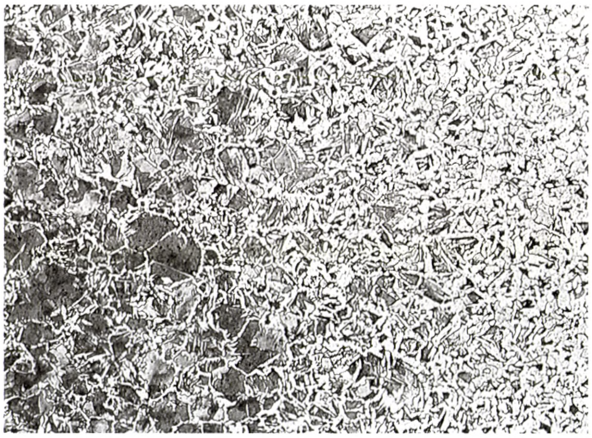


Fig. 118. Heterogeneous Widmanstätten structure with about 0.3% C and no phosphorus. Celtic sword 199 from the type locality La Tène, Switzerland. PES. Side 1.2 mm. Courtesy FORCE Technology.

solution, but in P-richer parts, up to about 0.8% P and 0.3 mm grain size, the ferrite displays many etch grooves. In several ferrite grains there appear phosphide needles, precipitated from the supersaturated ferrite (phosphide needles are often present in ancient iron objects, but have erroneously been described as nitrides). The high hardness is due to a contribution from P in solid solution and some coldwork. The slags suggest that the sword was forge-welded from a single bloom made from an unusually phosphorus-rich iron ore.

No. 594 (Pl.1993: 89) is from Malomerice, Moravia, about 200 B.C. The blade has midrib and is 652 mm long. Incisions near the middle show primarily phosphorferritic structures, ranging from 0.1 to 0.35% P in solid solution. Locally there are P-ghost structures and etch grooves. Coldwork has formed Neumann bands and cracked the slag inclusions. The average carbon level is below 0.05%, but locally a few ferrite-pearlite patches may be identified.

No. 510 (Pl.1993: 97) is from Zemplin in eastern Slovakia, about 100 B.C. The sword was bent before deposition, see Figs.11 and 19 in Pleiner (1993). The straightened length appears to be about 950 mm (?), by far the longest sword in this collection. It carries an inscription in Latin letters xVxTILICIxO, stamped 55 mm below the hilt. Fragments of a copper/bronze scabbard, ornamented in an openwork style of late La Tène Noric type, were found together with the sword. Two samples were taken from the edge in two different places. Along a major part of the surface an up to 40 μm thick iron oxide scale is present. It is clearly the complex FeO (innermost) – Fe_3O_4 (middle) – Fe_2O_3 (outermost) scale type that develops when an iron object is placed in an open fire. In the present case it is proof that the sword was put on the funeral pyre and was afterwards bent (when hot?) and placed together with the other grave goods. The structure was originally pearlitic-ferritic with 0.3-0.6% C, but due to the late heat treatment on the funeral pyre the structure is now somewhat spheroidized and the hardness has dropped appreciably from the coldworked high values, generally encountered in the Celtic swords. The presence of many fragmented slags and broken fayalite laths inside the slags still reveals that much coldwork was inflicted upon the sword during manufacturing. There are only traces of phosphorus, but manganese and magnesium are high, suggesting an ore from Noricum, similar to that used for the swords Nos. 595 and 603. In the present case also the stamp and the scabbard are witnesses to the fact that No. 510 was in all probability once a fine sword of Noric steel.

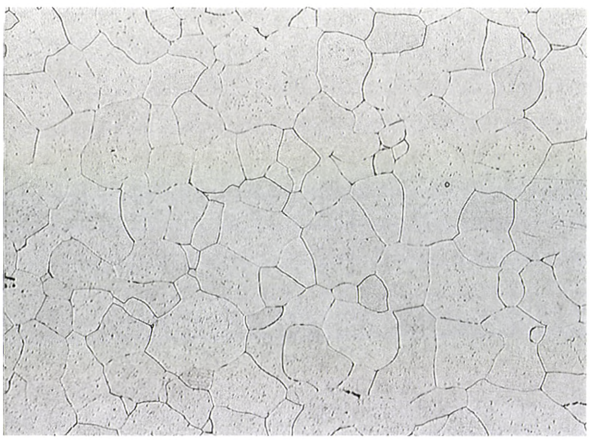


Fig. 119. Detail of the phosphorferritic part of the same La Tène sword, Fig. 118. Fine phosphides have precipitated in the ferrite grains. PES. Side 0.6 mm. Courtesy FORCE Technology.

Fig. 120. Severely distorted slag inclusion with fragmented fayalite laths. From the Celtic sword Malomerice No. 594. PS. SEM. Scale bar 0.01 mm.

No. 597 (Pl.1993: 91) is from Holubice, Moravia, 350-100 B.C. The sword, with midrib, is 705 mm long. Samples were taken along the edge at three different places. All samples show dominating ferritic structures, with grain sizes ranging irregularly from 10 to 500 μm in diameter. Some grains are coldworked, others display Neumann bands, therefore the rather high hardness for almost pure ferrite. The slag inclusions are broken, and are surprisingly rich in SiO_2 for the observed ferritic structure, which raises the question whether the blade during manufacturing unintentionally became partly decarburized. The sword was apparently forged from material similar to that of Nos. 592 and 594.

No. 600 (Pl.1993: 92) is from Holubice, Moravia, 350-100 B.C. The 729 mm long sword with midrib had adhering iron-sheet scabbard fragments when discovered in an inhumation grave. Samples were taken from opposing edges midway on the blade. The texture is irregularly laminated, but in general composed of ferritic-pearlitic streaks with 0.2-0.4% C, and of ternary Fe-C-P structures with 0.1-0.2% C and 0.1-0.3% P. Some P-ghost structures are also present. The hard-

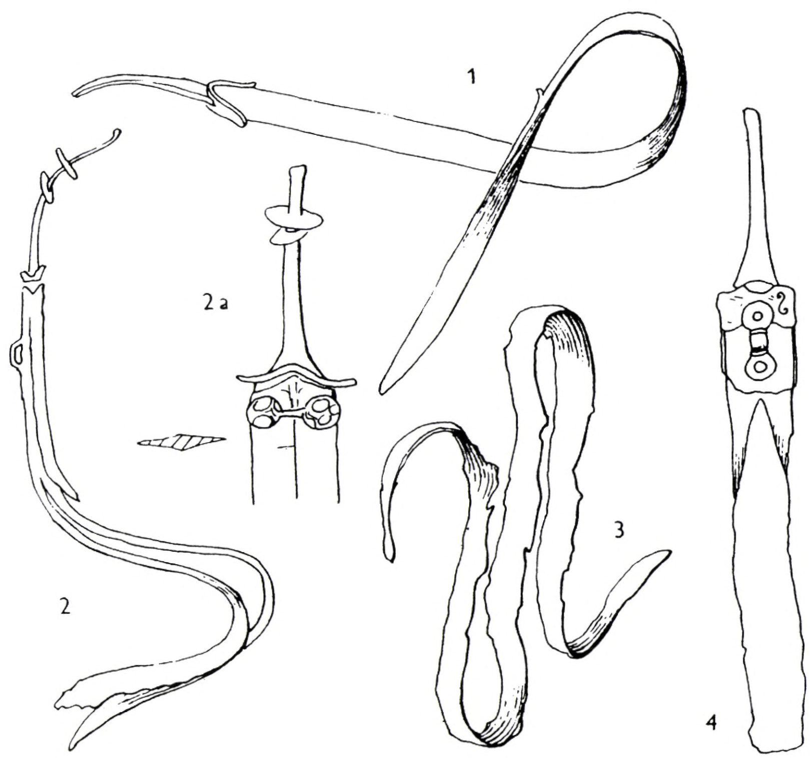


Fig. 121. Ritual destruction of Celtic swords. From Pleiner 1993:161.

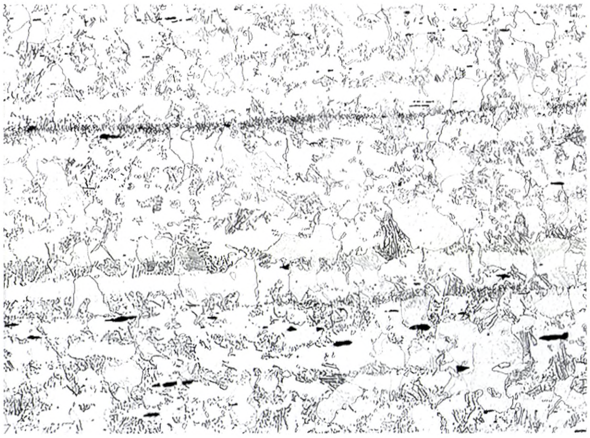


Fig. 122. Annealed ferritic-pearlitic structure of the Celtic sword, Zemplin 510. Elongated, broken slags witness the extensive forging. PES. Side length 0.6 mm. Courtesy FORCE Technology.

ness is elevated due to coldwork, and the slag inclusions, both the glassy ones in the ferrite-pearlite and the wüstite-fayalite-glass ones in the ternary structures, are fragmented.

No. 613 (Pl.1993: 83) is from Tuchomysl, Bohemia, 350-100 B.C. The sword is 710 mm long. The blade is almost flat with an adhering iron-sheet scabbard. Two samples were taken from opposing edges. The texture is very heterogeneous, mainly displaying fine-grained pearlitic-ferritic networks with 0.2-0.6% C, but also with phosphorus-rich ferrite patches. The slags, broken as usually by coldwork, are glassy and in composition similar to those of Nos. 596, 605 and 598, suggesting a close relationship. Interestingly, these four swords also have a copper content above the generally low background in the metallic matrix.

No. 614 (Pl.1993: 84) is from Tuchomysl, Bohemia, 350-100 B.C. The sword is 635 mm long and has a rather indistinct midrib. Samples were taken at three different places along the edges. The textures display large heterogeneities, but mainly there are ferritic-pearlitic zones with 0.1-0.3% C and minor parts of phosphorferrite with 0.1-0.2% P in solid solution. Coldwork has hardened the metallic matrix and fragmented the slags, glasses in the pearlite, and fine-grained wüstite-glasses in the ferrite. The slag is rich in manganese and magnesium, suggesting a Noric steel somewhat similar to Nos. 595, 603, and 510.

No. 615 (Pl.1993: 85) is from Tuchomysl, Bohemia, 350-100 B.C. The sword is 720 mm long and has a flat blade. Two samples were taken from opposite edges. The texture is extremely heterogeneous, both in terms of metal and in composition of the slags. Major parts are ferritic-pearlitic with 0.2-0.5% C and distinct Widmanstätten patterns. Fully pearlitic zones, 0.7% C, as well as ternary Fe-C-P zones also occur. Finally there are extended bands of 50-200 μm ferrite grains with up to 0.4% P in solid solution and with some precipitated phosphide needles. The slags are glassy in the pearlitic zones, but composed of wüstite, fayalite and glass in other areas. All are fragmented due to coldwork. The sword was manufactured by a rather irregular faggoting of several bars, which themselves were heterogeneous.

The general impression of the Celtic swords, here covering a period from roughly 650 to 100 B.C., is that the blade was normally manufactured from a single iron bar of no particularly good quality. The same material could as well have been utilized for nails. No deliberate attempt at carburizing – or decarburizing – can be observed. It happens that a pearlitic hard steel is located along the edge or at the point, but just as of-

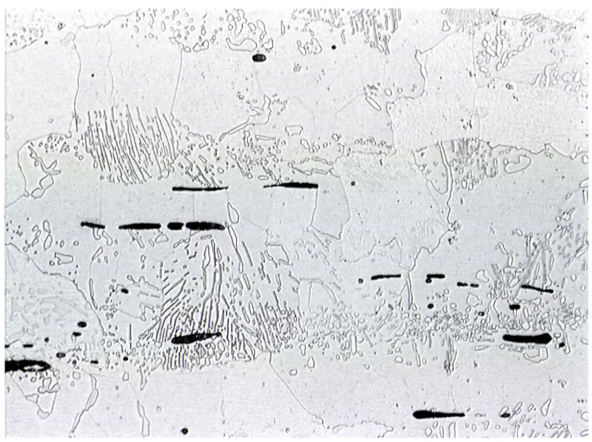


Fig. 123. Detail of the Zemplin sword, Fig. 122. Broken glass slags and annealed ferritic-pearlitic structure. The annealing stems from the funeral pyre. PES. Side 0.15 mm. Courtesy FORCE Technology.

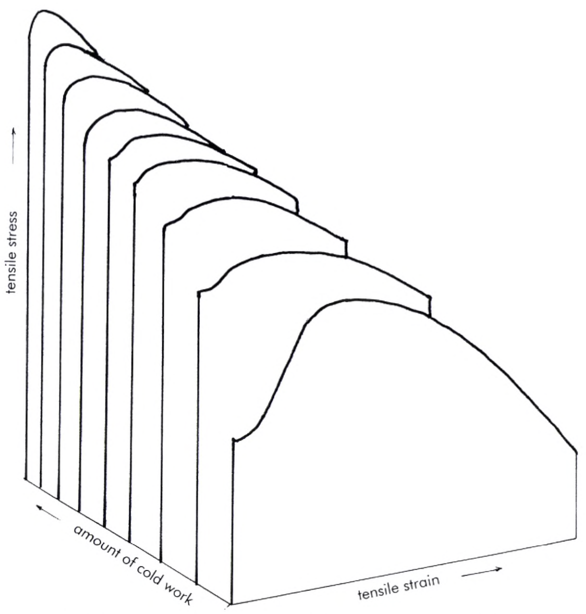


Fig. 124. Stress-strain curves for mild steel, or wrought iron, with about 0.1% C. The first curve shows a tensile test on annealed (normalized) material. The following eight show tests on the same material in increasingly coldworked states, for example after more and more rolling. The curves show that the tensile stress, and the hardness, increase with deformation, while the ductility (elongation) decreases.

ten the soft ferritic zones are located here. The laminated textures are due to the original heterogeneous nature of blooms and bars, and not to some deliberate piling of material with known carbon- or phosphorus content. The forge-welding has succeded well in most cases, although weaknesses have occasionally been observed along certain slag-loaded welding-seams.

Common to all the Celtic swords is the extensive coldwork that has taken place. Judging from the appearance of the slag inclusions, the coldwork, that is the plastic deformation below the austenitic temperature region, took place in connection with manufacturing. The coldwork was evidently the finishing part of the blacksmith's usual hotwork, only that he continued hammering in the temperature range 800-600°C, thereby crushing and displacing the slags and the already segregated fayalite laths of many slag inclusions. Significant coldwork at room temperature must also have taken place, since the metal is work-hardened to high hardnesses and displays slip lines and Neumann bands. Some ferritic zones are visibly distorted and have not afterwards recrystallized, proving that this deformation happened when cold.

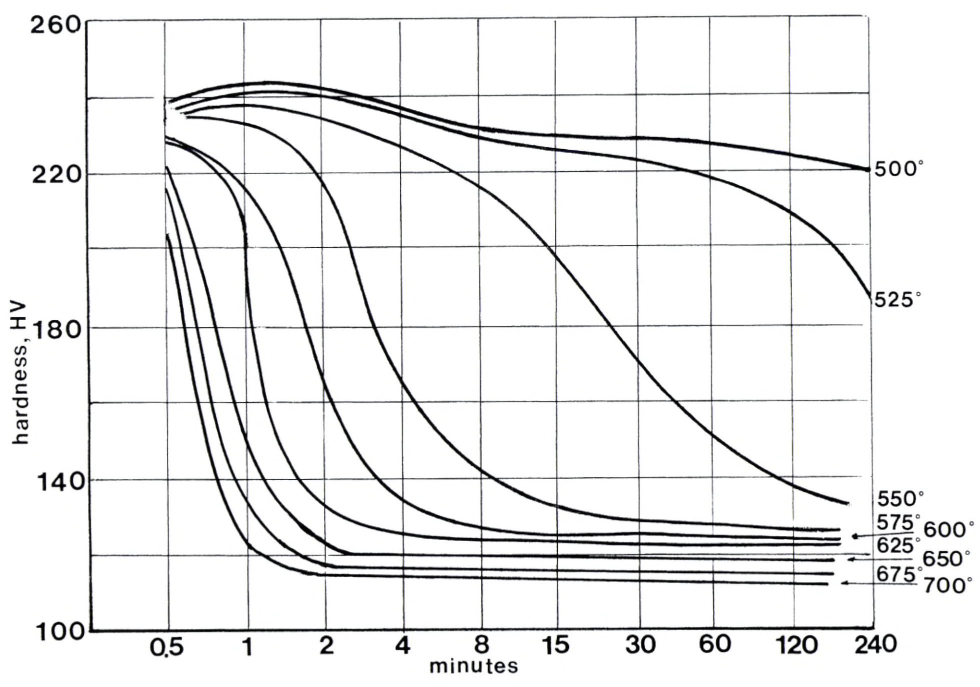


Fig. 125. After coldworking of iron, Fig. 124, reheating above 500°C will gradually soften the material. The recrystallization temperature may be defined as the temperature where the material within 30 minutes has lost half of its workhardening. According to the diagram the recrystallization temperature for 0.1% C iron is about 550°C.

The 24 swords do not show any metallurgical development with time, except for one, the oldest, from Hallstatt. That one seems to be a rather mediocre sword based on an improper ore and an inexperienced blacksmith. The ore type has not been met with in the later material.

The other 23 swords are rather similar in terms of cutting edges (they were probably originally ground, but the evidence is lost due to corrosion), hardness and coherence, with a tendency for three of them, Nos.595, 603, and 510, to be of superior quality, being pearlitic-ferritic and probably representing the famous Noric steel. If this argument, based on slag composition and structure – and an inscription on No. 510 – holds true, the manufacture of Noric steel began as early as 300 B.C.

None of the 24 Celtic swords were hardened by quenching in water. Perhaps the Celtic blacksmith was satisfied with coldhammering the edges for sharpness and springiness, in much the same way as the farmer of the 19^{th} century sharpened his scythe every day.

Noric steel

"Durior est ferro quod noricus excoquit ignis", "Harder than iron manufactured in Noric fire". This quotation from Ovid's Metamorphoses (Song 14 :712) illustrates well the reputation enjoyed by the iron coming from Noricum to the Roman world 2000 years ago.

The Austrian Alps of present-day Salzkammergut, Styria (Steiermark) and Carinthia (Kärnten) had for centuries been important for their salt and iron production, and some gold and silver had also been mined. The general Roman name for this region, situated between Raetia in the west and Pannonia in the east, became Noricum, a province which in 16 B.C. was incorporated in the Roman empire. The salt was mined around Hallein and Hallstatt, hall in Celtic meaning salt.

The iron came from in particular two areas: Erzberg (I) in Görschitztal at Hüttenberg in Carinthia, 40 km NNE of Klagenfurt, and Erzberg (II) in Styria, at a tributary to Enns between present-day Eisenerz and Vordernberg, about 60 km north of Erzberg (I). It appears that Erzberg (I) at Hüttenberg was already worked in the La Tène period, while Erzberg (II) at Eisenerz is first documented in early mediaeval times. A memorial tablet from 1632 A.D. in the church of Eisenerz mentions 712 A.D. as the opening year of the mine (Beck 1891: 730). The ores of both occurrences are siderite, $FeCO_3$, and its limonitic weathering products. In the siderite molecule, iron may be substituted by manganese, calcium and magnesium, and when particularly enriched in calcium is called ankerite or Braunspat. The ankerite varieties were rarely mined, being too low in iron. Prime ore from Hüttenberg, as roasted, holds, e.g., 50-54% Fe, 6% CaO, 5% MnO, 1% Al_2O_3, 1% MgO, 0.03% P_2O_5 and 0.08% SO_3. This is a very good quality for steel making. At Eisenerz the open quarrying has transformed the Erzberg (II) mountain to a characteristic landmark, Fig. 126, but presently the operations are coming to a halt. Voest – Alpine AG has, however, plans to maintain some interesting visiting facilities and the mining museum.

In the late Celtic Iron Age the most important trading center was Magdalensberg, 16 km NE of Klagenfurt in Carinthia (Straube 1996). Here a large number of specialized blacksmiths manufactured scythes, knives, weapons etc. from blooms derived from furnaces near Hüttenberg. The finished products were mostly sent south, in particular to Aquileia, a Roman trading port in the Gulf of Trieste (Strabo, Geography, Book 5: 1,8). Commercial inscriptions on walls of tabernae close to the temple district in Magdalensberg date from the birth of Christ and concern the deliveries of iron bars of different shapes for several

Fig. 126. The Erzberg iron mine in Austria as seen from Mount Polster (1910 m). In the background Mount Kaiserschild (2085 m). Centuries of mining activity has reduced Erzberg's highest point to 1465 m.

Mediterranean markets, including Africa (Straube 1996: 155).

The history of the Styrian ores and iron production has been treated by Beck (1891), Schmid (1932) and Sperl (1982; 1993). By the kind cooperation of Dr.G.Sperl, a slag from the Erzberg (II) area can be included in this study. It is a tapslag fragment of 49 g from Feistawiese (Sperl 1980: 33) which comes from a production furnace, originally thought to be Roman from the 3rd or 4th centuries A.D., Table 5.2. There is, however, some uncertainty as to the age, and it could be mediaeval (Sperl 1982; Pleiner 2000: 186). However, the slag is certainly from a bloomery which was operated on the typical sideritic ores, so the slag may be taken as representative of the Noric province. In Table 5.1 three of the swords, Nos. 510, 603, and 595, were singled out as having been manufactured from Noric iron. Common to the slag inclusions of the swords, to the Feistawiese production slag, and to the Hüttenberg sideritic ore is a significant MnO level, above 5%, and a very low phosphorus level. Both criteria must be fulfilled if the ancient iron master was to succeed in making pearlitic steel. It is not enough that the ore is manganese-rich. If it also contains phosphorus, the ore is not suited for steel making. The sword No. 199 has for example 15% MnO in the slag inclusions, but the simultaneous presence of phosphorus ruins the steel and produces, at best, a mixture of phosphorferritic and pearlitic structures.

Almost all the Celtic swords here examined were of


10°
0°
20°
60°
50°
40°
Trøndelag
Valdres
Dalarna
Telemark
Närke
Skagerak
Gotland
Småland
Öland
North Sea
Hadrian's Wall
Randbøl
Baltic Sea
Bornholm
Elbe
Britanny
Forest of Dean
Weald
Cassiterides
Oder
Weichsel
Masovia
Biskupice
Holy Cross Mts.
Ruhr
Siegerland
Koblenz
Maas
Trier
Rhine
Seine
Neu Ulm
Kaisheim
Münsingen
Holubice
Zemplin
Vix
Alesia
Hallstatt
Danube
Loire
Bibracte
Augst
La Tène
Raetia
Noricum
Erzberg
Hüttenberg
Magdalensberg
Pannonia
Aquilegia
Dordogne
Padus
Po
Stari Majdan
Garonne
Montagne Noire
Rhone
Massilia
Arezzo
Populonia
Etruria
Elba
Roma
Nemi
Pyrenees
Ebro
Jucar
Nova Carthago
200 km

good quality and would undoubtedly have yielded good service. It is thus very difficult to accept the statement by Polybius (200-118 B.C.)(Book 2: 33) when he describes the fight between invading Celtic armies and a Roman army under Consul Flaminius in the Po Valley 223 B.C. Polybius says "The swords of the Celts are such that only the first cut is dangerous; then the swords become bent and assume the shape of a strigil, so that the men have to have time to put the swords down and set them straight with the foot. Otherwise the next blow is entirely without effect". This appears to be a tall tale, or sheer nonsense, because it is impossible to deform a Celtic sword, generally of a 45 x 5 mm cross section so that it is bent both lengthwise and crosswise as a strigil, and secondly it is still more impossible to rectify the situation with the foot. It would require reheating to forging temperature and hammer and anvil. Tholander (1982) and Pleiner (2000: 34) are of the same opinion.

No, the Celtic sword and the Celtic warrior were feared by the Romans and other potential enemies: "Very terrifying too were the appearance and the gestures of the naked warriors in front, all in the prime of life and finely built men, and all in the leading companies richly adorned with gold torques and armlets. The sight of them indeed dismayed the Romans, but at the same time the prospect of winning such spoils made them twice as keen for the fight" (Polybius, Book 2: 29). The famous, classic statue of the Dying Gaul (marble copy in Museo Capitolino, Rome) well illustrates this passage from Polybius. The Roman fear was remembered centuries after these events took place. Thus Plutarch (45-120 A.D.) wrote: "So great had their terror been that the Romans made a law exempting priests from military service, except in case of a Gallic war", and "Knowing that the prowess of the Barbarians lay chiefly in their swords, which they plied in true barbaric fashion, and with no skill at all,

Fig. 127. Finds of iron and steel bars of early Europe. // Oboli, or spieti, Greek-Etruscan, 700-400 B.C., ◆ Celtic double pyramid bars (Spitzbarren), 600-1 B.C., ▬ Roman iron bars, 500 B.C.-400 A.D., ▮ British currency bars, 300-1 B.C., ⫯ Valdres (Norway) spoon-shaped steel bars, 300-600 A.D. ʌʌʌʌ Roman Limes at 200 A.D.

Fig. 128. Tap slag from Feistawiese, near Erzberg. The upper, later slag layer solidified in a fine grained texture, the fayalite laths radiating away from the lower, cold substrate. PS. SEM. Scale bar 0.1 mm.

in mere slashing blows at head and shoulders, Camillus had helmets forged for most of his men which were all iron and smooth of surface ... " (Plutarch's Lives, Camillus, Chapters 40 and 41).

Considering the nonsense-statement by Polybius, one comes to think of the many ritually S-bent swords which have been found in Celtic graves. Perhaps the contemporaneous writer was aware of these deformed weapons and misinterpreted them. These swords must have been bent still hot when withdrawn from the fu-

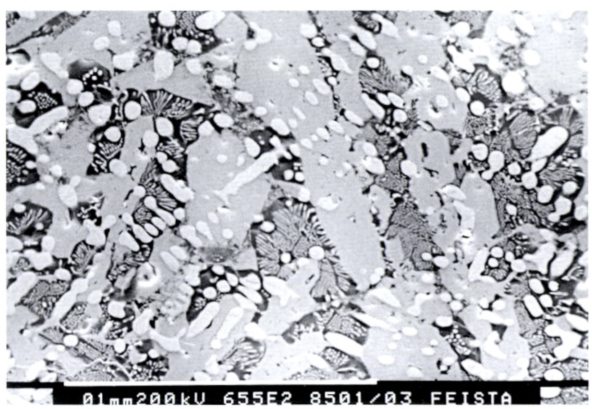


Fig. 129. Tap slag from Feistawiese, near Erzberg. Fayalite laths (grey), wüstite dendrites (white), and a matrix with leucite (black). Poor in phosphorus. SEM. PS. Scale bar 0.1 mm.

Fig. 130. Roman tombstone from Aquileia, 35 km NW of Trieste, Italy. The blacksmith is seated when performing delicate work. The assistant operates double bellows directed towards an open hearth. Hammer, tongs, a lancehead and an unidentified object in the lower right corner. Note the typical four-legged Roman anvil. Straube 1996: 142.

neral pyre. They have a relatively low hardness and a spheroidized structure after the reheating in the fire (No. 510) as compared to the usual structure of the hard, coldworked swords.

The Romans learned, however, how to tackle the Celts. The Roman warrior had a large shield and a short sword, the gladius, about 50 cm long (Pleiner 1993: 5), Fig. 295. After javelins and spears had been spent, and the men came into close combat, it became difficult for the Celtic warrior to wield his long sword. The Roman, protected by his shield and often using it offensively, could stab his opponent. In the end, the Celts succumbed to Roman might, and it was only in marginal regions, such as Ireland, which Rome failed to dominate, that Celtic society survived in a recognizable form.

The double pyramid bars, or the bipyramidal bars

The double pyramid bars, bipyramidal bars, or spindle-shaped bars, or in German Spitzbarren, are a characteristic of the La Tène period, Table 4.6. They occur mainly within the Celtic provinces of Switzerland, eastern France, Württemberg, the Rhineland-Palatinate and Bavaria (Pleiner 1980: 391). Stray finds have been reported from several places, e.g. Brittany (Galliou 1983). In shape and size they are rather similar to the enormous hoard of bipyramidal bars discovered in the Assyrian palace of Sargon II at Khorsabad (Place 1867), see Chapter 3.

The bars are in the shape of double pyramids with rectangular or quadratic cross sections of 5-10 cm. They are 30-55 cm long and have weights of 3-10 kg. They may be elongated and slender, or short and bulky. The two ends may be blunt or pointed, one end often displaying a hook or an eye for transportation purposes. They are often found in hoards, e.g. 26 at Monzenheim, 14 km NW of Worms (Beck 1891:533), 27 at Kaisheim, 5 km north of Donauwörth, Bavaria; and 13 at Neu Ulm, Bavaria. The Sauggart hoard comprised 24 bars weighing 151 kg, and the Rodalbern hoard 9 bars weighing 42 kg (Pleiner 1980).

In Scandinavia only one is known, a 4.13 kg bar, which was ploughed up in Skærhølgårds fields, near Randbøl and Hærvejen (the military road) in 1918. It is 31 cm long, has a rectangular cross section of 74 x 65 mm, and is provided with a hook in one end. Its specific gravity may be estimated to 7.5 g/cm^3, so the bar must be quite massive and rather free of slag inclusions. It is now in Vandel Museum (Mortensen 1939: 144, 200).

Bipyramidal bars have been well studied by Haneman (1930), Daeves (1940) and Keesman (1961). Rädeker & Naumann (1961) examined two bars of 5 and 6 kg from Kaisheim and Neu-Ulm, cutting them lengthwise and crosswise, thereby exposing their extreme heterogeneity. The hardness range was correspondingly from 78, that is very pure ferrite, to 271 HV, that is hypereutectoid pearlite with cementite. Many of the higher values were due to phosphorus in solid solution, up to 0.45% P being recorded. Three-phased wüstite-fayalite-glass slags occurred in the soft, ferritic zones. The slag composition of their Table 6, prepared by the tedious and time- consuming electrolytic isolation of individual slag particles – to be replaced a few years later by the electron microprobe examination – is very similar to the results presented in Table 5.1, the Celtic swords.

Fig. 131. The only double pyramid bar in Scandinavia was found near Hærvejen (the Military Road) and Vandel, Jutland. It is 31 cm long and weighs 4.13 kg.

Therefore it is almost certain that the bipyramidal bars were the raw material for the manufacture of the majority of the Celtic swords, with all the heterogeneities that followed. Of course, agricultural tools, horse bits and general household articles would also have been made from the bars. High-grade swords, knives, files and chisels would have been fashioned from Noric steel bars.

The western parts of the Celtic domain, ancient Gaul (present-day France and Belgium) were inhabited by numerous tribes, Helvetii, Arverni, Pictones, Bituriges, Sennones, Treveri, Belgae and others. Caesar gave a first-hand description of the situation in Gaul during his campaigns 58-50 B.C., and he mentioned iron in passing. He was impressed by the ships of the Veneti, built of heavy oaktimber and finger-thick iron nails, and using anchor chains of iron instead of rope (De Bello Gallico, Book 3: 13). He ascribed the ingenuity of the Gauls in undermining the Roman fortifications to their familiarity with iron-mining (ibid. Book 3: 21, Book 7: 22), and he presented a glimpse of the warfare when he described the action of the long Roman javelin, the pilum. In hitting the enemy's shield, the point fastened and the thin iron shaft behind the point often bent, so the attacked warrior could no longer hold his shield and had to throw it away (ibid. Book 1: 25).

Graves and hoards and large slag heaps bear witness to the extensive Gallic iron industry. Emperor Napoleon III, who was quite interested in archaeology, initiated the excavations of Bibracte (20 km west of Autun), the central fortification, or Oppidum, of the Ædui which was conquered by Caesar in 52 B.C.

Fig. 132. The famous bronze vase from a Celtic princely grave at Vix, Chatillon-sur-Seine, about 530 B.C. Archeological Museum, Chatillon-sur-Seine. René Joffroy 1954: Le trésor de Vix.

(ibid. Book 7: 55). The results of the excavations were published by Bulliot (1899). In recent years, French archaeologists have instigated archaeometallurgical researches and examined, in particular, the region west of Dijon (Mangin et al. 1992), the Montagne Noire north of Carcasonne (Domerque 1993) and the four departments of Aude, Gard, Hérault, and Tarn at the Mediterranean west of the Rhône (Feugère & Serneels 1998).

From the princely grave at Vix, Châtillon-sur-Seine (Pare 1992: 231) a fragment of 17 g of a bloom has been examined by the author, through the kind cooperation of Professor H.Moesta, Saarbrücken. The sam-

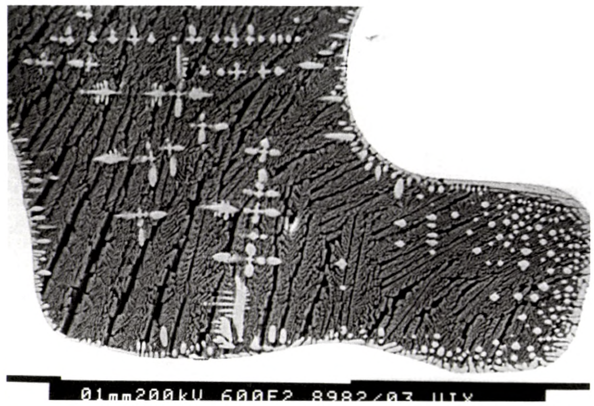


Fig. 133. Slag inclusion, Vix 5, in an iron bloom from Vix. When the slag solidified, the solid iron wall nucleated tiny wüstite crystals. The bulk of the slag solidified as wüstite dendrites, fayalite laths and intercalated glass. SEM.PS. Scale bar 0.1 mm.

Table 5.2. SEM-EDAX analyses of a slag from Feistawiese and four slag inclusions from Vix. Weight %.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Other	Sum	F
F.II/3	30.1	43.4	8.7	0	3.0	8.4	5.0	0.9	0.3	0.2	-	100	3.58
Vix av.	32.4	52.7	0.6	0.7	2.9	7.2	2.4	0.5	0.4	0.2	-	100	4.50
Vix 3	19.1	71.1	0.4	0.7	1.8	4.6	1.4	0.3	0.3	0.2	0.1 Cr	100	4.15
Vix 4	21.9	68.0	0.4	0.8	2.2	4.4	1.3	0.4	0.3	0.3	-	100	4.98
Vix 5	29.4	55.2	0.5	1.0	3.7	6.7	2.5	0.3	0.3	0.3	-	100	4.39
Vix 6	59.1	16.4	1.2	0.1	3.7	13.0	4.6	1.0	0.8	0.1	-	100	4.55

Fig. 134. Another slag inclusion, Vix 3, in the iron bloom from Vix. The high FeO-content gives rise to bulky wüstite dendrites. The rest is fayalite laths in glass. SEM. PS. Scale bar 0.1 mm.

ple, estimated to be from 530 B.C. consists of equal volumes of iron and slag. The iron is ferritic-pearlitic with hardnesses of 133-142-166-171 and 173 (HV 200 g), the relatively high hardness being caused by phosphorus in solid solution, Table 5.2.

"Vix av" is the average of four different slag inclusions, 3-6, in the ancient bloom. They are widely different in appearance and in composition, and are apparently unrelated. Their internal harmony and close relationship will, however, be revealed and discussed in the next chapter.

From Pre-Roman Great Britain come a dozen or more hooked iron blocks. Two of these, weighing 2.7 and 1.6 kg, have been thoroughly described and analysed (Fell 2003), who found that the low-quality iron was consistent with their probable function as billets or partly worked trade iron.

Currency bars

Iron working on any noticeable scale did not begin in Great Britain until after 200 B.C. Archaeological evidence for Early Iron Age iron-smelting sites consists mainly of associated slag, charcoal, and ore. Only very few furnaces have been found (Tylecote et al. 1971). In 54 B.C. Caesar invaded Britain. During his brief campaign he noted that the inhabitants mined tin and a little iron near the coast, probably from the Weald in Sussex-Kent, whereas they imported copper. They used either bronze (hardly brass) or iron staves regulated to a certain weight for coins (De Bello Gallico, Book 5: 12) "Utuntur aut aere aut taleis ferreis ad certum pondus examinatis pro nummo" (Rambaud 1974). From this observation was born the 19th century expression "currency bar" for the peculiar, flat bars which have been found in the hundreds in England,

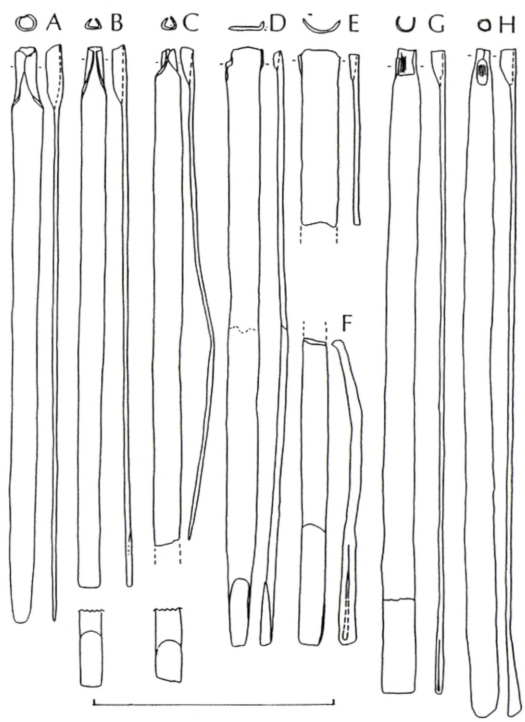


Fig. 135. Different types of currency bars, some of them with welded tips. Scale bar 25 cm. Crew & Salter 1993.

often in hoards (Allen 1967; Haldane 1970: Hedges & Salter 1979; Hingley 1990). All agree that they belong in the period 300-1 B.C., Table 4.6. About twenty types of currency bars have been recorded from Great Britain. The different shapes of the bars are possibly an indication of the metal type and its qualities (Crew & Salter 1993). A significant number of 'spit-shaped' bars have been found clustered around the Forest of Dean, which is one of the major sources of phosphoric iron ore in Britain. A few currency bars have been discovered outside Britain, e.g. in Switzerland, Germany (Jacoby 1974) and France (Martin & Ruffat 1998).

Many currency bars have been examined. They are generally of a heterogeneous nature, displaying phosphorferrite and ferritic-pearlitic mixtures. Evidence of

On forging and hardening temperatures

The normal forging temperatures are about 1100-750°C. The corresponding colours are from bright yellow to cherry red. The ancient blacksmith judged his smithing operations from the colours. Therefore his smithy was only dimly lit through a small window on the northern side.

Colour	Temperature, °C
White	1200
Bright yellow	1100
Yellow	1050
Citrus yellow	980
Yellowish red	930
Bright red	870
Bright cherry red	810
Cherry red	760
Dark cherry red	700
Dark red	650
Brownish red	600

Between 300 and 400°C, iron is blue brittle and must not be hammered. If carbon-rich, the object may develop microscopic cracks that later, e.g. in a hardening operation, may expand and ruin the material. The iron may also be heated too much. Then it burns, emitting white sparks, and the workpiece loses vital parts, particularly thin edges and points. The burned parts must be removed with the chisel.

Iron is a poor heat conductor, so it is important to learn the correct holding time in the forge fire. Normally the workpiece should have acquired the same temperature throughout, before further operations like forging or hardening are carried out. The time for equilibrium is clearly dependent on the dimensions of the workpiece, from half a minute for a knife to many minutes for larger objects.

The starting temperature for martensite hardening is usually about 50° above the line GSK in the iron-cementite equilibrium diagram, Fig. 57. Using higher starting temperatures will result in unwanted coarse-grained structures, and perhaps a decarburized surface. But, on the other hand, the martensite transformation will penetrate deeper into the workpiece.

coldworking has sometimes been observed, but it seems to have been unintentional. According to Table 30 in Tylecote (1976) they are normally low in carbon, <0.1%, but may have much phosphorus, up to 0.95%. Slag inclusions are common.

The currency bars are far from being a high-quality material, fit for swords, sickles, or knives. They are rather the local semiproducts, intended for trade and sale for the ordinary household and utilitarian articles. They have been forged into a particular flat shape, but have apparently not been cut to a particular weight. If the manufacturing blacksmith wanted steel for his work, he had to look elsewhere, for phosphorus-free material.

An important study of Pre-Roman British ploughshares. sickles, and blades, which may have been produced from currency bars, has been published by Ehrenreich (1984).

On martensite and annealing

In modern practice 0.3% C or more is required for a hardening operation, and alloying additions play a major role. In ancient time, before about 1700 A.D., the object to be hardened was an undetermined mixture of ferritic, pearlitic and phosphorferritic parts, so it is difficult to be precise as to the correct hardening temperature. The result would be a complex mixture of correctly hardened martensitic parts, and unhardened ferritic and phosphorferritic parts. The hard martensite was as often as not located in the cutting edges.

A fully hardened martensitic object is rather brittle. It is today common practice immediately to follow up on the quenching operation with an anneling treatment. The least one has to do is to expose the hardened object to boiling water or to hot oil. The table contains recommendations that aim at removing internal stresses, and some of the hardness, simultaneously conferring ductility corresponding to the expected applications.

Colour	Tempering temperature, °C	Objective
Grey	325	Generally too high for tempering
Blue	300	Hammers, screwdrivers
Dark blue	290	Saws
Violet	280	Edge tools for wood work, knives
Purple red	270	Edges of axes
Reddish brown	260	Chisels, drills for stone
Dark yellow	240	Files
Straw yellow	225	Very hard edge tools

The annealing colours are followed on a small part of the object, which is brightly polished with emery paper. The higher the annealing temperature, the softer and tougher becomes the steel, Fig. 65. Larger objects, such as chisels and axes, may be hardened and annealed in the same operation. The (chisel) edge is quenched in water, then withdrawn and rapidly polished. The remaining heat of the massive part will creep towards the edge, giving a perfect result: Tempered, hard edge and tough back with smooth transition zones.

Chapter 6
The bloomery process II. From ore to manufacture

Schmiede das Eisen, wenn es glüht,
pflücke die Rose, wenn sie blüht.

German proverb.

Let us for a moment leave the chronological development and examine the chemical-metallurgical aspects of the ancient direct iron production method. For this purpose we will visit several well-studied Scandinavian iron production sites and examine their differences, if any. The quality and composition of the Scandinavian bog and lake iron ores will be illustrated by appropriate examples.

Fig. 136. Twin furnaces at Jernvirke, Tvååker, Halland, from the 12th century. Their inside diameter is 25-30 cm, and the distance from center to center 1.5 m. Before the excavation in 1993 they were entirely covered by a slag heap. Buchwald 1998: 13.

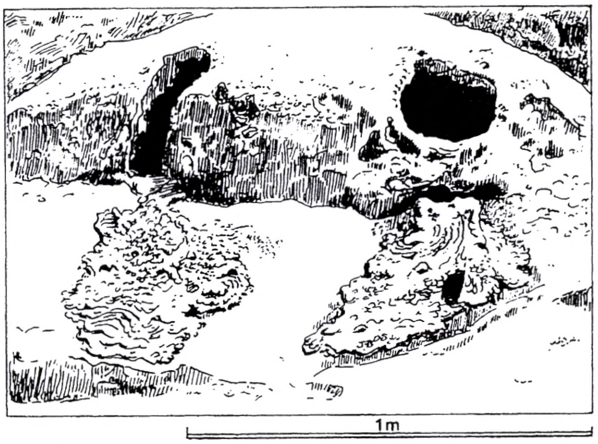


Fig. 137. Twin furnaces at Köszegfálva, Hungary, from the 12th century. Tapped slag covers the surface. Drawing by Pleiner 2000: 266.

1.Tvååker, Halland. Excavations 1993-1995 have revealed a number of furnaces, some of them working in pairs (Andersson ed. 2004). The typical Södra Järnvirke furnace, figure 136, was rather small, about 20 cm in interior diameter, and with a volume of 22 l. Two such closely situated low shaft furnaces with slag tapping (RAÄ 85) were found partly buried in a slag heap with an estimated volume of 10.6 m^3. A 4 x 3 m depression nearby has been interpreted as a charcoal pit. The ore was massive bog iron ore from the immediate vicinity. The average analysis of ten samples of unroasted ore is presented in Table 6.1, first line. The average analysis of twelve tapslags from the same site is presented in the first line of Table 6.2.

Less than a kilometer north of these furnaces, another production site, Ugglehult (RAÄ 84), was located at a small rivulet, Sandabäcken. C-14 dating gave ages similar to those of Järnvirke, that is the 12th century. However, at Ugglehult the iron master had taken advantage of the water power, had built a dam and installed a waterwheel. It is assumed that the waterwheel powered one or two bellows for the furnace. The site has become known from contemporary Latin documents as Jernmøllen, the Iron mill (Andersson ed. 2004).

Unfortunately, later activities on the site have destroyed the furnace(s), but slag heaps totalling about

Table 6.1. SEM-EDAX analyses of three bog and four lake iron ores

	SiO_2	Fe_2O_3	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum
1	11.0	82.0	0.5	0.5	0.3	4.6	0.3	0.2	0.1	<0.1	0.4	100
2	9.2	85.5	0.5^b	0.4	0.1	3.2	0.1	0.4	<0.1	-	0.5	100
3	2.9	95.1	1.0	-	0.3	0.4	-	-	-	-	0.3	100
4	5.6	82.5	3.9^c	0.8	0.3	5.6	0.1	0.7	0.1	-	0.4	100
5	10.9	79.3	0.8	1.3	0.2	5.8	0.4	0.1	0.9	0.1	0.2	100
6	5.6	86.9	0.9	0.4	0.1	4.6	-	0.9	-	-	0.6	100
7	4.7	91.3	0.9	0.1	0.1	2.2	-	0.4	-	-	0.3	100

b also 0.1% BaO c also 0.3% BaO

1. Tvååker, Järnvirke ; Halland. Unroasted bog iron ore, average of ten samples.
2. Brunkelstorp, Scania. Unroasted bog iron ore.
3. Tranemo, Vester Götland. Roasted red soil. With a few chalcopyrite particles.
4. Huseby, Småland. Unroasted lake ore, bean – pearl type.
5. Pickelsjö, Scania. Unroasted lake ore, coin type, 13 mm diameter.
6. Vidöstern, Scania. Unroasted lake ore, coin type, 35 mm diameter.
7. Tohmajärvi, Carelia. Unroasted lake ore, coin type, 20 mm diameter.

Fig. 138. Tap slag from the Jernvirke furnace, Fig 136. Ropy surface of a 360 g slag fragment, F3 Skakt 4. Scale bar in cm.

Fig. 139. Tap slag, No. 11, from the Jernvirke furnace. Wüstite dendrites (white), fayalite laths (grey) and glass. Only 0.6% P_2O_5 in the slag. PS. SEM. Scale bar 0.1 mm.

120 m^3 have remained untouched until the archaeological excavations started. The ores applied were the same as at Järnvirke (Table 6.1), and roasting had taken place, as witnessed by the presence of roasted ore on the "floor" around the production site. The average analysis of 21 slag samples from Ugglehult's Iron mill is presented in Table 6.2, line 2.

On the Ugglehult site some purification work had taken place as documented by a number of planoconvex slags (Kalotschlacken). The average analysis of three planoconvex slags of, respectively, 445 g, 535 g, and 407 g is shown in line 3 of Table 6.2. Numerous slags from Jernvirke and Ugglehult have been examined and discussed in detail by Buchwald (2004 b).

Table 6.2. SEM-EDAX analyses of slags and slag inclusions from Southern Sweden (Denmark)

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	24.7	59.0	0.8	0.6	2.5	8.0	1.9	0.4	0.2	0.1	0.3	98.5	3.09
2	33.7	45.9	2.0	0.5	2.9	9.9	2.8	0.6	0.4	<0.1	0.2	99.0	3.40
3	33.3	47.0	0.3	0.4	3.4	9.5	3.5	0.5	0.4	<0.1	0.2	98.5	3.51
4	45.0	35.4	2.6	0.5	1.9	10.1	3.2	0.6	0.4	-	0.3	100	4.45
5	29.8	57.3	0.5	0.8	1.6	7.2	2.2	0.1	0.3	-	0.2	100	4.14
6	30.8	48.5	1.3	1.0	3.0	12.0	2.3	0.5	0.3	-	0.2	100	2.57
7	29.9	52.4	0.4	0.7	4.1	7.9	3.7	0.5	0.2	-	0.2	100	3.78
8	28.2	55.8	0.8	3.0	2.1	6.5	2.0	0.8	0.3	-	0.5	100	4.34
9	25.0	52.9	4.6	1.8	1.9	10.4	2.3	0.3	0.3	-	0.3	100	2.40
10	21.6	61.4	1.0	0.8	3.5	8.8	2.2	0.4	0.1	-	0.2	100	2.45
11	32.2	43.7	5.3	2.6	3.5	8.1	3.2	0.7	0.3	-	0.4	100	3.98
12	30.8	43.5	7.2	0.7	2.2	11.4	2.6	0.5	0.5	-	0.2	100	2.70
13	37.4	37.4	4.5	0.7	2.2	13.5	3.1	0.2	0.5	0.2	0.1	100	2.77
14	38.2	30.0	3.4	1.2	3.9	18.1	3.9	1.0	0.2	-	0.1	100	2.11

1. Järnvirke, Tvååker. Tapslag, average of 12 samples
2. Ugglehult, Tvååker. Water mill. Tapslag, average of 21 samples.
3. Ugglehult, Tvååker. Water mill. Planoconvex slags, average of three samples.
4. Ugglehult, Tvååker. Water mill. Slag inclusions in a bloom, 84: F 12.
5. Ugglehult, Tvååker. Slag inclusions in a 14 g nail, 84: F 107 a. Ferritic. HV 200g: 108-112-112-120-131.
6. Hishult, Halland. Bottomslag, No. 22-1.
7. Halmstad and Trulstorp. Average of four purification slags.
8. Halmstad and Trulstorp. Average of slag inclusions in four iron objects.
9. Vittsjöborg and Ubbalt. Average of production slags from three furnaces, run on lake iron ores. Also 0.2% BaO.
10. Vittsjöborg. Purification slag.
11. Vittsjöborg. Average of slag inclusions in cross-bow bolt and a horseshoe.
12. Stenså, Halland. Production slags at watermill. Average of five samples. Also 0.4% BaO.
13. Hörja, Scania. Production slags at water mill. Average of three samples. Also 0.2% BaO.
14. Brunkelstorp, Scania. Production slags at water mill. Average of two samples.

A fragment of a bloom was also found. The average of various slag inclusions in the bloom is shown in line 4, Table 6.2. Finally, a 14 g nail, which had been discovered on the site and judged to have been produced there, is included in line 5, Table 6.2. The nail is ferritic with less than 0.05%P in solid solution, and the hardness is correspondingly low, 108-131 HV.

The Tvååker data serve to show how a good bog iron ore, low in manganese and phosphorus, results in ferritic, soft wrought iron, low in phosphorus, <0.05%.

The production slags left on the sites are different from the ores in certain respects. First, the slags are enriched in CaO, K_2O and MgO relative to the ore applied. If Al_2O_3 is used as an internal standard (Al_2O_3 is mainly derived from the ore, it is not reduced in the process, and it is not dissolved in the metal), it is seen that, comparing the two first lines of Table 6.1 and

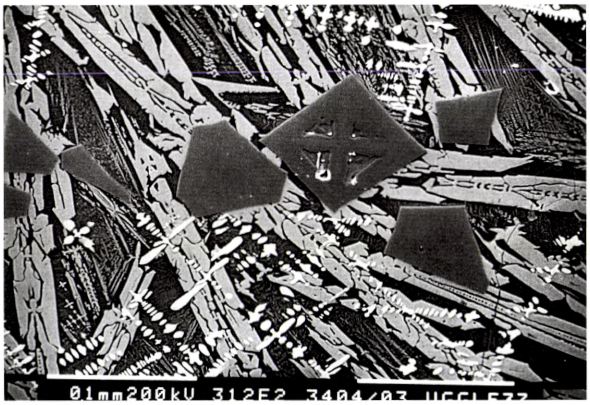


Fig. 140. Tap slag, No. 37, from the Ugglehult furnace. Conspicuous cubic hercynite crystals with 1.3% V_2O_5 and 0.9% TiO_2 in solid solution. The background is wüstite dendrites and fayalite laths in a fine grained, decomposed glass phase. PS. SEM. Scale bar 0.1 mm.

Table 6.2, the ratio CaO/Al_2O_3 increases from 0.06 to 0.31, the ratio K_2O/Al_2O_3 from 0.06 to 0.24, and the ratio MgO/Al_2O_3 from 0.04 to 0.05. These changes are due to a significant addition of CaO, K_2O and MgO from reaction with the charcoal ashes, see Table 4.5. Similar enrichments are evident if comparing also line 2 of Table 6.2 with line 1 of Table 6.1.

Secondly, the slags from the water mill installation, Table 6.2, line2, have less FeO and more SiO_2, i.e. are more reduced than the slags from the furnaces with hand-operated bellows, Table 6.2, line 1. This means that the iron mill gave a significantly better yield in iron than the contemporary furnaces with hand-operated bellows. It also means that the resulting wrought iron was slightly richer in carbon, 0.1-0.2%, than the iron from the hand-operated furnaces with only 0.05% C.

Thirdly, when purifying the primary blooms, Step 3 in Table 4.4, the resulting planoconvex slags became somewhat depleted of MnO and P_2O_5, compare Table 6.2, line 3 with lines 1-2. It is perhaps not so convincing here where the general manganese and phosphorus levels for the bog ore were low, but we shall see better examples below.

Fourthly, still applying Al_2O_3 as an internal standard, we see that the Tvååker site may be characterized – besides by its relatively low MnO and P_2O_5-levels – by SiO_2/Al_2O_3-values, hereafter called the F-ratio, between 3.1 and 4.5. The F-value is lowest for the production slag, and somewhat higher for slag inclusions in manufactured objects, probably because sand (SiO_2) was added during manufacturing, while Al_2O_3 was not.

The enterprise at Ugglehult, Tvååker, had its maximum activity about 1200 A.D. after which time it rather rapidly disappeared. The much debated latin sentence in Absalon's letter of donation, 1197 A.D., "de molendino ubi fabricatur ferrum" must be translated "from the water mill where iron is produced" (from bog iron ore). Although some authors (e.g.Lindroth 1955, Vol.II:81) have suggested that it was an advanced mill, where iron was forged by water-powered hammers, the excavations 1993-1995 have been unable to support this farfetched and anacronistic idea. No foundation for a hammer, no hammer scale and no hammer slags were found. The enterprise was similar to other contemporary or slightly later iron-producing bloomeries at water mills in Halland and Scania, such as Hörby, Stenså and Bölinge (Buchwald 2004 b).

2. In the southern part of Halland there was an intensive iron-smelting activity up to about 1600 A.D.,

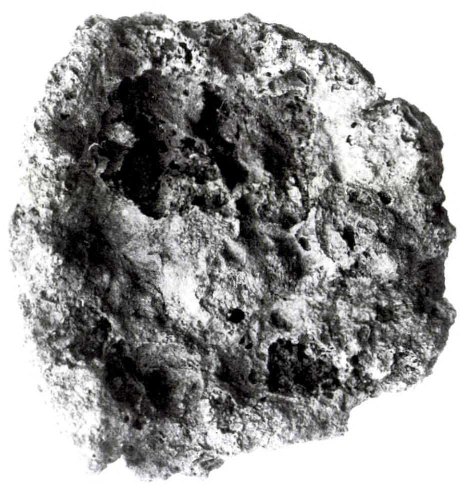


Fig. 141. Purification slag of the kalot-type, seen from above. No. 2 of 535 g, approximately 10x10x4 cm. Ugglehult, Tvååker.

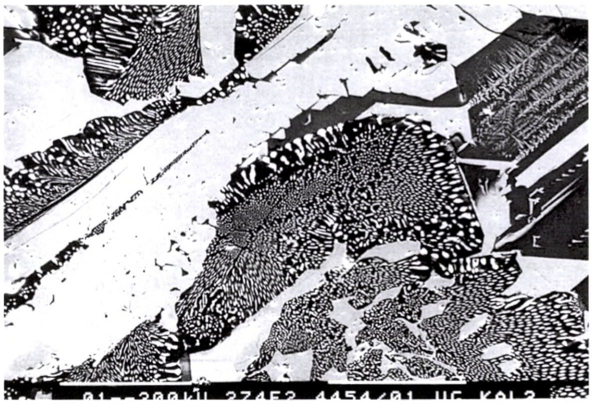


Fig. 142. The interior structure of the kalot slag Fig. 141. Prominent fayalite laths in a matrix of leucite (black) and fine grained wüstite. PS. SEM. Scale bar 0.1 mm.

and many furnaces were, like Ugglehult, placed at a small rivulet, such as Stensån, with dam and wheel-powered bellows. From this province (Danish until 1645A.D.), we will examine production slags, purification slags and nails which in all probability belong to the same production chain. In Table 6.2, line 6, is shown the average composition of two production slags from Hishult, about 1400 A.D. The slag is significantly richer in phosphorus than those from the Tvååker sites. Unfortunately the corresponding bog iron ores have as yet not been identified and analysed.

The four-fingered blooms, the so-called kloder, Table 4.6, were from the production sites transported to the smithies in the various settlements and towns, where they were purified and gave rise to planoconvex purification slags. These have been found in the hundreds in particular in the coastal towns of Halmstad, Laholm and Helsingborg. In Table 6.2, line 7, analyses of medieaval purification slags are presented, being the average of two kalots from Trulstorp (160 and 525 g) and two from the town of Halmstad (76 and 380 g). In line 8 is entered the average of slag inclusions in four iron objects, which in all probability were manufactured from local blooms. A 5.6 g horseshoe nail (F 210) from Trulstorp, a 12.6 g nail (F 211) also from Trulstorp, a 15 g nail from Halmstad (HM 17416: 105 S) and a 9 g hook from Halmstad (HM 18403: 1521 H).

The iron objects have a heterogeneous structure of ferrite-pearlite, but as indicated by the significant P-content of the slag inclusions, the ferrite is generally rich in phosphorus (0.1-0.4%) and there are etching grooves and local precipitates of phosphide needles. The hardness ranges from 100 to 186 HV, that is, the material is no longer the soft wrought iron we met at Södra Järnvirke from northern Halland.

The sequence production slag → purification slag (lines 6-7) again supports the general observation that MnO and P_2O_5 decrease significantly in the purification step, for the same initial ores. Phosphorus becomes concentrated in the metallic object and in the slag inclusions of the object, the ratio being difficult to quantify because the metal in general is rather heterogeneous. However, with an average of 3.0% P_2O_5 in the slag inclusions, the average phosphorus concentration in the adjacent metal may be estimated at 0.15-0.30%, Fig. 148.

3. The next example is based upon three furnaces with hand-operated bellows in Scania (Danish until 1659). The furnaces are from the 14th century and were charged with lake iron ores. One is the Ubbalt furnace on the shore of Vittsjön, the others are from "Skansen" and "Gustaf Adolf" in Vittsjöborg, one kilometer west of Ubbalt, at the same lake (Ödman 1992). The Ubbalt furnace was small, without slag tapping, the other two were slag tapping furnaces. The average composition of the slags is given in line 9 of Table 6.2. In line 10 is presented the analysis of a purification slag, a 360 g kalot with charcoal inclusions, from Vittsjöborg. In line 11 is given the average of slag inclusions in two metal objects from Vittsjöborg. One is a 17.4 g crossbow bolt (L 632), and the other is a 22 g fragment of a horseshoe (L 637), evidently produced on the location.

The lake ore from Vittsjön is rich in manganese and phosphorus (compare Table 6.2, line 9 to lines 1-2 and 6), but as usual, the purification slags have been significantly depleted of these components, line 10. In the production slags some barium was identified together with manganese, but barium is absorbed in the production slags and cannot be detected, except in trivial amounts, in the purification slags or the slag inclusions of the metallic artefacts. The metal is heterogeneous. Almost phosphorus-free ferrite (HV 97-108) grades into P-ghost zones (HV 141-186) and into phosphorus-rich ferrite with up to 0.6% P (HV 200). Ternary Fe-P-C zones also occur (HV 210-220), but pearlite proper is not present.

4. The following examples will serve to show the trend when bog iron ores from the same province, here northern Scania and southern Halland, are used for iron production with new methods, in furnaces operated by water-powered bellows. The analyses are of production slags from Stenså, south Halland, and Brunkelstorp, and Hörja, both northern Scania. All are from the 15[th] century A.D. and located at water mills. It has not been possible to identify purification slags or iron objects that with certainty could be referred to this production line.

In Table 6.2, line 12 is presented the average analysis of five different, kilogram-sized slag fragments from a tapping furnace at a water mill site at Stensåen, Halland (Nihlén 1939: 21f). In line 13 is the average of two slags from the water mill site at Brunkelstorp at Helgeån, 7 km west of Osby. The furnaces have so far not been excavated, but the slag heap is large, comprising some 400 m^3 (Ödman, pers.comm.).

In line 14 there is, finally, the average of three production slags from the water mill site at Hörja. All the furnaces were apparently operated on the basis of the local bog iron ores which here occur in profusion (Nihlén 1939, maps). They must have been quite rich in manganese since they give rise to such MnO-rich production slags. The Brunkelsborg production slag, line 14, contains sufficient phosphorus to have resulted in iron manufacture with heterogeneous ternary Fe-P-C structures, similar to what is present in No. 11 of Table 6.2. The Stenså and Hörja slags, lines 12-13, are apparently slags which will result in ferritic-pearlitic material with little phosphorus. The F-values are, not surprisingly, similar to those of the nearby sites, Nos.6 and 9. The F-values of the slag inclusions in corresponding manufacture may be predicted to be some-

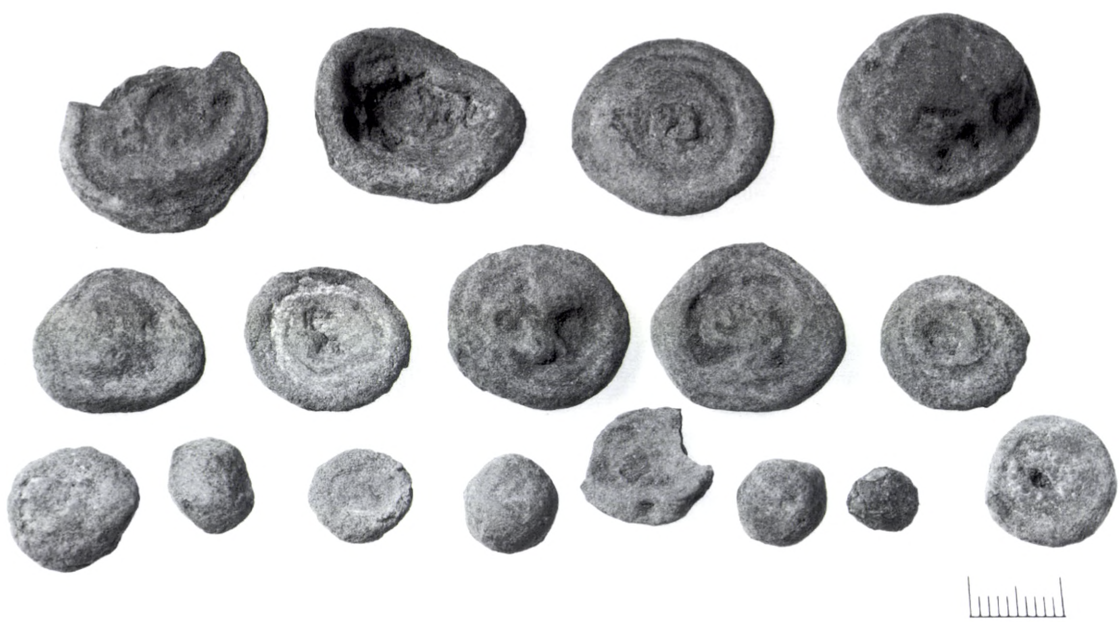


Fig. 143. Lake ore, socalled coin ore (Danish, pengemalm) from Odalen, Storsjöen, Norway. Photo Ole Bang Berthelsen. Scale bar in mm.

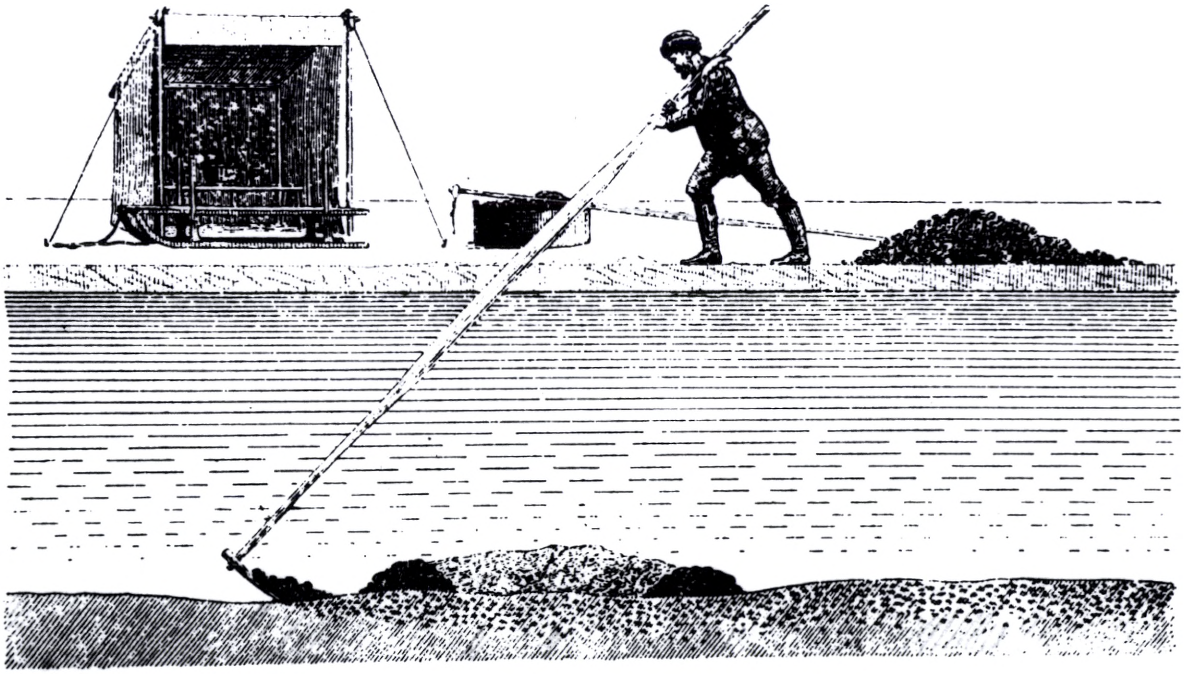
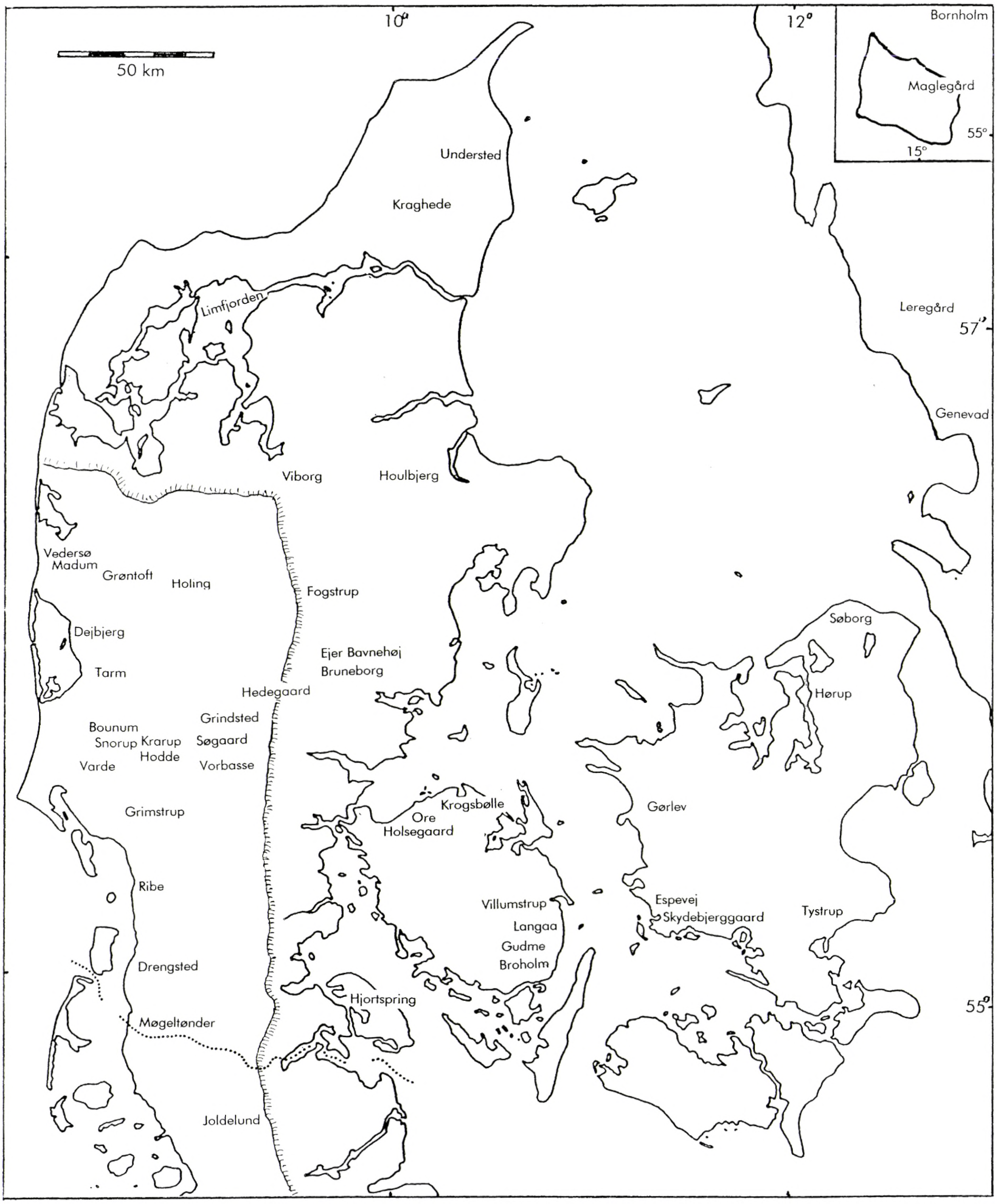


Fig. 144. The recovery of lake ore often took place in winter time through a hole in the ice-covered lake. Wood cut from the 19th century.

what higher (4-4.5). However, such material has so far not been identified.

When comparing production slags from furnaces with hand-operated bellows (Table 6.2, lines 1,6 and 9) with similar production slags from furnaces operated with mechanically, water-powered bellows (lines 2, 12, 13, 14), it becomes evident that the latter have less FeO and thus have yielded more free iron to the resulting bloom. The continuous and stable air flow over hours and days resulted in a higher yield. However, the iron bloom has also become more reduced, i.e. has absorbed more carbon, about 0.1-0.2%, so the bloom was no longer the ultra-soft wrought iron, met with in line 1. From this point of view, there has not been a slow, continuous development in the iron technology, but rather a conspicuous discontinuity when the water mill was introduced. In Scandinavia this happened in the 12th century, documented by, e.g. the famous Latin judicial decision that about 1220 A.D. divided the forests of Tvååker between the farmers and the Cistercian monks (Andersson ed. 2004). The new iron products were a little different, but the yield from the same ore was better. The metal still had the same heterogeneous iron-phosphorus-carbon structure, because the ores were of this nature.

5. To get an idea of the nature of bog and lake iron ore, take a look at Table 6.1. In it are assembled the analyses of two massive bog iron ores (Nos.1-2), one red soil (No. 3), three lake ores from Sweden (Nos.4-6) and one lake ore from Finland (No. 7). The ores are representative of the Scandinavian occurrences, and all were at one time or another used for iron production. None of these were exposed to roasting. The


10°
12°
Bornholm
Maglegård
55°
15°
50 km
Understed
Kraghede
Limfjorden
Leregård
57°
Genevad
Viborg
Houlbjerg
Vedersø
Madum
Grøntoft
Holing
Fogstrup
Dejbjerg
Søborg
Ejer Bavnehøj
Bruneborg
Tarm
Hedegaard
Hørup
Bounum
Grindsted
Snorup
Krarup
Søgaard
Hodde
Varde
Vorbasse
Krogsbølle
Gørlev
Ore
Holsegaard
Grimstrup
Ribe
Espevej
Villumstrup
Skydebjerggaard
Tystrup
Langaa
Gudme
Broholm
Drengsted
Hjortspring
55°
Møgeltønder
Joldelund

analyses were taken with the Scanning electron microscope on massive, impregnated sections, and care was taken to analyse the matrix only, evading any large or small particles of quartz, feldspar, ilmenite, zircon etc. (Buchwald 1998).

The analysed ores were dried at 20°C, but they did contain chemically bound water. This will disappear at ignition at 1000°C, and constitutes on the average 18-20% by weight. Therefore the iron values of Tables 6.1 and 6.3 have to be corrected by a factor of about 0.8. The content of iron can thus be calculated as 0.8 x 2 Fe/Fe_2O_3 = 0.8 x 112/160 = 0.56, a factor to multiply with to obtain the true iron content of the ore. For example for line 1, 82.0% Fe_2O_3 corresponds to 82.0 x 0.56 = 45.9% Fe in the ore. To qualify for an ore in ancient Scandinavia, it would have required 45-50% iron, and certainly more than 35% iron.

The ore analysed this way, omitting the foreign particles, appears rich, but of course in real life, the ore was always polluted by sand, feldspar and other minerals of weathering. And in the charcoal production process, if one was careless, additional contamination might occur from mixing in of "soil" and the other material which was used to cover the charcoal pit.

It is remarkable that bog and lake iron ore contains so much SiO_2, MnO, Al_2O_3, and P_2O_5, see the Tables 6.1 and 6.3. These components are not present as definite mineral particles, but appear in colloid form in the amorphous FeOOH-gel. The ore can thus not be mechanically purified to a better FeO-level than shown in the tables. In the production process in the furnace, the intimate mix of these Fe-Si-Mn-Al-P-oxyhydroxides was exposed simultaneously to the reducing CO-gas. Some decomposition may already have occurred in the roasting step. The elements became finally separated from each other when solid metallic iron with phosphorus in solid solution sintered together, while liquid slag was formed from FeO, SiO_2, Al_2O_3 and MnO from the ore, and CaO, K_2O and MgO from the charcoal ashes.

Fig. 145. Map of Denmark with iron handling locations and important finds from the early Iron Age. The line through Jutland marks the end moraines of the last Ice Age. West of the line the soils are depleted of, especially, calcium.

It appears that lake ores are slightly enriched in manganese and phosphorus, relative to the bog iron ores, but it is not always the case and can only with caution be taken as a guide line.

In passing, it should be mentioned that lake ores were dredged and used for several blast furnaces as late as in the 20th century (Grabe 1920; Ranløv & Henriksen 1941, Vol.2: 131). Åminne Bruk in Småland used lake ore from the lakes Vidöstern and Bolmen (Berlin 1997), and Huseby Bruk, also in Småland used lake ores from the lakes Salen and Åsnen until 1930 (Larsson 1993). The Tohmajärvi lake ores were utilized by the electric blast furnaces in Värtsilä, Carelia, up to the Second World War.

There exist late historical descriptions from Sweden and Norway of the ironmaster's search for good bog ores. Linné (1734) in his diary for the 3rd of August, on a visit to Lima and Transtrand, Dalarna, observed how

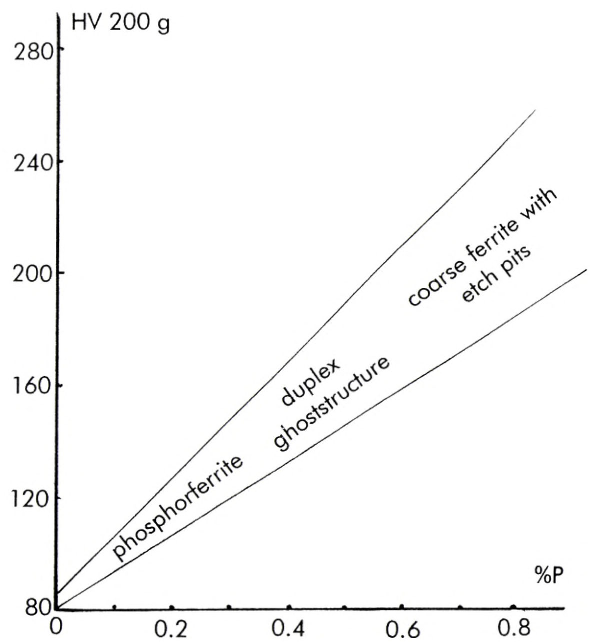


Fig. 146. The natural Vickers hardness (200 g load) of ancient iron-phosphorus alloys, without carbon, silicon and manganese. Typical structures are indicated.

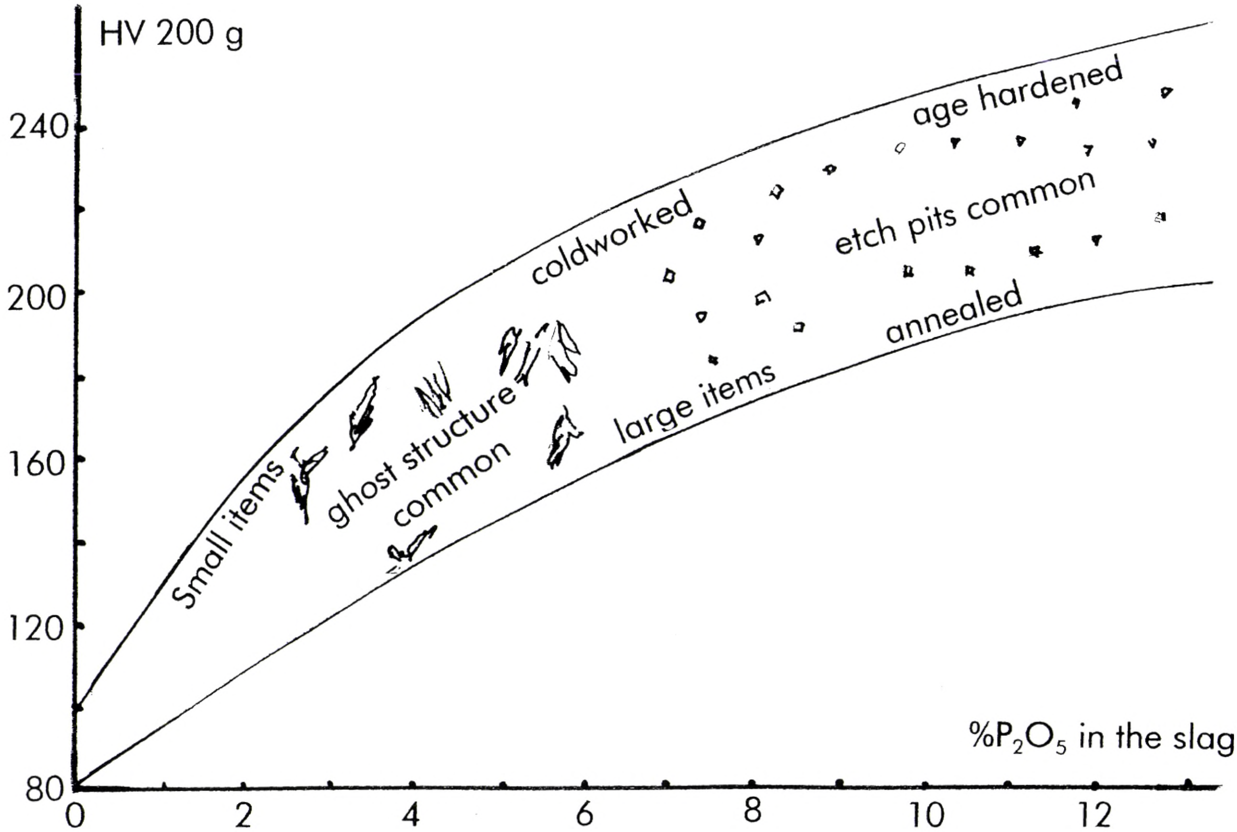


Fig. 147. The natural Vickers hardness (200 g load) of the metal around slag inclusions with various phosphorus contents.Coldworked material, above, will be harder than massive, annealed objects for the same slag composition.

the ironmaster proceeded. The bog was examined systematically with a twisted iron rod, which was pressed into the soil. When withdrawn, the adhering soil was tasted, and a good iron ore would be recognized from its iron-like taste with an astringent character. When identified, the ore was shuffled up in the dry summer period and put to drying. The bog ore is, according to Linné, reformed within 100 to 200 years. He continues with a thorough description of the Dalarna bloomeries, as they probably had been operated since about 1400 A.D.

Similar "organoleptic" analyses were also known in Norway, where Evenstad (1782) in somewhat more detail described the field work. With the iron rod the bog was searched, and the ore was put into the mouth and chewed." When sweet and adhering to the teeth it is of the best quality, it is iron-rich and dry. If tasteless, it may be used, but it is not rich. But if it tastes of Spanish Green, salt or vitriol, it is of no use".

6. In Denmark there are no lake ores or ores of the Swedish-Norwegian types, but massive bog iron ores are locally abundant. They were in particular demand in the Roman and Germanic Iron Age, and again in the 14-16th centuries. The interest was revived in the mid-20th century, when Denmark exported about 50,000 tons of bog iron ore annually to Belgium, Holland, England and Germany (Buchwald 1998). The ores were much in demand as a cheap absorbent for the poisonous sulphureous gases that developed when burning pit coal in gas works.

Table 6.3. SEM-EDAX analyses of a dozen Danish and two foreign bog iron ores.

	SiO_2	Fe_2O_3	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum
1	5.9	88.3	0.6	2.3	0.3	2.0	0.3	0.2	<0.1	-	100
2	4.4	92.0	0.7	1.4	0.4	0.6	0.2	0.2	0.1	-	100
3	8.5	76.0	2.1	9.0	1.3	1.6	0.1	0.4	-	1.0	100
4	6.7	83.3	2.7	4.5	0.6	1.0	0.1	0.7	0.1	0.3	100
5	6.3	83.5	0.9	5.5	0.8	2.3	<0.1	0.3	-	0.3	100
6	6.9	82.3	2.3	5.9	0.5	1.4	0.1	0.4	-	0.2	100
7	11.5	82.4	0.3	2.5	1.3	1.2	0.4	0.3	0.1	-	100
8	2.7	83.4	1.5	9.1	1.8	0.6	<0.1	0.4	0.1	0.3	100
9	11.2	81.6	0.4	3.4	1.4	1.2	0.1	0.6	0.1	-	100
10	6.6	82.8	0.5	6.4	1.7	0.7	<0.1	0.9	-	0.3	100
11	8.8	73.6	3.6	8.6	2.8	1.2	<0.1	0.9	-	0.4	100
12	10.3	74.3	2.4	7.2	3.4	1.3	0.2	0.3	0.2	0.4	100
13	8.2	81.9	6.4	1.6	0.3	0.9	0.1	0.4	-	0.2	100
14	9.6	84.6	0.5	0.2	-	1.1	-	-	-	-	96

1. Snorup, Varde, Jutland. Roasted ore isolated from the bottom pit of Iron Age furnace No. 4075
2. Ibid. Roasted ore, isolated from the bottom pit of Iron Age furnace No. 4081.
3. Bounum, Varde, Jutland. Unroasted, massive ore, analysis 3.
4. Holing, Herning, Jutland. Unroasted, crumbling ore, from ancient production site.
5. Madum, Ulfborg, Jutland. Unroasted, massive ore.
6. Vedersø, Ulfborg, Jutland. Unroasted, globular ore. Black parts with up to 30% MnO and 5% BaO!
7. Hjorthede, Kvorning, Jutland. Unroasted, massive ore. Locally aluminium-rich (3-4% Al_2O_3).
8. Bruneborg, Østbirk, Jutland. Unroasted, massive ore WU, from an ancient production site.
9. ibid. Unroasted, massive ore. KF.
10. Søborg, North Sealand. Unroasted,brown, massive ore. 9-63 B.
11. ibid. Unroasted, black, massive ore. 9-63 S. Also 0.3% BaO.
12. Pederstrup, Ballerup, west of Copenhagen. Unroasted, massive ore.
13. Joldelund, Niebøl, Nordfriesland. Unroasted, massive ore, from Iron Age production site.
14. Elverum, Østerdalen, Norway. Roasted granular ore. Espelund 1993.

In Table 6.3 are presented analyses of twelve typical Danish bog iron ores, to which is added an ore from Joldelund, an Iron Age production site in Slesvig, and a red soil from Østerdalen, Norway, where there was some activity in mediaeval times.

Comparing the Danish ores of Table 6.3 with the foreign ores (Table 6.1 and the two last lines of Table 6.3), it is seen that the Danish ores are unusually rich in phosphorus, on the average perhaps ten times richer than the bog ores and lake ores of Sweden, Finland and Norway. It is therefore not surprising when we discover that Danish slags and iron objects are also unusually rich in phosphorus.

It is not obvious why the Danish environment is so enriched in phosphorus. Perhaps it is due to glauconite particles and the slightly phosphorus-enriched caenozoic deposits, specific to Denmark. By weathering and reorganization during the Ice Ages, phosphorus may

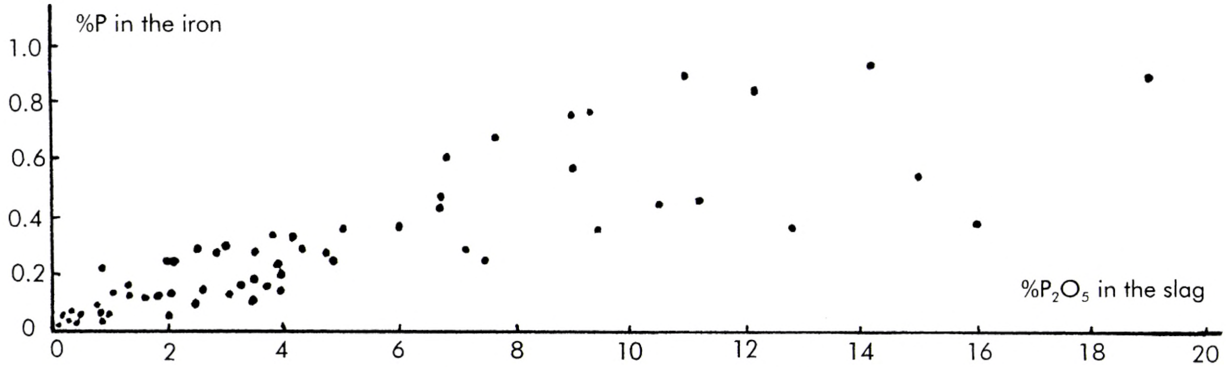


Fig. 148. The amount of phosphorus in solid solution in the iron is weakly correlated with the P_2O_5-content of the slag. Carbon, silicon and manganese are absent in the metal phase.

have been introduced into the topsoil, from where it again became mobilized, and later precipitated together with iron to form bog iron ore.

The ancient ironmaster was, no doubt, able to distinguish and sort the various bog iron ores. The common ore was reddish-brown, while the phosphorus-enriched variety was greenish-yellow or had yellowish streaks. According to Ussing (1913: 302), vivianite, $Fe_3(PO_4)_2$, 8 H_2O, may be found in the massive Danish ore. The mineral is located in voids which, when fresh, appears as a whitish powder, but in open air changes and displays a characteristic, beautiful, blue colour.

Manganese is almost always present, but in quite variable amounts. In Denmark, manganese-enriched ores occur along the N-S running demarcation line (the Weichsel line) that separates West Jutland's eroded and washed-out moraines of earlier Ice Ages from the hilly moraines of East Jutland's last Ice Age deposits, Fig. 145. Along this zone, e.g. at Bolderslev near Åbenrå, there are ores with more than 10% MnO. Some ores even have more MnO than Fe_2O_3. These deposits were excavated to serve for electric battery production during the 2nd World War, when Denmark was cut off from the regular supply of manganese salts.

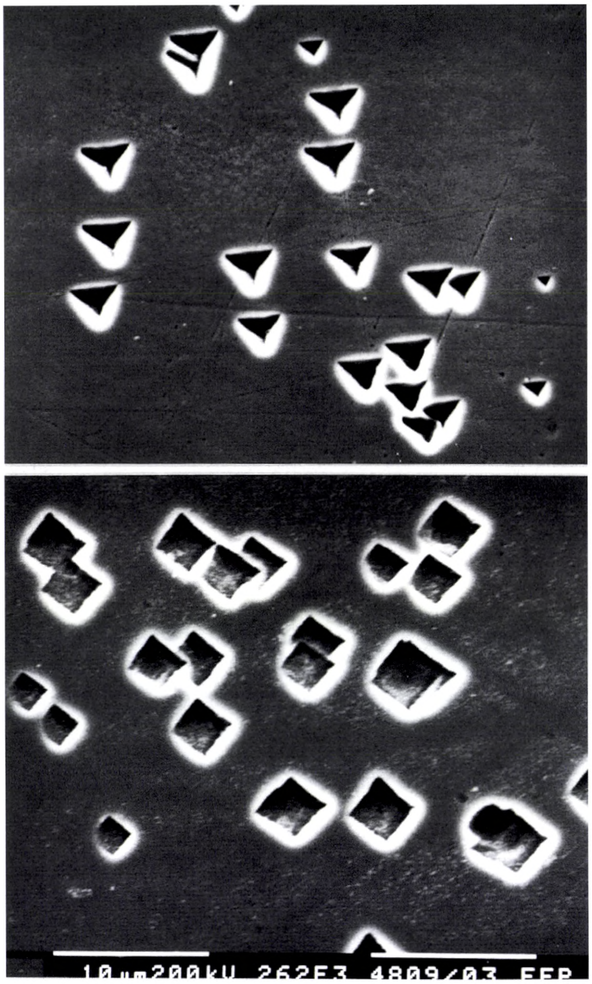


Fig. 149. Etch pits in phosphorferrite with about 0.8% P in solid solution. The etch pits are oriented after the ferrite-crystallography. Here two photographs of adjacent grains. PES. SEM. Scale bar 0.01 mm.

One and the same ore locality may exhibit wide variations in the manganese content, in vertical as well as in horizontal directions. It is not uncommon that the top layer of a 30-50 cm thick bog ore deposit contains 15-20% MnO, while the lower part only contains 2-3%. The two analyses from Søborg, Table 6.3, lines 10-11, were taken less than a meter from each other, but their manganese content varies by a factor of seven. This would have been obvious to the ironmaster, because the fracture surface of the manganese-rich ore is black, while the other is yellowish -brown. He would be able to select and sort according to his purpose. The black appearance is probably due to poorly defined black manganese oxides like psilomelane and wad, MnO_2 (Ramdohr & Strunz 1967). Barium and manganese are correlated in bog and lake ores, barium occurring at a level of 5-10% of manganese. With the scanning electron microscope with energy dispersive equipment (EDAX), generally applied in this work, there is a risk that barium may escape detection, partly because it occurs on a low level, and partly because the Ba L_α line almost coincides with the Ti K_α line.

Comparing Tables 6.1 and 6.3 reveals a number of regional analytical differences. Phosphorus was discussed above, but also aluminium is important, since on the average, in Swedish ores, it is enhanced 2-3 times to that normally found in Danish ores. Calcium, on the other hand, occurs on a significantly higher level in Danish than in Swedish ores. It is particularly clear for the ores from east of the demarcation line in Jutland, lines 8-9, and from Sealand, lines 10-12, while the ores from west of the line, lines 1-6 of Table 6.3, display somewhat less CaO, because calcium has been washed out from the surface deposits. The relatively calcium-rich ores of Denmark must be due to the omnipresence of cretaceous chalk and tertiary limestone deposits, which during the Ice Ages were eroded and incorporated into the Danish moraine.

Another regional trend is the occurrence of vanadium in Swedish ores. It is, however, at a low level which is difficult to detect with the SEM-EDAX equipment.

Sulphur is almost omnipresent, perhaps occurring on a slightly higher level in the Swedish ores. This is, however, of little significance, since most of the sulphur would have been removed as SO_2 in the roasting process.

Trace elements have been examined in some ores (Arrhenius 1967; Alfsen & Christie 1972; Martens & Rosenqvist 1988). It appears that nickel, cobalt, zinc, chromium, and vanadium are not uncommon in Norwegian and Swedish material, but the elements occur, in general, at a level below 0.05%, and easily escape detection with the instrumentation applied in the present work.

The specific gravity of massive bog iron ore has been reported from 2.52 to 3.12 g/cm^3 (Nielsen 1924). These values are slightly lower than those found in the present study, 2.7-3.4 g/cm^3, on material from west Jutland, dried at 20°C.

In the literature many names for bog iron ore have occurred, limonite, brown hematite (Percy 1864: 200), Brauneisenerz, Raseneisenerz, Ocker (Ramdohr & Strunz 1967), brunjernsten (Noe Nygaard 1962), Örke (Swedenborg 1734: 131; Rinman 1782:384) and Jernahl (Pontoppidan Danske Atlas 1769, Vol. 5: 658,663). In modern Scandinavian literature there is a certain prevalence for limonite (e.g.Magnusson 1953; Noe Nygaard 1962). The terms cover ironoxide-hydroxide-rich sediments that originally were deposited as amor-

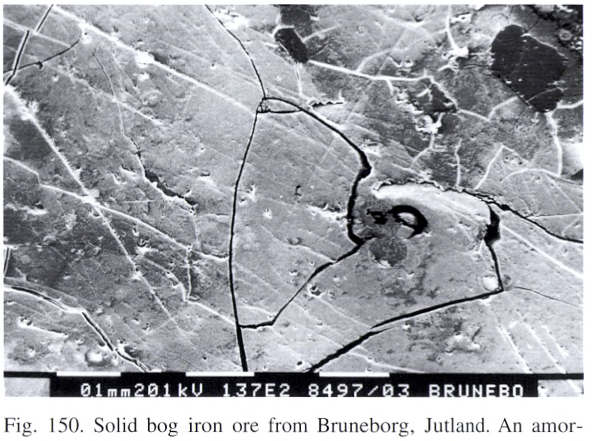


Fig. 150. Solid bog iron ore from Bruneborg, Jutland. An amorphous gel of oxides and hydroxides of iron, phosphorus, silicon, calcium, aluminium, and manganese.In the upper right corner a quartz grain (black). PS. SEM. Scale bar 0.1 mm.

Fig. 151. Bog iron ore used as decorative elements in a 13th century church portal. Ashlars of reddish brown bog ore alternate with ashlars of light granite. Vejerslev Church, 25 km SE of Viborg. Buchwald 1998: 21.

phous gels with varying contents of water and impurities of SiO_2, MnO, CaO, P_2O_5, and Al_2O_3. The iron precipitated as the trivalent ferric ion. In time the limonite lost water and ripened, and achieved a certain crystalline structure. X-ray examinations have shown that the bulk is still amorphous, and the crystalline component of limonite is goethite, α-FeOOH.

Limonite occurs in many variations, e.g. Nadeleisenerz, Brauner Glaskopf and Samtblende. Oolitic limonite is a main component of the valuable Minette ores in Alsace-Lorraine. Bog iron ore and lake ore are other variations.

From the massive Danish bog ore and from lake ore it is not too difficult to prepare polished sections. These reveal a porous texture where massive limonite alternates with cracked and open parts. The limonite is opaque and of brownish to blue-grey colours in reflected light. Scattered in the limonitic matrix are distinct quartz grains, 0.01-1 mm in size, often in profusion. Locally may be identified grains of feldspar, ilmenite, $FeTiO_3$, zircon, $ZrSiO_4$, and chalcopyrite, $CuFeS_2$. Often there are growth rings and voids which suggest an oolithic growth mode.

The lake ores display concentric limonitic zones, in which are embedded quartz, and, rarely, other mineral grains. Individual ore beans or pearls may be nucleat-

Fig. 152. Ashlars of brown bog ore in the apsis of the 13th century St. Jacoby Church in Varde, Jutland. Some weathered ashlars have recently been exchanged with new ones. Buchwald 1998: 16.

Fig. 153. As late as in the 19th century ashlars of bog ore were used as building stones in certain parts of Jutland where the moraine deposits were poor in large stones. Farm houses in Vester Tulstrup, north of Ikast. Buchwald 1998: 8.

ed upon mineral grains or on organic material that later has disappeared (Naumann 1922). The zones may be homogeneous with respect to the content of iron, manganese and phosphorus, or they may display systematic (climatically conditioned?) variations as exemplified in the following analyses of a 5 mm bean of lake ore from Huseby Bruk, Småland:

Exterior zone: 71.8% Fe_2O_3 – 15.7% MnO – 1.4% BaO – 0.3% P_2O_5

Central zone: 85.0% Fe_2O_3 – 2.2% MnO – trace BaO – 0.7% P_2O_5.

These variations within the individual lake ore particles or beans make a separation before smelting impossible.

X-ray examination of Danish bog iron ore powders, dried at 20°C, revealed the presence of only one crystalline phase, goethite. The diffraction peaks were, however, small and softly rounded, suggesting small grain sizes or poor crystallinity. Espelund (1991) has examined Norwegian bog ores and has also found goethite as the only crystalline component. There is apparently no correlation between crystallinity and chemical composition.

7. In the roasting process, step 1, Table 4.4, the bog iron ore was heated in the open air. On heating, the water evaporated and the limonitic matrix decomposed. Humus and organic remains burned away and sulphur became oxidized and disappeared as SO_2. Sulphur has always been feared in iron manufacturing, because low-melting ironsulphides may penetrate the austenite grain boundaries and ruin any forging operation. The risk of this so called hot-shortness (rødskørhed) could be reduced significantly by roasting

At temperatures between 350 and 675°C chemically bound water was removed from the ore and metastable, magnetic maghemite, γ-Fe_2O_3, was formed. Also stable hematite, α-Fe_2O_3, was formed, in particular at the higher temperatures.These new anhydrous iron oxides had a large interior surface that was easily accessible to the reducing gases in the production furnace.

In practice the temperature distribution in the roasting process was uneven, and chemical equilibrium was not achieved. The roasted ore had perhaps lost 15-20% by weight and was composed of indeterminate mixtures of maghemite and hematite. The mixture had a characteristic raspberry-red colour due to the hematite component, and was attracted to a pocket magnet, which a fresh bog iron ore never was. It was easily crushed to smaller pieces or even to a powder. 24 l of the Elverum roasted ore (Table 6.3, line 14) only weighed 18 kg (Espelund 1993). After roasting, the ore was best used immediately, or else stored indoors. A roasting place on an ancient iron production site may be recognized by the presence of reddish, magnetic iron oxides.

8. From the Swedish-Danish differences in ore composition we might expect that also the slag compositions and the iron objects were different. We will examine a Danish Iron Age production site at Snorup, 12 km north of Varde, Jutland. Systematic, annual excavations have revealed more than 5,000 furnaces in the small county (Voss 1962; 1993; Smekalova & Voss 2003). The production unit was a shaft furnace with underlying pit in which the bulk slag was collected. The large slag blocks weigh between 50 and 200 kg, even up to 500 kg, and have often been compared to the shape of an elephant's foot. Each slag block represents a furnace run of several days. When a pit was filled a new pit was dug and – perhaps – if possible the clay shaft was moved and reused over a new pit. The entire situation is rather similar to the operations at Biskupice and in the Holy Cross Mountains (Bielenin & Woyda 1978).

Table 6.4. SEM-EDAX analyses of slags, and slag inclusions in iron and steel

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	22.3	70.6	0.8	tr.	2.2	0.8	2.4	0.4	0.2	0.1	0.2	100	9.29
2	23.1	69.9	0.2	-	1.1	1.3	2.8	1.1	0.2	0.1	0.2	100	8.25
3	24.2	61.5	1.6	-	7.7	2.2	1.3	0.5	0.2	0.2	0.6	100	18.6
4	12.7	65.9	0.8	-	17.9	0.5	1.2	0.3	(0.5)	0.1	0.1	100	10.6
5	22.6	54.2	7.2	0.7	6.6	3.5	2.4	1.6	0.6	0.2	0.4	100	9.42
6	26.6	63.1	0.8	-	0.9	3.2	3.1	1.6	0.4	0.1	0.2	100	8.58
7	22.8	56.1	5.1	0.3	6.3	4.4	2.4	1.6	0.8	0.2	0.3	100	9.50
8	22.4	51.5	9.0	0.7	7.7	3.7	2.2	1.7	0.9	0.1	0.8	100	10.18
9	30.3	50.3	4.9	0.3	0.2	2.1	8.8	1.8	0.4	0.6	0.3	100	3.44
10	27.7	48.4	7.5	0.9	0.3	2.8	9.2	1.5	1.0	0.5	0.2	100	3.01
11	47.6	19.1	6.9	0.1	0.1	6.4	13.2	3.2	2.5	0.7	0.2	100	3.61
12	47.3	19.3	7.0	0.5	0.2	8.0	11.9	2.7	1.9	1.0	0.2	100	3.97

1. Snorup, Varde, Jutland. Iron Age. Production slag. Average of ten samples.
2. ibid. Purification slag. Average of three kalot slags of 1120, 752 and 500 g.
3. ibid. Average of slag inclusions in three blooms and fragments of blooms.
4. ibid. Slag inclusions in a lancehead from an Iron Age grave.
5. Central Jutland. Middle Ages. Production slag. Average of six slags from Rønbjerg etc, see text.
6. ibid. Purification slag. Average of twelve slags from Damsø etc. See text.
7. ibid. Slag inclusions in blooms. Average of six from Hinge etc. See Ttext.
8. ibid Slag inclusions in manufacture. Average of twelve objects from Horsens etc. See text.
9. Dokkfløyvann, Oppland, Norway. Production slag. Average of six slags from Iron Age etc. See text.
10. Beitostølen, Oppland, Norway. Production slag. Average of five Iron Age slags. See text.
11. Valdres steel bars. Average of five bars of 16-235 g. See text.
12. Valdres steel bars, excavated at Snorup. Average of three bars, each of about 125 g. See text.

Many production slags from Snorup have been analysed. The average composition of ten different slags, dated 300-500A.D., is entered in line 1 of Table 6.4. The samples come from blocks of 90, 145 and 193 kg, from a bottomslag of 10 kg, and from minor fragments. Many of the large blocks are not coherent and may disintegrate when excavated. Common to these bulky slags is a very coarse crystallization due to slow cooling in the pit. Fayalite forms mm-sized crystals, locally constituting a coherent matrix in which are found palmette-like precipitates of fine wüstite or, sometimes, well-developed normal wüstite dendrites. Intercalated are graftonite-like iron phosphate pockets, $Fe_3(PO_4)_2$, leucite, $KAlSi_2O_6$, and some hercynite, $FeAl_2O_4$.

In line 2, Table 6.4, is presented the average of three purification slags. They are of the planoconvex type and weigh respectively 1120, 752, and 500 g. They are heterogeneous, more fine-grained than the production slags and contain scattered irregular iron grains, 3-15 µm in size. Locally there are small amounts of leucite together with wüstite particles. The top side of No. 800, from excavation field 800, of 752 g, is glazed with a wavy surface due to the heavy wind from the bellows. Here are also magnetic particles in an otherwise unmagnetic slag, due to local surface oxidation to magnetite. The underside of the slag has a keel 4 x 1.5 x 1 cm, apparently an imprint of the small bottom of the purification hearth.

In line 3, Table 6.4, is entered the average of slag inclusions in a rectangular bar (MB 300 B; 1240 g), measuring 125 x 45 x 27 mm, and two unfinished blooms/bars. The slag inclusions are glassy due to the high phosphorus content that impedes wüstite precipitation, and the metallic part is ferritic to phosphorferritic with up to 0.8% P in solid solution and hardnesses of 200-220 HV (Høst-Madsen & Buchwald 1999). This bar composition is entirely different from the bars of both the Mediterranean region and of Sweden/Norway.

In line 4 is entered the composition of slag inclusions of a lancehead. The weapon was found in an Iron Age grave within the Snorup production site and has in all probability been forged from Snorup bar iron.

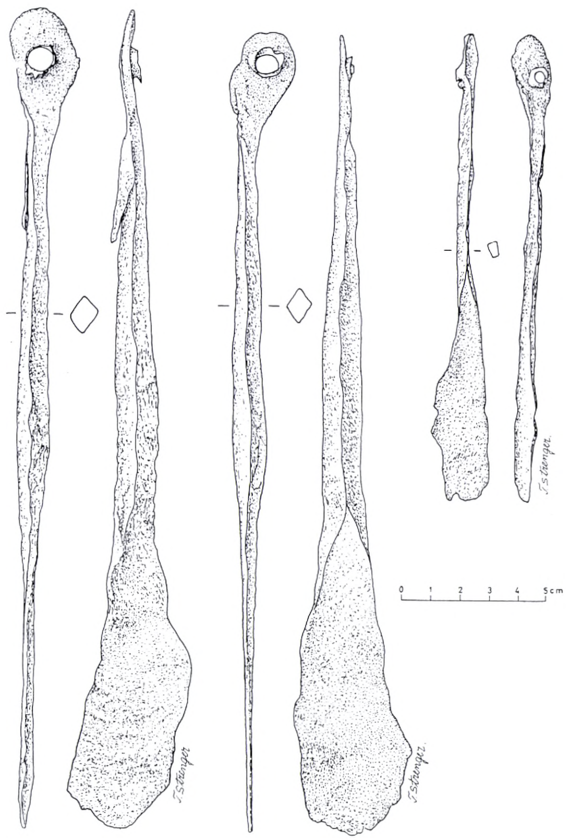


Fig. 154. Three spoon-shaped steel bars from Oppland, Norway. Two large of 160 g each (Trodalen C 23 191) and a smaller of 15 g (Prestgården, Gran, C 3549). Drawing by T. Strenger. Courtesy Hege Svane.

The iron is coarse-grained ferrite. In the ferrite there are many etch grooves, and the ferrite is very rich in phosphorus, 0.37-0.79%. The hardness is high, 200-220 HV, due to phosphorus in solid solution. There are no signs of coldwork which was so common to the Celtic weapons.

Comparing the sequence bog iron ore-production slag-purification slag-bloom-bar-manufactured object, several important observations may be made. The phosphorus-rich ore, Table 6.3, lines 1-2, results in phosphorus-rich slags, but particularly in phosphorus-rich manufacture, wherein phosphorus in the metallic material is above 0.4% and in many cases reaches 1%. Carbon is not present in the material.

CaO and K_2O are low in the ore, but become introduced through the charcoal ashes, so the production slags display 0.8% CaO and 0.4% K_2O. During the following purification step, an operation that requires much charcoal, the slag absorbs still more ashes and reaches 1.3% CaO and 1.1% K_2O (Table 6.4, line 2). A similar development may be observed, if we go back and examine Table 6.2, lines 1-3, 6-7 and 9-10.

Another compositional fact that distinguishes the purification slags from production slags is the significant decrease in manganese and phosphorus, Table 6.4, lines 1-2, Table 6.2, lines 1-3, 6-7 and 9-10. Unfortunately, these regular and logical developments may be difficult to discern if only one or a few analyses are available, while they become convincingly clear when a handful of analyses or more are performed.

The last compositional fact that can be derived from these analyses is the behaviour of F = SiO_2/Al_2O_3. In the Swedish material F moves around 2-5, but in the Danish material it has increased to values above 8. In the examples in this work we shall see that this is a general trend, which is due to the significant geological differences between Denmark and the other Scandinavian countries.

9. It was briefly mentioned above that a manganese-rich belt extended north-south through central Jutland. In the following example we will examine slags and manufacture from this region, and conclude that there are some regional differences in ore and slags, as well as in the slag inclusions in finished iron objects.

In Table 6.4, line 5 is shown the average composition of six production slags from mediaeval furnaces (1400-1500 A.D.) in central Jutland. One is from Rønbjerg (Mortensen 1939: 154), two from Tvilum monastery and three from Øm monastery, and all are from furnaces with hand-operated bellows. The slags are rich in phosphorus and manganese, and barium occurs on a 10% level of that of manganese. Calcium, potassium and magnesium occur on a higher level than in the Snorup production slags, because the central Jutland moraine deposits have not been washed and drained for so long a period as have the western Jutland deposits.

The twelve slags in line 6 are typical planoconvex, or kalot slags, found around purification hearths in cities, monasteries and at water mills, and all are dated to 1350-1500 A.D. The following places are represented. Horsens (317, 820, and 940 g), Grenå (500 g), Viborg (278 and 475 g), Aarhus Søndervold (250 g), Selkær near Grenå (491 g), Over Hornbæk near Randers (240 g), Als near Mariager (1309 g), Øm monastery (2250 g) and Damsø water mill near Skjern (499 g). The average analysis demonstrates how manganese, phosphorus and barium are dramatically reduced in the purification slags, while Ca, Al, K, and Mg are largely unaffected.

In line 7 is presented the average of six blooms or bloom fragments from Karup (8.3 and 2 kg, Buchwald 1991), Skjern (4.8 kg), Hjorthede (4.9 kg) and Hinge (0.1 and 0.2 kg). The smaller of the two Hinge fragments was highly carburized and resembled ledeburitic, white cast iron with phosphorus-rich parts. It is probably scrap from an unsuccessful furnace run Figs. 99-101. The other displayed coarse-grained, ferritic metal with much phosphorus (0.4-1.3%) in solid solution and a few eutectic pockets, corresponding to the phosphorus-rich slag parts of the bloom.

In line 8, finally, is entered the average of slag inclusions in bloomery iron objects from the 14-16th centuries. They were found at or near the sites listed above, and the probability is high that they were also produced there. The objects are mainly nails of 7-15 g, horseshoe nails of 3 g, and a single horseshoe fragment of 105 g. The locations are Tvilum monastery (5 nails), Horsens (3 nails), Sjørring Volde (2 horseshoe nails and a horseshoe) and Aarhus Søndervold (1 nail). Manganese and phosphorus are high, or very high, in the slag inclusions. There is no carbon or manganese (<0.05%) in the metallic iron, but phosphorus occurs on a medium to high level (0.3-0.9%). The metal is, as usual, very heterogeneous, even in the small nails. This fact is certainly not due to piling, but only due to the natural heterogeneity of the bloomery process. The hardness ranges from 101 in ferritic iron to 226 in places of phosphorus-rich ferrite.

As far as we know, the two regions of Jutland produced iron at widely different times. In west Jutland the activity was from about 200 B.C. to about 700 A.D. with maximum production between 300 and 500 A.D. (Voss 1993). In central Jutland iron production apparently took place from about 1300 (1350) to 1550 (1600) A.D., but little is known, since the medieaval slag deposits and furnace remains so far have attracted little interest. Furnaces and slag heaps from between 700 and 1300 A.D. are almost unknown in Denmark (Buchwald & Voss 1992). In that period we received the iron and steel from elsewhere, mainly from Norway, Halland and Scania.

10. So let us in the last part of this chapter turn our attention to Norway and Småland in order to examine two steel-producing regions. First Norway.

In southern Norway there are numerous hoards of so-called iron bars, "vævjern", which were noted already in the 19th century, and since then have been discussed at many occasions (Petersen 1918,1923; Hauge 1946; Martens 1981; Resi 1995; Buchwald 2002). At more than a hundred locations a total of more than 8,500 bars, totalling about 800 kg, have been found. A very large hoard was found at Kjøstad, in Løiten, Hedmark (Petersen 1918: Fig. 11). It consisted of 573 almost identical, "spoon-shaped" bars with an average weight of 104 g, and lengths between 25 and 30 cm. In 1987 another large hoard of 568 bars was discovered at Nordre Bjerke in Gran, Oppland (Resi 1995, Fig. 1-2). The bars were similar to those at Kjøstad, with an average weight of 136 g, ranging from 109 to 158 g, and lengths of 25-30 cm. See also Fig. 154.

Many other hoards have also been found and also single specimens. Lists with numbers, sizes and locations may, e.g., be found in Hauge (1946) and Resi (1995), see also Chapter 10. It is unusual to find pottery or other datable objects together with the hoards, so their age is generally known only very approximately. Many, e.g. Kjøstad, have been loosely associated with the Viking Age. Most bars were provided with a hole in one end, evidently for bundling and transporting, and some of the newer finds, which have been excavated professionally, show that the buried bars had often been carefully arranged, with the punched holes in the same direction as if a number of bars had been tied together.

Most hoards and single finds of bars have been discovered in the valleys and/or near settlements on trading routes, see Fig. 158. The production furnaces must, however, have been in the remote seters, uphill and generally near the forest line at a level of 800-1000 m. When one is searching for the sources of the bars, the iron-producing areas of Dokkfløyvann and Beitostølen seem to be interesting possibilities.

In Table 6.4, lines 9-11 are presented slag analytical data for production slags and for some steel bars. Line 9 is the average of six production slags from the excavations at Dokkfløyvann (Larsen 1991). They are all very similar, being rich in manganese (2.0-7.3%) and poor in phosphorus (all less than 0.4% P_2O_5). They also contain some barium, positively correlated with the manganese, as noted earlier. Titanium is rather high, which is typical of Norwegian ores and slags, and vanadium is absent, i.e. below 0.05% V_2O_5. The six slags come from furnaces of different ages, 400-1400 A.D.

Table 6.4, line 10 presents the average of five production slags from Beitostølen in Valdres, about 50 km west of Dokkfløyvann. The slags have been dated to the Iron Age, and they are rich in manganese (1-16% MnO) and poor in phosphorus (all less than 0.5% P_2O_5).

The slags from Beitostølen and Dokkfløyvann, situated in the ancient district of Valdres, are thus of a rather distinct nature, which we have only met with once before. The Norwegian slags are not much different from those of Noricum, Chapter 5, which were associated with the famous Noric steel.

In Table 6.4, line 11 is presented the average analysis of five steel bars from different Norwegian hoards. They are all rather similar and belong to the smaller weight category, below 250 g. A 16 g bar, C 3454, is from Prestgården, Gran, a 15 g bar, C 3549, is from the same hoard. A 160 g bar, C 23191, is from Trodalen, Øyer. A 235 g bar, C 24705, is from Nørdstevold, Gausdal, and, finally, a 135 g bar, C 39270-94, is from the newly found hoard at Nordre Bjerke. The slag inclusions are closely correlated with the production slags of lines 9-10, and the F-ratios are also similar. Of particular importance is the high manganese and titanium content, and the low phosphorus content. The metal of the bars is pearlitic, or pearlitic-ferritic, rarely with phosphorus, and the hardnesses range from 110 to 270. The bulk of the values is above 190 HV, and all the bars may be characterized as being excellent steel, with more pearlitic parts than ferritic. The metallurgy of the bars and the chemical composition of their slag inclusions correlate so well with the rather unique furnace slags of Beitostølen and Dokkfløyvann that it must be concluded that i) the bars are of steel intended for knives, tools and steeling, ii) the steel bars, at that time in high demand, were for export to other parts of Norway and to Sweden and Denmark, and iii) some of the important production sites must have been at Beitostølen and Dokkfløyvann.

Beitostølen lies in Valdres, Dokkfløyvann a little east of Valdres, but I am tempted to propose that the term "Valdres iron", which is known from a 13th century document (Olafsen 1916), in fact refers to these highly appreciated steel bars.

In line 12 are entered analytical values for slag inclusions in steel bars found at Snorup, west Jutland, and dated to about 330-560 A.D. (Høst-Madsen & Buchwald 1999). The Snorup hoard contained about 200 slender bars. Just over 100 of them were 26-30 cm long and weighed between 120 and 160 g. There were also about 100 smaller bars, 16-20 cm long, which weighed between 25 and 30 g. All were in miserable condition, severely corroded and fragmented. Three of the better preserved, larger bars were examined. Bar 56 weighed 111 g, bar 70 125 g, and bar 92 also 125 g. In shape they were indistinguishable from the Norwegian bars of line 11 and Fig. 154. Also the metal is similar, consisting of pearlitic-ferritic structures, with sporadic phosphorus streaks, and with a hardness range 114-330, with the bulk of the measurements falling above 200 HV. The chemical composition of the slag inclusions is the same as that of the Norwegian bars.

It must therefore be concluded that the Snorup steel bars originated in Valdres, Norway. Since the Danish depot may be dated to 330-560 A.D., we here have a fixed point for dating the early Norwegian steel production.

Another fixed point may come from the Iron Age settlement Dankirke near Ribe, Jutland. Here a Norwegian steel bar was found together with a rich collection of imported objects, which have been provisionally dated to about 520 A.D. (H.J. Hansen 1991). The presence of Norwegian steel bars in Denmark means that Iron Age knives and steel tools found in Danish excavations may very well be of Norwegian origin, either imported as finished items, or forged from imported bars, see also Chapter 10.

11. Another Scandinavian province which in the Viking Age and the Middle Ages was known for its

Fig. 155. Three steel bars from Småland, socalled Kalmar iron. Weights 496, 406 and 501 g, and 70 cm long. They have an asymmetrical cross section with a rather thick back of 5 mm, upwards, and a thinner edge of about 2 mm, downwards. Found in a hoard at Törnsbotten, Öland.

Table 6.5. SEM-EDAX analyses of slags, and slag inclusions in steel bars from Småland

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	29.0	52.1	3.1	0.8	1.8	10.6	2.2	0.1	0.2	0.1	-	100	2.74
2	33.1	31.5	8.3	0.2	3.7	15.3	6.1	0.5	1.0	0.2	0.1	100	2.16
3	18.9	35.8	19.7	0.5	1.3	20.0	1.0	0.9	0.8	0.6	0.5	100	0.95
4	49.8	22.1	4.8	0.1	4.7	9.8	6.5	0.7	0.7	0.2	0.6	100	5.08
5	30.5	57.8	1.1	0.2	2.0	6.1	1.4	0.5	0.3	tr.	tr.	100	5.00

1. Karlslunda, 92, västra Varpet, Sönder Möre, Småland. Production slag, 446 g (Nihlén 1932: 182).
2. Skåningsmåla (RAÄ 120), Bäckebo, Norra Möre, Småland. 99 g hardened steel bar fragment. HV 200: 150-235-245-358-391.
3. Törnsbotten KLM 23314-2, Öland. From a mediaeval hoard. 496 g scythe-shaped steel bar. 70x3.0x0.4 cm. HV: 135-235-317-341.
4. ibid. KLM 23314-3. From the same hoard. 406 g scythe-shaped steel bar. 70x3.2x0.3 cm. HV 200: 144-196-202-250-280.
5. ibid. KLM-23314-1. From the same hoard. 501 g scythe-shaped steel bar. 70x3.0x0.5 cm. HV 200: 120-162-231-244-258.

steel bars is Småland in southern Sweden. The so-called "lieformade ämnen", or scythe-shaped currency bars (Haglund 1978), occur in hoards in Småland, Öland and Gotland, see e.g. map and list in Nihlén (1939: 98 f). The bars have a peculiar shape, Fig. 155. With a rather uniform width of 25-30 mm, they are 65-75 cm long and have asymmetrical, softly rounded ends. In cross section they are triangular, the thickness varying from max.5 mm to about 2 mm along the thin edge, which is reminiscent of a single-edged sword or a scythe. The weights are generally 400-500 g, but individual specimens are different enough, so they cannot be accepted as payment of standard weight, "currency bars". They are rather a convenient and for centuries a solidly accepted shape of a steel product, intended for trading beyond the production areas.

The bars were apparently, in particular, manufactured in southeastern Småland, in Handbörds herred and in the two Möre herreds ("hundreds"), from where they were exported through the coastal settlement of Kalmar, later to become a fortress. The export probably went to Öland, to northern Germany (Danzig, Lübeck) and to Denmark. The city of Kalmar may very well have had this steel trade as a background for its foundation and development since about 1200 A.D. (Larsson & Rubensson 2000: 20,312). Already Nihlén (1939) suspected this connection. The present author (Buchwald 1999) would like to stress that the contemporary term Kalmarjern (Iron from Kalmar) must have meant the scythe-shaped bars, which we shall see are really steel bars of excellent quality.

In Table 6.5 are listed a production slag from Karlslunda sogn in Söndre Möre herred; a rod-shaped steel bar from Skåningsmåla, Bäckebo sogn in Nörra Möre herred; and three scythe-shaped steel bars from a hoard found on the island of Öland, opposite Kalmar. All five are dated to 1100-1400 A.D. The Karlslunda slag, line 1, is similar in composition to the two Valdres slags, lines 9-10 in Table 6.4. Manganese is high, but variable, and phosphorus is low, requirements to be fulfilled if the ironmaster wanted to produce good steel in quantity with minimum effort. The slag contains numerous 10-20 μm hercynite crystals with vanadium. The presence of a little vanadium, and the relatively high potassium and magnesium content are characteristics that may distinguish the Småland ores from that of Valdres. The ores were either bog ore or lake ore, similar to those listed in lines 4-5 in Table 6.1.

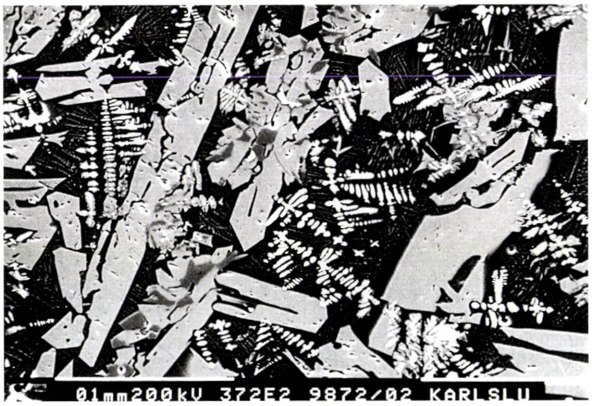


Fig. 156. Production slag, 466 g, from Västre Varpet, Karlslunda, Småland. Small wüstite dendrites, fayalite laths with 5-6% MnO in the molecule, and cubic hercynite crystals with 0.4% V_2O_5 and 0.8% TiO_2. PS. SEM. Scale bar 0.1 mm.

The steel made from these ores was manufactured into two shapes. The rod-shaped bars, typically of 100-200 g weight, had rectangular cross sections of $^1/_2$ – $^1/_4$ inch and were up to 50 cm long. The one here examined was a fragment,weighing 99 g and with the dimensions 23 x 1.3 x 0.6 cm. It was found on a production site at Skåningsmåla (Nihlén 1932: 172) and it had been quench-hardened. But the hardness was relatively low, 150-391 HV, which is due primarily to a generally low carbon content of only 0.25-0.35%, and secondly to the fact that water-quenching only sufficed to martensite-harden the exterior parts of the rectangular bar. The interior displays unequilibrated ferritic-pearlitic structures.

The scythe-shaped bars, on the other hand, were not hardened. They come from a mediaeval hoard found at Törnsbottom on Öland (Hofrén 1927; Larsson & Rubensson 2000: 20). Each of the three long bars was sectioned at the ends, and at one third and at two thirds from the end. All sections were chiefly pearlitic, or pearlitic-ferritic, with 0.4-0.7% carbon, without phosphorus, and with hardnesses correspondingly high, generally well above 190 HV, indicating high-quality steel. But as is always the case with ancient material, the bars are far from being as homogeneous as a modern steel bar would be. Nihlén (1939: 103) cited an analysis of one of the Vimmerby scythe-shaped bars as 0.67% C and 0.006% P, fully in line with the present observations.

The agreement between the slag compositions of the first two items which are known to have been produced in Möre herred, and the three scythe-shaped bars found in a hoard on Öland strongly suggests that these bars were also produced in Möre. In few other places in Scandinavia are found so many bloomery sites from the Middle Ages as in Möre. Larsson & Rubensson (2000) assume that the Swedish crown had a strong foothold in Möre at this time, and that a majority of the iron- and steel-producing furnaces were dependent on the crown.

The Fagerhult county, 70 km NW of Kalmar, was still rich in legends about ancient smithing, when Hofrén (1927) reported the finds of many "sinnerskuten" (large slag lumps) near the Velandshögen barrow. He also reported iron-rich lake ores in the adjacent lake. More than 200 (Nihlén 1932: 95 reported 400) steel bars were found buried at about 50 cm depth in a stone cairn. The slags and the "sword-shaped" bars were by the local tradition tied to the mediaeval legend about the master smith Vølund. He was said to have had his forge here. The Velandshög has been excavated, but no grave was discovered, so the mound must rather be characterized as a cenotaph than a burial site.

In the Hänsisches Urkundenbuch from the early 14th century (Larsson & Rubensson 2000: 20) there is preserved a document from the Danish city of Flensborg, giving information on contemporary trade and duty rates. Relative to the iron trade, three little understood terms have been used: " Toln ... for hundrith climp jern eldær Blekungs jern eldær Kalmars jern sex penninge", that is " duty ... for one hundred climp iron, or Blekinge iron, or Kalmar iron is six pence". If we assume that the custom rates reflect the value of the objects, then the value of 100 climp irons, 100 Blekinge irons and 100 Kalmar irons should have been the same. I have proposed earlier (Buchwald 1999) and would like to once more suggest that climp iron was the 2-3 kg slag-rich fourth part of a four-fingered klode, a mediaeval Danish bloom (Table 4.6), the Blekinge iron may have been the rectangular, hard-

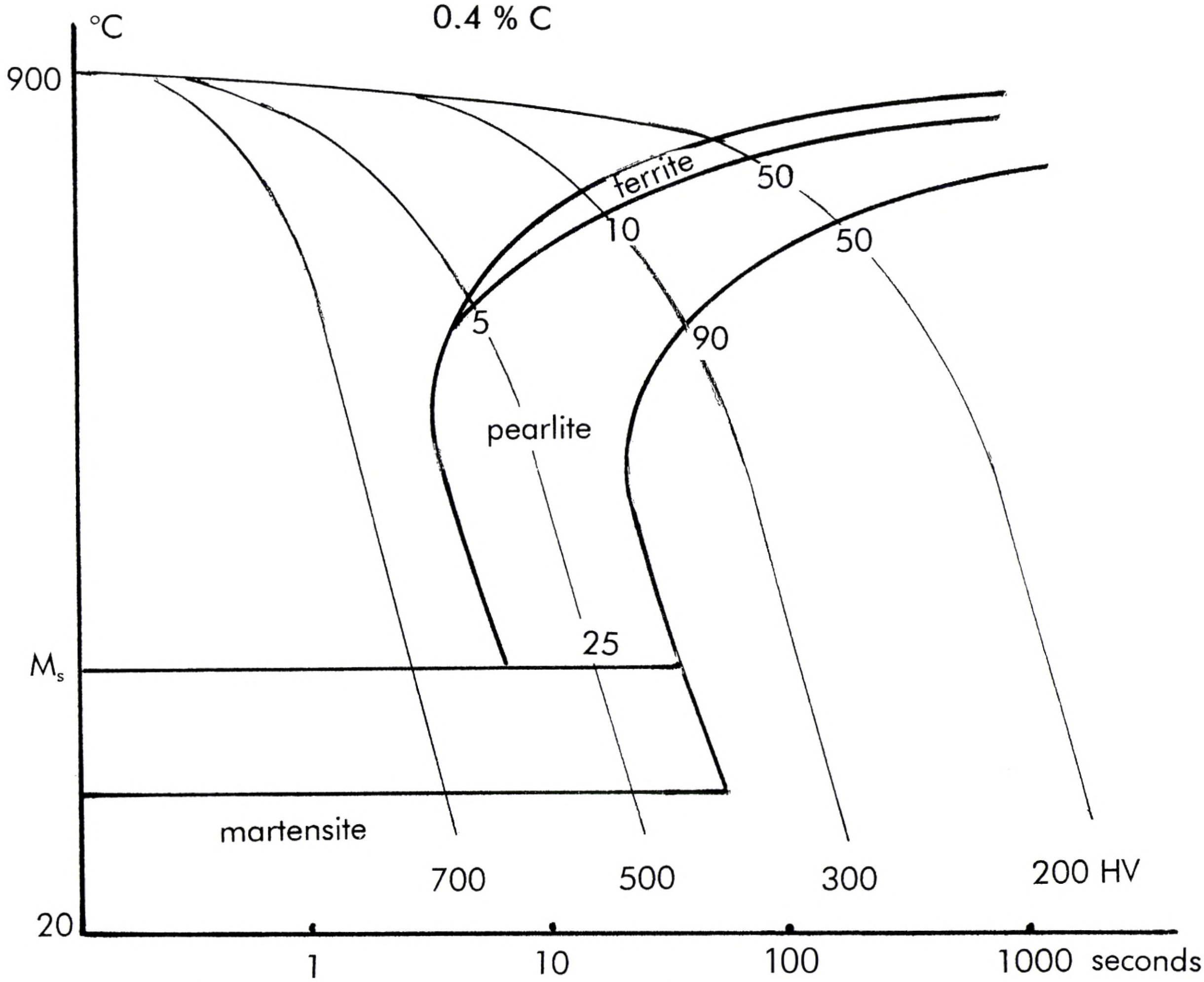


Fig. 157. Continuous Cooling Transformation diagram (CCT-diagram) for a steel with 0.4% carbon. The steel has been heated to equilibrium in the austenite region at 900°C, and then cooled with different velocities. It requires a rapid quench to produce martensite with a hardness of 700 Vickers. At a slightly lower cooling rate, the austenite transforms during cooling to 5% ferrite, 25% pearlite, and 70% martensite and the end hardness is 500 HV. A still lower cooling rate gives 10% ferrite, 90% pearlite and no martensite, with a hardness of 300 HV. Finally, a low cooling rate gives a structure of 50% ferrite and 50% pearlite, approaching the equilibrium structure, with a hardness of 200 HV.

If we apply the diagram to a heated massive steel rod, which is dipped into cold water, the first curve relates to its surface, while the other curves relate to still deeper parts of the rod. Because steel is a bad heat-conductor, the quenched rod will display very different structures and hardnesses from the surface and inwards. – Other diagrams, quantitatively different in terms of time, temperature and transformation products, apply to steels of other compositions (carbon, manganese, chromium, nickel etc.). Such CCT-diagrams are available in socalled Atlas of Steel Transformation.

ened steel bar of about 200 g, and Kalmar iron the scythe-shaped, unhardened, pearlitic steel bars of about 500 g. In a semiquantitative way we here have the three materials presented and evaluated. For the same amount of silver, you could acquire either about 200 kg of unrefined, slag-rich, soft wrought iron, or 50 kg of hardened steel in rod-shape, or 20 kg of unhardened pearlitic quality steel in scythe-shape.

Further research must try to clarify these relations and terms.

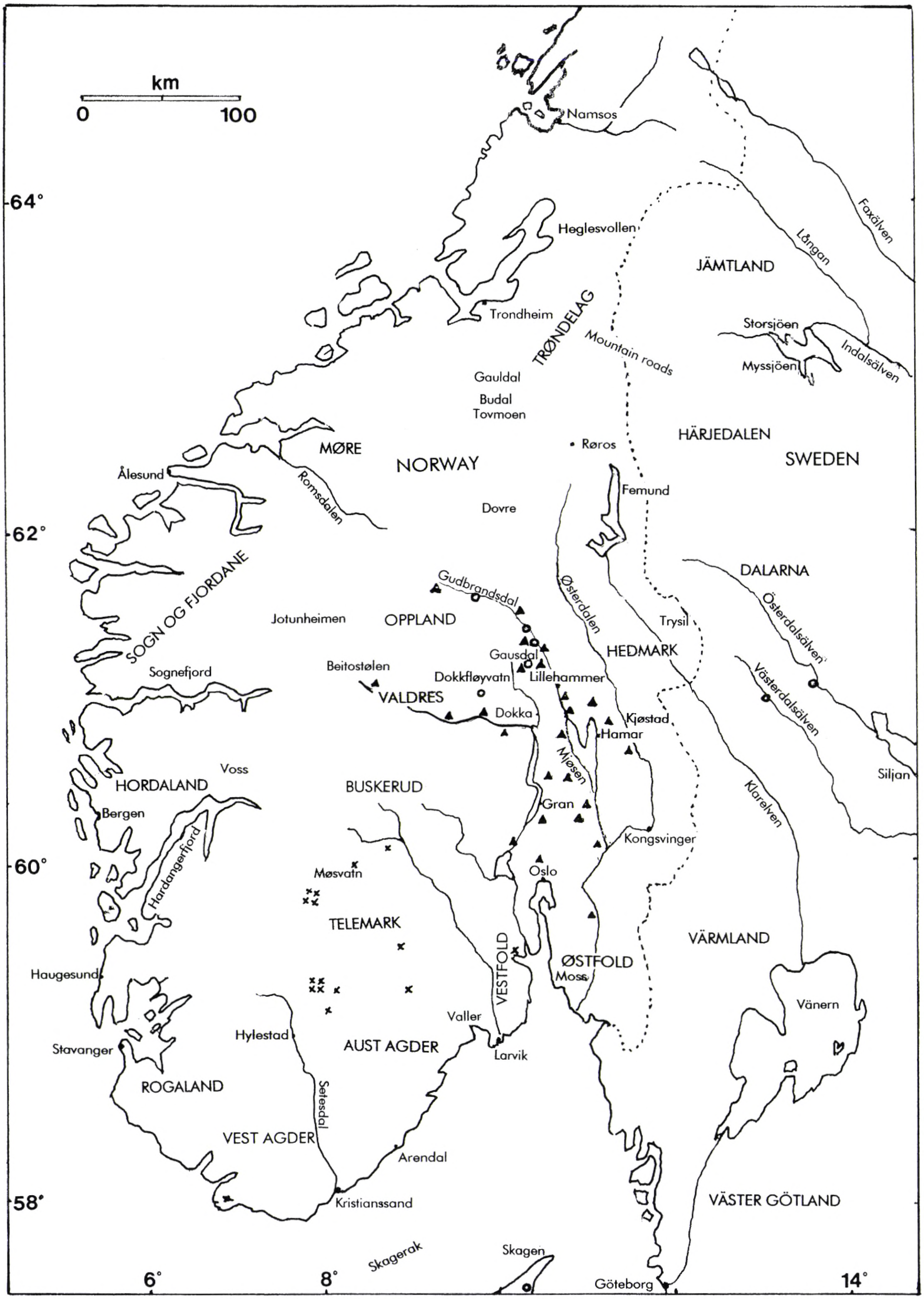


Fig. 158. Map of southern Norway. The location of finds of Fellujern (split blooms) **x**, of spoon-shaped steel bars **▲**, and of steel wedges **O**. Only the most important hoards are marked.

Chapter 7
The analytical method and the significance of phosphorus

The devil snatches seven coldsmiths every New Year's night.

Danish proverb.

In an early examination of a 750 g Viking Age axe (Buchwald 1976) the author was given permission to divide and subcut the axe in any conceivable direction. One of the results of the examination, not fully understood at that time, was the discovery of a systematic variation of the metallic structure and the adjacent slag inclusions. It was found that any forged object, roughly speaking, was built up of parallel zones that could be very different. Within each elongated zone the metal had the same structure and the slags the same composition, while a neighbouring zone within itself would be homogeneous, but its metal and slags might be quite different from the first zone. A cross section may thus be described as being built up of a number of different zones which are often repeated, e.g. A-B-C-A-C-D-A-B-D etc. If only examining small sections one runs the risk that, e.g., only one or two zones are represented, and a true average is not obtained.

In order to get a true picture of an ancient object it was therefore decided to work with "large" sections, 2-4 cm^2, if at all possible, and to analyse a number of the zones and from these data calculate the average composition of the metallic phases as well as the slag inclusions. The method of drilling for analytical purposes which has been used regularly up to our time was rejected because the drillings would be an undetermined mixture of metal, slag inclusions, and corrosion products. For the same reason, former analyses based upon drilling will rarely be quoted in this work.

Many objects are simply built, for example a nail. But some may be complicated. A knife may have been forged by bending plate-shaped material back on itself, so specific zones are repeated in inverse order. It may also display an inserted wedge of another piece, perhaps of steel, to form a cutting edge, Fig. 321. These scenarios are usually easily observed on a good section, but may pass unnoticed on small samples.

Bulk slags from production and purification were often prepared in even bigger sections to provide an overview of possible stratifications, as they may often be observed in tapslags. Normally, polished sections of inch-size were prepared.

In selecting the objects, recent finds were given priority, partly because they were well dated from the archaeological context, and partly because polished specimens could be secured before any conservation methods were applied.

Two or more samples were cut from the same object, preferentially cross-and lengthwise, and they were embedded in plastic and polished by routine metallographic methods. Grinding was performed on wet abrasive papers to No. 1000, while polishing took place on rotating disks impregnated with diamond powder, finishing with 3 or 1 μm powders (Struers A/S).

Etching was not applied until after the analytical work had been finished, for fear of selectively dissolving sensitive components from the objects. The polished section was studied and slags to be examined were marked under the microscope. After finished analytical work, the metallic samples were etched, normally with 2% Nital, that is 2% HNO_3 in 96% ethyl alcohol, and the structure was examined, photographed and its hardness tested.

The hardness test was performed on a Leitz Durimet, usually making at least 5 impressions at a load of 200g. The hardness was measured in the various zones and the corresponding microstructure noted. In presenting the hardness data, they have been arranged according to increasing number, and the structures have been commented upon in the running text.

Tensile testing was performed on a 10 ton Instron machine. In the present study, tensile testing was restricted to the 18th century and later, since the earlier material was either too corroded or too costly to be subjected to the tensile test, which requires rather much material.

Compositional analyses were performed on a Philips scanning electron microscope (505) with attached energy dispersive spectroscopical equipment (EDAX 9900) at 20 KV. About 7,000 analyses have been taken, partly as spots in individual phases and inclusions of minimum 5 μm size (wüstite, fayalite, hercynite, leucite, magnetite, iron phosphate, zircon, ilmenite, hibbingite etc.), partly as averages. Care was taken to exclude corroded parts of the slags. Averages were usually taken over areas of 300 x 200 μm, but in many forged items the slag inclusions were thin and averages had to be taken over 30 x 20 μ. For each sample two to five average analyses were taken over zones A-B-C etc., and it is the grand average of these analyses that has been entered in the database and the tables of this work.

A total of twelve elements were determined in the slags, namely magnesium, aluminium, silicium, phosphorus, sulphur, potassium, calcium, barium, titanium, vanadium, manganese, and iron. Counting times were 50 live seconds. Chromium was sometimes detected and then included in the analysis. Sodium was apparently always present, but we did not believe in the data, so sodium was excluded from the analyses.

The metal was analysed for phosphorus, nickel and copper, and arsenic was looked for, but only rarely detected (detection limit about 0.05%). All iron of the slags is reported as divalent iron, FeO, since the analytical programme was unable to distinguish between divalent and trivalent iron. The decision to present all iron as FeO is based on the fact that the ironoxides usually occur in a heavily reduced environment, closely associated with free iron. Iron in bog iron ores, was, on the other hand, reported as trivalent iron.

The EDAX program converts the analytical data into weight percent FeO, SiO_2, Al_2O_3 and so on. The standard error on elements present in concentrations above 2wt.% oxide is below 5%, while elements in lower concentrations are no better than ±10%. Early cross checks on the JEOL microprobe at the Geological Museum, Copenhagen University, showed that our data for phosphorus were systematically high, so all our analytical data have been reduced by subtracting 0.3% P_2O_5 from the numerical, measured values before they were entered in the tables. When barium was present, the titanium value became uncertain, because of the proximity of the signals for BaL_α and TiK_α.

The scanning electron microscope is not the optimal instrument for determination of average analyses, but it has some major advantages. It is possible to observe what is being analysed and so exclude corroded zones. It is a relatively rapid method and therefore cheap. And it is possible to photograph the analysed areas and later verify the analytical data with planimetry. In the present work the majority of the SEM-EDAX data were obtained between 1985 and 2000, with the same instrument and with the same competent operator, Mrs. Inger Søndergaard, to whom I am greatly indebted. Therefore all data are compatible within the present study.

In a few cases the <u>same</u> production slag has been analysed at <u>different times</u>, by <u>different operators</u>, but on the <u>same instrument</u>. In Table 7.1 two such cases have been illustrated. In lines 1-2 are the results on a Roman Iron Age production slag from Biskupice, Poland, in lines 3-4 are the results on a contemporay production slag from Myssjön, Jämtland. One operator concentrated on determining the presence of barium and had to be satisfied with noting, qualitatively, the simultaneous presence of titanium. The other operator evidently had decided on the opposite approach. The analyses agree very well, supporting the good quality of the instrumentation, and the stability over time. Note also the consistent F-values, being 13.9± 0.4 for Biskupice, and 4.9 ± 0.1 for Myssjön.

The reproducibility was also tested on slags from Scandinavian charcoal-fired blast furnaces. The slags

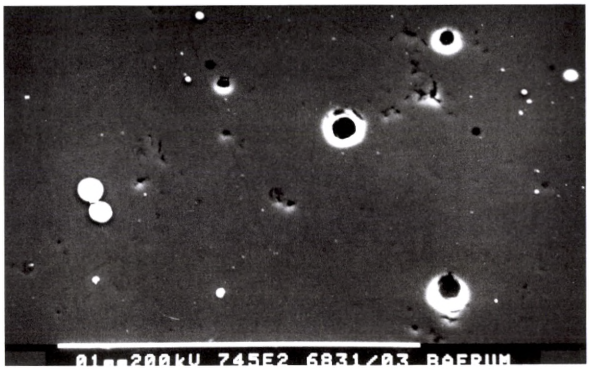


Fig. 159. Blast furnace slag from Bærum, west of Oslo. About 1800 A.D. The slag is homogeneous glass with porosities (gasholes, black) and minute inclusions of pig iron (white). PS. SEM. Scale bar 0.1 mm.

were homogeneous and glassy under the microscope, but contained disseminated microspheres, 5-20 µm in diameter, of carbon-rich raw iron. The analyses were taken over areas with a minimum of iron spheres, Table 7.1, lines5-8. The four lines represent four different areas, 0.5x0.4 mm in side.

In Table 7.2, lines 1-4, are entered the analyses of four different areas, each 0.7 x 0.5 mm in size, of a 19th-century blast furnace slag from Engelsberg, Bergslagen, Sweden. In line 5 is found the Engelsberg average. These examples also illustrate the normal procedure for the individual steps that are necessary to obtain the average analytical values presented in the tables.

The composition of the Norwegian blast furnace slag from Bærum is characterized by a significant titanium and aluminium content, while the Engelsberg, Bergsslagen slag is characterized by a significant manganese and chromium content and a rather small aluminium content. All the blast furnace slags are very low in P_2O_5 and SO_3, and V_2O_5 is near the limit of detection for the instrument. The analyses confirm the impression from the microscopic examination that the blast furnace slags are homogeneous glasses. The

Table 7.1 SEM-EDAX analyses of various slags

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F	G
1	22.26	61.74	4.00	0.23	5.08	4.42	1.64	0.45	0.18	+	-	+	100	13.57	9.5
2	23.83	60.18	3.36	+	5.24	4.71	1.67	0.47	0.12	0.26	-	0.16	100	14.27	10.1
3	25.99	60.34	4.27	0.38	0.16	1.87	5.25	1.12	0.20	+	-	0.42	100	4.94	12.9
4	25.60	60.72	4.31	+	0.15	1.93	5.28	1.14	0.31	0.22	-	0.35	100	4.85	13.3
5	52.68	4.46	0.31	-	0	20.55	10.38	0.75	9.23	1.49	0.15	0	100	5.08	857
6	52.57	4.96	0.46	-	0	20.82	9.97	0.75	8.91	1.52	0.04	0	100	5.27	746
7	52.89	4.28	0.31	-	0	20.36	10.28	0.72	9.63	1.37	0.03	0.13	100	5.14	893
8	52.61	4.41	0.45	-	0	20.49	10.26	0.80	9.44	1.49	0.05	-	100	5.13	843
9	52.7	4.4	0.4	-	0	20.6	10.2	0.8	9.3	1.5	<0.1	<0.1	100	5.17	852

1. Biskupice, Poland. Roman Iron Age. 150 g production slag. Operators I.Søndergaard and VFB. 20 July 1992
2. ibid. Operator Helle Wivel. 24 August 1995.
3. Myssjön, Jämtland. 355-561 A.D. 772 g production slag. Operators I.Søndergaard and VFB. 31 August 1994.
4. ibid. Operator Helle Wivel. 24 August 1995.
5. Bærum Ironworks. 1800 A.D. 319 g charcoal blast furnace slag. Homogeneous glass. 25 September 1996.
6. ibid. 1 cm distant.
7. ibid. 2 cm distant.
8. ibid. 3 cm distant.
9. Bærum Ironworks. Average of lines 5-8.

Table 7.2. SEM-EDAX analyses of blast furnace slags from Engelsberg, Sweden

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Cr_2O_3	Sum	F	G
1	55.89	6.28	2.39	0	25.87	1.81	0.54	6.97	-	-	0	0.25	100	31	406
2	55.99	5.81	2.41	0	25.89	2.04	0.54	7.03	-	-	0.11	0.18	100	27	432
3	56.05	5.92	2.41	0	25.92	2.02	0.50	6.86	-	-	0.09	0.23	100	28	424
4	55.66	6.17	2.34	0	25.56	2.06	0.58	6.95	0.08	0.10	0.20	0.30	100	27	413
5	55.9	6.0	2.4	0	25.8	2.0	0.5	7.0	<0.1	<0.1	0.1	0.2	100	28	420

1. Engelsberg Ironworks. 19th century. Charcoal blast furnace slag, 225 g. Operators I.Søndergaard and VFB
2. ibid. 1 cm distant
3. ibid. 2 cm distant.
4. ibid. 3 cm distant.
5. Engelsberg Ironworks. Average of lines 1-4.

somewhat high iron values may be due to the presence of a few minute iron nodules within the analysed field.

Slags from the bloomery practice are much less homogeneous and cannot be used to test the reliability of the instrumental procedures.

We will now examine the common situation when iron objects with slag inclusions are analysed. On the polished section a number of uncorroded slags are selected, marked and sometimes photographed. The section is then carbon-coated and transferred to the scanning electron microscope and subjected to energy dispersive analysis, Table 7.3. The case illustrated is a Norwegian Iron Age steel wedge (Skjelle, No. C 28600 of 2.1 kg, Oldsaksamlingen, Oslo). Sections have been taken from both the cutting edge and from the shaft, and a total of nine slag inclusions have been analysed (Buchwald & Wivel 1998).

At first sight it is difficult to accept that the bewildering sets of analyses in Table 7.3 belong to the same object. However, the nine analyses, here arranged according to decreasing content of FeO, reflect the fact that there were small operational variations inside the bloomery furnace, particularly with regard to gas composition and temperature, whereby slag and metal reached different equilibria locally. The same ore and the same charcoal thus lead to different slag and metal

Table 7.3. SEM-EDAX analyses of 9 slag inclusions in a Norwegian steel, C 28600

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G	Micro
1	21.94	56.12	9.55	tr.	0.51	1.43	7.73	1.34	0.67	0.42	0.29	100	2.84	17.0	Ferrite
2	23.09	55.34	9.27	tr.	0.30	1.44	8.04	1.26	0.68	0.36	0.22	100	2.87	17.6	Ferrite
3	25.61	49.58	10.49	0.93	0.89	1.83	8.47	1.38	0.82	tr.	tr.	100	3.02	20.2	Ferrite
4	28.95	41.24	14.17	0.98	0.15	2.05	9.86	1.50	1.10	tr.	tr.	100	2.94	25.6	Fer-pearl
5	31.35	40.52	11.55	+	0.71	1.50	9.88	2.19	0.92	0.64	0.64	100	3.17	27.5	Fer-pearl
6	46.27	19.98	13.21	+	0	2.08	13.48	2.83	1.45	0.82	0	100	3.43	59.8	Pearl-ferrit
7	43.16	14.64	18.77	1.55	0	3.16	14.71	2.41	1.60	+	0	100	2.93	62.6	Pearl-ferrit
8	48.16	8.58	18.66	1.77	0	3.12	15.23	2.78	1.70	+	0	100	3.16	78.9	Pearlite
9	47.21	5.30	21.00	2.02	0	3.73	16.06	2.67	2.01	+	0	100	2.94	86.0	Pearlite
Av	35.1	31.4	14.1	1.4	0.3	2.3	11.5	2.0	1.2	0.6	0.1	100	3.05	36.0	Fer-pearlit

composition according to the state of reduction. At relatively low temperature and limited reducing power of the CO-CO_2 gas, the metal phase formed as carbon-free iron (ferrite), and the corresponding slag became FeO-rich, line 1. When we examine the cold object, we therefore observe a wüstite-rich slag in a ferritic matrix, low in carbon, and with a Vickers hardness of 110 ± 5 HV.

At higher temperature and stronger reducing power of the CO-CO_2 gas within the furnace, the metal phase becomes carburized austenite and the corresponding slag is depleted in FeO, line 9. When the cold material is examined, the structure appears as wüstite-free glass in pearlitic steel with a Vickers hardness of 225 ± 20 HV.

The other seven analyses of Table 7.3 are representative of intermediate situations, each one revealing local equilibrium in terms of ferrite-pearlite, i.e. carbon content of the austenite phase, with slag inclusions of wüstite, fayalite and glass. The hardness range of one and the same object is correspondingly large, from 100 to 245 HV, an enormous range compared to what is achieved in modern technology. As has been stated before, the ancient objects are, indeed, heterogeneous, with regard to slag and metal composition as well as to hardness and structure. But there

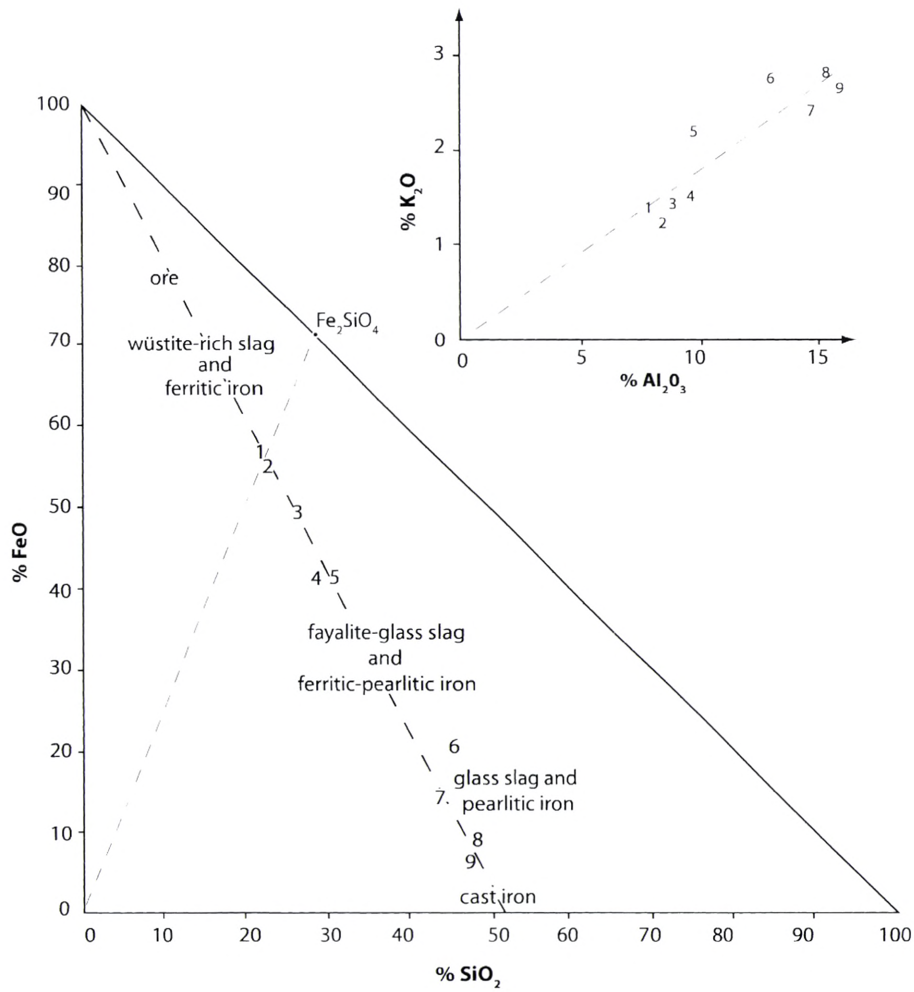


Fig. 160. SiO_2-FeO diagram, and auxiliary Al_2O_3-K_2O diagram for plotting slag compositions. Nos. 1-9 are the analytical results for nine different slag inclusions in the same Norwegian 2 kg steel wedge, No 28 600, see Chapter 10. The nine inclusions represent different degrees of reduction, No. 9 being the most reduced and approaching glass in equilibrium with pig iron. Data from Table 7.3.

is a close harmony between slags, metal, structure and hardness.

Whenever reduction transforms FeO from the ore/slag into iron of the metallic phases, the other constituents of the ore/slag become relatively enriched, Figure 160. Slag inclusions from the same charge will be located on a line through the point (0% SiO_2, 100% FeO), and with a slope that is characteristic of the amount of impurities. If the sum of impurities (MnO, BaO, CaO etc.) is small, the line will fall near the 45° line towards the point (100% SiO_2,0% FeO). If, on the other hand, there are many impurities, the line will swing towards smaller SiO_2- values on the abscissa.

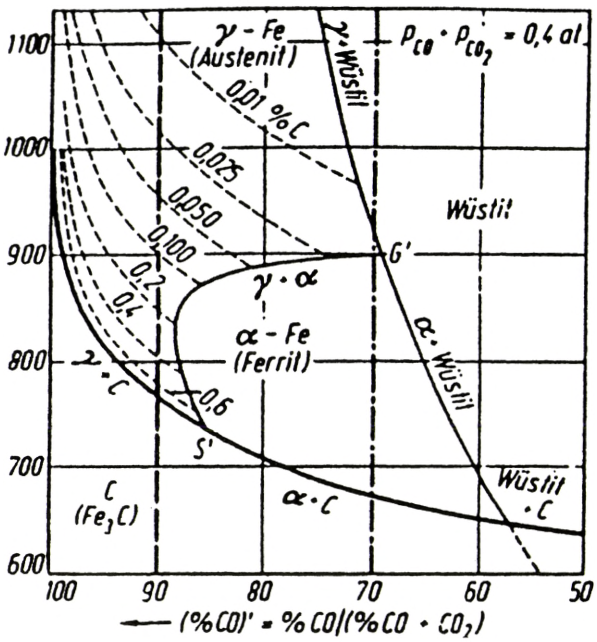


Fig. 161. Equilibrium diagram for iron, carbon and iron oxide in a hot gas mixture of carbon monoxide (CO) and carbon dioxide (CO_2). Nitrogen constitutes 60% of the gas mixture, but remains neutral. On the X-axis the ratio%CO/%CO+%CO_2 is shown, 100% corresponding to pure carbon monoxide. According to the diagram wüstite may be reduced to ferritic alpha iron already at 700°C in a mixture of a little more CO than CO_2. If the temperature is raised to, e.g. 1000°C, and the CO pressure is also increased, the wüstite is transformed to carbon free austenite. If, however, the CO pressure is further increased at the same temperature, e.g., in a different part of the furnace away from the tuyeres, the reduced iron will dissolve more and more carbon. In other words, parts of the bloom may be low carbon iron, while other parts at low oxygen pressure away from the tuyeres may become steel. It should, however, be remembered that the diagram represents ideal equilibria, a situation which is rather remote from the ancient bloomery praxis.

The correlation between selected oxides, such as Al_2O_3/FeO, MnO/SiO_2, K_2O/Al_2O_3, and CaO/Al_2O_3, may be shown in different figures. As the slags become depleted of FeO, the other oxide components increase correspondingly, but their ratios (i.e.the slope of the lines) remain the same, because none of these oxides can be reduced in the bloomery process, and they cannot enter the metallic phases.

The analytical ratios that have proved to carry the most useful information are F = SiO_2/Al_2O_3, SiO_2/FeO, Al_2O_3/CaO, and K_2O/MgO. Since SiO_2 and Al_2O_3 are so closely correlated, either one or the other could be used as a reference or calibration factor, but in this work the F- value, SiO_2/Al_2O_3, has been preferred. Other ratios, as well as absolute quantities, such as MnO, P_2O_5, TiO_2, V_2O_5, and Cr_2O_3, may also prove helpful and will be used for support when evaluating provenance and structure.

The mediaeval Scandinavian "klode", clot, Table 4.6, may serve as another example of ancient heterogeneity, but internal harmony (Buchwald 1995). The clot is a bloom of 5-15 kg which was formed in a production furnace, generally of about 50 l reaction volume, without, or sometimes with, slag tapping facilities. The furnace was of bowl-shape or a relatively low, cone-shaped furnace which was easily accessible from above., e.g. of types 1,4 or 12. It is speculated that the operator in the last part of the process might work the bloom from above with a spit or a rod, and thus press slag away and somewhat preshape the bloom (A.Espelund, pers.comm.). After four to six hours, the bun-shaped bloom was gripped with tongs and removed from the furnace. The bloom was then immediately, when glowing hot, cleft with an axe. With three cuts, the bloom was opened, but it was not entirely split. The purpose, it is assumed, was to satisfy the ironmaster that his iron was of good quality, that it was easy to grip for transportation, and that the individual fingers had an appropriate size for later full separation, so any blacksmith could easily detach and

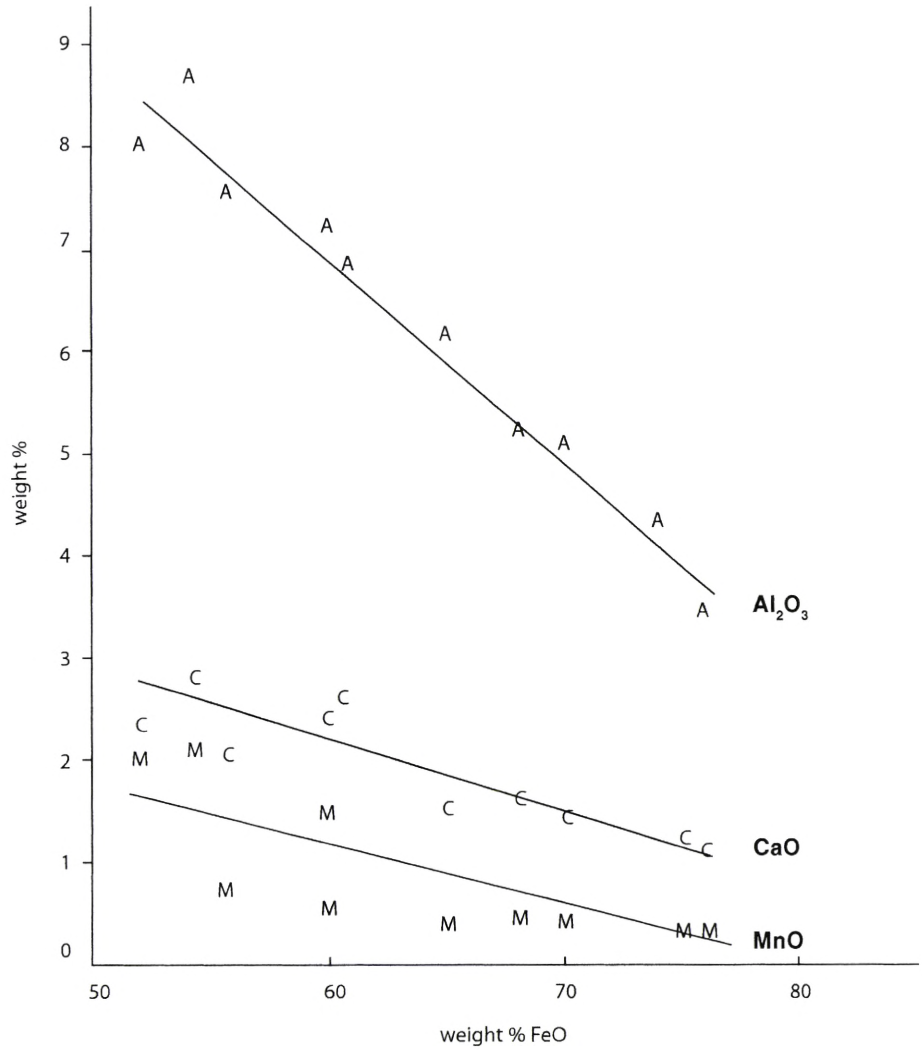


Fig. 162. The composition of the slag inclusions is dependent on the oxidation/reduction states in the production furnace. As the FeO-content of the charge is reduced, the amount of Al_2O_3 (**A**), CaO (**C**) and MnO (**M**) increase. The diagram reports ten different slag inclusions in the same object.

handle the fingers. The fingers went, in Denmark, under the name of Climp iron.

An examination of a 3.1 kg inner finger (or Climp iron) from a clot in Bölinge, Halland (Buchwald 1995) showed that the clots were heterogeneous in a systematic way. That part of the clot which had been exposed to the oxidizing air from the bellows had been decarburized and was now ferritic, while parts away from the air blast and protected by the slag bath were carbon-enriched and consisted of phosphorferrite and some pearlite. The two inner fingers were somewhat compacted, spec.grav. 5.85 g/cm^3, while the two outer sections of the clot, spec.gr. 5.09 g/cm^3, had suffered no or very little compacting. When the blacksmith handled the inner fingers, he must no doubt have felt the difference between the hard austenite with carbon enrichment, and the soft austenite with low carbon content. This last material constituted most of the clot. Because of the hardness differences at forging temperatures, the finger became less reduced in thickness in the carbon-rich end. It would require little ingenuity on the part of the ironmaster to separate this hard part

Fig. 163. The typical Danish bloom, slightly consolidated and cleft with three axe cuts. The socalled klode (Buchwald 1991). The photo shows one of 8.2 kg, lost on crossing a rivulet near Karup sometime in the 15[th] century. Scale bar 20 cm. Specific gravity about 5 g/cm^3. Vejle Museum No. 964x1.

Fig. 164. 16 clots (kloder like Fig. 163) have been split into 64 fingers, called klimpjern, and hoarded near Bölinge, Våxtorp, Halland. Now in Technical Museum, Stockholm. Courtesy the Museum.

Table 7.4. SEM-EDAX analyses of slag inclusions in a bloom from Bölinge, Halland

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	48.78	22.15	6.77	1.12	1.40	12.94	5.04	0.26	0.63	0.81	0.10	100	3.77
2	46.79	19.64	8.38	0.67	2.63	14.05	5.27	0.76	0.75	0.96	0.10	100	3.33
3	30.95	41.22	7.49	1.74	2.63	11.10	2.90	0.85	0.51	0.23	0.38	100	2.79
4	30.37	40.13	6.95	1.76	3.52	11.77	3.57	0.80	0.54	0.13	0.46	100	2.58
5	28.96	43.64	7.64	0.75	3.53	11.25	2.75	0.64	0.49	<0.1	0.35	100	2.57
6	28.09	43.39	7.82	0.86	3.48	11.85	2.68	0.77	0.56	0.15	0.35	100	2.37
7	1.11	41.17	4.93	-	-	47.80	-	2.25	1.37	1.37	-	100	-
8	31.19	50.73	12.26	-	1.37	2.03	0.20	2.10	0.12	-	-	100	-
av	35.7	34.8	7.5	1.2	2.9	12.2	3.7	0.7	0.6	0.4	0.3	100	2.93

1. Bölinge, Halland. 1200-1500 A.D. 9 kg bloom. Fron the carbon-enriched part.
2. ibid. From the same part.
3. ibid. From a carbon-poor, ferritic part.
4. ibid.
5. ibid. From another carbon-poor, ferritic part.
6. ibid.
7. Hercynite inclusion: Manganese-magnesium-titanium-vanadium hercynite.
8. Average of three fayalite crystals: Manganese-magnesium-calcium fayalite.
9. Bölinge, Halland. 9 kg bloom. Average of lines 1-6.

Fig. 165. Klimpjern No. 12 of 3101 g from the hoard, Fig. 164. It has been sawn into sections in order to examine the detailed composition. No. 12 was originally one of the two middle fingers in a klode like Fig. 163. There are no signs of forging. Scale bar 18 cm.

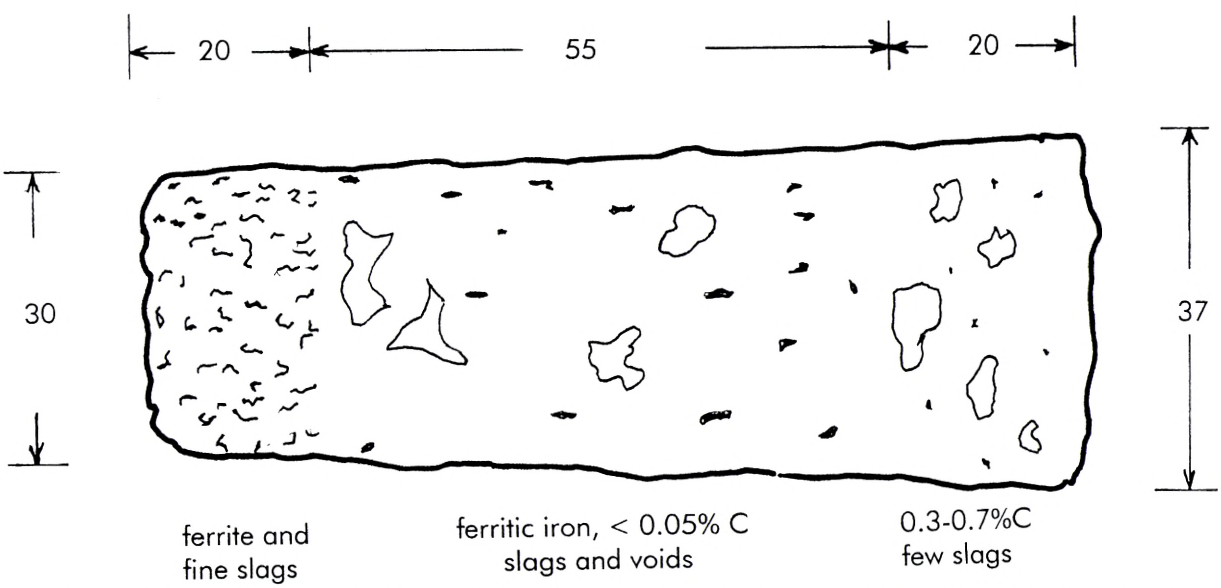


Fig. 166. Slice No. 1 from Fig. 165, polished and etched. One side is carbon-free, phosphorus-rich ferrite, the opposite side is pearlitic steel.

Fig. 167. Section through the bloom Fig. 165, showing the initial phases of iron consolidation. The iron is ferritic and the slag is wüstite-fayalite-glass with hercynite crystals, Table 7.4. PS. SEM. Scale bar 0.1 mm.

with a hot-chisel and reserve it for steeling purposes. In other words, there was in any production scenario a chance of preserving a minor part of the blooms as steel, provided i) that the local ore was phosphorus-poor, below about 1% P_2O_5 and ii) that the ironmaster had some experience. This possibility has been with the bloomery process from the very beginning, so steel has, no doubt, been known for just as long a time as soft wrought iron.

The present Bölinge bloom would, because of an appreciable phosphorus content, have produced only a mediocre steel, far inferior to the Valdres and Kalmar steel, discussed in Chapter 6, and to the Siegerland steel (Gilles 1936).

From the analytical data of the Bölinge bloom in Table 7.4 it is evident that a bloom is very heterogeneous from the beginning so it should come as no surprise that the resulting manufacture may also be quite heterogeneous, in slag compositions as well as in the metallic structure. Already Gilles (1936, Table 5) showed that blooms usually had a variable composition with respect to the most important elements carbon and phosphorus. In one bloom he found a variation from 0.28% C-0.10% P in one end, to 0.07% C-0.07% P in the opposite end. In another bloom he found 0.11% C-0.18% P in one end, and 0.76% C-0.02% P in the opposite end, this part being eminently suited for a steel bar.

The ores used for the Bölinge production furnaces have so far not been identified, but they were probably similar to ores listed in lines 4-5 in Table 6.1, quite rich in aluminium, manganese, magnesium, titanium and vanadium. Therefore the slags contain fayalite, Table 7.4, line 8, where iron is substituted with significant amounts of manganese and magnesium. The numerous cubic hercynite crystals, 10-20 μm in size, show substitutions with manganese, magnesium, titanium and vanadium, Table 7.4, line 7.

The harmony between slag inclusions and metallic matrix has here been documented with examples from the ancient bloomery process. When the blast furnace was introduced in the 12th century and wrought iron was produced in a new way, through a fining process, the conditions only changed little. In the fining process wrought iron was produced batch-wise, 25-100 kg raw iron being oxidized on the hearth, mixed and puddled while the iron was pasty and embedded in slags. Again local equilibrium in "apple-sized" volumes was achieved, but during further work all these differently equilibrated volumes were forced and forged together to form the final bar. A cross section

Fig. 168. Bölinge. The ferritic part of the bloom with wüstite-fayalite-glass slag inclusions. The ferrite is pure with low hardnesses of 75-92 HV. PES. Side length 0.3 mm. Courtesy FORCE Technology.

Fig. 169. Bölinge. The ferritic-pearlitic part, about 0.4% C, with glassy slag inclusions (and some corroded spots). The hardness is about 120 HV. PES. Side 0.3 mm. Courtesy FORCE Technology.

clearly shows the variously decarburized parts and the corresponding slag inclusions. It was, in fact, as late as in the second half of the 19th century, with the introduction of the Bessemer-, Thomas-, and Siemens-Martin processes, that liquid iron and steel became the normal product, and society suddenly had access to an entirely new homogeneous and almost slag-free material.

To serve as an illustration of the composition of fined Norwegian iron from the 18th century, take a look at Table 7.5. The table shows the average composition of slag inclusions in five different supporting iron anchors (murankre) from the church at Hatting, near Vejle, in Jutland. The anchors may be identified by their stamps as coming from the Bærum Ironworks,

Fig. 170. Slag inclusions in an iron bar (stangjern) from Hatting Church, Jutland. The iron was manufactured about 1770 A.D. at the Bærum Ironworks, Oslo, by a blast furnace process, followed by fining. PS. SEM. Scale bar 0.1 mm.

Table 7.5. SEM-EDAX analyses of slag inclusions in bar iron (stangjern) from Hatting Church. Produced at Bærum Ironworks

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F	G	Micro
1	28.9	52.3	1.1	1.9	7.6	4.6	1.6	1.3	0.3	0.2	0.2	100	6.28	27.3	Phosphorferri
2	37.3	41.0	1.7	0.6	8.4	6.2	1.5	1.8	0.7	0.6	0.2	100	6.02	41.3	Ferrite
3	37.2	38.5	1.4	1.8	10.7	5.9	2.0	1.5	0.5	0.3	0.2	100	6.31	48.2	Ferrite
4	44.3	29.4	1.9	0.6	10.2	7.5	2.3	2.3	0.8	0.8	tr.	100	5.91	69.6	Ferrit-pearlite
5	46.3	22.8	1.9	0.1	14.9	7.9	2.3	2.3	1.0	0.4	0.1	100	5.86	110	Pearlit-ferrite
Av	38.8	36.8	1.6	1.0	10.4	6.4	1.9	1.8	0.7	0.5	0.1	100	6.06	-	-

1. Hatting Church 951005, supporting iron anchor from Bærum Ironworks. HV: 97-98-127-132-136.
2. Ibid. Iron 951003. HV: 111-118-124-131-138.
3. Ibid. Iron 951006. HV: 97-98-104-108-140.
4. Ibid. Iron 951004. HV: 99-104-15-172-207.
5. Ibid. Iron 951007. HV: 125-134-154-193-194.
6. Bærum Ironworks. Average of five iron bars, about 1770 A.D.

15 km west of Oslo, Fig. 367. The church repair took place about 1770 A.D., so the iron bars which were delivered as stangjern (bar iron) must have been produced shortly before. The Ironworks used magnetite ores from the mines at Arendal.

When the analytical data are entered according to decreasing FeO-content, the initial bewildering aspect slowly disappears. As in Table 7.3 there is a close correlation between all chemical data, and the F-ratio remains rather constant at 6.06 ± 0.25. We are thus satisfied that all five bars were produced by the same ironworks as, in fact, we already knew from the factory stamps. The bars show the variation which may be expected within a supply of iron bars. As suggested by the decreasing FeO-content in the slag inclusions from bar to bar, the metallic structure becomes more and more reduced, that is, it becomes richer in carbon. While line 1 is a bar rich in ferrite (phosphorferrite) with hardnesses ranging from 97 to136, lines 4-5 correspond to bars with much more carbon, up to 0.5%, no phosphorus, and a pearlitic-ferritic structure with a hardness range from 99 to 207.

All the bars are heterogeneous, but the top ones are chiefly ferritic, the bottom ones chiefly pearlitic, in harmony with the slag inclusions. The slags are relatively rich in titanium and vanadium, due to the Arendal mine's magnetite ores. These two components are concentrated in the wüstite-dendrites that contain up to 2% TiO_2 and 0.9% V_2O_5.

In the last column of Table 7.5 is entered the characterizing G-value, or glass value. It is an empirical quotient: $G = (CaO + Al_2O_3 + K_2O + MgO) \times 100/(FeO + MnO + BaO + P_2O_5)$. In the numerator are listed oxides that chiefly come from the charcoal ashes, from the impurities of the ore, and from any furnace construction material. In the denominator are oxides that chiefly come from the iron ore and are difficult to separate from it, mechanically or chemically. A slightly reduced slag, which is rich in wüstite, has small G-values (5-50), and is in equilibrium with ferrite. With G-values of 50-200 the slag has become rich in fayalite and is in equilibrium with pearlitic steel. And with G-values of 400-5000, the slag is chiefly FeO-depleted silicaglass in equilibrium with carbon-rich iron, raw iron. This situation occurs in a blast furnace with glassy slags above fluid raw iron, compare the high G-values of the blast furnace slags in Tables 7.1 and 7.2.

Phosphorus and iron

The iron-phosphorus equilibrium diagram is shown in Figures 55 and 171. The body-centered cubic α-phase can dissolve phosphorus in appreciable quantities, up to 2.5 weight%P at 1048°C. Ferrite with more or less phosphorus in solid solution is called phosphorferrite. The presence of phosphorus as substitutional atoms in the lattice has a significant hardening effect, more pronounced than that caused by silicon, manganese and nickel atoms in the ferrite.

The face-centred cubic γ-phase has lattice dimensions that allow for fewer phosphorus atoms in solid solution, up to only 0.3 weight% at 1100°C. On normal cooling the phosphorus-containing austenite transforms into unequilibrated phosphorferrite.

At temperatures between 910° and 1400°C, there is an interesting two-phase field, within which α with high P-content is in equilibrium with γ with low P-content. Take as an example an ancient forged iron object with an average phosphorus content of 0.4%. Assume that the forging temperature was 1025°C. At that temperature the object was two-phased: Ferrite with 0.54% P was in equilibrium with austenite with only 0.28% P. The microstructure would consist of equiaxial ferrite and austenite grains in about equal amounts, and the grain size would have been about 0.1 mm, the ferrite grains being somewhat larger.

On cooling the ferrite grains do not change, because they remain within the α-portion of the equilibrium

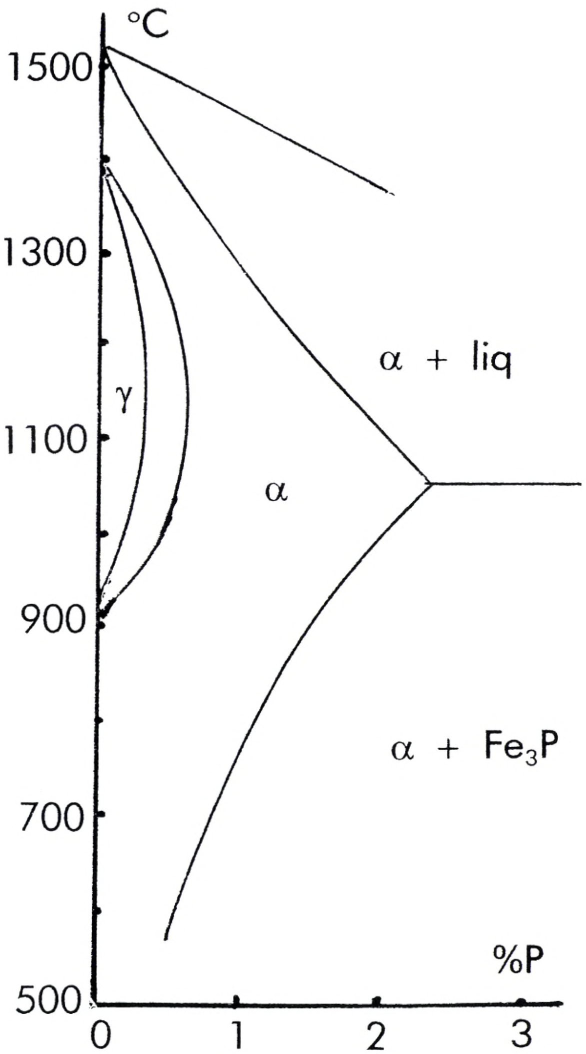


Fig. 171. The left part of the iron-phosphorus equilibrium diagram, Fig. 55.

diagram. The γ-phase, on the contrary, must start the transformation to α-grains. In practice, the new α-grains nucleate on the existing α-grains and grow into the γ-phase. The final structure is 100% α. However, about 50% is α with 0.54% P, while the other half is α with only about 0.28% P. The crystal transformation γ → α occurs more or less spontaneously, but the diffusion of phosphorus is so slow that the phosphorus differences at 1025°C are almost maintained at room temperature. Upon etching, the two types of ferrite behave differently, the one with high phosphorus being the slower etching phase. The resulting networks of high-and low-temperature grain boundaries, and of two phosphorus levels, give rise to a bewildering structural appearance, called the phosphorus ghost structure (Buchwald & Wivel 1998). The ghostly appearance in the microscope is due to the different surface levels of the etched components, which makes it impossible to bring the whole field of view into focus at the same time.

From Figure 171 it may be seen that the same average phosphorus content, e.g. 0.4%, at different temperatures, will result in variable equilibria between high-phosphorus ferrite and low-phosphorus austenite. These will upon cooling give rise to many variations in the ghost structure. If, on the other hand, any of these unequilibrated structures, developed above 950°C, is cooled slowly through the range 950-800°C, there is a chance that the phosphorus atoms have time to diffuse and form an equilibrated α-structure with 0.4% P everywhere. This will be coarse-grained, displaying 0.2-0.5 mm grains, because body-centred cubic structures show high growth rates at elevated temperatures. The self-diffusion coefficient of iron in α-iron is about 100 times larger than for iron in γ-iron.

The phosphorus-enriched α-phase often displays etch pits when etched with Nital, Figure 149. The etch pits are angular and their shape and symmetry reveal the orientation of the ferrite crystal. Etch pits within one ferrite grain are uniform in shape and orientation, but they usually appear different in neighbouring grains.

From the equilibrium diagram we see that the α-phase can dissolve much phosphorus at high temperature, but only small amounts at room temperature. The low-temperature part of the diagram is calculated and experimentally difficult to prove, because phosphorus diffuses very slowly in iron. Ancient phosphorus-containing objects are, however, indirect "experimental" proof that the calculated portions of the diagram are pretty good. In many samples, 200 years old or more, we observe needle-like precipitates inside rather large ferrite grains. I have identified these as phosphide nee-

Fig. 172. Experimental work at the DTU (Danish Technical University) in the early autumn 1990. The Scharmbeck-Snorup furnace type is operated with two bellows, and the furnace temperature is monitored in three places. Bog iron ore from Bounum, west Jutland, was used, and the iron bloom became rich in phosphorus, with above 0.5% P in the metal phase.

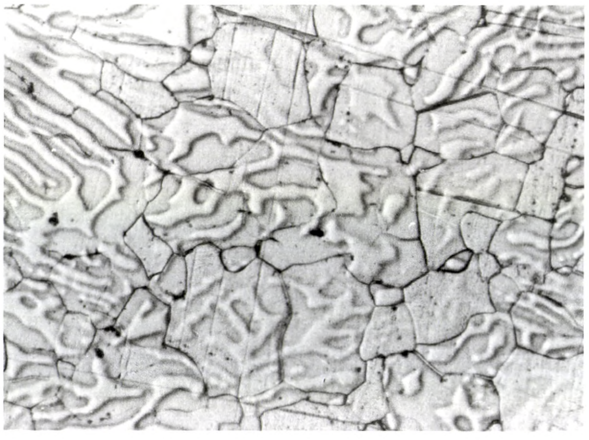


Fig. 173. Phosphorus ghost structure. Best seen at low magnification (<100 x) on samples which are not polished too well (!). Iron from Snorup, Denmark. PES. Side length 0.4 mm. Courtesy L.H.Madsen.

dles, Fe_3P, that at ambient, low temperatures have slowly exsolved from the supersaturated large α-grains. Apparently these needles have been observed before, but they have been misinterpreted as iron nitride precipitates, which they are generally not. The phosphide needles are usually found in old objects, which are phosphorus-rich and coarse-grained. Already Köster (1931) predicted the precipitation of phosphides from phosphorus-supersaturated ferrite.

As noted above, iron is hardened by the presence of phosphorus. But the hardening effect is dependent on the precise structure, whether it is an equilibrated α-structure, a ghost-structure, or a structure with precipitated Fe_3P-needles. So in a hardness diagram, Figs. 146-147, the hardnesses are displayed as a band rather than as a line. In the histogram, Figure 175, hardness results for about 150 ancient, carbon-free bloomery

Fig. 174. Precipitates of phosphide particles (needles) in ferritic phosphorus-rich iron. Hardness 85-104 HV. Nail 1D from Søborg Castle ruin, about 1200 A.D. PES. Side 0.4 mm.

products (nails, horseshoes, knives, swords, ploughshares etc.) are presented, and along the hardness axis the approximate phosphorus content is shown.

From a measurement of the hardness and from the structural appearance it is often possible to estimate the phosphorus level of an unanalysed object. This is because the ancient items are rather simple systems of only three components, iron, carbon and phosphorus. It is well known that the carbon component, in pure iron-carbon alloys, gives rise to characteristic structures of ferrite, pearlite, martensite, ledeburite etc, and that it is possible, within certain limits, to estimate the carbon content from the structure. After some exersise the same is possible with iron-phosphorus alloys. It is somewhat more difficult when it comes to ternary alloys of iron, carbon and phosphorus. In this work several photomicrographs will explain the situation.

Phosphorferritic material is slightly more corrosion-resistant than ordinary ferritic or pearlitic material. Phosphorferrite also etches rather slowly when one is preparing a microsection in the laboratory, and the ferrite grain boundaries are indistinct. If forge-welded to normal ferritic or pearlitic material, and polished and etched (e.g. with plant acids or acetic acid which have been available since ancient times), the phosphorferrite will appear shiny and metallic unattacked against the more greyish and dull ferritic-pearlitic parts. Apparently this behaviour has been known for at least 2000 years and has been much appreciated for decorative purposes. Swords from Nydam, Denmark, about 300 A.D., display complex decorated surfaces from pattern-welding of phosphorus-rich with phosphorus-poor iron bars (Chapter 11).

A recent find emphasizes the role of phosphorus. In a mediaeval smithy in Tommarp, Scania, a number of very small tongue-shaped iron bars had been cautiously stored separately from other iron material. Twelve small bars weighed 15.4-15.2-13.2-13.0-11.6-10.4-10.1-10.0-9.2-9.0-8.9 and 5.9 g The larger, least corroded tongues measured 80 x 20 mm and were 3-4 mm thick. They were coated by smooth, chocolate-brown corrosion oxides, different from the usual rough oxides covering ancient objects, suggesting that the composition was unusual. Sections were prepared through five of the tongues, Table 7.6, lines 10-15. The rather homogeneous structure was composed of carbon-free phosphorferrite with ghost-structures, etch pits and local soft grains with phosphide needles. The hardness was variable, but in general high, due to phosphorus in solid solution. Various P-analyses of the metal phases showed a range of 0.3 to 0.6%.

Archaeological examinations of the thrifty mediaeval (1100-1200 A.D.) town of Tommarp revealed a significant number of purification slags and some blooms and manufactured articles, but no production slags (Thun 1967). The most likely scenario is that the iron production furnaces were located in northern Scania, e.g. at Ubbalt and Brunkelstorp, from where the blooms were transported south to Tommarp. Here they were cleaned, and phosphorus-rich parts were separated and forged into the characteristic phosphorus-enriched tongues. These were evidently in some demand, since one tongue has been identified at Eketorp's Borg on Öland (Statens Historiska Museum P 22-60, found 23 June 1966), and another has been found in Vestby, Denmark, Tables 12.4 and 12.13.

Table 7.6 is an attempt to reconstruct a production sequence according to this scenario. In the first three lines are entered production slags from places likely to have supplied the blooms. In the next three lines are entered purification slags from Tommarp, displaying

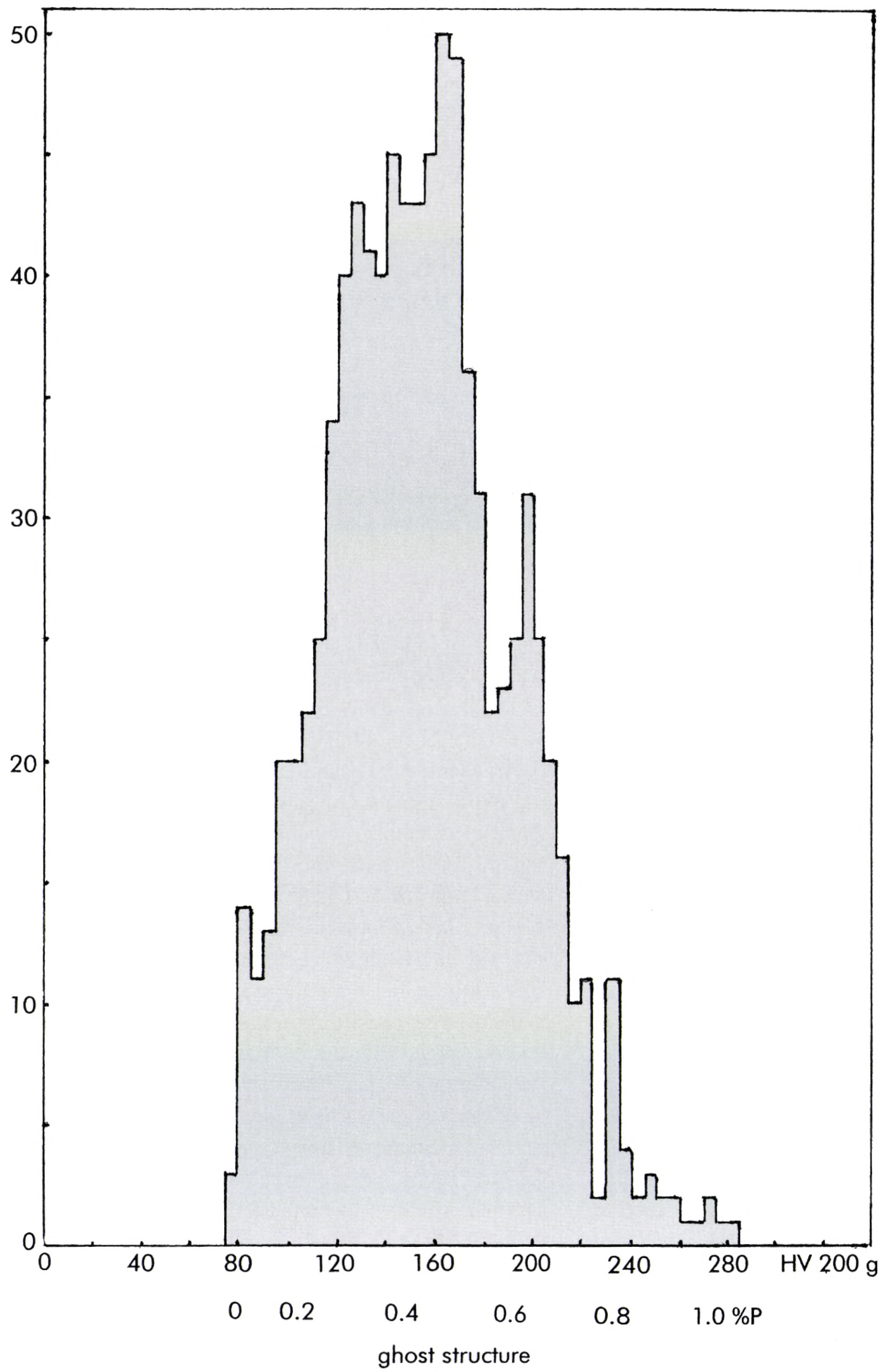


Fig. 175. The hardness, Vickers at 200 g load, of 150 iron objects with phosphorus in solid solution. There were 5-10 hardness impressions in each object. Carbon only present in trivial amounts. The approximate phosphorus content along the X-axis.

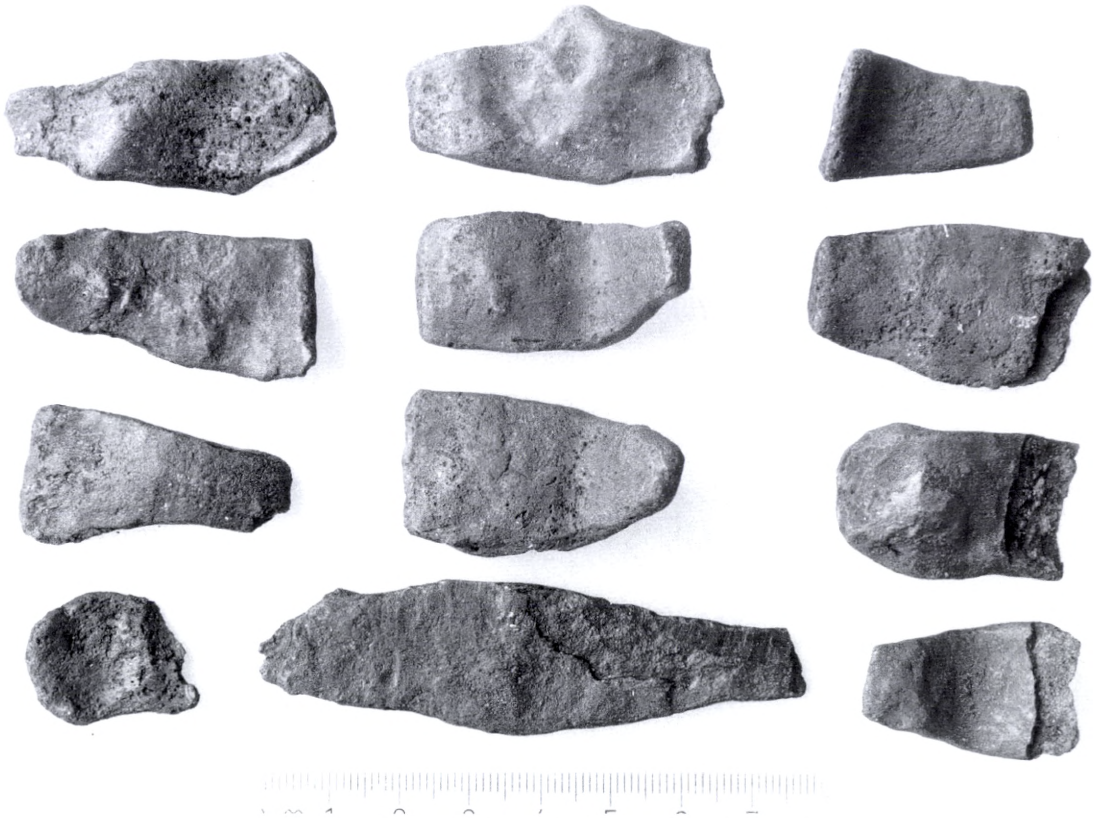


Fig. 176. 12 phosphor-tongues from Tommarp, Skåne. About 1100 A.D. Scale bar 8 cm. See Chapter 12.

the usual drop in manganese and phosphorus content. Then follow three lines with blooms and raw material for the P-tongues. And finally there are entered the slag inclusions in five of the P-tongues, No. 774-2 having been analysed in two different sections. Line 16 is the P-tongue from Eketorp which is almost indistinguishable from the Tommarp-tongues.

In the last line of Table 7.6 is entered the analysis of a 705 g purification slag from the town of Vä in northern Scania. It displays the normal depletion in MnO and P_2O_5. In the king's forge at Vä (Ödman 1992: 49) a large amount of similar slags were found, suggesting that blooms from the north were also here transformed and manufactured in the 13-14th centuries. A single bloom was also found (Ödman 1992). It measured 255 x 60 x 30 mm and weighed 3.46 kg. It was clearly a

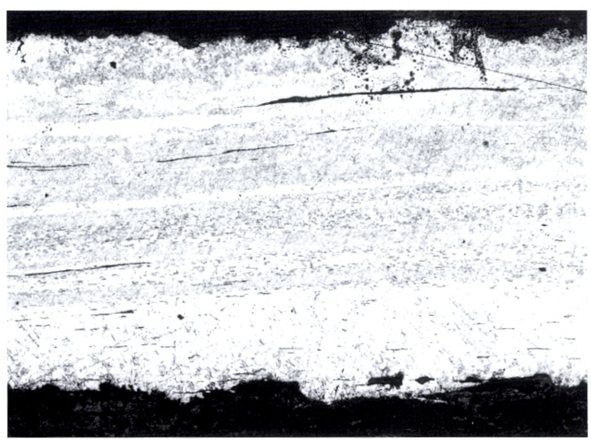


Fig. 177. Heterogeneous structure of the Tommarp tongue 774-1. Phosphorferrite alternates with ghost- structures and slightly carburized zones. PES. Side length 4.5 mm.

Table 7.6. SEM-EDAX analyses of slags and slag inclusions in Scanian material

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	41.8	26.2	3.2	1.2	3.2	18.7	4.0	1.4	0.2	0.1	tr.	100	2.24
2	34.6	33.7	3.6	1.1	4.5	17.5	3.8	0.7	0.3	-	0.2	100	1.98
3	22.3	55.4	4.7	2.2	1.9	10.7	2.0	0.1	0.4	-	0.3	100	2.08
4	22.5	69.1	0.2	0.2	1.3	4.4	1.6	0.2	0.3	-	0.2	100	5.11
5	30.5	59.6	0.3	0.6	1.5	5.3	1.4	0.3	0.3	-	0.2	100	5.75
6	34.1	52.7	0.1	1.6	2.5	5.8	2.4	0.3	0.4	-	0.1	100	5.88
7	23.6	47.4	1.7	3.9	4.0	10.1	4.8	1.2	0.6	0.1	2.6	100	2.34
8	28.2	48.4	0.9	2.9	9.8	5.5	2.6	1.1	0.3	-	0.3	100	5.13
9	28.1	56.7	3.7	2.3	1.6	4.8	1.9	0.3	0.3	-	0.3	100	5.85
10	26.3	56.9	1.4	2.7	2.1	7.1	2.0	0.8	0.4	-	0.3	100	3.70
11	24.5	50.8	5.0	7.5	2.1	5.6	3.0	0.7	0.4	-	0.4	100	4.38
12	23.0	54.5	5.2	6.8	1.6	5.0	2.3	0.6	0.5	0.1	0.4	100	4.60
13	26.1	55.1	4.7	1.0	2.8	5.8	2.3	1.0	1.0	-	0.2	100	4.50
14	38.9	33.4	9.7	1.6	3.8	7.7	3.3	0.9	0.4	-	0.3	100	5.05
15	32.9	48.8	1.0	1.4	5.8	5.6	2.5	1.0	0.5	0.2	0.3	100	5.88
16	29.0	44.9	2.8	7.0	5.0	4.8	3.5	1.8	0.4	-	0.8	100	6.04
17	30.1	53.9	0.3	0.7	4.3	7.1	1.8	1.0	0.4	-	0.4	100	4.24

1. Brunkelstorp, Scania. About 1500 A.D. 150 g producton slag with P-rich iron inclusions.
2. ibid. 750 g production slag.
3. Ubbalt, Scania. About 1450 A.D. 100 g production slag. From a lake ore similar to Table 6.1, line5.
4. Tommarp, Hemmet 1100-1200 A.D. Purification slag. 142 g kalot with charcoal fragments.
5. ibid. 99 g kalot fragment
6. ibid. 250 g kalot, No. 126 II.
7. ibid. Bloom fragment. 76 g. No. L 27-35.
8. ibid. Bloom fragment. 38 g. No. 23 II.
9. ibid. Wedge-shaped bloom. 1097 g. No. 191 II.
10. ibid. 15 g tongue-shaped bar. No. 774-4.
11. ibid. 10.4 g tongue-shaped bar. No. 774-2 B.
12. ibid. The same, another section.
13. ibid. 11.6 g tongue-shaped bar. No 774-5.
14. ibid. 15 g tongue-shaped bar. No. 774-1.
15. ibid. 13.2 g tongue-shaped bar. No. 774-3.
16. Eketorp's Borg, Öland. 16 g tongue-shaped bar. No. P 22-60.
17. Vä, Scania. 1250-1360 A.D. Purification slag. 705 g "hollow" kalot with magnetic parts and charcoal.

climp iron of the kind shown in Table 7.4. The climp irons were very common throughout the entire Middle Ages in Scania and the rest of Denmark.

The Vä analysis and the climp iron fit nicely into the Scanian picture and point to important iron production centres in northern Scania, in Ubbalt, Brunkelstorp, Vittsjö and other places in the Middle Ages (Nihlén 1939; Ödman 2001).

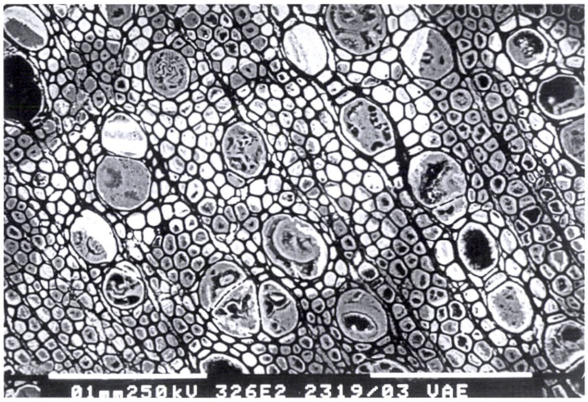


Fig. 178. Inclusion of charcoal in a purification slag (kalotslagge) from Vä, Skåne. The cell walls of the charcoal have been preserved by impregnation with iron oxides. PS. SEM. Back scattered electrons. Scale bar 0.1 mm.

Phosphorus does not follow the rules of correlation under changing redox conditions. The behaviour of phosphorus is mainly controlled by the temperature and by the acidity of the slag. Slags of high acidity, i.e. SiO_2 >50%, do not usually host phosphorus except for trivial amounts, less than about 0.2 weight% P_2O_5. The metal around the slags is highly reduced, contains 0.4-0.8% carbon, and normally displays pearlitic structures, that is, the material is phosphorus-free steel. Slags from the same furnace run, but less acidic, 20-30% SiO_2, may contain 10-100 times as much P_2O_5. The surrounding metal is ferritic, when the slag is relatively low in P_2O_5, and phosphorferritic when the slag is phosphorus-rich.

The Norwegian steel bar, Table 7.3 and Figure 160, contains not only acidic SiO_2-rich slags, lines 6-9, that are virtually devoid of phosphorus, but also, in the vicinity, less acidic slags, lines 1-5, that contain as much as 0.9% P_2O_5. This level is typical of many Norwegian objects which have been produced from red soil and bog iron ore with about 0.4% P_2O_5.

In figure 179 are shown the SiO_2-P_2O_5 relationship for a number of ancient objects. Many ancient Danish objects have 10-20% P_2O_5 in the slag inclusions, and correspondingly up to and even beyond 1% phosphorus in the metallic matrix.

The diagram shows that maximal P_2O_5 in the slag occurs with a slag acidity of 10-30% SiO_2. Simultaneously the adjacent metal will display maximum phosphorus in solid solution. When reduction in the furnace is carried beyond these values, and SiO_2, Al_2O_3, K_2O etc. increase systematically (Figures 160,162), FeO and P_2O_5 decrease, and above 45-50% SiO_2 only very small amounts of phosphorus are present in the metal and in the slag inclusions.

The brittle behaviour of iron and steel has been known for centuries, but what caused the much feared behaviour was unknown. Sven Rinman, an ingenious observer and experimenter in the 18th century, found the brittleness to occur chiefly in iron bars made from Småland's lake ores or from Grangerde's (= Grängesberg's) apatite-magnetite ores (Rinman 1782: 195, 197, 355, 453; Carlberg 1879 : 297,287). We know today that these ores contain more than ten times as much phosphorus oxide (2-5%) as the eminent Swedish ores from Dannemora, Norberg and Persberg. The Grängesberg apatite ores first became useful with the introduction of the Thomas process in the 1880s. In the 20th century the Grängesberg ores were the most important of Sweden's iron ores (Geer 1946: 200).

Sven Rinman devoted several chapters of his magnificent book (1782: 453 ff.) to the brittleness of iron (Swedish: kallbräckt jern). It was a nuisance, the phenomenon was little understood, and it turned out to be impossible to improve the brittle material by alloying or by introducing specific fluxes during smelting in the blast furnace. The practical solution for Rinman and his contemporaries was to avoid the unpredictable ores, or restrict their use to cast iron objects for which they proved quite useful. For some trivial objects, such as lock and watch parts, or buttons, which do not require coldwork, brittle iron was well-suited because it took a good polish and had a good corrosion resistance (Rinman 1782:49).

The blacksmith experienced the phosphorus-rich irons as pleasant to work with in the heat. They were easy to forge-weld, and they could be worked at all temperatures from a white heat to a dull red. They could be bent and twisted in any way and they behaved like the softest wrought iron. They were used all over Europe because the majority of the European ores contained phosphorus. The finished manufacture was nice, free of flaws, slightly harder to the file, and more free of inclusions than ordinary wrought iron. But when cold, that is room temperature and especially below, the phosphorus-enriched iron was sensitive to hammering, to shock and to bending. In the worst case, a brittle iron bar would fall into several pieces when hit hard at the end with a hammer. The fracture surface would then display a number of large grains with mirrorlike facets, the typical brittle fracture of ferrite. Perhaps the ancient slogan: "Strike while the iron is hot" was coined by blacksmiths who had observed the brittle behaviour of some qualities. Even if many irons would not display brittle behaviour, it was better to be on the safe side and always work while the iron was hot. It also required less effort.

Apparently the majority of the ancient reports on brittle failure, in use or in testing, concerns massive irons like bars and anchor chains. The behaviour of small items like nails, wires and lock parts has been little discussed. Perhaps they just survived daily use. Even phosphorferritic nails stood up to the hammer strokes. This is, in fact, quite surprising. It may be suggested that the different behaviour of massive and small objects, with the same composition, may derive from the microstructure. The massive objects had during forging and subsequent relatively slow cooling a chance to develop large α-grains with phosphorus in solid solution. The coarse-grained structure would be quite sensitive to shocks at low temperature. Anchor links of about 700 g and 20 mm cross section (Valloon iron, 1700 A.D.) may thus be broken by a hammer stroke, and the fracture surfaces exhibit 0.2-0.4 mm phosphorferritic grains with beautiful, shiny facets.

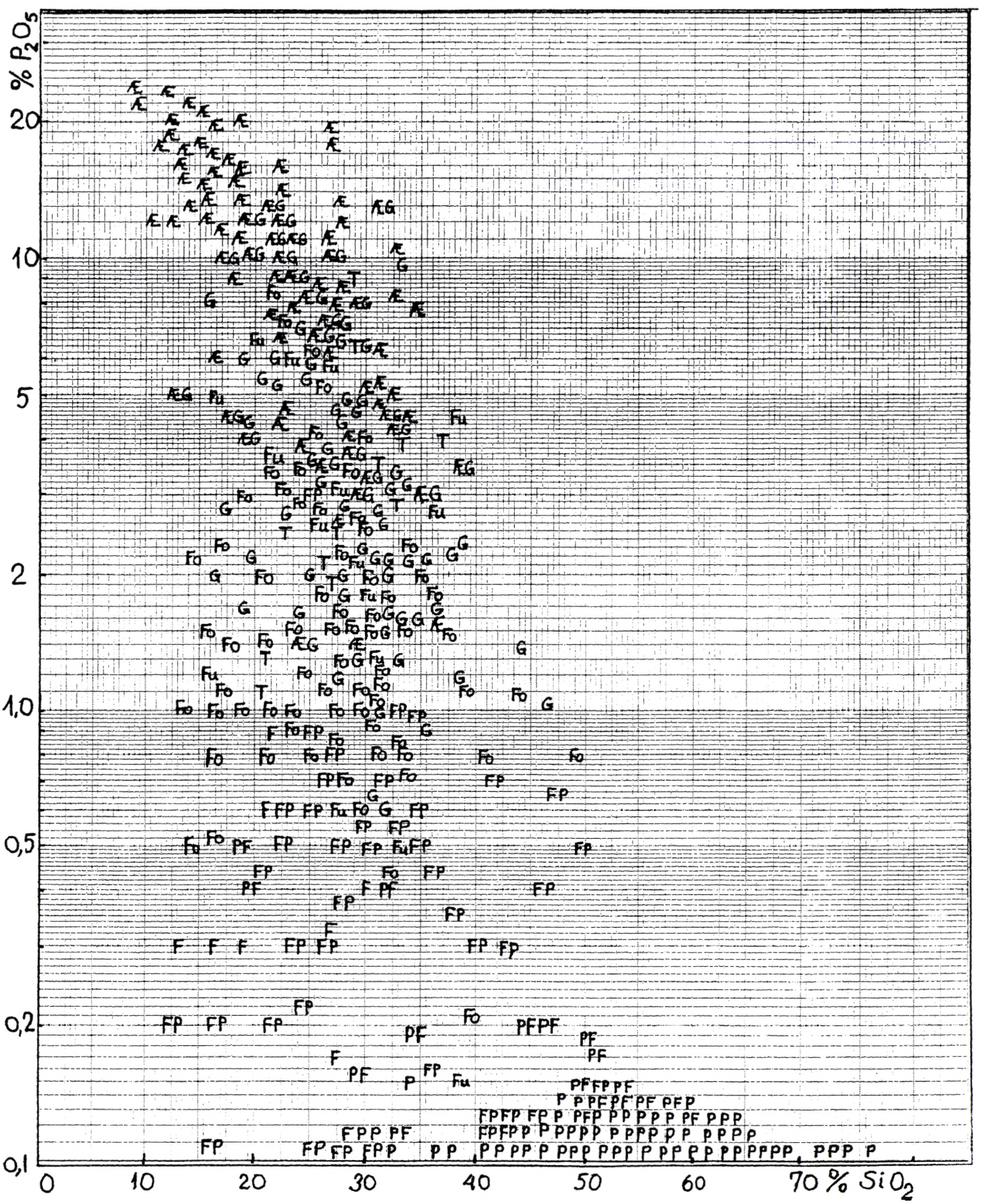
Small objects suffered a much more rapid cooling and tended to develop fine-grained phosphorferritic ghost structures, which evidently were less sensitive to brittle fracture.

In the northern countries like Norway and Sweden, the brittle behaviour was, no doubt, more feared than in the Mediterranean region. But of course, any ship sailing in northern waters would have been exposed to the risk of brittle failure of its iron components.

When engines, motors, rotating and reciprocating machinery, and railway transport became common in the 19th century, brittle failure became a real threat, often causing expensive and even catastrophic failures. Modern steel is now tested by shock-loading methods,, e.g. pendulum hammers according to Charpy and Izod standards, and they are rated according to the so-called transition temperatures (see e.g. ASM Handbook 1961: 225 ff). The brittle behaviour is kept under control, chiefly by the introductiom of strict requirements to keep phosphorus in steel below 0.04%, and sometimes even below 0.01%. Constructive measures, avoiding stress concentration raisers, are also applied when designing components. On the other hand, there are some sintered alloy steels on the market, where the addition of 0.3-0.6% P strengthens the material without seriously affecting its shock sensitivity (Lindskog et al. 1977).

The analytical methods described have their limitations. First, it is necessary to cut and remove a metallographic section, which in some cases may be undesirable from a museum standpoint. Second, there are cases when the sections are too small or happen to be so devoid of slag inclusions that it is difficult to find proper particles for analysis.Third, the material may prove too corroded. Many ancient wrought irons that have been excavated from the soil are severely corroded. If chlorine, introduced from the long exposure to groundwater (Buchwald & Clarke 1989), is present in the slag analysis, it is better to discard the analytical result. Chlorine detection is a warning that the elemental ratios may have been altered by selective leaching.

Fig. 179. The harmony between the slag inclusions and their surrounding metal phase is visualized in this diagram. About 250 iron objects have been examined. **F** ferrite, **Fo** phosphorferrite, **Fu** phosphorferrite with phosphide precipitates, **FP** ferrite-pearlite, **PF** pearlite-ferrite, **P** pearlite, **G** ghoststructure, **Æ** phosphorferrite with etch pits, **T** ternary Fe-C-P structures. Buchwald 2002.


% P_2O_5
20
10
5
2
1,0
0,5
0,2
0,1
0
10
20
30
40
50
60
70 % SiO_2

Some wrought irons contain mainly wüstite slags. This is probably due to the application of rather pure iron oxide ores or, in later times, to the exclusion of coal ashes such as occur in the puddling process. If the slag inclusions are 100% wüstite, the method breaks down. Vanadium, titanium and manganese in the wüstite may, however, give some suggestion as to provenance or process type, or both.

The metal detector and the Danefæ law

The metal detector is an electronic instrument for the detection of hidden objects, mainly of metal. The typical portable detector contains an electronic circuit, supported by 9 or 12 volt batteries. The high-frequency electromagnetic field (100-800 kHz) becomes slightly modified when the detector is moved over electric conducting objects. The signal change is amplified and transmitted to a loudspeaker, a display, or a meter. The sensitivity is dependent on the detector-spool's size, usually 20-25 cm in diameter, and on the object's mass, distance, and conductivity. A simple detector will easily reveal a coin 5 cm under the surface, or a water-pipe 20 cm down. Advanced detectors allow for a certain sorting of the signals in order to discriminate between fine conductors like silver, copper and gold, medium conductors like iron and steel, and bad conductors like ores and slags.

Metal detectors are used to find landmines, or, by craftsmen, to locate buried water-pipes and wires, and, of course, in the security check-points in airports etc. There exists specialized equipment for underwater work.

Permission to work with metal detectors varies from country to country. Since 1991 Sweden has prohibited all detector-hunting for ancient relics (Nielsen & Petersen 1993). In Denmark it is prohibited to enter private property, to search in the State forests and on protected antiquities. All objects which belong under the law of Danefæ ("dead man's property belongs to the king") must be delivered to the authorities, against a proper reward. This well- known law, which goes back to Jyske Lov (1241 A.D.), secures a fine cooperation between the detector-armed layman and the archaeological institutions.

Objects which are considered Danefæ are typically coins, jewellery, gems, and worked or decorated objects of amber and ivory. Bronze- and iron objects, and glass, will also be considered Danefæ, if their age, rarity and state of preservation speak for it (Glob 1980; Lund & Ørsnes 1982).

Chapter 8
Iron in Scandinavia in the Pre-Roman Iron Age

Then again smith Ilmarinen, on the evening of the third day,
stooped him down, and gazed intently to the bottom of the furnace,
and he saw the Sampo forming with its many-coloured cover.
Thereupon smith Ilmarinen, he the great primeval craftsman,
welded it and hammered it, heaped his rapid blows upon it,
forged with cunning art the Sampo, and on one side was a corn mill,
on another side a salt mill, and upon the third a coin mill.

Runo 10, Kalevala, translated by W.F.Kirby 1907.

In Scandinavia there is scattered evidence of local acquaintance with iron from about 700 B.C. The evidence is mostly in the form of insignificant slag occurrences, but occasionally a few iron objects have been identified. For many centuries iron was not produced here, but was imported as bar iron or as manufactured goods. The stray find of a Celtic bipyramidal bar in Jutland, Fig. 131, corroborates this viewpoint. Trading in metals had, of course, been known for about 2000 years, since neither copper nor tin were in those days extracted from Scandinavian ores.

While the knowledge of iron in the shape of bars, fibulae, jewellery and weapons goes back to the last phases of the Scandinavian Bronze Age, as already predicted by Montelius (1921), it is necessary to identify and date either iron production furnaces, or iron production slags, or both, in order to definitively establish the earliest home production stages. But slags and other traces of iron technology have unfortunately only entered the archaeological consciousness rather late, and many slag heaps and furnace remains which were reported by amateurs, e.g. Mortensen (1920), have in the meantime been lost due to intensive farming activities. The lack of interest was chiefly caused by the uncertainties associated with keeping slags of different categories apart from each other. In addition, furnaces and slags were difficult to date before the C-14 analytical method was introduced in the 1950s (e.g.Libby 1954; Levi & Tauber 1976). Another problem is connected with our forefathers' reuse of ancient bloomery slags. In Sweden and England this occurred already in the 18th century (Rinman 1782: 356), and in France, Germany and Italy it is at least documented from the early 20th century (Chapter 3: 10), when modern blast furnaces were charged with excellent "ores", i.e.ancient bloomery slags with 45-50% iron.

Denmark

In Denmark slags of unknown age were reported already by Langebek (1758: 455) from Vrads in central Jutland. Mortensen (1920; 1939) meticulously recorded 138 slag occurrences in Jutland, south of the Limfjord, some of which (Møgeltønder and Snorup) were to prove of the utmost importance as the central points

Table 8.1. SEM-EDAX analyses of slags and slag inclusions from Bruneborg and Grøntoft

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	16.3	72.0	2.3	-	1.3	2.7	3.4	1.3	0.2	0.2	0.3	100	4.79
2	20.2	67.0	2.2	tr.	0.9	1.8	5.6	1.7	0.4	0.2	tr.	100	3.61
3	24.1	61.4	4.7	0.3	2.2	2.1	3.5	1.3	0.1	0.3	0.2	100	6.89
4	28.4	59.9	1.1	-	1.0	1.5	5.9	1.6	0.2	0.3	0.1	100	4.81
5	23.8	64.1	1.1	-	4.2	2.6	2.1	1.0	0.4	0.2	0.5	100	11.3
6	27.3	59.2	2.3	-	2.1	4.2	3.0	1.1	0.2	0.3	0.3	100	9.10
7	20.3	72.8	0.5	-	1.9	1.1	2.3	0.4	0.4	tr.	0.3	100	8.83

1. Bruneborg, Ovsted sogn. 260 g heterogeneous slag. 500 B.C. Mrk.WX.
2. ibid. The same, another section.
3. ibid. 377 g heterogeneous slag. 500 B.C. Mrk.FC.
4. ibid. 597 g heterogeneous slag. 500 B.C. Mrk. VFB 1A.
5. ibid. 5 g nail. 500 B.C. Mrk. KVA 120.
6. ibid. 570 g tapslag, production slag. 200 B.C ? Mrk. VFB 2.
7. Grøntoft, Nørre Omme sogn. 750 g purification slag. NM M3/705, slag 209.

for later Danish research. Nielsen (1924) and Frydendahl (1931) produced further evidence for early Danish iron production, but as time went on many of the recorded traces were destroyed by agricultural machinery or road building.

A score of small iron objects, chiefly knives, bracelets, tweezers and pins, have been found in a variety of graves of early date, from the transition from the Bronze Age to the Iron Age. An elaborate list of these occurrences has been published by Nørbach (1998: 72). It is generally assumed that the objects are of foreign origin. For a short history of Danish iron research, the reader is referred to Voss (1991), Nørbach (2003) and to various papers in Hvass & Storgaard (1993).

Since the 1960s the situation has improved significantly, and a few old production sites from the last five centuries before Christ have been excavated.

In preparing the new E 45 motorway between Horsens and Skanderborg a small Iron Age settlement, Bruneborg, was identified (Jacobsen 1979; 1994; Jensen 2003: 502). Culture layers with ceramics and two buildings pointed to an age about 500 B.C. From a heap of more than 50 kg of roasted bog iron ore two test samples have been analysed. They show quite a variable composition, Table 6.3. More than 20 kg of slags were also recovered, but no furnace was found.

Fig. 180. Planoconvex slag of 377g, 9 cm in diameter, from Bruneborg, mrk.FC. 500 B.C. The surface near the tuyere at right (arrow) is weakly magnetic.

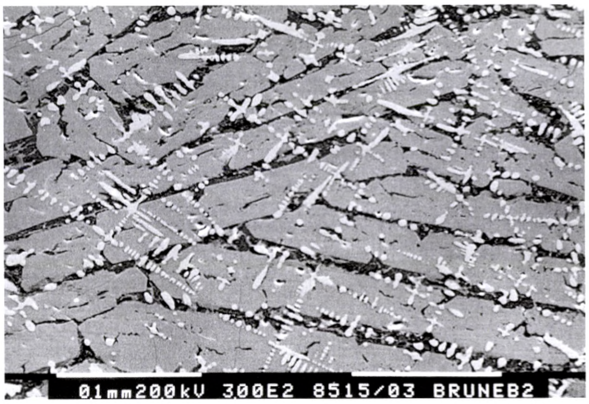


Fig. 181. Tap slag from an unidentified production furnace at Bruneborg, mrk VFB 2. 200 B.C. Fayalite laths, fine wüstite dendrites and duplex matrix. PS. SEM. Scale bar 0.1 mm.

A few iron objects, severely rusted, were discovered: a pair of tweezers, a knife, three fragments of rods or nails, and three objects impossible to identify. After a pause of about 300 years, iron handling was resumed on the site, resulting in more slags, but again no furnace could be found, and finished objects were utterly few. By the kind assistance of Jørgen Jacobsen, Odense, and Niels Th. Andersen, Moesgaard, material from the excavation was made available for this study.

In Table 8.1 are entered the analyses of three slags and a nail from the first phase, lines 1-5, and one slag presumably from the second phase, line 6. The three old slags are irregular, but display imprints of the bottom of a small, bowl-shaped hearth. The top sides of the slags are rather level, and two of them have

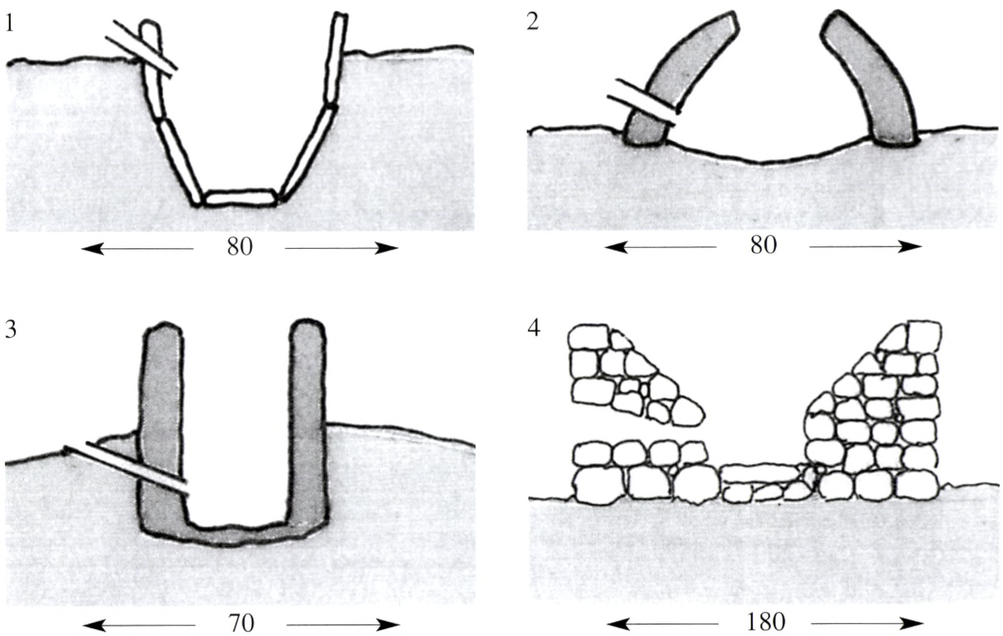


Fig. 182. Reconstruction sketches of four bloomery furnace types without slag tapping facilities. **1**, bowl furnace (Norwegian hellegryte). It is easily fed, e.g. with wood, and the bloom can be manipulated and removed with tongs from above. In use 0-1700 A.D. **2**, bowl or hearth furnace, possibly covered by a clay dome. Charcoal fired, semi-permanent structure (Wynne & Tylecote 1958). **3**, low shaft furnace, dug into well-drained ground. Built from clay, easily repaired and fed with wood or charcoal. Slag and bloom removed from above. **4**, stone-built low shaft furnace, known from Norway, Sweden and Finland 1400-1850 A.D. and often blown by water-mill driven bellows. Lately much used for experimental research of ancient iron production (Espelund 1993).

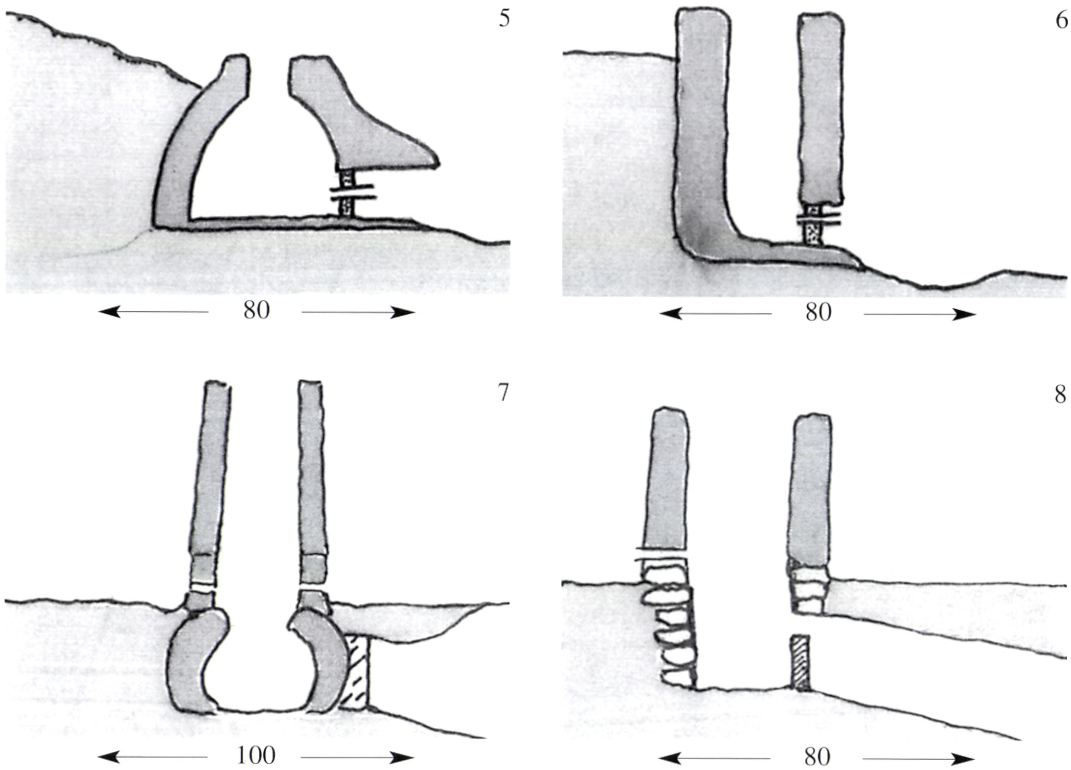


Fig. 183. Reconstruction sketches of four slag-tapping furnace types. So many furnaces are fragmentary, especially shaft furnaces, so it may be difficult from the remains to decide whether they were, in fact, bowl furnaces or the remains of shaft furnaces. **5**, domed furnace as found in England and Siegerland, and common in the La Téne period (Pleiner 2000: 158), **6,** the Roman low shaft, provincial furnace, e.g., at Ashwicken, Norfolk, from 200 A.D. (Tylecote 1987: 171). **7**, the Skovmark type, known from Denmark and North Europe, 200 B.C.-200 A.D. Charcoal fired, bellows operated. Thick walled and partly buried. The opening to the pit was reinforced by stones, possibly to ease raking the slags away from the furnace bottom (Voss 1994; 2003). **8**, slag-pit furnace from Heglesvollen, Norway, apparently of the same age as No. 7. Probably wood-fired, reusable. Often operated in batteries of 4-5. The slag was raked out through the pit and thrown down the slope, Figs. 235-236 (Espelund 1991:83).

impressions of the tuyere. The slags are heterogeneous, partly layered, and composed of rather coarse-grained wüstite, manganese-rich fayalite and a glass phase.

The slags are unusual by their shape and heterogeneity. For the interpretation as production slags speak their rather high manganese and phosphorus contents, the presence of barium, the amount of 20 kg slags and the presence of roasted iron ore. On the other hand, their layering, shape and tuyere imprints point to an interpretation as purification slags. In that case, the activities must have been based on iron blooms imported from the Celtic areas.

I am inclined to favour the first explanation, and would suggest that the furnace was a small bowl-shaped hearth, which is easily destroyed and lost from the record. The low F-values fall outside the typical Danish values perhaps because the slag material is very heterogeneous and difficult to interpret.

The rusted nail, of 5 g, had been annealed by the

Rosenberg method, so hardness determinations were less meaningful. The structure was phosphorferritic with ghost-structures in accordance with phosphorus-rich ores, and the F-value points to a Danish production site.

The younger slag, line 6, was of an entirely different kind. It was a typical tapslag, a plate of 570 g with worm-like, tubular surface features. Sections showed a number of consecutive runs from the furnace, but all layers were similar in composition and fine-grained structure. The fine grains were caused by the relatively rapid cooling of the tapslag outside the fur-

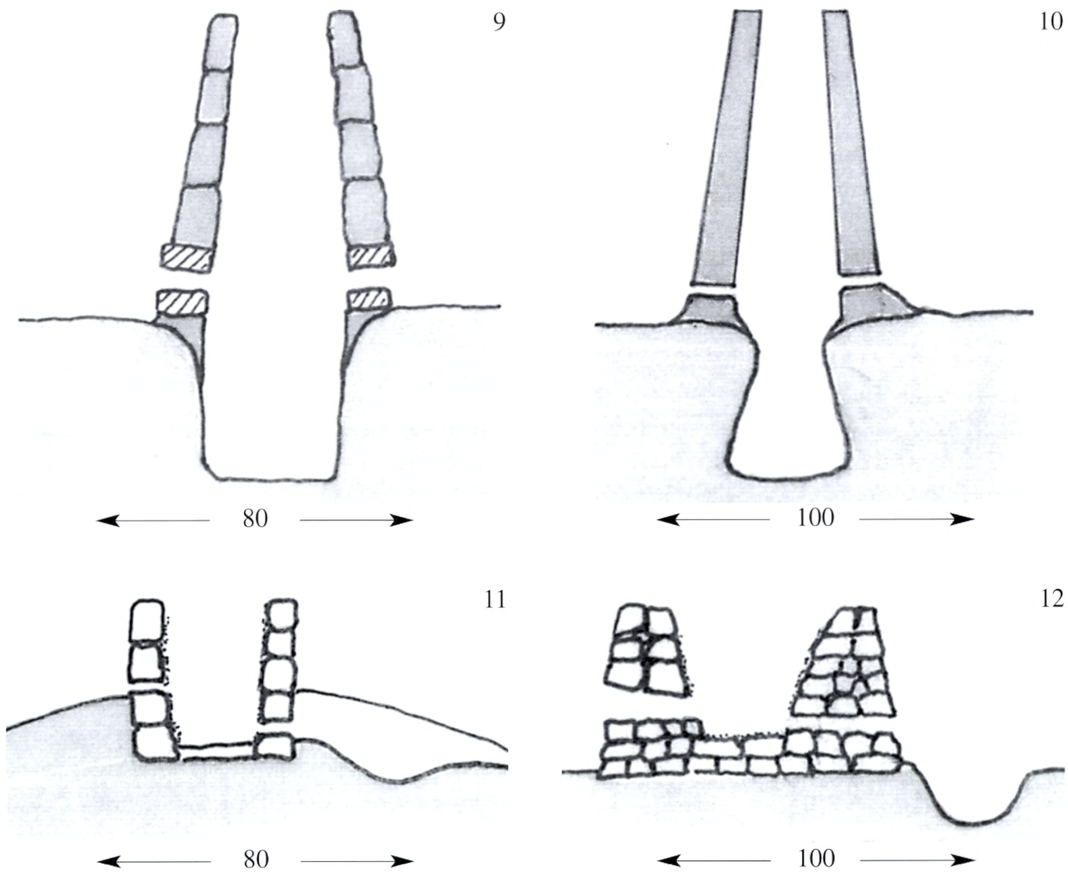


Fig. 184. Reconstruction sketches of four slag-tapping furnace types. **9**, slag pit furnace. Clay built cylindrical shaft over a deep pit filled with wood to carry the initial charge. Charcoal fired, and left when the pit had run full of slag, 100-500 kg. Often arranged in batteries, as in Biskupice and the Holy Cross Mountaíns in Poland, 100-500 A.D. (Bielenin 1983). **10,** the Scharmbeck-Snorup type slag-pit furnace of approximately the same age. Clay built cylindrical shaft. Charcoal fired operation as No. 9, but the pit was slightly different in shape and was filled with straw. At least 8000 furnace sites have been identified in Jutland (Voss 2003). **11,** clay or stone built low shaft furnace, partly embedded in a clay mound. Charcoal fired, permanent structure. Medieval bloom taken with tongs from above, slag tapped in an open groove in front of the furnace (Swedish: Fårskalle slag). Often operated in pairs, e.g., at Tranemo, Jernvirke and Sunnanäng (Serning 1973; Englund 2002). **12,** free-standing stone built, permanent furnace with mechanical blowing (water-mill) and slag-tapping. Wood fired, bloom manipulated and taken with tongs from above. Common in Norway, Finland and Sweden 1400-1850 A.D. (Nihlén 1932: 67; Englund 2002).

nace. Perhaps the unknown furnace was of the Skovmark type.

The first furnace of this type was excavated at Skovmark, 17 km north of Aalborg, in 1966, but since then another 15 sites from all over Denmark have been found and C-14 dated to between 200 B.C. and 100 A.D. (Voss 2003). Only those parts of the furnaces which were below the cultivated topsoil are preserved. It appears to have been a slag-tapping furnace, operated by bellows (tuyere-plates of clay have been found). Similar ones are known from northern Germany (Jöns 1992), southern England (Money 1974) and Bohemia and Ukraine (Pleiner 2000: 167). A tentative reconstruction (Voss 2003) is shown in Figure183[7]. The Skovmark furnace type was reusable. Nevertheless only limited amounts of slags, 20-200 kg, surround them. All are apparently associated with settlements.

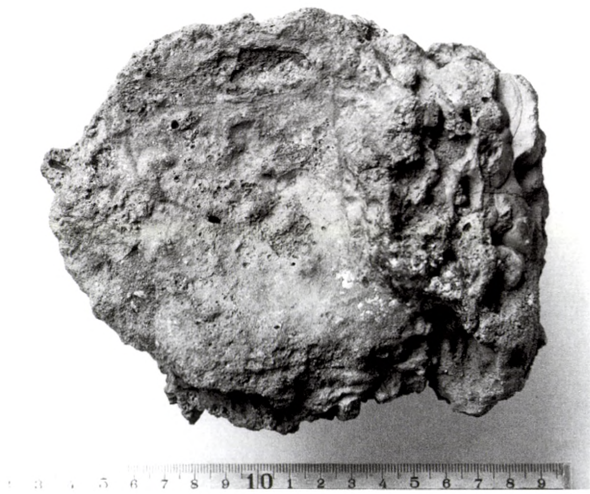


Fig. 186. Purification slag (kalotslag), 750 g, 16x13x6 cm, from Grøntoft. Nat.Mus.1967. M3/705, slag 209. About 100 B.C.

Fig. 185. A Swedish furnace from about 1000 A.D. Type 11. Sunnanäng near Lake Siljan, Dalarna. The clay built furnace in the foreground has an inner diameter of 40 cm. The structure in the background supported the bellows. Outside was a large tap slag, a "fårskalle". Serning 1973.

Common to all slags in Table 8.1 are a high FeO-content and a high specific gravity, indicating an early step in the iron technology when much iron had to remain in the slags. As in the majority of Danish objects, the phosphorus content is high in slags as well as in manufacture.

Near Grøntoft, Nørre Omme sogn, 20 km NE of Ringkøbing, two Iron Age settlements (Pre-Roman Iron Age periods I-II) were excavated from 1961 to 1966 (Becker 1968; Jensen 2003: 27). Thirty years earlier Hatt (1936) had discovered a number of slags on the site. He described a circular clay pan, about 2.6 m in diameter, associated with charcoal of oak and some bog iron ore, which apparently came from the slightly lower fields northwards towards Pøl. An anvil stone of quartzite was also found. Hatt was much confused about both the clay pan and the slags.

From the National Museum, Copenhagen, one of these slags, a 750 g planoconvex slag, labelled "1967. M3/705, slag 209" was obtained. The slag is of the typical purification kalot type, 16x12 cm across and 4-6 cm thick. The underside is unmagnetic and has impressions and mineral grains from the purification hearth. The topside has magnetic parts where the blast from the bellows has oxidized iron

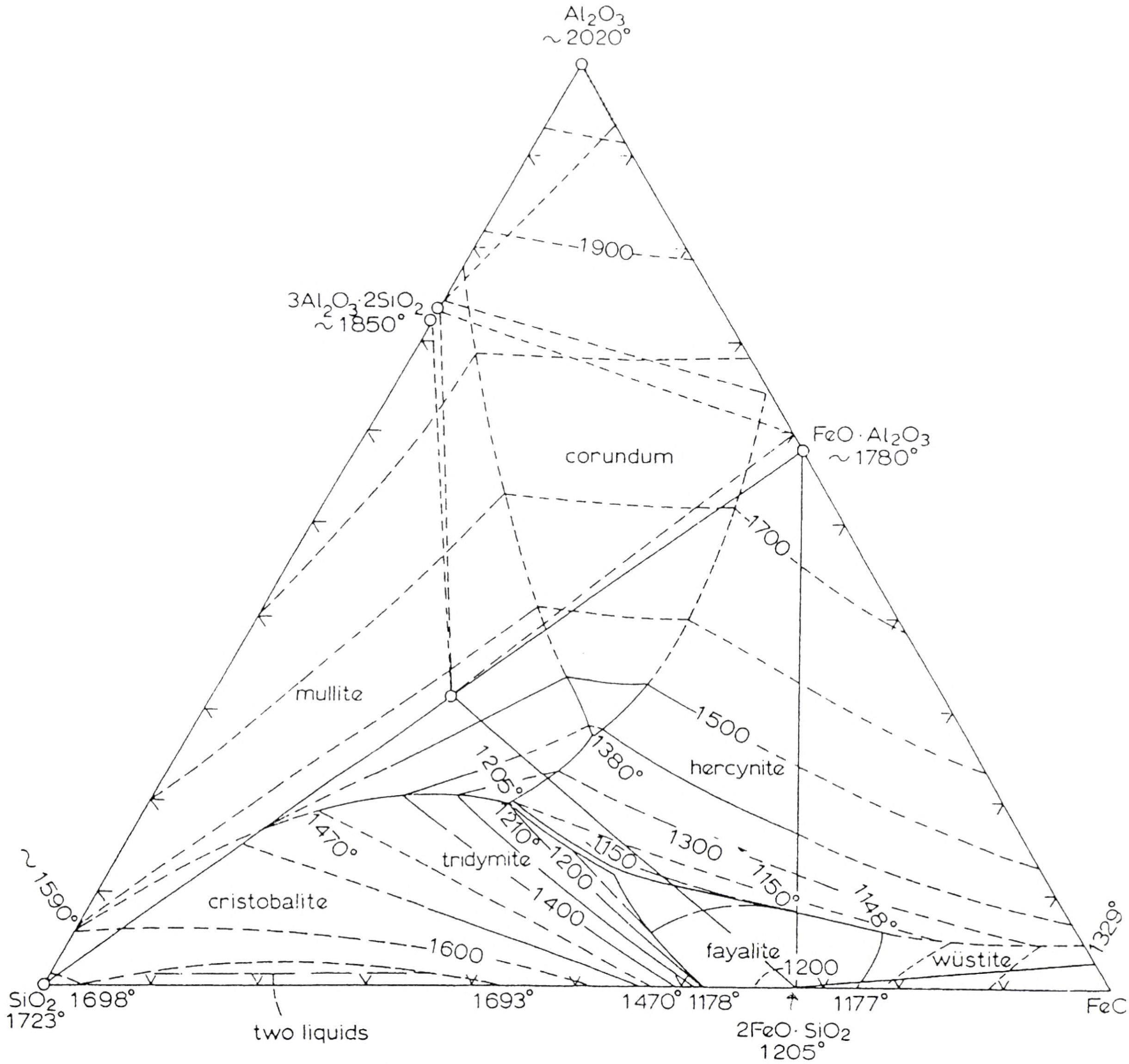


Fig. 187. Ternary diagram for FeO-SiO_2-Al_2O_3. The phases wüstite, fayalite, hercynite etc. are the first to crystallize from a liquid slag within the fields indicated. E.M. Levin et al. 1956.

oxides to magnetite. The sections display a rather homogeneous, dense slag with some gasholes. The phases are 60% massive rather pure fayalite, interwoven with 10-15 μm wide wüstite dendrites (25%), and a glassy matrix. Part of the matrix is pure leucite, $KAlSi_2O_6$.

The Grøntoft scenario is best interpreted as a settlement where only the first step (Table 4.4), the roasting pan with associated bog iron ore and oak fuel, and the third step with purification slags have been identified. It appears as if the production furnace(s) and the production slags might have been located in the vicinity.

Hatt (1936) also described an iron production site in Fogstrup, Them sogn, 12 km SSW of Silkeborg. The furnace was not found, but several clay pans, about 3.5 m in diameter, were identified. Modern ploughing has thoroughly destroyed the site, but numerous slags could be collected, many of them being found in the dikes, as they had been removed from the tilled fields. At least some of the slags appear to be of the purification type. Mortensen (1939: 154), who visited the site after Hatt, found a clay-lined production furnace, about 50 cm in diameter, but it is not clear whether this installation is contemporary or not. The Fogstrup site in general is rather similar in appearance and age to Grøntoft and has been accepted as an early Pre-Roman Iron Age site (Nørbach 1998).

In the years 1921-1922 the remains of a boat with a large number of iron weapons were excavated (Rosenberg 1937; Broholm 1960; Kaul 1988, 2003; Jensen 2003: 67). The Hjortspring boat, a 19 m long rowing boat, had been deposited in a small lake, 50 m in diameter, about 3 km from the Baltic Sea, Fig. 276. The boat was built of lime with a few supporting staves of oak, and it had oars of Danish maple (naur). Iron nails or rivets had not been used. C-14 dating of the wood places the sacrificial burial in the Pre-Roman Iron Age, period I, about 350 B.C. It is thus 600-700 years older than the better known Nydam boat and the many Scandinavian weapon-sacrificial sites. A modern replica of the Hjortspring boat has been tested for seaworthiness, and contrary to earlier opinions, been found to behave brilliantly on the open sea. Rowed by 22-24 oarsmen – there was no mast or sail – its range was about 100 km in a long day's sailing (Kaul 2003).

The weapon deposit consisted of 8 rather short, single-edged swords, 138 lance- and spearheads of iron and 31 of deer antler and sheep's bone, and some minor fragments. The cache of more than 64 oblong to rectangular shields is a treasure and the best from the prehistory of Europe. The weapons have been studied by Becker (1948) and Randsborg (1995). Some of the swords and spears were ritually bent or damaged before deposition.

Another important find from the Celtic Iron Age, but perhaps 100 years younger, comes from a stone-laid Iron Age road in Krogsbølle sogn, 19 km north of Odense (Kjær 1901). After a fight, the victorious warriors had sacrificed 7 iron swords, 5 of which were single-edged, 23 spearheads of iron, and 19 of pointed bones. Some of the spears had their points driven violently down through the pavement, indicating that the road was still older. Becker (1948) has convincingly argued for a dating of the weapons to the Pre-Roman Iron Age, period II.

The Hjortspring and Krogsbølle sacrifices are good illustrations of Caesar's statement in De Bello Gallico, Book 6: 17: "To him (Mars) when they have resolved to engage in battle, often they vow those things which they may take in war; the animals which may have survived when captured they sacrifice; and bring together the remaining things into one place. In many

Fig. 188. Knife fragment, HOM 151x684, from grave A 2018 at Hedegaard. Annealed by the Rosenberg method. 19 cm long.

states there may be seen piles built of the things in consecrated places. Nor does it often happen that any one, religion being disregarded, should dare either to conceal at his home the things captured, or to take away the things deposited, and the most grievous punishment with torture has been ordained for this thing."

It is the general opinion that the iron weapons belonged to the intruders and were not produced in Denmark. The shields in the Hjortspring boat are of Celtic origin, and at least one of the Krogsbølle swords (Becker 1948: Fig. 17-1) is a two-edged sword and very similar to the Celtic swords, discussed in Chapter 5, Table 5.1.

During the planning of a pipeline for natural gas through central Jutland, an Iron Age settlement was discovered at Hedegaard, Ejstrup sogn, about 11 km east of Brande. The site was excavated 1986-1993 and, importantly, yielded both an older settlement with its cemetery, and a 100-year-younger settlement, partly covering the cemetery (Madsen 1992; 1999; Jensen 2003: 163). Many of the oldest graves from about 50 B.C. to 50 A.D. were rich cremation graves, while the younger ones, from the Early Roman Iron Age, were inhumation graves.

In 1987, a well-preserved iron furnace of the Skovmark type was excavated about 16 m south of the southern fence (Voss 1988). The furnace may be dated to the beginning of our time reckoning. Iron slags were found here, as well as in the up to 1 m thick culture layers inside the older of the settlements. In Table 8.2, line 1 an analysis is presented. It is a production slag, slowly solidified inside the furnace, with very coarse, blocky fayalite crystals. The fayalite is rich in manganese, with 4-6% MnO in the molecule. In the glassy matrix are pockets of barium-rich (4-6% BaO) calcium-iron phosphates. Further were identified hercynite with 1% TiO_2, and wüstite with 1% MnO. The slag is a typical Danish production slag of the western Jutland variety with a rather low calcium content (Chapter 6).

A 14 g fragment of a knife found in Grave A 2018 may have been produced in this furnace or another

Table 8.2. SEM-EDAX analyses of slags and slag inclusions. Hedegaard, Espevej, Skydebjerggaard and Holsegaard.

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	25.7	60.1	4.8	0.3	4.6	1.0	2.6	0.4	0.2	<0.1	0.2	100	9.88
2	30.1	56.5	2.7	-	6.1	1.6	2.2	0.4	0.3	<0.1	-	100	13.7
3	66.5	4.5	3.4	-	0	12.2	9.4	2.1	0.7	0.9	0.3	100	7.07
4	31.8	42.6	0.7	-	13.2	3.8	4.9	1.8	0.6	0.6	-	100	6.49
5	28.0	58.1	2.1	0.1	3.2	3.8	3.2	1.0	0.1	0.3	0.1	100	8.75
6	25.4	60.4	2.2	0.1	3.4	3.7	3.0	0.9	0.4	0.3	0.2	100	8.47
7	36.6	50.3	2.9	-	2.1	2.7	3.6	0.8	0.6	0.3	0.1	100	10.2
8	53.5	22.6	0.1	-	1.4	10.2	9.1	1.2	1.1	0.7	0.1	100	5.88

1. Hedegaard, Ejstrup sogn, Aarhus amt. 150 g production slag. About the year 1.
2. ibid. Grave HOM 151 x 684. A 2018. Fragment of corroded knife. Annealed. HV: 156-157-162-170-177.
3. ibid. Grave HOM, A 1086. Iron ring, 6x6 mm, 26 cm diam. Annealed. HV: 135-136-148-154-174.
4. ibid. Grave HOM 151x1088. A 4153. 24 cm long knife. Annealed. HV: 167-178 192-196-203.
5. Espevej, Boeslunde sogn, Sorø amt. 38 g production slag. About 100 B.C.
6. ibid. 64 g production slag.
7. Skydebjerggaard, Boeslunde sogn, Sorø amt. 200 g production slag. About 100 B.C.
8. Holsegaard, Brenderup sogn, Odense amt. 78 g manufacturing slag, sinder. About the year 1.

Fig. 190. A gold spiral and two massive gold beads from the rich grave A 1086 at Hedegaard. See the Box.

> Hedegaard, grave A 1086, 50-1 B.C.
> In the urn with burnt bones were small bronze objects, two massive gold beads and a gold spiral. The best preserved gold bead weighed 6.4 g, while the other, damaged first on the funeral pyre and later by selective corrosion, weighed 6.0 g. The gold spiral was made from a band with rectangular cross section. Microprobe analysis gave the following results:
>
> - 6.4 g gold bead: 80% Au, 16% Ag, 4% Cu. That is better than 19 carats.
> - 6.4 g gold spiral: 96.5% Au, 3.5% Ag. That is better than 23 carats.
>
> The gold bead was made of a good-quality casting alloy. The gold spiral was made of almost pure gold, notable for its ductility and eminent for wire drawing or hammering into band shape. From other sites, ancient small anvils have been reported, provided with a furrow for the hammering of wire.

similar, local one. In line 2 is the average of the slag inclusions, which is in harmony with the production slag, line 1. The knife was annealed on the funeral pyre, and again by the Rosenberg method, so its structure and hardness have been significantly altered. The structure now consists of equiaxial 100-250 μm phosphorferrite grains with about 0.4% P in solid solution.

Grave A 4103 contained a black-burnished, meander-decorated vase with burnt bone. Next to it was a much rusted conglomerate of a 16 cm long pair of shears, a 16 cm spearhead, and a 35 cm long dagger with its decorated iron sheath (Madsen 1999, Fig. 22 A). The rather unique knife is of the Roman legionary type, pugio, mainly used in the first 50 years of our time reckoning.

In another very rich grave, A 1086, were found an urn with burnt bone and various small bronze objects, a gold spiral, and two massive gold beads. Under the urn were many iron and bronze objects, among which may be noted a bronze belt, an iron sewing needle, an awl, and a straight-backed iron knife. On top of it all was a circular iron ring with a square section of 6 x 6 mm. Its outer diameter was 26 cm. Its purpose is not understood. Perhaps it had once served as a reinforcing ring in a bronze cauldron? Three small samples were taken from the ring and analysed.

The ring had originally been a fine pearlitic steel with 0.6-0.7% C and no phosphorus. It had been thoroughly annealed and somewhat decarburized because it had been placed on the funeral pyre. The structure is now Widmanstätten ferrite-pearlite with 0.2-0.4% C and a corresponding hardness. The ring is covered by a 0.4-0.5 mm thick scale of high-temperature oxides from the annealing: Innermost wüstite, FeO, followed by a major magnetite layer, Fe_3O_4, and a thin outer hematite layer, which is glowing red under crossed Nicols. Late corrosion has created significant pockets of hibbingite and akaganeite.

The slag inclusions, Table 8.2, line 3, are foreign to Danish material. It appears, in fact, that the ring is related to the steel types found in the Celtic swords, Table 5.1, e.g. Nos. 601, 510, and 597. Perhaps the

Fig. 189. A Roman dagger, a so-called pugio, with its decorated sheath, from a grave at Hedegaard. Corrosion has sintered the dagger to other grave gifts, such as a pair of scissors. Courtesy Orla Madsen.

Fig. 191. A straight-backed knife of 92 g, HOM 151x1088, from grave A 4153 at Hedegaard. Annealed on the funeral pyre and again by the Rosenberg conservation method. Probably imported from a Celtic environment. 24 cm long.

ring was manufactured from a steel bar from the Celtic area?

In grave A 4153, a 24 cm long knife of 92 g was found. It is similar to Fig. 10-3 in Madsen (1999), though smaller. It had been annealed on the funeral pyre and now displays a heterogeneous structure of Widmanstätten pattern and 0.15-0.25 mm phosphor-ferritic grains, ranging from 167 to 203 in hardness. The phosphorus content is high, 0.7-0.9%. The slag inclusions, line 4, are very rich in phosphorus, but do not

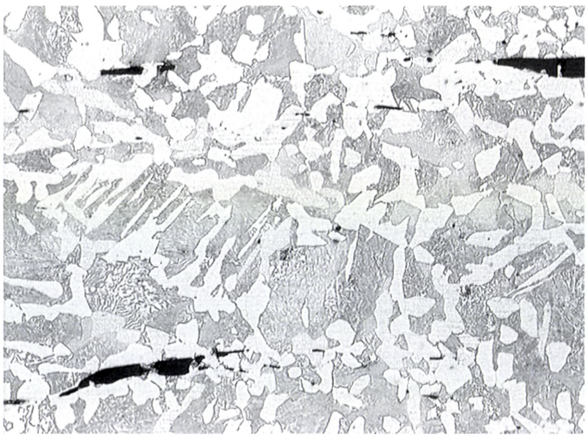


Fig. 192. Ferritic-pearlitic part of the knife, Fig. 191. The Widmanstätten structure is due to the relatively rapid cooling in soda after the Rosenberg annealing. PES. Side length 0.6 mm. Courtesy FORCE Technology.

belong in a Danish scenario. The knife, like so many of the bronze- and gold objects in the cemetery, rather belongs to a Celtic environment.

In grave A 4137 were found a single-edged sword, two knives, a spearhead, and an iron-ring mail shirt (Madsen 1999, Fig. 28). The total weight of the (corroded) mail shirt was about 10.3 kg. Each ring, measuring only about 5 mm in diameter, was made of soft wrought iron wire, 0.9-1 mm thick. Each ring interconnected with four others, every second ring being closed by riveting. Corroded mail shirts were also reported from Hjortspring, but as yet the Hedegaard mail shirt is the earliest well-preserved grave find from Denmark.

A boat grave was also found, chiefly as an impression in the soil, 3.65 m long and 0.6 m wide. An attempt was made to make a preparation of five identical iron clamps, evidently from a repair in ancient times. All that could be learned was, however, that the wood had been oak, while the iron had been entirely converted into rust.

The general impression of the Hedegaard community is that of an impressive contact with the Germanic and Celtic neighbours. The bronze cauldrons, the gold objects, and a major part of the iron objects came from there. Perhaps a few iron objects for daily use were made in the settlement, as witnessed by the furnace, the few production slags and the knife from grave A 2018.

Slags from about the same time as Hedegaard have been examined from the iron production sites with furnaces of the Skovmark type, Espevej and Skydebjerggaard, Sjælland (Voss 1988;1991). The Espevej furnace is small, horseshoe-shaped, with an inner diameter of about 30 cm and an estimated height of 50-100 cm. It was dug about 50 cm into the soil, appreciably deeper than the contemporary Hedegaard furnace, which it resembled. The lower part of the furnace was covered with a removable clay-plate with a hole for the bellows, and there was a working pit in front. Presumably two bellows had been operated from the pit.

A total of 8 kg of slag was found in small fragments. In addition, two large slags of 4.8 and 8 kg were found. These presumably represented the bottom shape of the furnace. Two of the smaller fragments have been analysed and are entered in Table 8.2, lines 5-6 They have stalactite morphology and are fine-grained mixtures of about 10% wüstite, 50% fayalite and 40% P-Ca-rich matrix. The fayalite is calcium- and manganese-enriched.

The Skydebjerggaard furnace is situated only 4.5 km SE of the Espevej furnace, and it is very similar and from the same period, about 100 B.C. One of the few slags on the site was analysed, Table 8.2, line 7. Its structure is 50% manganofayalite and 50% fine-grained matrix.The slag displays some unusual spotted rims, which apparently are unequilibrated leucite-glass mixtures, Fig. 194. In composition the Espevej- and Skydebjerggaard slags are rather similar, and distinct from the Hedegaard/Jutland slags by their higher calcium, potassium and titanium, and lower manganese and barium content. No iron objects were discovered at the furnace sites.

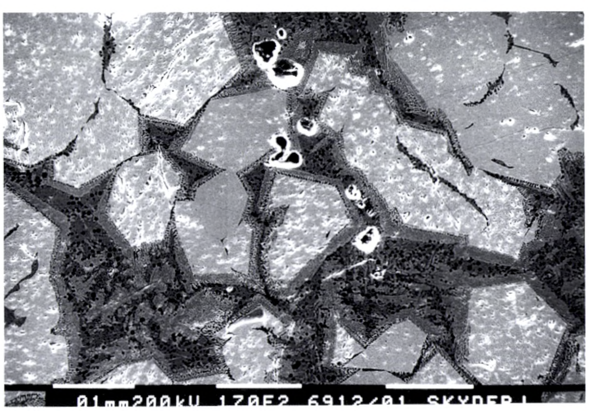


Fig. 193. Production slag from Skydebjerggaard, Sjælland. No wüstite, but a 1:1 mixture of fayalite with 4% MnO and an unusual matrix. PS. SEM. Scale bar 0.1 mm.

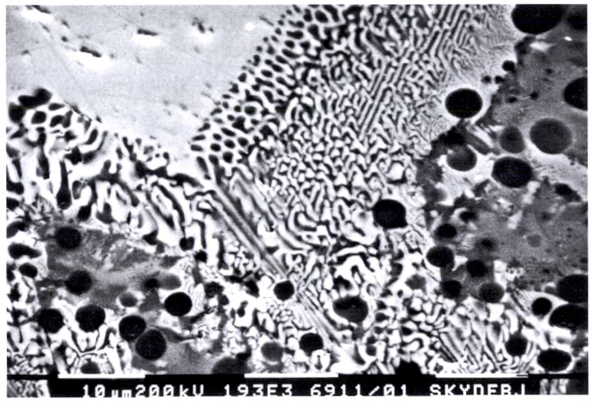


Fig. 194. Detail of the matrix in Fig. 193. Perhaps an "eutectic" of some sort. 44% SiO_2, 36% FeO, 6.5% Al_2O_3, 4.8% CaO, 3.2% P_2O_5 and 2% MnO are the essential components. PS. SEM. Scale bar 0.01 mm.

On the island of Fyn, at Holsegaard, Brenderup sogn, several slags were found (Albrectsen 1956; Henriksen et al.1997:21) and estimated to be from the beginning of our time reckoning. One slag of 78 g was found in the ploughed field 0.8 km NE of Holsegaard in 1987 by Peter Mortensen. It is a rather heterogeneous manufacturing slag, a sinder, with undissolved quartz and feldspar grains, ranging from 50 µm to 2 mm in size. It has a low density, about 2 g/cm^3. The structure is heterogeneous and glassy, locally with many skeleton magnetite crystals. The average slag analysis is entered in Table 8.2, line 8. The nature of the slag suggests that there once was a forge, a smithing hearth, where bars from elsewhere were manufactured into finished objects, or perhaps just ordinary repair work was practised.

Iron objects of the late Pre-Roman Iron Age are almost never found in association with furnaces or hearths; they have to be studied from contemporary grave finds. Some graves are extraordinarily rich, and a few are wagon graves. The Langaa graves, about 5 km north of Gudme, Fyn, contain a Celtic bronze cauldron, Etruscan bronze works, a dinos from Capua ("Langaakedlen"), gold fingerrings and the remains of a wagon. Some of the cauldrons have rims reinforced with 6-8 mm thick iron bars, and swords, spears and shields are common (Sehested 1878).

At Møllegaard, Broholm, 2 km east of Gudme, a large cemetery was excavated by Sehested (1878; 1884). In the many graves were plenty of iron weapons, knives, scissors, and fibulae, but also iron rings and bars of uncertain definition. In grave 117 was a 17 cm long iron axe, and in grave 152 an iron spur with a 4.6 cm long pig. These items are apparently early in a Scandinavian context. Almost all objects have been on the funeral pyre and have been placed with semi-melted bronze objects and burnt bones in or near the clay-built urn.

At Kraghede, 4 km south of Sønder Brønderslev, Vendsyssel, an important settlement and cemetery, which was in use both before and after 0, was excavated. One of the rich cremation graves contained a broken bronze cauldron with iron-reinforced rim, a razor, a knife, a single-edged sword with sheath, a spearhead, and two pairs of scissors. Another grave, from 100-50 B.C., contained the remains of a bronze-decorated wagon, a knife, scissors and a spearhead. All had been severely damaged on the pyre, but it was clear that the wheel-nave had been reinforced by iron as we saw in Chapter 5.

At Dejbjerg, 8 km NW of Skjern, the two famous Dejbjerg wagons were excavated in the 1880s (Petersen 1888; Jensen 2003: 195). The bronze ornaments and many other details point to a Celtic tradition, and perhaps even a Celtic origin. The wheels had rims of ash which were in one piece, and the rims were covered by iron bands in one piece, which had been fitted on while glowing hot. About 1 km WSW of the Dejbjerg find a small contemporary cemetery with at least one astonishing grave was found (Hansen 1991). In the cremation graves were the usual iron knives and fittings for the clothing, but five graves contained swords, spears and shields. The larger pieces had been bent before they were placed in the narrow grave pit. A unique grave consisted of a 3 m long coffin, only partly buried and placed under a wooden roof. The grave contained two cups, a beaker, a single-edged sword and a spear. The grave is unique for its time and could have been the last resting place for a person of high status from the Dejbjerg society.

Many other graves and grave fields from the same period have been examined, and they commonly contain weaponry and other objects of iron. The iron objects are unfortunately often corroded, or damaged by the funeral pyre, or they are inaccessible because of their rarity. Examples are Dankirke, Årupgaard and Aarre in Ribe amt, and Fredbjerg in west Himmerland.

Norway

In most of Europe the new iron metal entered a culture where bronze had been the most important material for household and warfare. This situation was different in Norway where bronze had been only sparsely used. In Norway the new metal replaced stone, flint, wood, horn, antler and bone. The coming of iron represented a very important new factor in the Norwegian economy, because there were plenty of bog iron ores and plenty of fuel. Brøgger (1940) considered it a revolution.

Finds of graves from the Pre-Roman Iron Age are not too common. The graves are in general cremation graves, but grave gifts were not common (Solberg 2000 :40). In the last part of the period, grave gifts became a little more common. In a stone cist in a large grave mound at Tjelta, Sola, 15 km SW of Stavanger, a bronze cauldron was filled with burnt bone. The cauldron, which had a reinforcing iron rim and ears of iron, had been imported from Celtic Germany. Similar cauldrons, used as cremation urns, have also been found on Jæren and in Vestfold, A few needles and fibulae of iron have been found among the burnt property, and some spearheads and special knives have also been found. Horse bits of iron from Forsand, Ryfylke, and a double-edged La Tène sword from Hotvedt, Vestfold, were, no doubt, imported. The general impression is that few iron artefacts in the Pre-Roman Iron Age were made in Norway and still fewer were deposited in graves, compared to what has been discussed from Denmark.

The archaeological evidence with respect to slag heaps and furnaces in Norway has been summarized by Espelund (1995; 2004). Three major iron production periods may be distinguished. Phase I from 200 B.C. to 600 A.D., phase II from 700 to 1300 A.D., and phase III from 1400 to 1800 A.D. The early part of phase I falls in the Pre-Roman Iron Age, but few sites are presently known well enough to be presented in this study (Stenvik 2003). The presentation of the Norwegian material will therefore be referred to Chapter 9, where the very important production in the Roman period will be discussed.

Finland

Finland has a very long tradition as an iron-producing country. The iron technology came first to northern Finland from the East, through Carelia. Iron-smelting pits and slag heaps of Pre-Roman Iron Age have been found near Kemijärvi in northern Finland at Neitilä and Räisälä, 60 km, respectively 90 km east of Rovaniemi, and at Äkälänniemi, Kajaani (Taavitsainen 1990: 198). In the Kajaani region, where there is plenty of lake ore as well as bog iron ore, the bloomery iron production continued up through the Middle Ages to at least 1700 A.D. (Nikander 1928). Even as late as in 1999 local iron masters in the Kajaani region produced their own iron/steel for knives from local manganese-rich lake ores (Lars Hukkinen, pers.comm.).

The source of the eastern tradition was apparently rooted in the Ananjino-culture, which was located at the Kama River in eastern Russia, near Perm, Fig. 74. Already in the Bronze Age there were trading connections between Carelia and the other Finno-Ugrian speaking people at the Uka and Kama Rivers. Ananjino, which has given its name to the culture, is a gravefield near the city of Jelabuga at a tributary to the Kama River. The many skeleton graves from 600 to 200 B.C. were richly endowed with grave gifts of bronze and iron. The bronze was noteworthy for its high tin content. The Ananjino influence may be traced by the finds of bronze objects and casting moulds along the route to Finland, and it is likely that the iron followed the same route, finally to spread through the Finnmark and into northern Norway, where the first influence may be dated to 500 B.C. (Solberg 2000).

By the kind cooperation of Professor Taavitsainen,

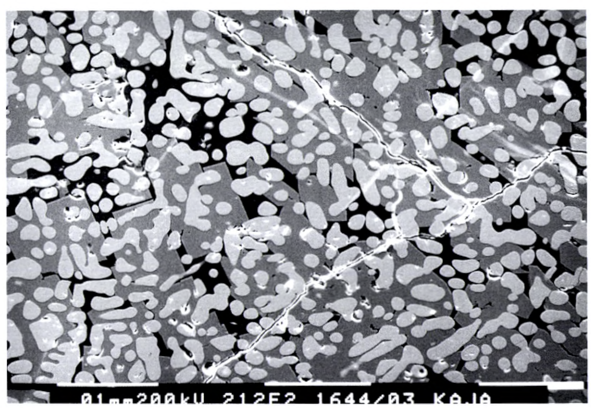


Fig. 195. Section through a small purification slag from Äkälänniemi, north Finland, 300-200 B.C. Rich in wüstite, 73% FeO-19% SiO_2. PS. SEM. Scale bar 0.1 mm.

Table 8.3. SEM-EDAX analyses of three slags from northern Finland.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO	SO_3	Sum	F
1	22.6	69.1	0.9	0.4	1.7	3.7	0.9	0.4	0.1	0.2	100	6.11
2	20.4	72.1	1.6	0.1	1.0	3.5	0.7	0.3	0.1	0.2	100	5.83
3	39.9	42.1	0.8	0.9	5.2	7.5	2.1	1.2	0.2	0.1	100	5.32

1. Äkälänniemi, Kajaani. 160 g purification slag. Helsinki No. 22229:281.
2. Neitilä, Kemijärvi. 13 g purification slag. Helsinki No. 15671: 1320.
3. Räisälä, Hovinsaari. 19 g manufacturing slag, sinder. Helsinki No. 2592: 145.

the University of Helsinki, slags from three sites of northern Finland's early iron production sites were obtained. In Table 8.3 the two first entries concern purification slags, while the third one is a sinder, a manufacturing slag, Step 4 in Table 4.4.

The Äkälänniemi slag is a small planoconvex slag, 7 x 5 x 4 cm, of 160 g. It is rust-brown because small iron blebs inside the slag have corroded and formed limonitic crusts. Sections show a heterogeneous structure where fayalite-rich parts alternate with wüstite-rich parts. The local (lake?) ores have, no doubt, had more manganese and phosphorus than shown in the analyses, but these elements have as usual become depleted in the purification step. The site has been C-14 dated to 300-200 B.C. (Schulz 1986).

Fig. 196. Another section through the slag, Fig. 195, at almost the same magnification, with much less wüstite, 64% FeO-27% SiO_2. The structural variation is typical of purification slags that occur in small batches. PS. SEM. Scale bar 0.01 mm.

The Neitilä slag is a 13 g spray slag (2.5 x 2.0 x 1.5 cm) from the purification of a bloom, like the preceding one. A few grains of charcoal are included, and minute iron particles are also present, giving rise to some interior corrosion. Manganese and, in particular, phosphorus are low, and the F-value is similar to the preceding slag. The structure consists of 65% fayalite (with 2.2% MnO), 25% wüstite and 10% matrix. About 230 kg of slag has been recovered from the site, which is estimated to be from the last century before Christ (Purhonen 1982).

The Räisälä slag is a 19 g blistery and porous fragment, measuring 4.5 x 2.5 x 2 cm. It is black, i.e. not rusted, and therefore without free iron in the slag. In section it displays a greenish-grey tint and it is very heterogeneous, glassy parts abruptly meeting glass with feathery skeleton crystals, or glass with magnesium-enriched fayalite (4% MgO). The slag is a sinder, related to the previous two slags, but much contaminated by calcium, aluminium, potassium and magnesium from the manufacturing process.

The three slags support the very early presence of iron technology in northern Finland, more or less simultaneously with early Danish examples, which came from Germany. In southern Finland iron appeared somewhat later (Kivikoski 1964).

Sweden

In a significant analytical survey, Hjärthner-Holdar (1993) presented evidence of very early iron artefacts and slag occurrences in Sweden south of a line from Göteborg to Uppsala. The amount of slags which can be associated with the transition period Bronze Age – Iron Age, about 800-400 B.C., is, however, small, and the slags are often highly scattered. They are usually found in settlements where the activity of the bronze smith can be proven. No suitable iron ore has been found on the sites, and evidence of roasted ore has not been presented.

The ancient iron artefacts were primarily small tools, rings, hooks, chaplets for bronze casting and for repair work. For example, a bronze bit dated to 500 B.C. by Montelius had been repaired by inserting an iron rod (Montelius 1917, No. 1450). Many of the artefacts bear a Hallstatt period imprint and may have been imported from Celtic Europe. Apparently the artefacts were chiefly functional, and contrary to what we have seen in the Middle East they were only to a minor degree in use as decorative items or jewellery.

The area around Lake Mälaren was already during the Bronze Age in contact with the people of the Perm-Kama district, near the Ural Mountains. This is proven by the presence of ceramics with stripes and textile impressions, and "Mälardal" bronze axes (Kuziminych 1983; Meinander 1985). Since the presence of iron artefacts in central Sweden before 500 B.C. can hardly be explained as having passed through northern Germany and Denmark, where at that time iron objects are missing, it has been proposed (Serning 1984; Hjärthner-Holdar 1993: 264) that iron technological knowledge was introduced into Sweden from the East. Evidently we here have a parallel to the observations from Finland.

With respect to the presence of iron artefacts in Bronze Age settlements, one should not overemphasize the importance of the bronze smiths. Bronze technology and iron technology have at this stage <u>very little in common</u>.

The bronze smith collects and buys scraps of bronze, and new metal bars of copper and tin are imported. He mixes the metal in order to form an alloy, fitting for his purpose, and brings the mixture to the melting point in a crucible. He prepares a mould of clay or soapstone, and forms his object by casting. The object may now be finished, or it may be further worked by cold-hammering and annealing, perhaps in several cycles, finally to be ground and polished. Several pieces may be tin-soldered or silver-soldered together to form a complex object.

The blacksmith collects bog or lake iron ore and roasts it. He builds a rather large bowl- or stone-framed pit furnace, and charges it with a mixture of charcoal and roasted ore. He maintains the fire for many hours. He extracts a heterogeneous bloom from the furnace. The iron-rich part is isolated and made into a bloom, which is purified. The iron is forged into a bar and into manufactured objects by hot-forging. The finished item may be filed, ground and polished, but it is rarely cold-hammered. Several pieces may be forge-welded together to form a complex object.

The iron procedure is thus entirely different from the bronze procedure. No doubt, the iron master and blacksmith of the new era faced a much more difficult task than that of the bronze smith. It required totally new knowledge, much trial and error, and probably, in the beginning, the performance of specific rituals at crucial parts of the process.

The bronze or copper smith could use next to nothing of his prior experience when he met with the new metal. Apart from his knowledge of fuel and fire, which the potter knew as well, he had to start from scratch.

What is probably the oldest, well-examined iron production site in Sweden was first described by Wedberg (1984). At <u>Röda Jorden</u> (i.e. Red Soil), 3 km SW of Riddarhyttan in Skinnskattebergs sogn, Vestmanland, seven sites were identified, each containing 1-4 production furnaces. Within an area of about 1 x 1.5 km^2, many concentrations of red soil occurred. Red soil is an ochrous, limonitic surface precipitate, in contrast to the bog iron ore which is normally found below

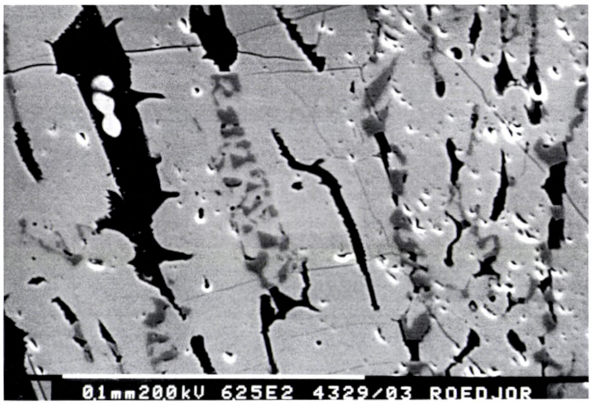


Fig. 197. Experimental production slag of 100 g from Röda Jorden, May 1995. Fayalite laths (light grey) with tiny skeleton crystals of hercynite with 0.4-0.9% V_2O_5 and 1.2% TiO_2 (dark grey), PS. SEM. Scale bar 0.1 mm.

ploughing depth. The red soil may contain up to 80% FeO and it is easily reduced in the bloomery furnace, as Wedberg proved experimentally. The red soil occurs in spots and, just below a humus layer, it may cover from a few to several hundred square meters. New formation of red soil can be proved in the area. The furnaces had the shape of oval pits, about 0.4 x 0.6 m in inner diameter, and 0.4-0.5 m deep, and were lined with flat stones. These could be tightened or entirely covered by clay. The furnaces had tuyeres for the bellows, and the slag was tapped during a run.

The Röda Jorden site has attracted much attention, and local amateurs arrange annual iron production and charcoal-making. Recently the site has been revisited and additional C-14 analyses have been taken (Grandin & Hjärthner-Holdar 2001; 2003). They con-

Table 8.4. SEM-EDAX analyses of Pre-Roman Iron Age slags from Sweden

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	44.1	36.8	1.1	-	1.3	13.7	2.1	0.4	0.3	-	0.2	100	3.22
2	30.6	55.6	0.9	0.4	1.0	9.4	1.3	0.2	0.3	0.1	0.2	100	3.26
3	88.0	2.3	<0.1	-	0.8	6.2	1.7	0.6	0.2	-	0.1	100	14.2
4	18.8	70.9	1.5	0.4	0.8	5.6	0.8	0.3	0.3	0.2	0.3	100	3.36
5	26.2	60.3	1.9	0.6	1.3	7.3	1.2	0.4	0.3	0.2	0.3	100	3.59
6	35.1	46.3	0.3	0.2	1.5	13.7	2.0	0.4	0.3	0.2	-	100	2.56
7	29.6	60.2	0.4	0.3	0.7	7.0	1.3	0.1	0.3	-	0.1	100	4.23
8	28.4	60.5	0.9	0.5	0.9	6.6	1.3	0.3	0.2	-	0.4	100	4.30
9	27.2	60.7	0.2	0.1	1.0	8.4	1.7	0.2	0.3	-	0.2	100	3.24
10	27.4	61.3	0.3	0.1	1.0	7.5	1.7	0.2	0.3	-	0.2	100	3.65
11	26.2	62.1	0.2	0.2	0.8	8.4	1.5	0.1	0.3	-	0.2	100	3.12

1. Röda Jorden, Skinnskattebergs sogn. 337 g production slag. Pre-Roman Iron Age.
2. ibid. 100 g production slag. Modern experiment May 1995.
3. ibid. 88 g manufacturing slag. Pre-Roman Iron Age.
4. Skäggared, Seglora sogn, Vester Götland. 670 g production slag. Pre-Roman Iron Age.
5. ibid. 50 g production slag.
6. Stalbo, Harbo sogn, Uppland. 203 g production slag. No. 107: 2. 300 B.C.
7. Genevad, Tjärby sogn, Halland. 440 g production slag. No. 3 B- 2: 1. 200 B.C.
8. ibid. 20 g production slag. No. 3 B- 8: 1. 150 B.C.
9. Leregård, Årstads sogn, Halland. 15 g purification slag. No. 18: 1. About 300 B.C.
10. ibid. 3 g purification slag. No. 18: 2.
11. ibid 23 g purification slag. No. 18: 3.

Fig. 198. A view from above on the furnace A1 at Finnbäcken, Närke (Hansson 1989, Fig. 82). The furnace pit was rectangular, about 1.2x0.8 m, and framed with large flat sandstones. The stones had probably been clay-covered. The fuel had been pine. The heap outside consisted of slags and heat-affected stones. Dated to about 150 B.C.

clude that there has been a rather continuous activity in the area from about 700 B.C. to 1 B.C. Little if any change in technology or product could be pointed out within this time span.

In Table 8.4 are entered three analyses, related to Röda Jorden. Line 1 is a production slag wih a fayalite-glass structure. The elongated fayalite staves contain about 2% MnO and 1% MgO. The red soil must be phosphorus-poor, since the (three) slags are so depleted of this element.

Line 2 is an experimental slag, produced from red soil by amateurs in 1995. The slag displays fayalite in a glass structure with some wüstite dendrites. Hercynite is present as 5-10 μm subangular, hard crystals, enriched in vanadium and titanium (0.4-0.9% V_2O_5; 1.1-1.3% TiO_2).

Line 3 is an ancient, undated manufacturing slag. It is glassy, pumice-like, and light. It derives from the smith's work, in manufacturing or repairing iron objects, and is debris from the forging hearth, step 4, as identified by Wedberg (1984).

In Table 8.4, lines 4-5, are entered analyses of two fragments of a 17 kg heavy slag mass, found by amateurs in 1993 (Erik Ahtiainen, Hembygdsföreningen, Seglora sogn, Vester Götland). The furnace is located at Skäggared, and the slag reached me through Dr. L.-E. Englund. It has provisionally been dated to the Pre-Roman Iron Age. One fragment is magnetic, because it is rich in lace-like iron, the initial steps of bloom formation. The slag is 25% wüstite, 50% fayalite (0.1-0.2 mm blocks) and 25% multiphased matrix. Local skeleton crystals approach hercynite composition.

In Närke, 25 km SSW of Örebro, two iron production places from the Pre-Roman Iron Age were described by Hansson (1985; 1989). At Finnbäcken five furnaces were excavated, dated to 200-150 B.C., while at Smedsgården only furnace fragments were found. To make up for it, many slags, estimated at 1000-1500 kg, and of similar age, were found in this place. The furnace pits were rectangular and framed with large, flat stones; they were compared to the furnaces at Röda Jorden. The fuel had been pine (76%), aspen (11%), alder (8%), lime (4%) and hazel (1%).

In Viby sogn, only five km west of the two previous places, another 25 furnaces were discovered. The oldest were of the same type as Röda Jorden and of late Bronze Age or Pre-Roman Iron Age (Hjärthner-Holdar et al. 1997).

Fig. 199. Production slag from Stalbo, Harbo sogn, about 300 B.C. Dominant fayalite laths, scattered hercynite skeleton crystals and a duplex matrix. PS. SEM. Scale bar 0.1 mm.

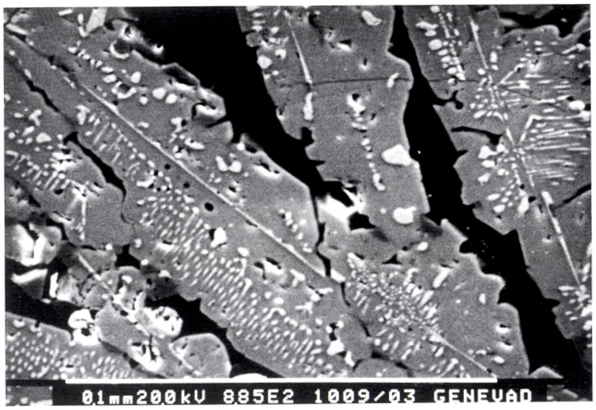


Fig. 200. Section through 440 g production slag 3 B-2:1 from about 200 B.C. Genevad. Fayalite laths with organized wüstite precipitates, and a glass matrix. PS. SEM. Scale bar 0.1 mm.

At Stalbo, Harbo sogn, Uppland, an ancient bloomery site was examined by Forenius (1990) and dated to about 300 B.C. A 203 g production slag of the stalactite type was analysed and entered in line 6 of Table 8.4.. The stalactite-shaped slag had dropped down and penetrated an underlying layer of charcoal. It displays adhering parts of a clay-covered stone plate. It has no wüstite, but 60% fayalite laths (1% MgO) and 40% fine-grained matrix. 0.01 mm angular hercynite crystals with up to 0.8% V_2O_5 are common. The general composition of the slag is rather similar to the slightly older slag from Röda Jorden.

In the district of Möre, Småland, in a forest near the coast, a Pre-Roman Iron Age furnace was described by Magnusson & Rubensson (2001: 337) and Englund et

Fig. 201. Four small slags from a purification hearth in the Pre-Roman Iron Age settlement Leregård, Halland. The bloomeries may have been situated some miles further east near Hishult. Scale bars in mm.

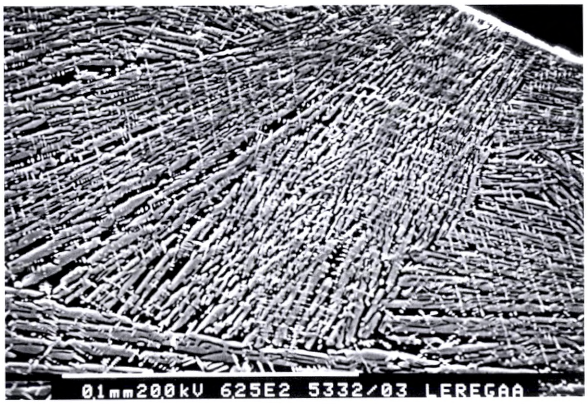


Fig. 202. A small, 3 g purification slag, 18:2, such as Fig. 201. In the very rapidly cooled surface, the wüstite-fayalite network is extremely fine grained, and the matrix has been sucked into the shrinking interior. Leregård. PS. SEM. Scale bar 0.1 mm.

al. (1999). It was located at Eket, (RAÄ 342), Söderåkra, 30 km south of Kalmar. Dated to 400-200 B.C., it is of the same stone-framed pit type as Finnbäcken and Röda Jorden, but it had apparently been topped by a clay-built shaft. The large number of bottom slags, perhaps 60 pieces, indicated that the furnace had been repaired and reused for a long period. The absence of a working pit in front of the furnace, the probable presence of a shaft, and the striking number of bottom slags, suggest a furnace type different from Finnbäcken and Röda Jorden.

In Halland, two Pre-Roman iron production sites have been detected. At Genevad (RAÄ 64), Tjärby sogn, the extension of the railroad Laholm-Halmstad revealed five furnace sites and four purification hearths (Wranning 1995). Furnace A 2 was a stone-framed hollow with a working pit in front, while the slightly younger furnace A 8 was a clay-built shaft furnace without a pit. C-14 dating indicated a period from 350 to 50 B.C. In Table 8.4, lines 7-8, analytical data for production slags from the two furnaces are presented. They are very similar, considering the fact that they are derived from different furnace types. Apparently the character of the bog iron ore is much more decisive. The slag structure displays 20-25% wüstite, 50-60% rather pure fayalite (30 μm wide lamellae with minute wüstite particles inside), and the rest is glass matrix. The material in harmony with such slags would have been an almost carbon- and phosphorus-free wrought iron.

At Leregård (RAÄ 160), 11 km east of Falkenberg in Halland, a (part of a) settlement with a few iron

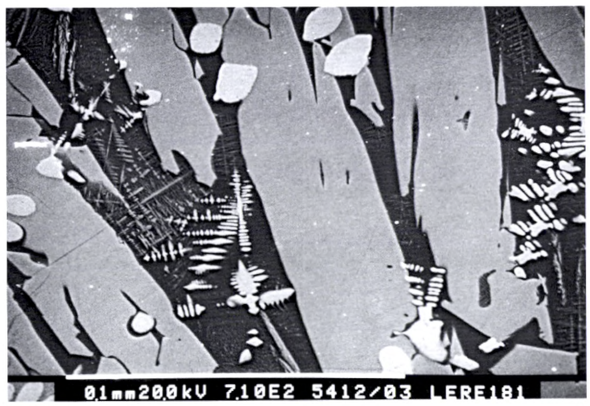


Fig. 204. Leregård. Section through a somewhat larger slag of 15.3 g, 18: 1. The slag is more massive, cooled more slowly than No. 18: 2, and therefore displays a coarser structure, and two generations of wüstite dendrites. Note: (Almost) same magnification and composition as Figs. 202 and 203. PS. SEM.

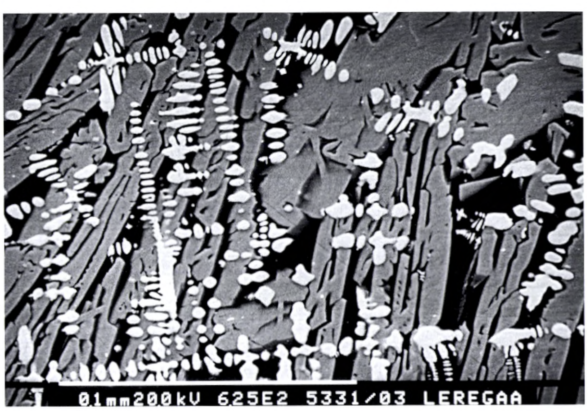


Fig. 203. The same 3 g slag as Fig. 202. The interior cooled more slowly and is massive, with distinct wüstite dendrites, fayalite laths and glass matrix. PS. SEM. Scale bar 0.1 mm.

slags was excavated in 1994-1995 (Wranning 1997). The iron slags were small and totalled only 848 g. No furnaces were identified, but two purification hearths were excavated. They were respectively 150 x 30 cm in size and 10 cm deep, and 28 x 30 cm in size and 6 cm deep. Around them were also found 22 pieces of small, spherical to dropshaped, spray slags, totalling 4.8 g, Fig. 201. The settlement and the associated hearths were dated to 400-300 B.C. and are the oldest dated remains of iron handling in Halland. While the iron production proper must have taken place elsewhere, probably further east in Halland, the blooms were apparently transported to the Leregård settlement to be purified in the hearths there.

In Table 8.4, lines 9-11, are entered the average analyses of three purification slags from Anläggning 18. They are individuals, released during hammering as are also the spray slags. They have a rapidly cooled, fine-grained surface, drained for matrix, and a "normal" interior of up to 20 μm thick pure fayalite laths,

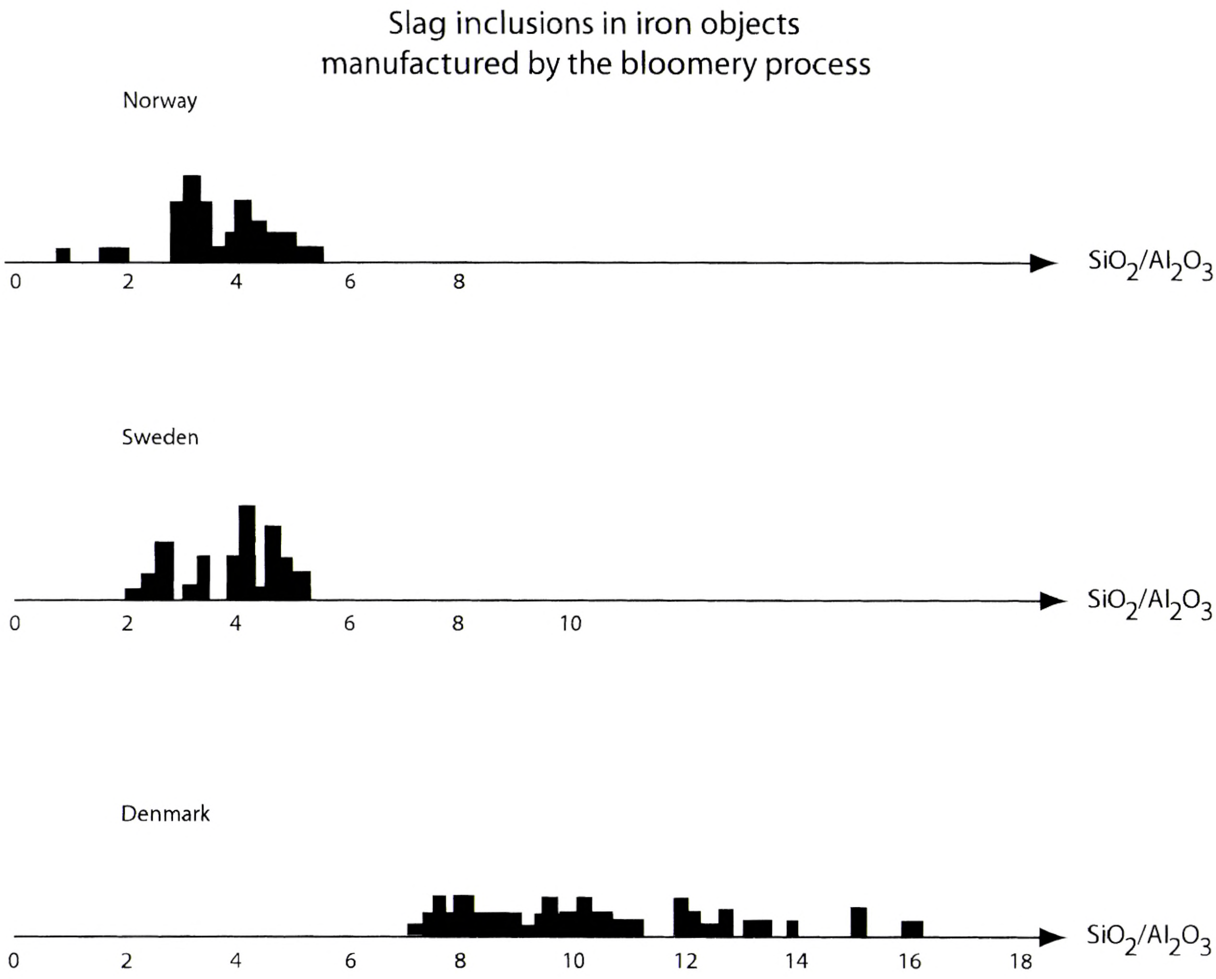


Fig. 205. The provenance of iron artifacts from Scandinavia may be estimated from an analysis of the slag inclusions, as compared to the production slags from known furnace locations. The ratio F = SiO_2/Al_2O_3 clearly separates Danish manufacture from Norwegian and Swedish. The preliminary figure is for slag inclusions in iron objects from between 100 and 1000 A.D. See also Fig. 366.

with some wüstite dendrites and additional minute wüstite particles in the glass matrix. The composition is not much different from that of Genevad, except that the MnO and P_2O_5 contents are relatively low as they usually are in purification slags.

The examination of early iron in the Nordic countries has revealed the presence of iron artefacts in settlements and graves from the younger Bronze Age, 800-500 B.C. The iron artefacts are few and scattered, of utilitarian value, knives being far more common than jewellery. Some objects have, on the basis of stylistic features, clearly been imported from the Celtic-Germanic areas, and it is not unlikely that all the others also have.

But from about 500 B.C. the remains of production furnaces and smithing hearths appear, with perhaps the oldest and best documented ones occurring in Vestmanland and Närke in central Sweden. The furnaces were apparently not located in or near the settlements, but rather in distant places where the best bog iron ore and red soil were available. It is speculated whether the contact through the Finnish-speaking peoples of central Finland and Carelia with the related people of the Perm-Kama region in present-day Russia brought the first knowledge of iron production technology to Scandinavia.

But only a little later, iron furnaces and slag heaps are documented from Denmark and southern Sweden, suggesting an input from Germany and the Celtic neighbours in the period 500-300 B.C.

Common to all the early sites is the almost total absence of iron, be it blooms, bars or manufactured items. The contemporary iron artefacts have to be sought in the graves, which in the second half of the Pre-Roman Iron Age were chiefly cremation graves. This means, of course, that especially the bronze artefacts were severely damaged, but also iron suffered

Rosenberg's method for conservation

Earthfound, ancient iron objects are rich in chlorine-containing iron compounds of the types akaganeite and hibbingite (Buchwald 1998). When excavated and moved indoors to a museum situation, the chlorine is activated and continues the attack on any iron left in the artefact. Rosenberg (1917) recommended that iron-containing artefacts were annealed at 800°C, then boiled in a saturated solution of sodium carbonate, finally to be soaked in water for a week or two, and dried and stabilized in microcrystalline wax. The maximum temperature of 800°C was typically maintained for 30-60 minutes, while the objects, wrapped in asbestos paper, were placed in a ceramic furnace with a normal atmosphere. The method has been extensively used in Denmark on corroded objects up to about 1990. The later introduced electrolytic methods have mainly been used on iron objects with minor corrosion attacks.

The Rosenberg method has been successful if correctly applied, in so far as it removed the chlorine and stabilized the artefact. However, the high temperature for half an hour or more removed all previous structures and thus cleaned the metallographic record of earlier events. All information concerning hardness, coldwork, edge hardening, and general structural heterogeneity was lost. The cooling in the soda bath introduced new structures, which might be brittle if martensite was formed. Since the concluding manual cleaning and removing of soil and corrosion products were rather cumbersome and time-consuming, the Rosenberg method has been abandoned in many museums; in the National Museum, Copenhagen, from about 1978.

It is recommended that samples for metallographic studies and slag analyses be removed from the artefact before the Rosenberg method is applied, if it must be.

greatly, since the internal structure was altered during the high temperatures and oxidizing environment of the funeral pyre.

As far as we can see, there were great distances between the production furnaces. They were small and the farmer/iron master produced only for local consumption. But as the millennium-shift approached, the stage was set for a significant leap in both production size and in the number of sites. This development will be examined in the next chapter.

Chapter 9
Denmark, 0-600 A.D., and the furnace clay material

Under the spreading chestnut tree the village smithy stands
the smith a mighty man is he with large and sinewy hands
and the muscles of his browny arms are strong as iron bands.

H.W.Longfellow, The Village Blacksmith, 1839.

At the beginning of the new millennium the people of northern Germany and Scandinavia must have been in a state of high alarm. The Roman legions advanced from the south and southwest, and established strong fortifications along the lower Rhine at Xanten (Castra Vetera) and Nijmegen (Noviomagus). The feelings towards the approaching Roman danger cannot have been much different from the feelings 1500 and 1600 years later towards the advancing Osmannic armies in southeastern Europe.

In the year 9 A.D. the Roman legate Publius Quinctilius Varus, with three legions, was annihilated by the Cheruscan chieftain Arminius (Herrman). Varus fell himself. The battle which apparently lasted three days took place in "the Teutoburger Wald", but exactly where has been a riddle for centuries. The areas around Paderborn and Hameln were suspected, but the solution turned out to lie scores of kilometers from these places.

In the 1990s German archaeologists finally identified the fighting zone as a 10 km long stretch near Kalkrieser Berg, at the Weser- Elbe- Mittelland Kanal, 10-15 km north of Osnabrück (Jensen 2003: 230). Arminius's victory put an end to Augustus's plans for the conquest of Germany to the Elbe, and established the Rhine as the future border between Latin and German territory. In the west, however, Claudius extended the Roman empire by invading Britain in 43 A.D., conquering Colchester in Essex (Camelodunum) and finally, in 51, capturing the British leader, Caractacus.

The proximity of the Romans, with their cultural curiosity, meant that first-hand descriptions of the peoples and habits of northern Europe now became available. We must be grateful to the industry of Cornelius Tacitus (55-116 A.D.), who in his books "Agricola" and "Germania" extended the earlier works of Caesar on Gaul, to cover the peoples of Britain and "Germany".

Tacitus was not impressed by the weapons he met with in Germany (Germania, §6, §13). From the general absence of swords (gladius) and heavy lances (lancea) he concluded that there were few iron resources in the North. He also noted (§5) that silver and gold were not mined, and that people in general showed little interest in these metals. Even the precious Roman gifts of silverware were rated little more than their home-made clay vessels.

It was customary that men always carried their weapons (§13). They were, however, simple, consisting of a light spear (framea) and a shield. The spear, which had a short, narrow and sharp iron blade, could either be hurled over a distance or used in hand-to-hand fighting (§6). Battle axes and bow-and-arrow were not mentioned. We know, however, from grave finds of arrowheads that at least the bow was used by the Germanic tribes.

Denmark

Although spears and knives are the most abundant iron objects in early Roman Iron Age graves, swords have also been found. At Lønhøjvej, in northwestern Tarm, Ringkøbing amt, a large gravefield was excavated in the 1980s (T.E.Hansen 1986). In twenty out of 150 graves there were weapons, single- and double-edged swords, spearheads and shield buckles. The habit of cremating the dead had not yet disappeared, so the iron objects had been thoroughly annealed and some of the swords had even been bent (no doubt while still hot) in order to fit into the grave urns.

The broken, double-edged sword tip from grave A 203, dated to about 140 A.D., was due to annealing on the funeral pyre, covered by a wüstite-magnetite-hematite scale, and the slag inclusions were significantly altered in their structure. The metal was heterogeneous, but in general consisted of annealed, equiaxial phosphorferritic grains, 75-300 μm across. The annealed hardness was 110-172. The average slag composition is presented in Table 9.1, line1, showing a high phosphorus content.

Another sword of the same age, but from grave A 211, was single-edged. Its scale was 0.3-0.4 mm thick and consisted of wüstite, magnetite and hematite, the last and outermost one constituting 10% of the scale. The metal was annealed phosphorferrite, of large grain size, up to 0.5 mm across. The annealed hardness was 114-185. The slag structure had been transformed upon annealing on the pyre, the composition had, however, been preserved, line 2.

Fig. 206. 19 cm long fragment of a double-edged sword, grave A 203, Skj 175x377, Lønhøjvej, Tarm. About 140 A.D.

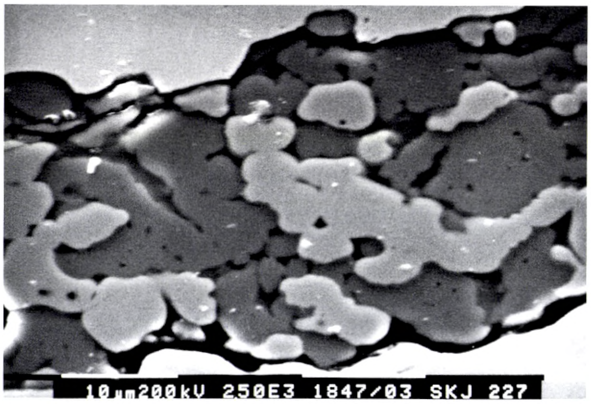


Fig. 207. Slag inclusion in a single-edged sword, grave A 211, Skj 175x227, Lønhøjvej, Tarm. Annealing on the funeral pyre has affected the morphology of the slag. PS. SEM. Scale bar 0.01 mm.

The F-values and the phosphorus content of the two swords suggest that they were produced from local bog iron ore. An iron production site in the vicinity of the gravefield has, in fact, been reported (AUD 1986: 123), and bog iron ore is known to occur in abundance in the neighbourhood.

Further south in western Jutland solid evidence of iron production now begins to appear. Already in the 1930s it was reported that the stone fence around the church at Hodde, 14 km NE of Varde, contained 31 large slag blocks (Mortensen 1939: 132) and an iron production site nearby was also noted. The farmers knew these slags and were annoyed, because they often damaged their ploughshares. One block of 131 kg was figured by Voss (1962), who also explained why it was huge and looked like an elephant's foot. By 1999 no less than 500 furnace sites had been identified in Hodde (Smekalova & Voss 2003). The analytical data of a small fragment, plucked from the churchyard's stone fence, are entered in Table 9.1, line 3. The structure is very coarse, with massive fayalite crystals in which supersaturation with iron oxide has led to fine precipitates of wüstite. Crystals 0.05 mm in size and ap-

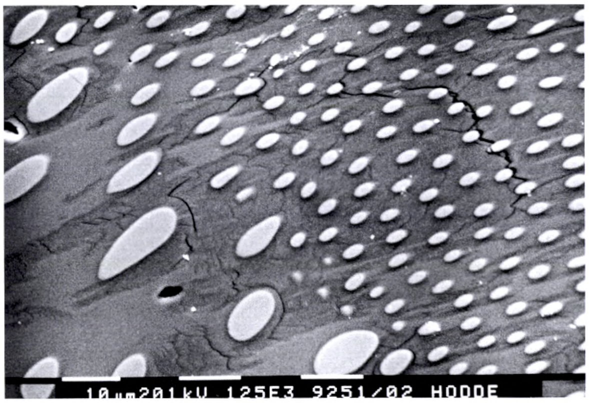


Fig. 208. Fragment of a large production slag, elephant's foot, from the fence around Hodde Church. The fayalite crystals are more than 0.1 mm in diameter and display precipitates of wüstite. PS.SEM. Scale bar 0.1 mm.

proaching hercynite, $FeAl_2O_4$, in composition, are common. The analysis is typical of western Jutland's phosphorus-rich and calcium-poor bog iron ores. Massive bog iron ores are abundant around Hodde and were in the 12th century applied as building material for part of the church (Buchwald 1998).

In the early 1970s the Iron Age settlement about 500 m east of the present Hodde church was excavated (S. Hvass 1975). Later examinations have shown that no less than three settlements, ranging from about 150 B.C. to 400 A.D., have existed, slightly changing their site through the centuries (L. Hvass 2001: 23).

A 28 m long house with stables in the eastern end is the largest house known from this phase of the Iron Age. A potter's furnace and two or three smithies were identified. They were located just outside the common fence, and each one was associated with its medium-sized farmhouse with stable. One of the smithies was permanent and could be followed through four steps of rebuilding of the adjacent farmhouse. Evidently the smith was a farmer of average status who besides his smithing job participated in the settlement's common farm work.

Also in Vorbasse slags were discovered at an early date (Mortensen 1939: 140). Systematic archaeological research north of the church has, since 1973, revealed at least 8 settlements and 5 minor gravefields. Within 1200 years these moved slightly within an area of about 1 km^2, from 100 B.C. to 1100 A.D. (Hvass 1977; Dehn-Nielsen 1999: 148). The three oldest settlements are contemporary with the Hodde settlements, while the fourth and fifth settlements, from 300-500 A.D., are the ones here of interest. They covered about 13.5 ha and comprised 20 farms, with longhouses which were considerably larger than Hodde's: Many reached lengths of 40 m, and one, 48 m long, was presumably occupied by the local chieftain.

Outside the fence nine shaft furnaces with underlying pits were identified, and slag blocks of several hundred kilograms were found in and around the pits. Inside the fence the farmhouse had a small smithy associated with the longhouse. Analytical data for slags from these sites are listed in Table 9.1. Line 4 is from a large production slag outside the fence. It is coarsely crystalline with massive fayalite, some wüstite and intercalated calcium-iron-phosphate glass and some leucite, $KAlSi_2O_6$. Line 5 is from one of the smithies, a 900 g purification slag, poor in manganese and phosphorus, but enriched in Ca, Al, K and Mg, and retaining the characteristic F-value of the site. The slag is heterogeneous and has inclusions of quartz and unidentified "stones". Under the top surface there is an enrichment of magnetite skeleton crystals.

Fig. 209. A 900 g purification slag, S1VO, from Vorbasse. Skeleton fayalite crystals and matrix. Elsewhere many magnetite skeleton crystals. PS. SEM. Scale bar 0.1 mm.

Table 9.1. SEM-EDAX analyses of slags from western Denmark's Iron Age.

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	17.4	69.7	0.4	-	9.7	0.4	1.8	0.3	0.3	-	-	100	9.67	3.51
2	13.1	75.5	3.6	0.4	4.7	1.1	1.1	0.2	0.2	<0.1	-	100	11.9	3.27
3	22.8	65.6	3.7	0.3	3.1	1.3	2.4	0.1	0.3	0.1	0.3	100	9.50	5.64
4	31.1	60.7	0.5	-	2.0	0.7	3.6	1.2	0.2	-	-	100	8.64	9.02
5	46.1	43.9	0.2	-	0.2	1.5	5.0	2.4	0.4	0.2	0.1	100	9.22	21.0
6	25.9	65.9	0.3	-	0.9	0.5	5.5	0.6	tr.	0.2	0.2	100	(4.7)	(9.8)
7	17.0	72.1	2.0	0.2	6.3	1.1	1.0	0.1	0.2	tr.	-	100	17.0	2.98
8	24.2	71.8	0.2	tr.	0.7	0.7	1.6	0.1	0.3	0.1	0.3	100	15.1	3.71
9	25.0	71.5	0.2	tr.	0.6	0.6	1.6	0.1	0.1	0.1	0.2	100	15.6	3.32
10	21.2	65.8	0.6	-	6.9	1.2	2.9	0.5	0.8	0.1	-	100	7.31	7.37
11	13.2	79.6	0.4	-	3.2	0.6	1.8	0.2	0.5	0.2	0.3	100	7.33	3.73
12	23.2	72.2	0.5	-	1.7	0.3	1.1	0.2	0.3	0.2	0.3	100	21.1	2.55
13	31.6	59.8	0.3	-	0.5	1.6	4.3	1.4	0.2	0.2	0.1	100	7.35	12.4
14	30.2	57.0	0.3	-	1.2	5.8	2.8	2.0	0.4	0.2	0.1	100	10.8	18.8
15	23.0	65.8	0.8	-	2.0	3.6	2.3	1.6	0.4	0.2	0.3	100	10.0	11.5
16	29.2	60.5	0.5	-	3.5	1.2	3.5	0.9	0.2	0.3	0.2	100	8.34	8.99
17	27.7	65.9	0.5	-	2.1	0.5	2.2	0.2	0.3	0.2	0.4	100	12.6	7.45

1. Tarm, Lønhøjvej, Ringkøbing amt. Double-edged sword, grave A 203. SKJ 175x377. HV: 110-154-172.
2. ibid. One-edged sword, grave A 211. SKJ 175x227. HV: 114-177-185.
3. Hodde church, Ribe amt. 150 g production slag, found in the churchyard stone fence. About 300-500 A.D.
4. Vorbasse, Ribe amt. Production slag, section from the bottom of a 100 kg block. S2VO1.
5. ibid. 900 g purification slag. Heterogeneous with quartz inclusions. S1VO.
6. Søgaard, Hejnsvig sogn, Ribe amt. Production slag, section from 80 kg block. Contaminated by furnace wall.
7. Sønderbygaard, Grindsted sogn, Ribe amt. 1 kg bloom, with iron lace works. 300-500 A.D.
8. Starup church, Ribe amt. 1.4 kg production slag, found in the churchyard stone fence. Analyst VFB, Sept.1993
9. ibid. The same polished section, but analysed by Helle Wivel, August 25,1995.
10. Østergaard, Grindsted sogn, Ribe amt. Production slag, 97 kg elephant's foot, drill core, SGr 1.
11. ibid. the same block, drill core SGr 2.
12. ibid. 900 g fragment from another production slag.
13. Drengsted, Døstrup sogn, Tønder amt. Production slag, 300 g fragment of a large elephant's foot. 200-400 A.D.
14. Brøns church, Ribe amt. Purification slag, 346 g kalot. From debris in the churchyard.
15. ibid. Purification slag, 401 g kalot.
16. Krarup, Tistrup sogn, Ribe amt. Production slag, 100 g fragment of an elephant's foot.
17. Houlbjergvej 12, Houlbjerg sogn, Viborg amt. Production slag, fragment of 50 kg elephant's foot.

At Søgaard, 4.5 km SE of Hejnsvig Church, Ribe amt, seven iron furnaces and some bloom fragments were reported by Mortensen (1939: 134). He excavated them, but he had as was usual at his time the wrong perception that the heavy elephant's foot slags had been turned upside down by the ironmaster in order to extract the iron bloom which was assumed to have been located at the bottom of the pit. A generation later, Voss (1962), who had worked with the Drengsted furnaces, correctly interpreted the situation and proved that the blocks were in situ, untouched, and that the blooms must have been located above the large slag blocks. In Table 9.1, line 6 there is an analysis of the top of an 80 kg elephant's foot from Søgaard. Its composition is atypical by displaying an unusually low F-value. Since fragments of the clay wall were enveloped in the slag sample, it is concluded that the analysis was severely contaminated by absorbing some Al_2O_3 from the clay wall, compare Table 9.6.

Both north and south of the town of Grindsted, Ribe amt, many Iron Age smelting sites were identified by Mortensen (1939: 137 f.). An imperfect bloom from Sønderbygaard, SE of Grindsted, has been included in this study. The 1.1 kg lump may have been overlooked and lost during the production process, or it may have been just scrapped owing to imperfection. The iron forms lace-work and is occasionally sintered together into nuts, enveloped in slag. The slag is complex with wüstite, a little iron sulphide, manganese-rich fayalite, pure hercynite, some leucite glass and some calcium phosphate glass, Table 9.1, line 7. The iron phase has 0.2-0.3% P in solid solution.

On both sides of Holme Å there was iron production in the early Iron Age. On the south side around Starup Church eleven elephant's foot slag blocks were reported (Mortensen 1939: 120), and on the north side a large field near Starup school was excavated in the 1980s (Albrethsen 1986: 27,130). Here were 338 slag pits, divided into three groups of 128, 36 and 174 furnaces. C-14 dating placed them at 130-210 A.D. Bog iron ore is common in the vicinity, and Starup Church was in the 12th century partly built from massive bog ore (Buchwald 1998). A fragment of a slag has been analysed, Table 9.1, lines 8-9. The two analyses were accidentally made on the same sample, but performed by different persons, in 1993 and 1995. The consistent results show the excellent stability of the SEM-EDAX instrumentation.

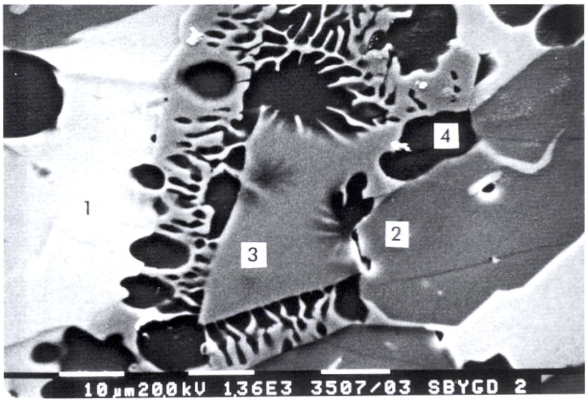


Fig. 210. Section through a 1 kg bloom from Sønderbygaard. The intricate slag structure consists of **1**, fayalite, **2**, calciumphosphate, **3**, hercynite, and **4**, leucite. PS. SEM. Scale bar 0.01 mm.

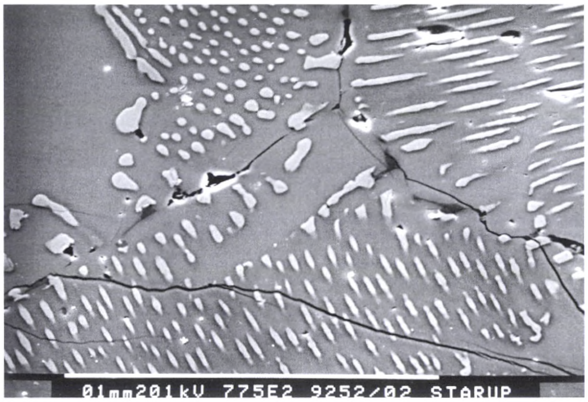


Fig. 211. Fragment of an elephant's foot slag in the fence around Starup Church. Coarse grained fayalite with wüstite precipitates that reflect the crystal structure of three joining fayalite grains. PS. SEM. Scale bar 0.1 mm.

At Østergaard, 400 m NE of Grimstrup Church, and in the fields of three other adjacent farms, a total of 89 elephant's foot slags were reported by Frydendahl (1931). According to him the large blocks were a nuisance to the farmers, so they were either smashed to pieces and used as macadam, or used in the construction of church stone fences, or – if of a decorative appearance – hauled to the gardens and displayed.

Frydendahl measured 15 of the blocks. The rather regular cylindrical top side was 35-60 cm in diameter, the irregular bottom shirt 45-76 cm in diameter, and

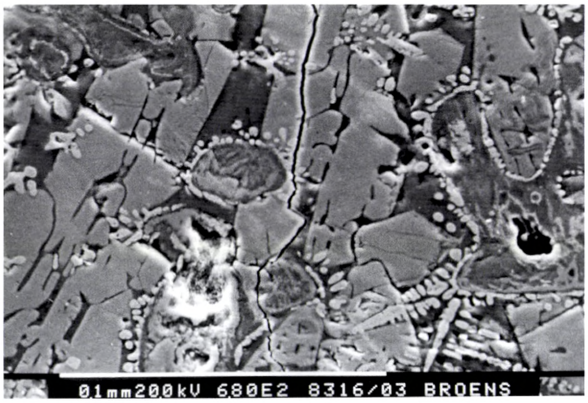


Fig. 212. Section through a 401 g corroded purification slag (kalotslag) from Brøns Church. Fayalite laths (grey), glass matrix (smooth black) and tiny wüstite particles (white seams) nucleated on what was once iron inclusions, but now by corrosion are converted to goethite (dark grey with indistinct structures). PS. SEM. Scale bar 0.1 mm.

the height 25-40 cm. Evidently the pits, which the slag blocks had filled, had been rather different in size. In the pits were found charcoal of oak and some hazel, and imprints of straw and heather.

One block of about 125 kg was sent to the National Museum, Copenhagen (figured in AUD 1986: 27). Another of 97 kg was acquired for this study in order to be examined in some detail by Kirsten Arndal and Arne Jouttijärvi. Drill cores, 25 mm in diameter, have been taken and analysed. Two of them are entered in Table 9.1, lines 10-11. In addition a 0.9 kg fragment from another block has been analysed, line 12. The structure is coarse-grained with equal amounts of wüstite and blocky fayalite in a matrix of Fe-Ca-phosphates and normal glass. In addition, there are many hard, cubic crystals, 20-70 μm across, approaching hercynite in composition.

When an Iron Age settlement at Drengsted, about 9 km NW of Løgumkloster, Tønder amt, was archaeologically excavated in 1962, slag pits with undisturbed slag blocks and charred straw were discovered (Voss 1962; 1976; 1991). During the systematic examination, it became clear that the earlier interpretations of the large slag blocks by Nielsen (1924), Frydendahl (1931) and Mortensen (1939) had been erroneous, as discussed above. In connection with farm houses, dated to 200-400 A.D., no less than 224 slag-pit furnaces could be identified, proving that iron production had been continued for generations. A fragment of a large block has been analysed, line 13. The structure is very coarse-grained, displaying blocky fayalite, wüstite dendrites and a glass matrix with leucite pockets. The structure and composition are similar to the Vorbasse material, except for a slightly lower phosphorus content, the lowest among any elephant's foot slag in this study.

On a visit in 1996 to Brøns Church, 15 km south of Ribe, two kalot-shaped purification slags were spotted among debris in the churchyard. They weighed 346 and 401 g. They are undated and may be either from the Iron Age or the Middle Ages, but they are included here, as they probably belong to the Iron Age activities in the Drengsted-Møgeltønder region. They are heterogeneous and contain disseminated 10-30 μm iron grains. The structure is 10-25% dendritic wüstite and 40-50% laths of fayalite, while the rest is a multiphased matrix, Table 9.1, lines 14-15.

At Krarup, 3 km east of Tistrup Church, Ribe amt, an iron production site was examined by Mortensen (1939: 126). A number of elephant's foot slags were found in situ, but many others had already been removed or destroyed by the farmers. The site was revisited and measured in the 1990s by geomagnetic

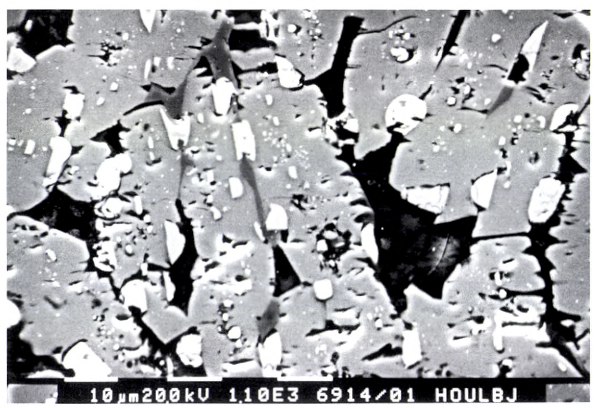


Fig. 213. Elephant's foot slag (50 kg) from Houlbjerg. The edgy appearance of the wüstite phase (white) is unusual. Fayalite (grey) and glass matrix (black). PS. SEM. Scale bar 0.01 mm.

Table 9.2. SEM-EDAX analyses of manganese- and barium-rich production slags

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	23.4	60.8	6.3	0.6	1.5	4.2	1.9	0.8	0.2	0.1	0.2	100	12.3	10.3
2	29.4	46.0	12.6	0.8	4.4	1.1	4.5	0.7	0.4	0.1	-	100	6.53	10.5
3	27.4	53.8	5.9	0.3	5.0	2.7	2.1	1.7	0.6	0.3	0.2	100	13.0	10.9
4	20.4	50.7	19.6	0.8	3.5	1.9	2.3	0.4	0.3	0.1	-	100	8.87	6.89

1. Ejer Bavnehøjskolen, Ovsted sogn, Aarhus amt. 200 g fragment from elephant's foot slag. Iron Age.
2. Engesvang church, Viborg amt. 300 g massive fragment. Iron Age or late Mediaeval.
3. Lemming church, Viborg amt. 250 g fragment from the stone fence. Iron Age or late Mediaeval.
4. Møgeltønder, Tønder amt. Part of a separate bottom slag, 4.5 kg, with straw imprints.

methods, which revealed no less than 1000 furnace sites (Smekalova & Voss 2003). A 100 g fragment of a large block has been analysed, line 16. It is very coarse- grained with massive fayalite blocks with imbedded wüstite dendrites and a little glassy matrix (15 vol%).

An Iron Age production site at Houlbjergvej 12, 1 km north of Houlbjerg Church and 4 km south of Langå, was excavated in 1977 by Randers Kulturhistoriske Museum (J.Nr.113/77). A fragment of an elephant's foot slag of approximately 50 kg was analysed and entered in Table 9.1, last line. The coarse-grained blocky fayalite displays wüstite precipitates and 10-20 µm crystals approaching hercynite in composition. Chemically and structurally this east Jutland slag is surprisingly similar to the many western Jutland slags of Table 9.1.

The following four examples come from manganese-rich production slags of central Jutland. During construction works at the Ejer Bavnehøj school, Ovsted sogn, only 2 km north of Bruneborg (Chapter 8), a small settlement with graves and ten pits with large elephant's foot slag blocks were found (Asschenfeldt-Frederiksen 1952). A 200 g sample was analysed and entered in Table 9.2, first line. It displays 65% coarse fayalite laths, 20% wüstite dendrites and 15% multiphased matrix. The wüstite contains 2% MnO, while the fayalite reaches 9% MnO and 2% CaO. The average analysis is rich in manganese and barium, this element being concentrated in the matrix, which has up to 4.5% BaO.

Around the old Engesvang Church and in the western farmed fields towards Kaptajnsgaard, many ancient slags have been found (Mortensen 1939: 157). The author has picked one of these slags from the field, a 300 g massive fragment, and analysed it, Table 9.2, line 2. It is composed of 80% fayalite and 20% multiphased matrix. The fayalite is extremely rich in manganese, up to 16% MnO, and the matrix contains about 5% BaO. Whether or not the slag is from the Iron Age, it provides clear evidence of local manganese- and barium-rich bog iron ores.

Another undated slag comes from the stone fence around Lemming Church, 6 km north of Silkeborg, Table 9.2, line 3. It is a 250 g fragment of a production slag and displays a fayalite-rich slag with about 15% wüstite and 15% multiphased matrix. In the matrix are black leucite cells and Ca-Fe-phosphates.

During excavations at the beginning of the 20th century for the barracks in the town of Tønder many (elephant's foot) slags were found – discarded and now lost. In the smaller town of Møgeltønder, 5 km west of Tønder, other slags were found (Mortensen 1939: 113). Already Gregersen (1933) had known this occurrence, although his description is rather naïve, even for his time. Through the kind cooperation of Olfert Voss, a 4.5 kg flat pancake of bottom slag from a slag pit of the Iron Age was acquired. The slag had beautiful imprints of the straw that had been placed in the pit

Fig. 214. Two large elephant's foot production slags from Snorup. The one to the left, 145 kg, turned upside down, the right one, 192.5 kg, in its correct position. Scale bar 40 cm.

before the furnace had been put into operation. The slag structure is 15% wüstite dendrites, 75% coarse fayalite and 10% homogeneous glass matrix, Table 9.2, line 4. The slag is extremely rich in manganese and barium: The fayalite has 25% MnO, and the wüstite 11%. The matrix is a Ca-Mn-Fe-phosphate glass with 1.2% BaO.

The four production slag analyses of Table 9.2 and the eleven of Table 9.1 demonstrate a rather conspicuous difference in the presence of manganese, barium, calcium, aluminium and potassium, the west Jutland ores in general being "the Purest", displaying the lowest G-values. Phosphorus is, however, present on a significant level in all the slags.

The most famous iron production site in Denmark is Snorup, Tistrup sogn, 12 km NNE of Varde. When Mortensen (1939: 124 f) first reported a number of large slags in the fields, and no less than 311 slag blocks of elephant's foot type were counted in the stone fences around Tistrup Church, 3 km to the east, he could hardly imagine that 65 years later over 8,000 slag pits had been identified within an 80 km^2 area around Snorup, due to systematic archaeological examinations (Voss 2003).

In cooperation with Varde Museum and supported by the Carlsberg Foundation, Olfert Voss has planned and participated in the excavations since 1982. In several publications the progress has been reported (e.g.

Voss 1991; 1993; 1995; 2003; Smekalova & Voss 2003), the last one stressing the importance of geomagnetic exploration,

The Snorup furnaces are unevenly distributed over 35 hectares, but are chiefly located north, east and south of the Snorup settlement, which has undergone a development similar to that of Vorbasse, 20 km east of Snorup. Smelting has apparently been practised, perhaps with interruptions, over a period of about 400 years (200-600 A.D.), with maximum activity around 350-450 A.D. The fuel came from oak- and hazel forests in the vicinity. A small reminiscence of the oak forests in ancient times is still to be seen in Krarup Lund, just north of Hodde.

The stakes for charcoal burning were most likely taken from 15-25 year old coppices (Voss 1995), harvesting the 5-10 cm thick, straight shoots from the oak stumps. While bog iron ore was abundant in the vicinity – and still is – it was probably the supply of fuel and charcoal that was the determining factor for when and where to start a new iron campaign.

Many planoconvex slags have been found within the smelting areas, but almost all are in secondary positions in the topsoil, in the filling of a well, or in postholes. They weigh up to 2.5 kg. Three of these kalot slags have been analysed, Table 9.3, lines 11-13. They are as usual depleted of manganese and phosphorus and enriched in calcium and potassium, relative to the production slags. Their structure is heterogeneous, with some undissolved quartz grains, and pockets of leucite.

Samples of ten different production slags are also

Fig. 215. Close up of the bottom of the 145 kg slag block in Fig. 214. The imprints of sheafs of straw are clearly seen. Side length 20 cm.

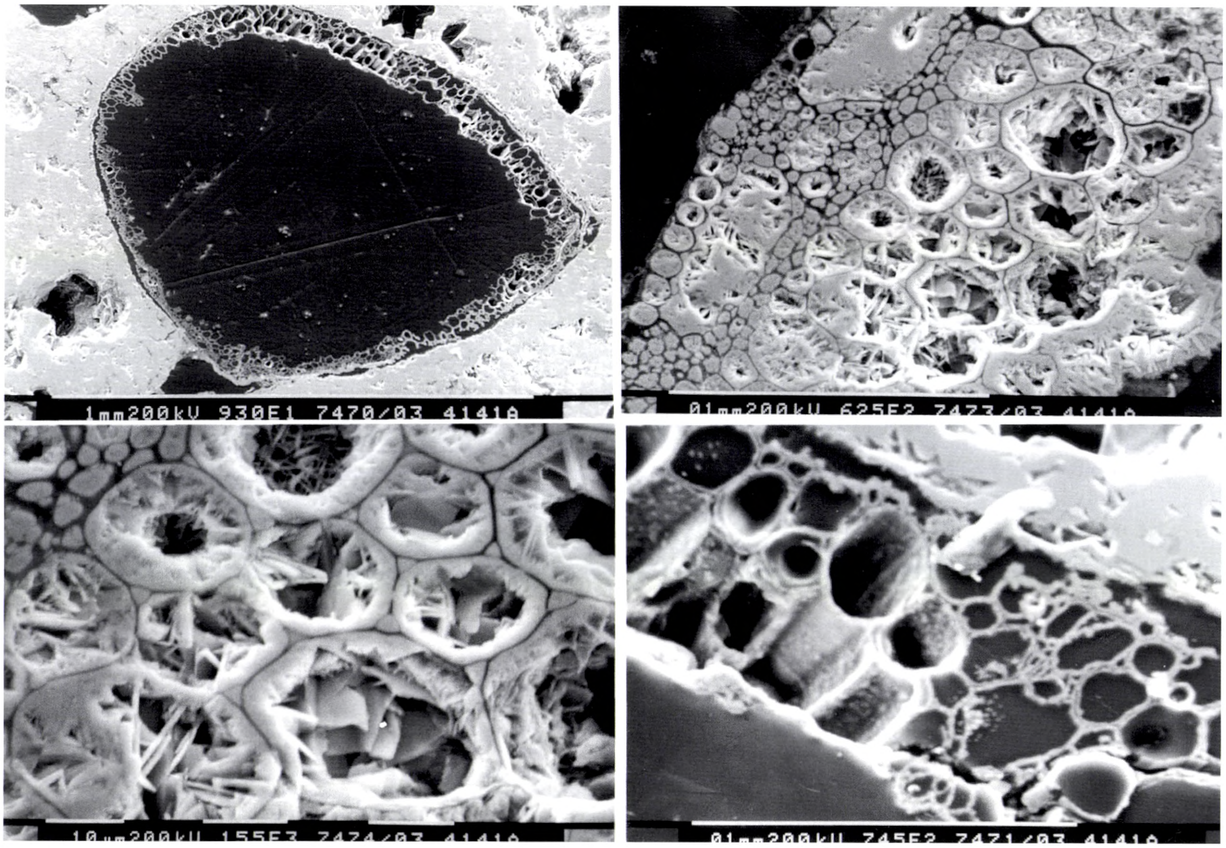


Fig. 216. Four sections through a Snorup bottom slag with straw inclusions, Fig. 215. The organic cell walls have been fossilized by an atom for atom replacement of iron oxides. PS. SEM. Scale bars as indicated. Sample 4141 A.

Fig. 217. A stalactite slag from the side of an elephant's foot slag block, compare Fig. 214. Snorup No. 105. Massive fayalite, wüstite dendrites, scattered hercynite skeleton crystals and some duplex matrix. PS. SEM. Scale bar 0.1 mm.

included in Table 9.3, lines 1-10. (The average of these ten samples was discussed in Table 6.4). The structures are in general coarse-grained, rather pure fayalite, some pure wüstite, and rather common hercynite crystals and leucite pockets. In several of the bottom slags, straw occurs in "fossilized" shape, Fig. 216. The cell walls of the straw are now formed by goethite. Mikkelsen (2003) has identified a number of plants among the fossilized debris in the slag pits, the most important being Hordeum (barley; byg), Secale (rye; rug), Raphanus raphanistrum (wild reddish; kiddike), Stellaria sp. (chickweed; fladstjerne), Rumex acetosella (common sorrel; rødknæ), Galeopsis sp.(hemp nettle; hanekro), and Spergula sp.(spurry; spergel).

The Snorup furnace type has only been identified in

Table 9.3. SEM-EDAX analyses of slags and slag inclusions from Snorup

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	23.3	72.1	0.2	-	0.8	0.3	2.8	0.3	0.1	0.1	-	100	8.32	4.79
2	13.8	81.9	0.1	-	0.4	0.3	2.4	0.3	0.2	0.2	0.4	100	5.75	3.88
3	24.3	68.2	0.3	-	2.2	0.6	3.0	0.3	0.6	0.2	0.3	100	8.10	6.36
4	21.6	73.8	0.4	-	2.0	0.7	1.0	0.2	<0.1	0.1	0.1	100	21.6	2.62
5	25.8	64.2	1.4	0.1	3.8	1.0	2.8	0.5	0.3	0.1	-	100	9.21	6.62
6	25.4	66.0	0.2	-	2.6	1.1	3.3	0.7	0.2	0.2	0.3	100	7.70	7.70
7	21.7	70.9	0.3	-	2.9	0.9	2.3	0.4	0.1	0.1	0.4	100	9.43	4.99
8	24.0	68.4	1.4	0.1	1.7	1.3	2.3	0.4	0.1	-	0.3	100	10.4	5.73
9	25.7	66.6	0.3	-	2.4	1.2	2.4	0.8	0.1	0.2	0.3	100	10.7	6.49
10	17.2	73.0	2.8	0.2	2.9	0.8	2.0	0.6	0.1	0.1	0.3	100	8.60	4.44
11	19.7	73.6	0.1	-	0.9	1.4	2.4	1.6	0.3	-	-	100	8.21	7.64
12	23.2	70.1	0.2	-	1.3	1.4	2.4	1.0	0.1	0.1	0.2	100	9.67	6.84
13	26.6	65.9	0.3	-	1.1	1.1	3.5	0.9	0.2	0.2	0.2	100	7.60	8.47
14	30.1	54.7	1.8	-	7.9	1.8	1.9	0.7	0.3	0.2	0.6	100	15.8	7.30
15	21.5	63.5	1.6	-	8.3	2.6	1.1	0.5	0.1	0.2	0.6	100	19.5	5.86
16	21.0	66.1	1.5	-	7.0	2.1	1.0	0.3	0.3	0.1	0.6	100	21.0	4.96
17	12.7	65.9	0.8	-	17.9	0.5	1.2	0.3	(0.5)	0.1	0.1	100	10.6	2.96

1. Elephant's foot, 192.5 kg block. Section through the centre.
2. Elephant's foot, 145 kg block. Section through the centre.
3. No. 105. 100 g stalactite slag from another slag block.
4. Snorup Øst 1. 269 g stalactite slag from a third block.
5. No 115. 105 g fragment from another block.
6. Lene 4088 a. 20 g fragment.
7. Lene 4141 a. Section through a 4 kg bottom slag with straw imprints.
8. No. 133. 183 g section through 3.5 kg bottom slag with straw imprints.
9. Lene 4141 b. 20 g icicle slag.
10. AYH. 226 g broken tapslag (?).
11. Purification slag. 752 g kalot slag from field 80. With a keel on the underside. Fig. 91.
12. Purification slag. 1120 g kalot slag, E 12. 15x13x4 cm.
13. Purification slag. 500 g kalot slag. SN 711 K.
14. Bar 300 B. 1240 g. 12,5 x (4-5) x 3 cm.
15. Initial stages of bloom. MA. 50 g.
16. Initial stages of bloom. MB 2. 60 g.
17. Lancehead from Iron Age gravefield at Snorup.

Jutland. The slag pits with freshly uprooted plants and with unthreshed straw imply that the furnaces were operated in midsummer, just before the harvesting season. This conclusion appears more plausible than the older opinion, that the furnaces were operated in September-October. The weather is at midsummer more suitable for the week-long, continuous work around the furnaces, even if protected by a shed, and

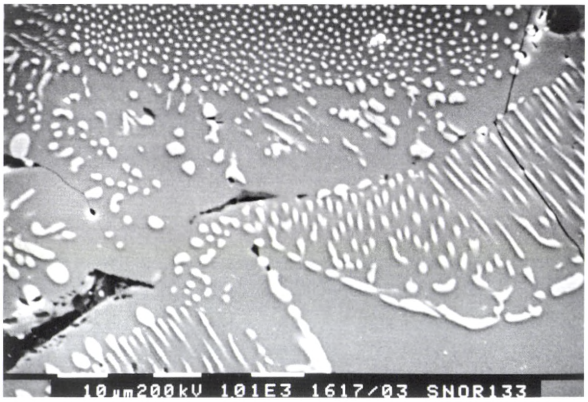


Fig. 218. Bottom slag, Snorup No. 133. Massive fayalite with exsolved wüstite particles in organized patterns. PS. SEM. Scale bar 0.01 mm.

the farmers had probably some time left over between hay harvest and corn harvest.

Only little iron has been found on the Snorup site. In the western part of the smelting area a small pit, 30x30 cm, with a total of about 20 kg rusted iron, was excavated. It contained 100 slender bars, 16-20 cm long with an average weight of 25-30 g, and 100 similar but longer bars with average weights of 135 g and lengths of 20-30 cm. At the bottom were six pieces of massive bar iron, totalling 3.2 kg (Høst-Madsen & Buchwald 1999). Only the massive bars belong to the Snorup production site, p. 151. The largest of the massive bars is rectangular, measures 125 x (40-52) x 27 mm, weighs 1240 g, and has a specific gravity of 7.6 ± 0.1 g/cm^3. It is thus pretty free of voids and slag inclusions, Table 9.3, line 14. As is usually the case, the P_2O_5-content of the slag inclusions has increased three to four times relative to the content in the massive production slags. The metal is rich in phosphorus, while carbon is absent. The coarse-grained ferrite has above 0.6% P in solid solution and the hardness is 183-232, while the ghost-ferritic structures contain 0.4-0.5% P and have lower hardnesses of 175-192.

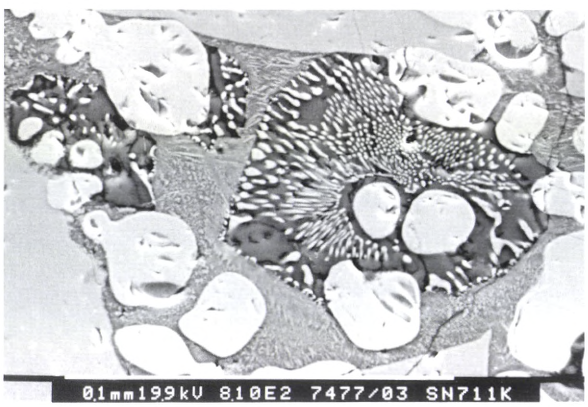


Fig. 219. A 500 g purification slag (kalotslag), Snorup No. 711 K. Fayalite (grey), wüstite globules (white), duplex matrix, and leucite (black)-wüstite eutectic. PS. SEM. Scale bar 0.1 mm.

Fig. 220. An 1120 g purification slag (kalotslag), Snorup No. E 12. Wüstite dendrites (white), fayalite laths (grey) and a matrix which has exsolved feathery fayalite skeleton crystals. PS. SEM. Scale bar 0.1 mm.

The composition of the 1.2 kg bar is in harmony with the production slags on the Snorup site, so perhaps we here have a unique example of the shape and size of the bars that left the Snorup proto-industrial area in ancient times.

In a contemporary grave, No. 1, in Snorup, a knife and a lancehead were found. Although severely corroded it was possible to prepare a few metallographic sections from the lancehead. The phosphorferritic structure had 0.4-0.8% P in solid solution, and the hardness was 200-204-207-210 and 220. The analysis,

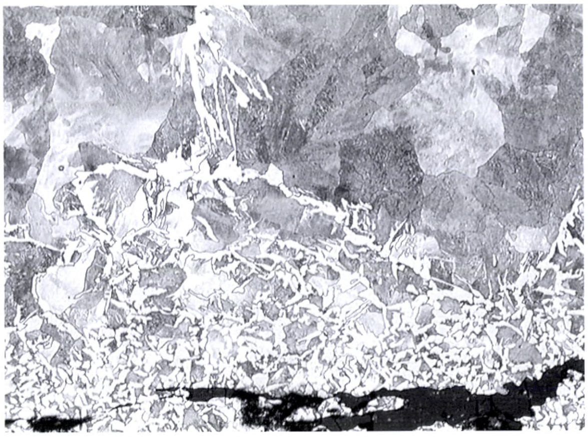
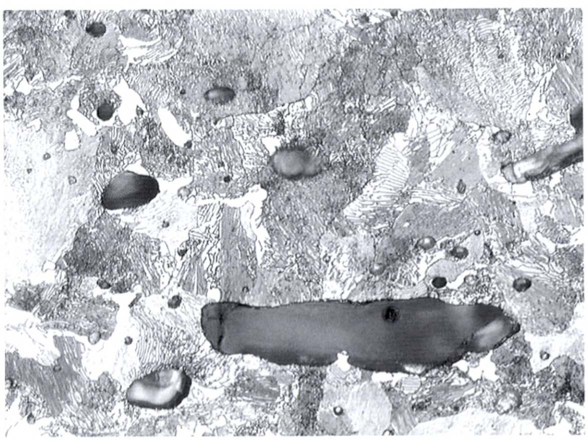


Fig. 221. Section through a Norwegian steel bar, 26 cm long and weighing 111 g, Snorup No. 56. Heterogeneous structure with glass slags, HV 146-210. PES. Side length 0.6 mm. Courtesy FORCE Technology.

entered in Table 9.3, last line, is in harmony with the Snorup ores, suggesting that the lancehead is an example of the local manufacture.

But not all iron was meant for the local farmers or their immediate neighbours, for they were also occupied by iron production. In the Iron Age settlements of Horne, Hindsig, Gødsvang, Krarup, Hodde, Hessel, Næsbjerg, and Yderik, all within 8 km from Snorup, several thousand furnace pits have been revealed by geomagnetic exploration (Smekalova & Voss 2003). Perhaps a part of the iron bars went north and east to other parts of "Denmark", but it it is also probable that an important part went south, by sea to Ribe and further away. About 15 km SW of Snorup lies Janderup, a trading place at Varde Å, which is known from the Middle Ages. Its church from about 1200 A.D. was partly built from tuff stones, sailed to Janderup from the Rhine quarries near Cologne. One might speculate whether this trading route could go right back to the Iron Age, so that one trading partner in ancient times was the Roman legionaries on the Rhine? Perhaps some interest should be concentrated on Janderup and similar landing sites along Varde Å, in order to find evidence for the trade in bar iron.

While a large and rather continuous iron production took place in southwestern Jutland from about 200 to about 600 A.D., little happened in other parts of Denmark. On the island of Sjælland few finds of Iron Age slags have been reported. The best examined occurrence is in connection with a settlement at Hørup, midway between Frederikssund and Slangerup (Sørensen 2000). The site has been interpreted as a craftsmen's centre, which was active from 100 to 500 A.D. On the basis of imported copper, bronze and gold, the local artisans provided the elite with bronze fibulae,



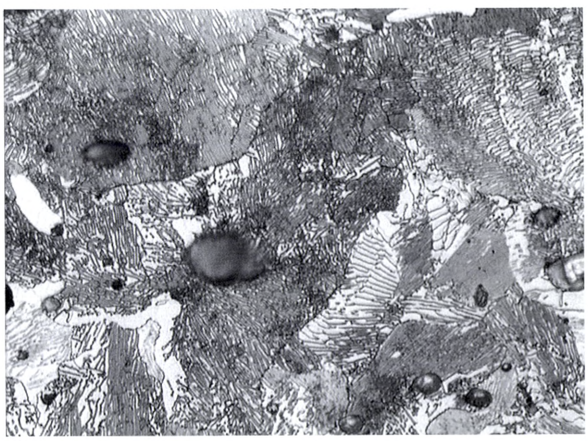


Fig. 222. Another view of the steel bar Fig. 221. Left, pearlitic steel with an elongated glass slag. HV 330. PES. Sidelength 0.15 mm. Right, enlargement. Side length 0.1 mm. Courtesy FORCE Technology.

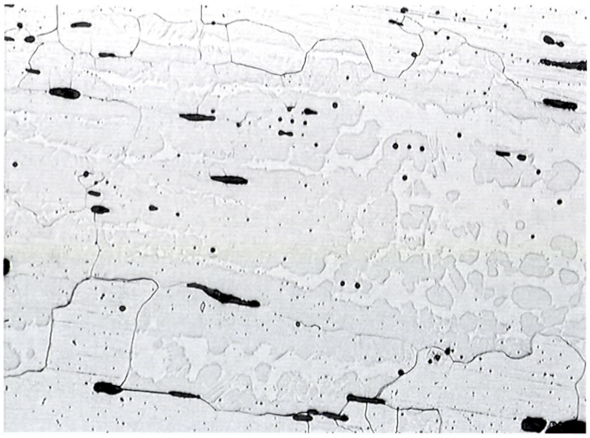


Fig. 223. Section through a lancehead manufactured from Snorup ore. Coarse grained phosphorferrite with ghost structure and glassy slag inclusions. PES. Side length 1.2 mm. Courtesy FORCE Technology.

brooches and other status symbols. Bone, cow's horns and iron were also worked. The debris from these activities includes a number of planoconvex slags. Roasted iron ore and several furnaces were also found. However, the furnaces on the site were unconnected with iron smelting and could have been potters' ovens. The roasted ores could have been used as pigments.

Several slags and a knife fragment were examined, Table 9.4. The first six are planoconvex slags or fragments of these. They are heterogeneous in structure and contain some charcoal and stones, which have been identified as calcined flint. It has been suggested (Sørensen 2000: 36) that flint was a substitute for the sand which was usually applied in the purification step. Sand and flint have the same chemical composition, being more or less pure SiO_2, and flint is omnipresent in the topsoil of Sjælland, derived from the cretaceous and tertiary deposits just below the present surface. In order to apply flint, it must have been calcined first in another fire to remove water. The small explosions associated with the calcination would have been too disturbing in the purification hearth. On the Hørup site, the pit FG may have served for the calcination. The pit was filled with charcoal and calcined flint.

In the slag analyses the presence of flint can, of course, not be detected. The slags are low in manganese and phosphorus as usual, and enriched in calcium and magnesium. The F-values for five of the six slags are not typical of Danish material, so perhaps the blooms to be purified were imported from elsewhere. One of the kalot slags, AF 165, contains a little copper, 0.1-0.2% CuO, an indication that the bloom may have come from a workshop that also worked with copper alloys. The slag inclusions in the knife, line 7, suggest that the knife was not produced in Hørup, but was imported, probably from southern Norway. The metal of the knife contains less than 0.2% P and is ferritic, with relatively low hardnesses, 118-122-126-132-134, making it a rather poor knife.

At Tystrup, Faxe sogn, 3 km SW of Faxe Church, an Iron Age settlement from about 200-300 A.D. was excavated by Benny Stål for Sydsjællands Museum. He found amber beads and a Roman silver coin with the portrait of Empress Faustina Augusta (about 170 A.D.), and glass beads imported from Cologne. Also a pair of iron furnaces and a purification hearth were found. The furnaces were presumably of the Skovmark type. Three slag fragments have been examined, Table 9.4, lines 8-10. They are similar in structure and composition and well illustrate eastern Denmark's calcium- and phosphorus-rich bog iron ore. The ore may have come from fields at Guldagergård, 1 km to the

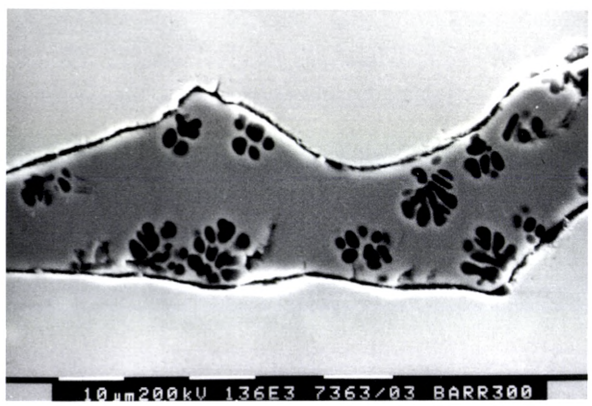


Fig. 224. Section through a bloom of 1240 g, Snorup No. 300 B. Phosphorus-rich glass slag with palmate exsolutions of a SiO_2-Al_2O_3 rich glass phase (black). PS. SEM. Scale bar 0.01 mm.

Table 9.4. SEM-EDAX analyses of Iron Age slags from Sjælland.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	29.3	57.8	0.2	0.4	3.4	5.0	3.5	0.1	0.2	0.1	100	5.86	20.5
2	20.5	72.5	0.1	0.4	0.7	4.1	1.4	0.1	0.2	-	100	5.00	8.63
3	28.4	58.7	0.1	1.6	3.0	4.7	3.0	0.3	0.2	-	100	6.04	18.2
4	24.0	67.8	0.2	0.7	2.1	3.5	1.3	0.3	0.1	-	100	6.86	10.5
5	24.0	66.4	0.2	1.7	2.0	3.6	1.6	0.1	0.1	0.3	100	6.67	10.7
6	20.6	70.6	0.2	0.9	3.9	2.4	1.1	0.1	0.1	0.1	100	8.58	10.5
7	22.8	68.7	0.2	0.7	0.5	4.7	0.8	1.1	0.2	0.3	100	4.85	10.2
8	18.6	62.2	1.9	8.5	5.5	2.0	0.7	0.2	0.2	0.2	100	9.30	11.6
9	18.4	62.6	2.5	7.7	5.2	2.1	0.8	0.4	-	0.3	100	8.76	11.7
10	17.3	64.5	1.8	8.6	5.3	1.6	0.5	0.2	0.1	0.1	100	10.8	10.1
11	24.5	58.4	1.6	6.6	4.7	2.3	1.0	0.3	0.4	0.2	100	10.7	12.5
12	19.8	68.0	1.1	3.4	4.1	2.1	0.9	0.2	0.1	0.3	100	9.43	10.1

1. Hørup, Slangerup sogn, Frederiksborg amt. Purification slag. 86 g, AF 56.
2. ibid. Purification slag. 205 g, AF 166 A.
3. ibid. Purification slag. 63 g. AF 166 B.
4. ibid. Purification slag. 30 g. AF 166 C.
5. ibid. Purification slag. 330 g. AF 175.
6. ibid. Purification slag. 50 g. AF 165.
7. ibid. 7.7 g fragment of a knife. 58/92.
8. Tystrup, Faxe sogn, Præstø amt. Production slag. 4.2 kg slag with adhering furnace wall. A 286.
9. ibid. Production slag. 50 g fragment. A 678.
10. ibid. Production slag.111 g fragment. A 689.
11. Gørlev, Holbæk amt. Production slag. 700 g fragment. SGø1, drillcore.
12. ibid. Production slag. 600 g fragment. SGø2.

northeast. The farm name even suggests the presence of yellow ("gul") ores. The more phosphorus, the more yellowish the ore is normally. The structure of the slag consists of about 60% manganofayalite (2% MnO), 20% manganowüstite (1% MnO) and a glassy matrix with leucite pockets. The total amount of slag was so small (<50 kg?) that the production must have been casual for the farmer himself and his neighbours.

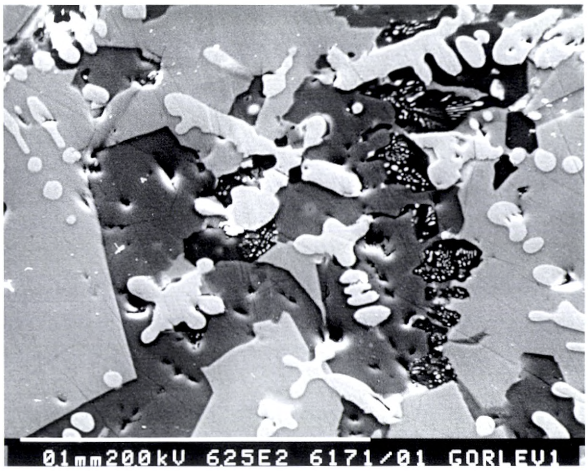


Fig. 225. Drill core through a massive production slag from Gørlev, SGø1. Wüstite dendrites (white), fayalite blocks (grey), calciumphosphate (almost black) and small leucite-wüstite pockets. PS. SEM. Scale bar 0.1 mm.

From an Iron Age furnace excavated at Gørlev, 4 km southwest of Tissø, the following two slags were analysed, Table 9.4, lines 11-12. The furnace type is unknown. The composition and structure of the slags are rather similar to the previous three from Tystrup. There are coarse- grained fayalite blocks (0.1 mm) across, wüstite dendrites and a matrix of leucite pockets with wüstite parties, and calcium-iron-phosphate glass.

Fyn

Thanks to the amateur archaeologist, Peter Mortensen, Odense, who kindly provided me with new material, it has become possible to include a number of slag occurrences from the island of Fyn. The slags are surface finds from cultivated and ploughed fields, so the original context has been destroyed. The approximate datings come from the presence of ceramics found together with the slags.

The first is from Nørreløkkegård, 2½ kmWNW of Hårslev Church. The samples were taken from an approximately 90 kg massive production slag of the Roman Iron Age, just west of a north-south going stone fence. The structure consists of 70% coarse-grained, blocky manganofayalite (5% MnO, 1.5% CaO), 20% dendritic manganowüstite (2% MnO), and a matrix rich in calcium-iron-phosphate. The average chemical composition is found in Table 9.5, line 1.

From Hårslev Mark, 2½ km NNE of Hårslev Church, and 0.5 km east of Nyledhus, a number of slags were identified (Henriksen et al. 1997: 131). They were all purification slags, and one of them, a planoconvex slag of 606 g, was examined, Table 9.5, line 2. The structure is 70% pure fayalite, 10% pure wüstite and 20% glassy matrix. The slag could easily have come from the purification of blooms having been produced at Nørreløkkegård, which is only 3.5 km to the west.

On Oregård Mark, 1 km NW of Ore Church, many fragmented clay pots of the Roman Iron Age and some iron slags were found (Henriksen et al. 1977:140, No. 40). Two samples of the very heterogeneous slags were examined, lines 3-4. They are from the purification step and have a structure of 60-70% pure fayalite, 10-20% pure dendritic wüstite and a glassy matrix under decomposition. The two analyses show the variation that can occur within fragmented planoconvex slags from the same hearth.

In a field in Ore (No. 100.1), 150 m north of the church, iron slags and ceramics occur, presumably from the Roman Iron Age. A 292 g fragment of a planoconvex slag was examined, line 5. It is heterogeneous and has minute (0.01 mm) grains of free iron disseminated through the slag. This is 60% calcium-fayalite (2.7% CaO), 25% pure, dendritic wüstite, and 15% glassy matrix. The composition is very close to that of Hårslev Mark, line 2.

In another field in Ore (No. 148), 600 m east of the church, ceramics of the Roman Iron Age and some slags were found. A fragment of 119 g has been examined, Table 9.5, lines 6-7. The slag is a production slag, perhaps from a furnace of the Skovvmark type, now destroyed. It could easily be mistaken for a small planoconvex purification slag, but the chemical composition clearly shows that it is a production slag, and probably tapped from a small furnace. A similar problem was discussed under Bruneborg, Chapter 6. Its structure is 60% manganofayalite (13% MnO), 20% manganowüstite (4.5% MnO), and 20% polyphased matrix in which there is up to 7% BaO. The bog iron ore responsible for this type of slag must have been rich in manganese, barium and phosphorus. The nearest known occurrence of this quality is at Allested, 15 km south of Odense (Buchwald 1998:13), but similar ores are presumably also present in the county of Ore.

In the fields, 600 m SE of Villumstrup, and 1300 m west of Refsvindinge Church, Odense amt, a number of pot sherds and many slag fragments were found in 1985. The ceramics indicated the Iron Age. 1299 g

Table 9.5. SEM-EDAX analyses of Iron Age slags and iron objects from Fyn and Bornholm

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	20.7	60.7	3.9	-	6.5	5.1	2.1	0.6	0.1	0.3	-	100	9.86	11.1
2	29.5	60.2	0.2	-	0.3	3.9	2.9	2.4	0.3	0.1	0.2	100	10.2	15.7
3	30.0	56.1	0.4	-	3.5	4.7	2.8	2.0	0.3	0.1	0.1	100	10.7	16.3
4	28.9	63.7	0.6	-	1.6	2.0	1.5	0.8	0.7	0.1	0.1	100	19.3	7.59
5	27.5	62.6	0.1	-	0.3	3.2	3.2	2.6	0.2	0.1	0.2	100	8.59	14.6
6	24.2	55.8	10.2	0.6	2.2	3.5	1.9	1.1	0.2	0.2	0.1	100	12.7	9.74
7	25.1	53.7	9.8	0.6	2.5	4.0	2.4	1.2	0.1	0.4	0.2	100	10.5	11.6
8	25.9	53.6	7.2	0.7	4.5	3.6	3.0	0.7	0.1	0.3	0.4	100	8.63	11.2
9	63.0	18.9	3.7	-	1.2	4.3	3.9	3.6	0.9	0.5	-	100	16.2	53.4
10	35.4	40.5	2.8	-	10.8	3.7	3.8	1.7	0.5	0.4	0.4	100	9.32	17.9
11	23.7	61.5	0.3	-	4.2	3.4	4.1	1.6	0.4	0.3	0.3	100	5.78	14.4
12	40.4	24.8	3.5	-	1.1	6.6	17.7	3.8	1.4	0.5	-	100	2.28	100
13	46.1	15.5	4.1	-	-	7.5	19.5	2.6	3.4	1.0	0.1	100	2.36	168
14	27.5	53.3	10.0	1.0	1.2	2.7	2.8	0.7	0.4	0.1	0.3	100	9.82	10.1

1. Nørreløkkegård, Hårslev sogn, Odense amt. Production slag. 90 kg.
2. Hårslev Mark, Odense amt. Purification slag. 606 g. FOH 9229.
3. Oregård, Ore sogn, Odense amt. Purification slag. Fragments, totalling 260 g. Mrk.66 A. FOH 9215.
4. ibid. another sample. Mrk. 66 B.
5. Ore, 150 m north of the church, Odense amt. Purification slag. 292 g. Mrk. 100.1.
6. Ore, 600 m east of the church, Odense amt. Production slag. 119 g. Mrk. 148 A.
7. ibid. another sample. Mrk. 148 B.
8. Villumstrup, Refsvindinge sogn, Svendborg amt. Production slag. 1299 g. Mrk. 104.
9. Lundeborg, Oure sogn, Svendborg amt. Nail, 9 g, Mrk.1. 300-400 A.D.
10. ibid. Nail, 3.9 g, Mrk. 5 A, 300-400 A.D. HV 200 g: 123-171-189-197-207.
11. ibid. Nail, 7.7 g, Mrk.4 A., 300-400 A.D. With a little copper, and 0.15% V_2O_5.
12. Gudme, Gudme sogn, Svendborg amt. 2 kg bar, FSM 6220x190. 300-400 A.D. With 0.23% V_2O_5.
13. Lundeborg, Oure sogn, Svendborg amt. Boat nail, 20.1 g. Mrk. 2 B. 300-400 A.D. With 0.15% V_2O_5, trace of chromium.
14. Maglegård, Øster Marie sogn, Bornholm. 42 g tapslag. BMR 1331, furnace 4. 300-400 A.D.

slag fragments were received from Peter Mortensen and were analysed, Table 9.5, line 8. The structure consists of 70% blocky manganofayalite (11% MnO), 15% manganowüstite (3% MnO), and 15% multiphased matrix with 3% BaO. There is no barium in the other phases. The slag is similar to the production slag from Nørreløkkegård and Ore 100.1, and it is probably of the same age. In three different locations on the island of Fyn the ancient iron masters thus have had access to manganese-barium-phosphorus-rich bog iron ores.

The Gudme district in southeastern Fyn has in Scandinavia a reputation for being rich in silver- and gold finds from the Iron Age. In 1833, an impressive collection of gold rings (the largest weighing 1765 g), broken and cut gold bars, and seven gold bracteates were ploughed up in the Enemærket fields of the Broholm Manor. The find was handed over as Danefæ to

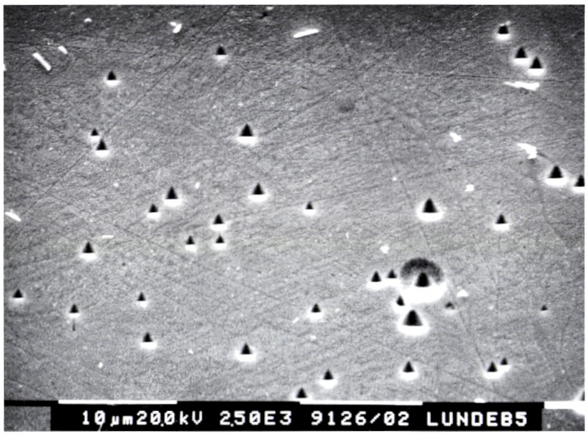


Fig. 226. Etch pits in phosphorferrite in the nail Lundeborg 5. Hardness 197 and 207, about 0.6% P in the ferrite. PES. SEM. Scale bar 0.01 mm.

the Crown. From then on, the Gudme-Hesselager-Broholm district has constantly been in focus. Broholm's owner N.F.B.Sehested excavated Bronze Age tumuli and many Iron Age graves, the most famous being Møllegårdsmarken east of Gudme (Chapter 8). Sehested's eminent publication (1878) also described the Broholm gold hoard, which was reported to have had a total weight of 4.15 kg. With later additions it now weighs 4.64 kg (Thrane 1993) and is thus of approximately the same weight as the two gold horns from Gallehus that unfortunately were stolen and lost for ever in 1802.

The place name Gudme may go back to the late Iron Age and probably means "home of the god". Other place names in the vicinity, such as Albjerg, Galdbjerg and Gudbjerg, also point to places of sacral importance. It appears that Gudme was a religious and cultural centre and probably also the seat of an important clan or family, a "royal" seat in the dawn of Danish history. In 1993 the remains of a large hall, 47 m long and 10 m wide, were found on the eastern outskirts of the modern town of Gudme. It appears that Gudme in the Iron Age had been a centre with about 50 longhouses. The hall, with two 2.5 m wide gates, may have served princely as well as sacral purposes and events (Michaelsen et al. 1993).

The Gudme centre was active in the period 200-600 A.D. Five kilometers to the east at Storebælt, it had a landing site and a strip of land on both sides of Tange Å. Here the activity was high in the summer season. No permanent settlement has been found, so people must have lived temporarily in tents or sheds, or on board the boats. Metal debris and the numerous remains of crucibles are evidence of the metalworkers, who cast gold, silver and bronze, and made iron fibulae. The last ones followed the shifting whims of fashion and are well-suited for dating purposes. Glass beads, amber fragments, and the remains of cow's

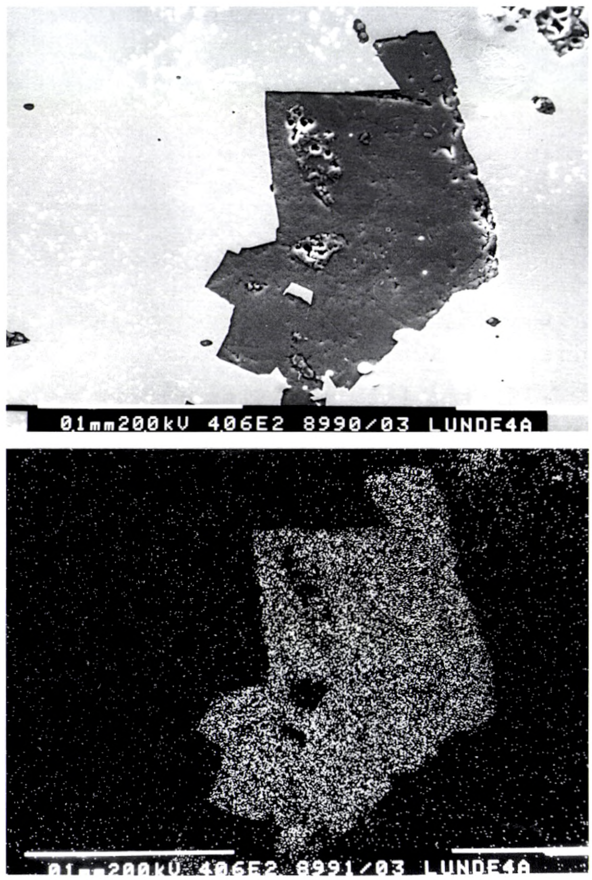


Fig. 227. Corrosive attack on the nail Lundeborg 4. An 0.1 mm crystal of hibbingite, $Fe_2(OH)_3Cl$, has developed in the metallic matrix. Above, SEM picture, white is unattacked metal. Below, Chlorine Kα picture, white is chlorine rich. PS. Scale bar 0.1 mm.

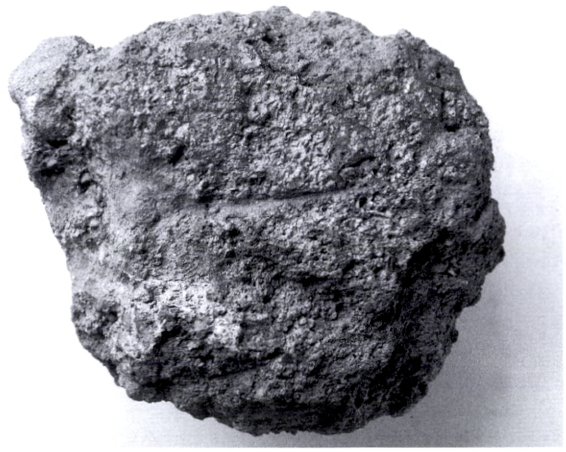


Fig. 228. A 2 kg bloom from Gudme, FSM 6220x190. 14x12 cm. Probably imported.

horns and antlers suggest that also makers of combs, drinking cups and other articles were active here.

On the site are found several thousand boat nails, ordinary nails, knives and tools, such as a carpenter's plane (Thomsen et al.1993:76). Apparently Lundeborg was a place where boats could be repaired. In winter time the craftsmen left the site and some moved "home" to Gudme, where workshops in precious metals have been identified. Lundeborg is thus a very early Danish site for specialized craftwork, similar to Hørup, but with a much longer lifetime, disappearing as late as about 800 A.D. (Thomsen et al. 1993).

Four of the nails from Lundeborg have been examined, Table 9.5, lines 9-11 and 13. They are all severely corroded, and could not all be hardness-measured. A 9 g nail, Mrk.1, still has some wood attached. The nail structure is phosphorferritic, but heterogeneous, with 0.1-0.4% P in solid solution. In the ferrite of the nail head there are Neumann bands from some heavy blows. The slags are glassy, or multiphased on a submicroscopic scale. Another nail, Mrk.5, is similar in structure, but has still more phosphorus in solid solution, 0.4-0.6% P. Some grains display numerous etch pits, and the hardness is high. The slag inclusions are glassy due to the high phosphorus content. The two nails were, no doubt, forged from bars of Danish bog iron ores, e.g. from Ore 148 or Villumstrup, located only 16 km to the northwest of Lundeborg.

The third nail, Mrk.4 A, is similar in shape, but different in composition. It has phosphorferrite, and there are traces of copper, which is unknown in a Danish context. Also the F-value falls outside the Danish values. The nail may have a southern origin, Siegerland perhaps (Gilles 1936). The fourth nail, Mrk. 2 B, is a rather large boat nail with a counter plate. It is a phosphorus-free steel-nail, consisting of pearlite-ferrite, and has a correspondingly high hardness.The slag inclusions are small and glassy, and very similar to those of the bar in line 12.

This bar, from Gudme, now in Svendborg Museum FSM 6220x190, originally weighed 2 kg. A small section was acquired for this study. The bar is heterogeneous and contains some charcoal, locked into the corroded crust. The structure is ferritic-pearlitic, without phosphorus, and the slag inclusions are rather few and small. They contain fayalite, glass and large (0.1 mm) hercynite crystals, in which there is up to 1.8% V_2O_5. The vanadium content and the low F-value point away from Denmark. The bar may have been imported from Germany (Siegerland, Schmalkalden), or, less likely, from southern Sweden. The boat nail, Mrk.2 B, was forged in Lundeborg from this or a similar imported bar.

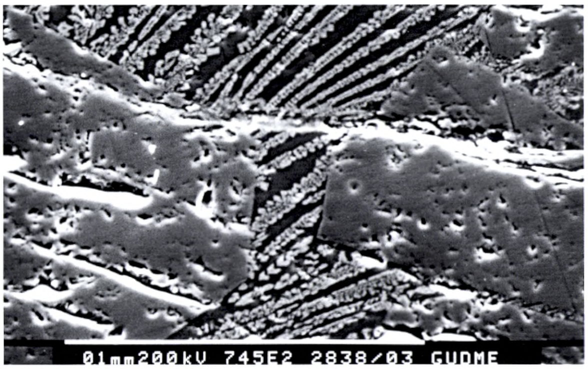


Fig. 229. Section through the Gudme bloom in Fig. 228. The slag contains large hercynite crystals with 1.8% V_2O_5 amd 1.5% MnO. The matrix is glass with fayalite skeleton crystals. PS. SEM. Scale bar 0.1 mm.

The import of iron and steel from Germany is perhaps not so surprising, considering Lundeborg's central role as an early Danish trading centre. There probably was a number of well-developed contacts to the Rhine area and the Cologne district. The iron/steel bar could well have come this way. Thus two simple nails are apparently from Fyn, while the two other nails and the bar probably came from Germany.

Bornholm

On the island of Bornholm little bloomery activity has been reported, probably because bog iron ore occurrences were limited. One site with five severely damaged furnaces has been examined at Maglegård, 1 km SW of Bølshavn, Øster Marie sogn (Appel 1986). The furnace remnants, which are situated among houses from the Germanic Iron Age, are apparently of the Skovmarken type. A total of 50 kg of slags were collected, and some of these have been analysed for this study, Table 9.5, last line. The tapslag is composed of 70% manganofayalite (0.1 mm wide laths), inside which a large number of fine wüstite particles have exsolved (15%). The remaining 15% is a polyphased matrix. Locally there are 3-10 μm iron particles, and

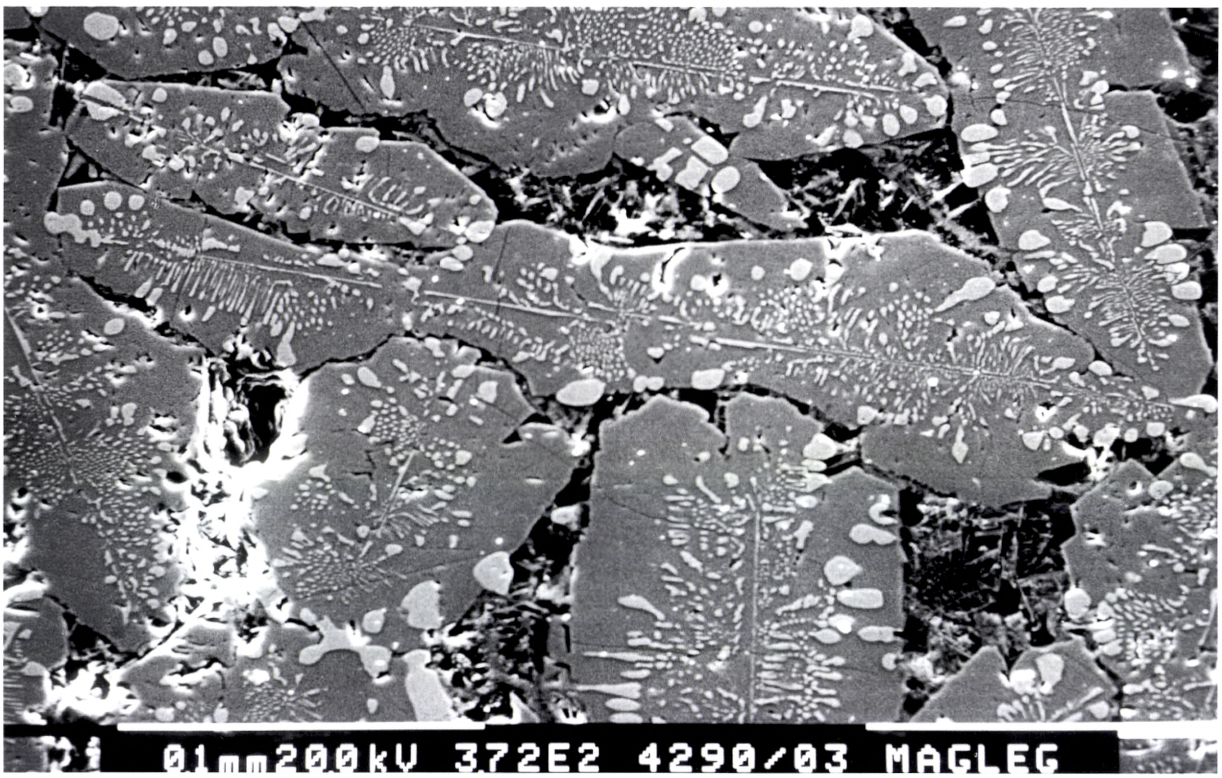


Fig. 230. Tap slag from a bloomery site at Maglegård, Bornholm. Tongue-shaped fayalite laths with exsolved wüstite particles. Duplex matrix. PS. SEM. Scale bar 0.1 mm.

surface-near areas have been drained for matrix during solidification shrinkage. The bog iron ore has not been identified, but apparently it has been a manganese- and barium-rich quality. The iron manufacture would have been phosphorus-enriched, soft, wrought iron for local consumption.

The furnace construction material

The ancient furnaces were often built from clay. In many cases they were built from stones and slates, but these would often have a finishing cover of clay. Also, tuyeres and plates to protect the bellows were normally constructed from clay. The following examples consist of hard-burnt clay walls and fragments of furnace

Table 9.6. SEM-EDAX analyses of clay material from Italy, Poland and Denmark

	SiO_2	Fe_2O_3	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	79.7	7.0	0.1	0	0.5	9.3	2.5	0.5	0.3	<0.1	100	8.57	180
2	58.5	16.2	0.2	0.6	3.4	14.0	5.5	1.1	0.4	0.1	100	4.18	141
3	81.6	4.0	0	0.6	0.9	10.0	2.0	0.4	0.5	0	100	8.16	289
4	69.9	14.2	0.3	0.2	1.5	10.3	2.5	0.4	0.6	0.1	100	6.79	100
5	60.6	7.2	0	0	0.2	27.3	2.4	1.0	1.1	0.2	100	2.22	429
6	76.7	11.6	0	0	0.2	8.8	1.6	0.5	0.6	0	100	8.72	96
7	72.0	7.2	0.1	0.1	1.3	13.7	3.3	1.2	0.7	0.4	100	5.26	264
8	74.3	6.2	0.1	0	0.9	13.1	3.5	1.1	0.8	0	100	5.67	295
9	63.9	12.2	0.3	1.4	2.6	13.4	3.6	1.8	0.7	0.1	100	4.77	154
10	52.0	23.0	0.3	1.7	5.7	9.9	5.1	1.6	0.5	0.2	100	5.25	89
11	52.3	7.5	0	0.3	23.4	11.9	2.8	1.2	0.6	0	100	4.39	504
12	66.5	7.1	tr.	tr.	1.0	20.6	3.5	1.3	n.d.	0	100	3.23	372
13	56.1	6.0	tr.	tr.	17.6	14.0	4.3	2.0	n.d.	0	100	4.01	632

1. Portoferraio, Elba, Italy. Furnace fragment. About 500 B.C.
2. ibid. Furnace wall with adhering iron slag. About 500 B.C.
3. Biskupice, Warsaw, Poland. 28 g furnace fragment. 400 A.D.
4. Bruneborg, Skanderborg, Jutland. Furnace wall with adhering slag. VFB 1 A. 300 B.C.
5. Snorup, Tistrup, Jutland. Furnace wall, 4072-2. 400 A.D.
6. ibid. Porous fragment of furnace wall with adhering slag. 157 g. 400 A.D.
7. Tystrup, Faxe, Sjælland. Furnace wall, Mrk.NNA. About 300 A.D.
8. ibid. Furnace wall, Mrk.286-9. 300 A.D.
9. ibid. Furnace wall, partially smelted, with adhering slag. A 286-9. 300 A.D.
10. Krogdal Vang, Gribskov, Sjælland. Porous, crumbling furnace wall with adhering slag and charcoal.
11. Technical University, Copenhagen. Experimental furnace wall. Clay from Wevers Teglværker, Hillerød, 1986.
12. Industrial clay for the production of normal red bricks, Denmark.1985.
13. Industrial clay for the production of normal yellow bricks, Denmark. 1985.

walls and hearths, which have sintered or smelted together with the iron slags. In many cases it has been possible to study and analyse the reaction zones between wall and slag. The results compare favourably with data published on furnace walls by Serning (1973).

Table 9.6 presents examples from Denmark, Italy and Poland, while Table 9.7 presents examples from Sweden and Norway.

The Portoferraio furnace fragment is red, Table 9.6, line 1, and is high in SiO_2. In fact, microscopic quartz grains are present everywhere in the clay matrix, showing that the furnace was built from a clay mixed with sand. The next fragment has some adhering iron slag. The black clay-slag reaction zone has been analysed, line 2, and found to be enriched in elements coming from the iron slag and the charcoal ashes: Fe, Ca, and K.

The Biskupice furnace wall, line 3, is also red-burnt and contains many quartz particles, suggesting a furnace built of a clay-sand mixture.

The Bruneborg clay fragment, line 4, has a reaction zone with increased iron and manganese contents, in line with contributions coming from a Jutlandish slag, rich in these components.

The first Snorup example is from a red-burnt furnace wall, unusually rich in Al_2O_3. The second one,

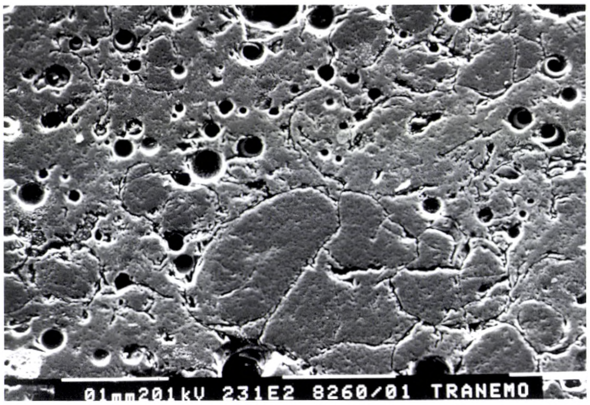


Fig. 231. Section B through sintered furnace wall from Tranemo, analysis Table 9.7, line 1. Gasholes in unequilibrated silica-rich matrix. PS. SEM. Scale bar 0.1 mm.

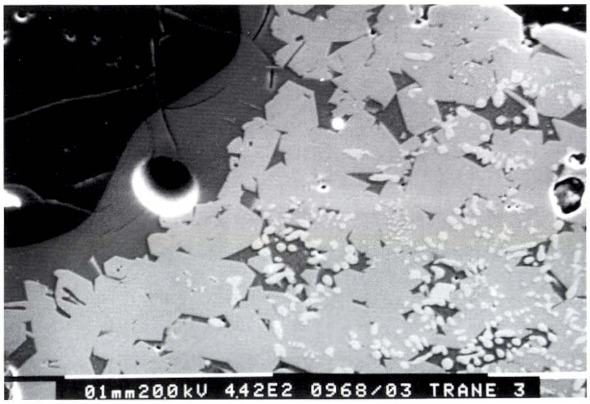


Fig. 232. The transition zone between furnace wall (left) and slag, Tranemo. Between the quartz grain (black) and the fayalite (light grey) is a 0.03 mm wide glassy reaction zone (dark grey). PS. SEM. Scale bar 0.1 mm.

line 6, is from the iron-enriched reaction zone, in which there are also quartz grains.

Two of the three Tystrup furnace walls are similar in composition, but the third, line 9, is from the iron-enriched reaction zone between clay and slag.

The Krogdal Vang furnace example is from the partly smelted, glassy and porous transition zone between clay and slag. The composition is strongly influenced by the slag components and the charcoal ashes.

In 1986-1990 a number of experimental furnaces were built at the Technical University of Denmark, in Lyngby. In line11 is the composition of one of the furnace walls, from 1986. In this one, too little sand was mixed into the clay, which explains the low SiO_2/CaO ratio, quite different from that of most of the ancient furnaces.

Lines 12-13 are analyses from Danish industrial clays, used respectively for the production of red and yellow bricks in the late 20th century. Fron the analyses alone, it appears that the majority of the ancient clay types are of a red-burning nature. The redox potential, however, of the combustion gases in the industrial furnaces also plays a role for the resulting colours.

In Table 9.7, line 1, is a furnace wall from Tranemo, Vester Götland. The many quartz grains give rise to a high SiO_2/CaO value.

Table 9.7. SEM-EDAX analyses of clay material from Sweden and Norway

	SiO_2	Fe_2O_3	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	74.9	8.2	0.2	0	1.1	10.9	3.3	0.7	0.6	0.1	100	6.87	190
2	69.6	6.0	0.1	0.1	1.6	15.1	6.1	0.8	0.6	0	100	4.61	381
3	65.7	9.7	0	0	1.6	16.1	5.3	0.9	0.6	0.1	100	4.08	246
4	60.9	10.7	0.2	0	2.2	17.6	5.9	1.5	0.9	0.1	100	3.46	250
5	65.3	6.1	0	0	1.6	19.4	6.8	0.6	0.2	0	100	3.37	466
6	64.4	10.8	0.3	0	2.3	16.2	5.4	0.2	0.4	0	100	3.98	217
7	61.7	10.9	0.2	0.4	1.6	18.1	4.6	1.3	1.2	0	100	3.41	223
8	62.0	5.6	0.1	0	2.2	20.6	8.0	0.9	0.6	0	100	3.01	556
9	67.9	10.0	0.4	0	4.4	10.8	3.1	1.6	1.6	0.2	100	6.29	191
10	61.0	10.1	0.1	0	4.5	18.0	3.3	2.1	0.9	0	100	3.39	274
11	49.6	17.5	0.2	0	4.0	17.2	4.1	5.7	1.4	0.3	100	2.88	175
12	69.4	6.6	0.1	0	1.3	16.5	3.8	1.7	0.6	0	100	4.21	348
13	55.3	17.7	2.2	0	4.8	13.1	4.0	2.4	0.5	0	100	4,22	122

1. Tranemo, Vester Götland. Furnace wall, sample B with undissolved quartz. 1100 A.D.
2. Jernvirke, Tvååker, Halland. Furnace wall, with adhering slag No. 12. 1150 A.D.
3. ibid. Furnace wall, with adhering slag No. 15. 1150 A.D.
4. ibid. Porous furnace wall, with adhering slag No. 13. 1150 A.D.
5. Ugglehult, Tvååker, Halland. 161 g slag with adhering burnt clay cover. 84: F 23. 1150 A.D.
6. Jernmølle, Tvååker, Halland. Slag with adhering burnt clay cover. 48x83 C. 1150 A.D.
7. Sannarp, Halland. Furnace wall, resembling a red brick. F 265 B. 300 B.C.
8. Vittsjö, Skåne. Furnace wall, 260 g. 1600 A.D.
9. Beitostølen, Valdres, Norway. Tuyere of burnt clay. Iron Age.
10. Dokkfløyvann, Oppland, Norway. Furnace wall with adhering slag. 154 g. C 37462 h. Iron Age.
11. Storbekken, Trøndelag, Norway. Inside, slaggy black furnace wall. Iron Age.
12. Lapphyttan, Vestmanland, Sweden. Fragment of blast furnace wall. A 3-8. 1300 A.D.
13. ibid. Blast furnace wall, impregnated by iron slag. A 3-7. 1300 A.D.

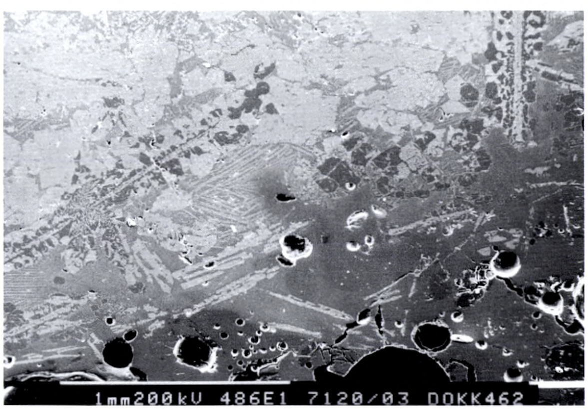


Fig. 233. The transition zone between furnace wall (below) and slag, Dokkfløyvann C 37 462 h. In the glassy transition zone are fayalite skeleton crystals, gasholes and undissolved feldspar and quartz grains. PS. SEM. Scale bar 1 mm.

The next three lines are from furnaces at Järnvirke, Halland. They are very similar in composition, line 4, however, displaying a reaction zone which is significantly altered due to contact with iron slag and ashes.

The Ugglehult example, line 5, is an analysis of a 2 mm thick rim of burnt clay that once covered the furnace construction stones, but now remains attached to a slag fragment found near the ruined furnace.

Jernmølle, line 6, is a similar, mm-thick covering clay layer, found sintered onto a loose slag. It has absorbed somewhat more iron and is black.

Sannarp, line 7, is from an ancient, destroyed and little understood furnace structure.

Vittsjö is from an almost entirely molten part of a furnace wall. The analysis is that of pure molten clay without contact with the inside slag. There are inclusions of small iron droplets and grains of undissolved potassium feldspar, which are one of the decomposition products of the local gneissic bedrock.

The following three examples come from Norway. Table 9.7, line 9, is from a broken tuyere used at Beitostølen, Valdres. The end of the tube has been partly melted and has absorbed some iron.

Dokkfløyvann is a heterogeneous, partly melted furnace wall, with skeleton crystals in the glass phase, and some iron absorption.

Storbekken is a fully melted, black and porous furnace wall with a considerable absorption of components from the slag and the charcoal ashes. The microstructure is glassy, locally with undetermined crystallites and skeleton crystals.

The two last analyses come from one of the early blast furnaces of Sweden, Lapphyttan. The ruby-red furnace wall, line 12, contains 0.05-1 mm quartz grains and represents the wall away from any contamination with slag and ashes. The wall is just sintered and burnt as a brick. In line 13, another, much more heated and transformed furnace wall is presented. The flux, probably of calcite, and the iron slag have significantly changed the composition of the partially molten reaction zone. The glass, which contains skeleton crystals of iron-titanium-oxide, is partly decomposed to feathery fayalite crystals.

Fig. 234. Detail of the central part of Fig. 233. Two feldspar grains are being dissolved to the right. On cooling, unequilibrated structures developed. PS. SEM. Scale bar 0.1 mm.

It is often stated that slag analyses are severely contaminated and influenced by the inmixing of worn furnace parts. This is exaggerated. Locally, as shown here, it is possible to find some slags with adhering furnace wall, but they are easily recognized and can – and should – be excluded from the normal average slag analyses. The essential production slag is formed inside the furnace, distant from any wall or bottom, and here the slag is the result of reactions between ore and charcoal ashes. On the purification hearth the conditions are different, because the slag volume is small and the contact surface between slag and hearth is large. The purification slag is therefore a result of the reaction between bloom, charcoal ashes, hearth bottom, and any additions the blacksmith would deem necessary, usually "sand". Production slags are, on the other hand, essentially the result of reactions between ore and ashes alone.

Comparing the 23 analyses of Tables 9.6 and 9.7 leaves one with the impression that the material for the ancient clay-built furnaces was of a surprisingly uniform nature. Little, if anything, has been done to produce a special refractory material. In almost all localities clay with a high ratio of Fe_2O_3 to CaO has been used. Perhaps this is just the most common clay type everywhere, since the examples cover geologically very different sites, from Elba to central Sweden, and from Poland to Norway. When burnt, this high ratio gives rise to reddish furnace material.

The examples in Table 9.7 cover a period of 1500 years. The clay required for furnace construction remained the same.

Finally, the F- and G-values should be noted. The F-value strays in an unpredictable way and is apparently of little use here. There is, perhaps, a tendency for lower F-values in Norway and Sweden, compared to the somewhat higher values for Denmark. This is the same trend as for production and purification slags from these countries.

The G-values are very high, generally well over 100, a fact which may be helpful when evaluating analytical data for a dubious object, a slag, a furnace wall, a hearth bottom, or some other ancient debris.

The three Norwegian examples are significantly enriched in magnesium and titanium. The same enrichment is also present in Norwegian slags and slag inclusions. It is evidently a result of the common occurrence of weathered, basic dark rocks ("metabasalts") in southern Norway.

It is also worth noting that manganese, barium, phosphorus and sulphur are practically nil in all furnace construction material. Where they increase slightly, the increase is due to the reaction with the slags.

Magnetic surveys for archaeological mapping

Already several centuries ago geomagnetic mapping was applied in the search for metallic ores in Sweden and elsewhere. In the 20^{th} century geomagnetic instruments have been much refined, and may be airborne. Since about 1970 the method has been systematically used in archaeology (Abrahamsen & Breiner 1993).

The Earth's magnetic field may be conceived of as lines of equal magnetic force that connect the magnetic poles. Theoretically the lines should be parallel, but due to ore bodies, railroad lines, cities etc. the lines deviate slightly, and the deviations can be registered with sensitive instruments and mapped.

The Earth's magnetic field is in Denmark presently about 49,000 nanoTesla (nT), but during the day it may vary 30-40 nT. Archaeological structures usually result in anomalies of 1-20 nT, while a 200 kg iron-rich slag of the elephant's foot type may show 20-2000 nT (Smekalova & Voss 2001; 2003; Risbøl & Smekalova 2001). Specialized instruments, such as a proton magnetometer, are required for fast and reliable data collection. Within a day's work an area of 0.2-0.5 ha may be laid out, and marked in narrow tracks,which have to be followed, measurements being taken every 0.5-1 m. The data are digitally stored and calibrated against a nearby fixed magnetometer, which registers the natural daily magnetic variation. The work usually requires a geophysicist and an assistant, and is conveniently performed in the early autumn when the crops have been harvested.

The method has given brilliant and fast results in the iron-producing counties in western Jutland. But the same procedure is also able to reveal the lay-out of archaic settlements in Greece, where crushed pottery has been used for paving the roads. The burned pottery displays a permanent magnetic susceptibility which stands in contrast to the soil on either side of the pottery-paved tracks.

Chapter 10
Iron and steel in Europe in the period 0-600 A.D.

Runes of victory shalt thou know,
if thou wilt have the victory,
and cut them on your sword hilt,
some on the hilt rings,
some on the plates of the handle,
and twice name the war god Tyr.

Sigdrifumal, the Elder Edda.

In an attempt to characterize the iron production in the period 0-600 A.D. we will now visit a few other European countries, Norway, Sweden, Poland, Germany, England and Spain. The choice has been made to provide examples to illustrate the general trend, and the examples are supported by analytical and structural descriptions and hardness determinations.

Norway

For a long time it was believed that bloomery iron production started rather late in Norway, perhaps during the Migration period (Hauge 1946; Martens 1968; Martens & Rosenqvist 1988) with many important production sites situated around Møsstrond in Telemark. Increased attention to iron slags and extensive construction of water reservoirs led, however, in the 1980s to the discovery of major iron-producing centres from the Roman Iron Age. One centre was located in Trøndelag, within a radius of about 100 km south, east and northeast of Trondheim, the best examined being the site of Heglesvollen, 20 km southeast of Levanger (Farbregd et al. 1985; Solem 1991). Another centre was situated around Dokkfløyvann in Oppland, about 30 km west of Lillehammer (Larsen 1991; 1992). A third, and probably minor one, was discovered at Eg, near Kristianssand in the southernmost part of Norway (Nakkerud & Schaller 1979). See the map p. 158.

It is characteristic of the Trøndelagen bloomery sites at Heglesvollen, Vårhussetra, Tovmoen, Myggvollen and Storbekken that the furnaces were arranged in batteries of three to five. They were situated near the edge of a terrace facing a river, a creek or a lake, and they were found in the upper tree belt, 500-600 m a.s.l. They were generally near the bog iron ore, but far from permanent dwellings.The geological setting, and the change from iron production to copper- and later to pyrite production in Budalen have been discussed by Nilsen (1993).

At Storbekken in Budalen, 64 km south of Trondheim, five furnaces of the Heglesvollen type have been identified (Espelund & Stenvik 1993). Around each furnace there was a characteristic set of 5-6 shallow pits, a "rosette", of unknown function. The furnace had a 1 m high clay-built shaft and an underlying 70-85 cm deep and 85 cm wide, cylindrical pit. The

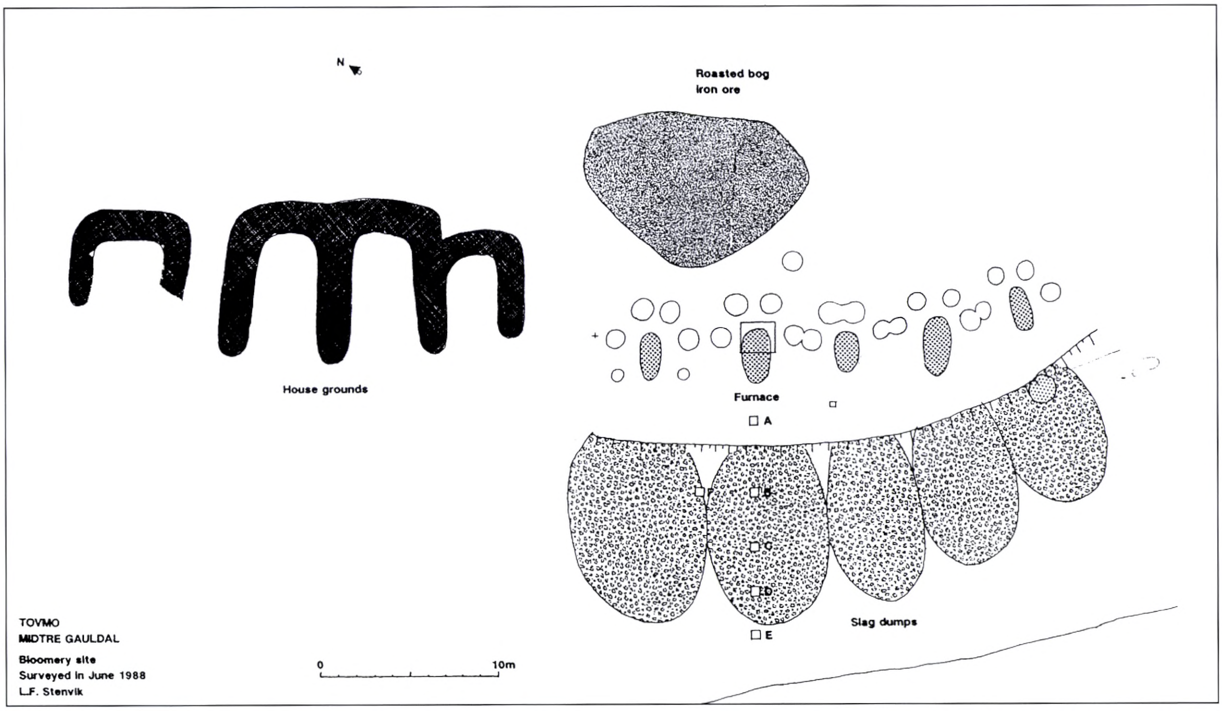


Fig. 235. Bloomery site at Tovmo, Midtre Gauldal. To the right five furnaces and their slag dumps. Rosette pits behind each furnace. The remains of houses to the left. Stenvik 1991.

stone-clad pit had a vertical 40 cm wide slit that opened towards a trench. Apparently the Heglesvollen-Storbekken furnace type is related to the contemporaneous Scharmbeck-Snorup type, except that the Heglesvollen furnace-pit could be emptied of slag through the slit, and therefore could be reused a number of times. The solidified slag was raked out and thrown down the slope towards the creek. It was estimated that the slag accumulation below the five furnaces at Storbekken amounted to 24-48 tons and that each furnace had been used perhaps a hundred times. The charge must have consisted of roasted bog iron ore and dried wood, while charcoal was not used. It appears that the furnaces were run on natural draught.

From a slag heap, C-14 dated to 350 A.D., a 200 g fragment was analysed, Table 10.1, line 1. The slag composition suggests that the ore, although not identified (Espelund & Stenvik 1993), must have held some manganese and aluminium, but very little phosphorus, in good accordance with two slag analyses presented by the above authors. The iron in equilibrium with such slag would have been excellent soft, wrought iron, with less than 0.1% carbon and no phosphorus. Unfortunately no iron products have been found on the sites. The yield of iron must have been rather small, since as much as 71% FeO has been retained in the slags.

At Dokkfløyvann the extensive archaeological excavations have revealed a more than thousand year long activity, with C-14 dated furnaces and slags ranging from 100 to 1400A.D. (Larsen 1991; 1992). We will here examine slags and iron objects from the first period, the Roman Iron Age. The Dokkfløy Lake lies 700 m a.s.l. The forest cover is today dominated by spruce, but in the Iron Age and the Middle Ages pine and birch would have been predominant. The bogs of the valley are rich in iron ore. The excavations have revealed a total of seven big shaft furnaces with underlying slag pits and dated to 100-600 A.D.

Fig. 236. An artist's impression (Inkalill) of organized ironmaking at Storbekken about 300 A.D. Compare Fig. 235. From right to left, five stages in furnace construction, burning and cleaning. Furnace type 8, Fig. 183. Courtesy Espelund & Stenvik 1993.

These furnaces are large compared to their contemporaneous cousins from western Jutland. The inner diameter was up to 1.5 m and the pit-depth was 0.7 m. Slags found in situ weighed between 250 and 450 kg. Apparently the pits were used again and again, since large slag heaps with blocks of slags measuring up to 1 m in diameter were found around the furnaces. Post holes indicate that the furnaces were protected by a building or a roof-covering, measuring 5x5 m. Other post holes suggest the application of three-legged hoists to remove the clay shafts and the slag blocks from the pits.

From the furnace site DR 222 (Larsen 1991: 58) a 65 g fragment from a large block was analysed, Table 10.1, line 2. The structure is very coarse-grained with 0.2 mm fayalite blocks and voluminous wüstite den-

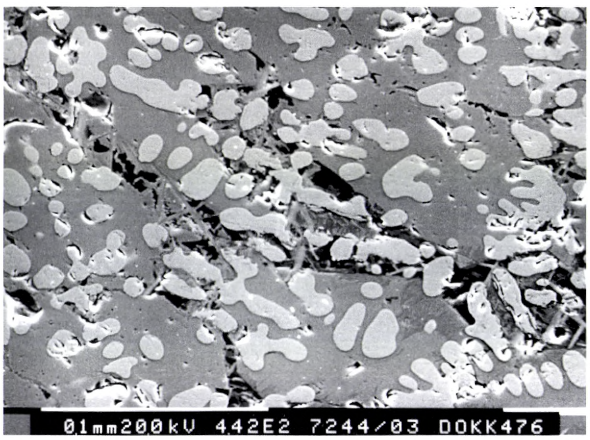


Fig. 237. Production slag, C 37 476, from Dokkfløyvann. Coarse grained wüstite and fayalite, and a little duplex matrix. PS. SEM. Scale bar 0.1 mm.

drites, in accordance with a slowly cooled large slag block. The matrix is enriched in barium (9% BaO), while the fayalite is enriched in manganese. Locally there is some enrichment in iron sulphide.

From another furnace site DR 75 (Larsen 1991: 83) a 308 g tapslag with a ropey surface was analysed. DR 75 is a complex site with several furnaces within a narrow area. One type is similar to the above-mentioned DR 222, while the other is a much smaller and slightly younger type, a slag tapping furnace. The analyses in lines 3-4 come from one of the tapslags, collected in the 4.3 x 3.5 m large slag heap found near the furnace. A transverse section through the slag reveals a complex layering from consecutive runs that have created the ropey surface. The two layers analysed are similar in composition, but deviate in the unusually high sulphide content of one of the layers. It may be derived from some (weathered) pyrrhotite in the bog iron ore. The slag is fine-grained with 0.1 mm fayalite laths and 5 μm wide wüstite dendrites, corresponding to a rapidly cooled tapslag. Locally there are 10 μm wide inclusions of free iron.

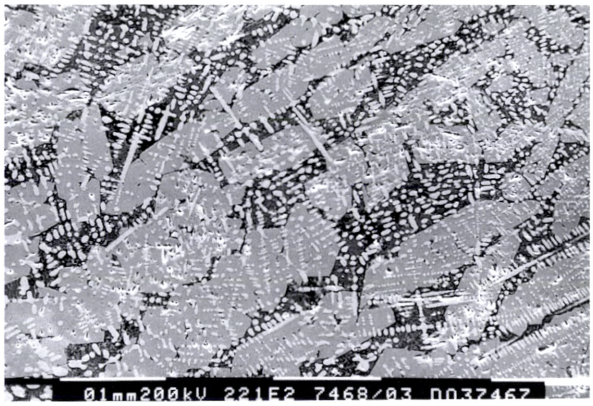


Fig. 238. A 308 g tap slag, C 37 467, from Dokkfløyvann. Fine wüstite dendrites, fayalite laths and glass matrix. PS. SEM. Scale bar 0.1 mm.

Table 10.1. SEM-EDAX analyses of slags from Storbekken, Dokkfløyvann and Beitostølen

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	18.0	70.9	1.8	-	<0.1	1.2	6.2	0.7	0.6	0.2	0.3	100	2.90	12.0
2	22.9	61.7	5.9	1.3	0.2	1.9	4.3	0.7	0.1	0.4	0.6	100	5.33	10.1
3	24.2	60.6	5.1	tr.	1.6	2.6	4.2	0.9	0.1	0.5	0.2	100	5.76	11.6
4	23.7	61.0	3.6	tr.	1.8	3.0	4.3	1.2	0.3	0.4	0.7	100	5.51	13.3
5	28.4	51.1	3.7	0.5	0.3	3.0	10.2	1.6	0.8	0.2	0.2	100	2.78	28.1
6	30.9	43.9	7.2	1.0	0.4	3.7	9.5	1.9	1.0	0.2	0.3	100	3.25	30.7
7	23.6	51.6	9.6	1.8	0.4	2.3	8.2	1.3	0.9	0.2	0.1	100	2.88	20.0
8	25.2	40.5	16.3	0.7	0.2	3.1	10.4	1.1	1.7	0.6	0.2	100	2.42	28.2
9	30.0	57.0	0.8	-	0.1	1.6	7.9	1.6	0.5	0.3	0.2	100	3.80	20.0

1. Storbekken, Budalen, Trøndelag. 200 g production slag with hercynite crystals. 350 A.D.
2. Dokkfløyvann, Oppland. Site DR 222, C 37476. Slag block. 300-500 A.D.
3. ibid. Site DR 75, C 37467. Tapslag. 350-550 A.D.
4. ibid. The same, but another layer in the tapslag.
5. Beitostølen, Valdres. 40 g tapslag. About 400-500 A.D.
6. ibid. 9 g tapslag.
7. ibid. 6 g tapslag.
8. ibid. 1.5 g tapslag.
9. ibid. 532 g purification slag.

About 50 km WNW of Dokkfløyvann, at Beitostølen in Valdres, another Iron Age production site has been identified (Hege Svane, pers.comm.). From this location a number of slags have been analysed, lines 5-9. Four are tapping slags, similar to Dokkfløyvann DR 75, while the fifth is a purification slag. The tapslags are fine-grained and composed of manganowüstite (-14% MnO), manganofayalite (-16% MnO, -3% MgO), chromehercynite (-0.8% Cr_2O_3, -9% MnO) and glass. The purification slag, on the other hand, is coarse-grained, poor in manganese and phosphorus, and contains leucite with wüstite particles.

The Beitostølen tapslags, lines 5-8, and the Dokkfløyvann block slag, line 2, are remarkable by their high manganese and low phosphorus content. As discussed in Chapter 6, this combination "automatically" leads to a carbon-enriched iron product, i.e. a steel with 0.4-07% C. It would be worth while to start a systematic investigation of these furnace sites – and others with similar slags – in the Valdres district to determine whether it was here that the many steel bars and steel wedges were produced.

The steel bars have been found in hoards only, Fig. 158. They number from a few to several hundred per hoard. Out of a total of 110 hoards, 100 come from a limited region in Middle Central Norway: The Gudbrandsdalen Valley and its naturally adjoining lowland farming districts (Svane 1991).

Fig. 239. Section through a 1.5 g tap slag, Beitostölen. Fine wüstite dendrites and fayalite laths. Dark, cubic hercynite crystals which solidified early. PS. SEM. Scale bar 0.1 mm.

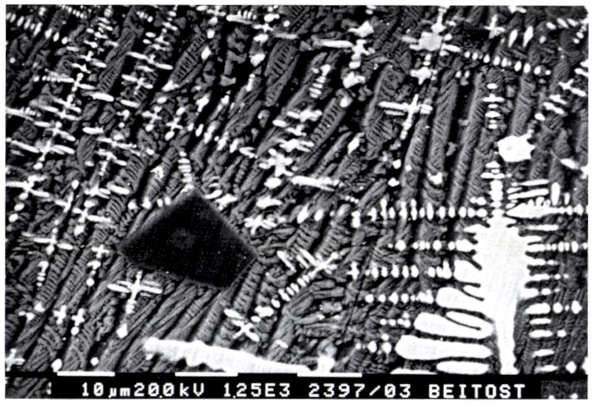


Fig. 240. Detail of Fig. 239. The hercynite crystal has 10% MnO and 0.5% Cr_2O_3 in solid solution and displays a narrow, heavy-metal enriched rim zone. PS. SEM. Scale bar 0.01 mm.

In Table 10.2 a selection of the steel bars are presented. They have been found "in the forest under the root of a tree" (Melby), "in a stone cairn" (Trodalen), "in a grave mound" (Prestegården), or, mostly, just buried in cultivated fields. The hoards unfortunately rarely contain datable objects, so the bars have for generations had an uncertain position in the archaeological system. In the Museum list of iron bars in Oslo's Oldsaksamling they are, with few exceptions, referred to the Viking Age. All the examples in Table 10.2 have thus been labelled Viking Age. With the new evidence, from finds in Snorup, Denmark (Høst-Madsen & Buchwald 1999), this opinion is no longer tenable. A significant number is, no doubt, from the Iron Age. This viewpoint is supported by a recent find on an Iron Age farm at Modvo at the head of the Sognefjord, where a 18 g steel bar, similar to those from Prestegården, was found together with many iron objects and smithy work that could be dated to 350-550 A.D. (Resi 1995). Also Svane (1991) stated that small iron axes of rhombic and octahedral cross sections are found in Norwegian graves dated to the Roman and Migration periods only.

Five of the steel bars in Table 10.2 have been examined and analysed. Although they are often se-

Table 10.2. A dozen examples of hoards of spoon-shaped steel bars, five of them analysed. See also Fig. 154.

Oslo Museum No. C	Found	Fylke	Number	Type Hauge: 164	Average weight g	Average length cm	Photo or Figure
3549	Prestegården, Gran	Oppland	130	84 e	12-15	12-15	-
4387	Bø, Østre Gausdal	Oppland	8	84 b	400-450	24-26	P: 172 H: 164
14908	Elvesveen, Kolbu	Oppland	112	84 e	12-15	14-18	-
21861	Seierstad, Hov	Oppland	200	84 d	(150)	30	-
23191	Trodalen, Øyer Østre Gausdal	Oppland	110	84 d	160	30	-
24705	Nørdstevold, Østre Gausdal	Oppland	14	84 b-c	235	25	-
24898	Hov, Gjøvik	Oppland	197	84 d	(150)	26-30	-
39270	Nordre Bjerke, Gran	Oppland	568	84 d	109-158	25-30	R: 132
37551	Hverven, Ringerike	Buskerud	137	84 d	52-144	23-33	R: 142
8445	Melby, Hurdal	Akershus	50	84 d	(150)	25	M: 369
21947	Kjøstad, Løten	Hedmark	573	84 d	100-120	25-30	P: 183 N: 107
26208	Sørum Nordre, Ringsaker	Hedmark	272	84 d	(120)	27-30	-

H: Hauge 1946, M: Martens 1969, N: Nihlén 1939, P: Petersen 1918, R: Resi 1995 and pers.comm.

verely damaged by corrosion, it has been possible to prepare polished sections through sound material. Two bars from Prestegården, No. 3549, were examined and entered in lines 1-2 of Table 10.3. They are similar in their heterogeneous structure and slag inclusions. They are mainly pearlitic steel with above 0.5% C, but do contain ferritic zones. The slag inclusions are mainly 100% glass, but some in the ferritic zones contain crushed manganofayalite (-15%

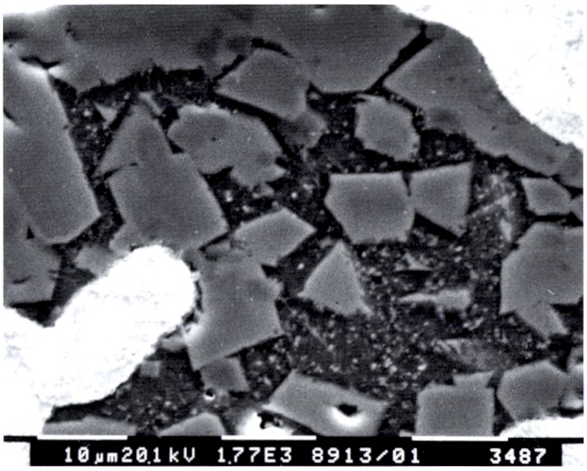


Fig. 241. In the 432 g steel bar from Bø, C 4387, the fayalite laths have been fragmented during the forging operations. PS. SEM. Scale bar 0.01 mm.

Table 10.3. SEM-EDAX analyses and hardnesses of Norwegian steel bars

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	41.2	26.4	6.5	tr.	<0.1	4.9	14.5	3.1	2.6	0.7	-	100	2.84	76.1
2	46.0	18.0	11.0	tr.	0.4	3.8	14.2	3.2	2.2	0.8	0.4	100	3.24	79.6
3	43.0	27.3	1.5	-	0.9	7.5	13.4	3.0	2.6	0.5	0.3	100	3.21	65.2
4	52.9	21.0	8.4	tr.	0	3.2	10.0	2.4	1.2	0.7	0.2	100	5.29	57.1
5	50.7	13.0	19.3	tr.	0	2.2	10.9	1.9	0.9	0.8	0.3	100	4.65	49.2
6	50.6	7.6	2.6	tr.	0	14.7	15.4	3.8	4.4	0.6	0.3	100	3.29	37.5
7	37.8	8.7	33.6	1.6	0	5.3	7.8	2.4	1.6	0.4	0.8	100	4.85	39.0
8	47.3	22.0	6.3	0.4	0	5.7	12.2	3.4	1.9	0.7	0.1	100	3.88	80.8

1. Prestegården, Gran, Oppland. 15 g steel bar, C 3549-1. Ferrite-pearlite. HV: 110-114-216.
2. ibid. 14 g steel bar. C 3549-2. Ferrite-pearlite. HV: 95-135-245.
3. Bø, Østre Gausdal, Oppland. 432 g steel bar. C 4387. Pearlite-ferrite. HV: 140-194-245.
4. Trodalen, Øyer, Oppland. 160 g steel bar. C 23191, edge. Pearlite. HV: 207-238-245.
5. ibid. Transverse section through 10 mm shaft Pearlite-ferrite. HV: 100-196-210.
6. Nørdstevold, Østre Gausdal, Oppland. 235 g steel bar. C 24705. Pearlite. HV: 213-242-266-270.
7. Nordre Bjerke, Gran, Oppland. 53 g half of a steel bar. C 39270-88. Pearlite-ferrite. HV: 187-247.
8. Ibid. 66 g half of a steel bar. C 39270-94. Pearlite-ferrite. HV: 181-190-209.

MnO) in a glass matrix. The rather heavy steel bar from Bø, No. 4387, is mainly pearlitic, even hyper-eutectoid in places, with 0.5-0.9% C, and the slag inclusions are glassy. Some contain fragmented, crushed magnesiafayalite (-10% MgO). The steel bar from Trodalen, No. 23191, was sectioned both in the flattened edge and through the 10 mm thick shaft. It was slightly heterogeneous, displaying 100% pearlite in the edge, but ferritic, rather soft zones in the shaft. While most slag inclusions are 100% glass, a few slags in the ferritic zones display manganowüstite (-3% MnO).

The steel bar from Nørdstevold, No. 24705, displays rather coarse pearlite, 0.6-0.7%C, in both the edge and the transverse section. The 15 mm thick shaft is poorly forged, with a prominent internal fracture, a so-called "smithing cross". Almost all slag inclusions are 100% glass, and they are unusually rich in manganese and calcium. The ore used for this steel bar falls a little apart from the other ores here met with. Or perhaps the charcoal ashes for once have added unusually much CaO, K_2O, and MgO?

The two fragments of corroded steel bars from Nordre Bjerke, No. 39270, lines 7-8, are pearlitic-ferritic with more than 0.5%C everywhere in the sections. Most slag inclusions are 100% glassy, but in the manganese-rich No. 39270-88 there occur 0.05 mm inclu-

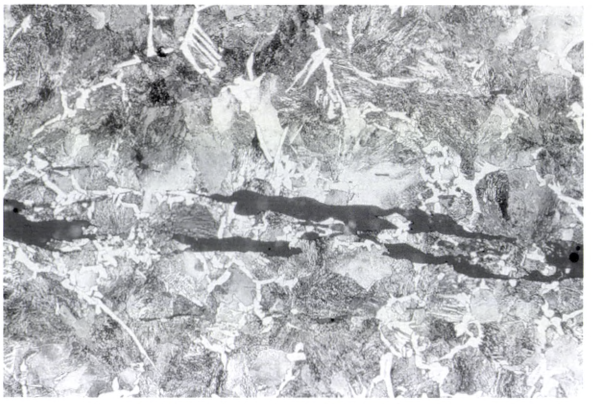


Fig. 242. Section through the steel bar, Nordre Bjerke C 39270-88. Pearlitic steel with some grain boundary ferrite, and glassy slags. PES. Side length 0.5 mm. Courtesy FORCE Technology.

sions of (Mn,Fe) O with 86% MnO, 2% MgO and 12% FeO!

Common to all are the practical absence of phosphorus in the metal and the presence of very much manganese in the slag inclusions. The characteristic shape of the bars signals their value as steel. Their small size is meaningful, for they fit well as inlays for the cutting edge of chisels, knives, drills, and axes, or simply as a starting point for a pearlitic-ferritic knife, ready for a water quench. The customers would be the smiths in the settlements in the populated Gudbrandsdal. Merchants would see to it that the steel bars were delivered abroad, especially to Denmark where the local phosphorus-rich ores would ruin any attempt to produce steel. In addition, the Norwegian merchant would have been able to deliver excellent whetstones, which in particular were quarried at Eidsborg at the western end of Lake Bandak, Telemark (Holtedahl 1960: 52; Espelund 2004: 100). Here the quartz schists have been quarried for whetstones since prehistoric times. In early Viking Age graves at Lindholm Høje, north of Ålborg, Denmark, almost every man was buried with his (Norwegian) knife and a Norwegian whetstone, see Chapter 12.

When Petersen (1918; 1923) first published a comprehensive study of the ancient Norwegian objects, he called them all <u>iron bars</u> and made efforts to establish a typological line of development. While the present author sees no major interest in following the typological approach, he will propose a division into just two groups, as in fact Petersen (1918) and Hauge (1946) also did. One group is the steel bars which were just examined, Tables 10.2 and 10.3. They are relatively small, 10-500g, are found in hoards only, and have a small hole punched at the end opposite to the flattened part. The hole was meant for joining the bars together in bundles for an easier transport as steel merchandise. Curiously enough, the small steel bars were when they were first recorded, catalogued as "lod til vævestol", i.e. weights for the weaver's loom (Rygh 1885, Fig. 438).

The other group consists of rather massive, 0.6-2.1 kg, wedge- or axe-shaped steel tools, with hexagonal to octagonal cross sections, and big shaft-holes opposite the cutting edge, Fig. 243. The wedges are usually found singly, or in a few cases up to six together. They come from the same districts, Akershus, Hedmark, Oppland, Buskerud and Telemark, as the steel bars, and are estimated to belong to the Iron Age and the Migration Age. When applying the wedges for forest work, they could be held and guided by a stick/shaft through the hole. Apparently they were never shafted for use as axes.

Five of these wedges have been examined, see Table 10.4. Three of them were analysed both in the cutting edge, the octagonal shaft and in the neck. The wedges here studied were unused or had been little used, since no cold deformation of the neck could be detected.

The <u>Nørdstevold</u> wedge, No. C 10776 a, displays a ferritic-pearlitic Widmanstätten structure with local transitions to phosphorferrite in the shaft. The carbon range is 0-0.4% and the phosphorus range 0-0.15%. The slag inclusions consist of glass in the pearlitic zones and wüstite-fayalite-glass in the ferritic zones. The wüstite has up to 14% MnO in the molecule. The edge is, surprisingly, softer than the shaft because of much ferrite. The wedge is forged and no quench-hardening has taken place.

The <u>Sylte</u> wedge, C 23007, is included in the Table 7 of Hauge (1946: 162). It was found together with a similar wedge under a big stone plate on the farm of Sylte and is estimated to be from 500-600 A.D. The edge is 100% pearlitic with glass slags; the shaft displays large ferritic parts of low hardness, 109-111 HV. The object is well forged and coherent and would have served excellently as a tough wedge with a hard, pearlitic edge, 0.7%C. Water-quenching was not attempted.

The <u>Holm</u> wedge, C 27975, displays slightly spheroidized pearlite, 0.6-0.8%C, with glass slags in the edge; and ternary Fe-C-P structures in the neck, with 0.4%C and 0.15%P. The slag inclusions are enriched in calcium and depleted of manganese relative to the other wedges, but the variation is still within the general Valdres ore composition. The wedge was found in a grave from the Migration Age.

The <u>Skjelle</u> wedge, C 28600, has been dated to 540 ± 90 A.D. (Svane, pers.comm.) It is 30 cm long, has a 5 cm wide edge, and an octagonal shaft, 3 cm thick. It

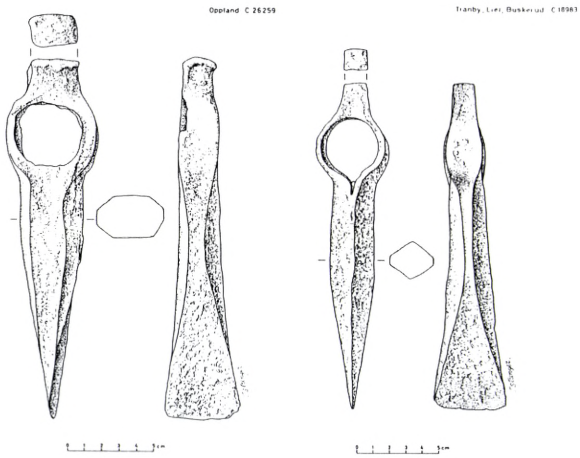


Fig. 243. Two steel wedges. Left, Haugtun, Oppland, C 26 259 of about 800 g. Right, Tranby, Buskerud, C 18 983, of about 700 g. Drawing by T.Strenger. Courtesy Hege Svane. Scale bar 5 cm.

weighs 2.1 kg and is a prototype of the large so-called "bleggøkser", or wedges for forest work. It is well forged, from one melt, without piling, as is true of the other wedges too. It is heterogeneous, like the other wedges, with prominent pearlite-ferrite, 0.2-0.6%C, in the edge, and Widmannstätten ferrite-pearlite, 0.2-0.4%C, in the shaft. A detailed examination of the metal and its slag inclusions was made in Chapter 7 (Table 7.3) where the harmonious heterogeneity of ancient objects was explained.

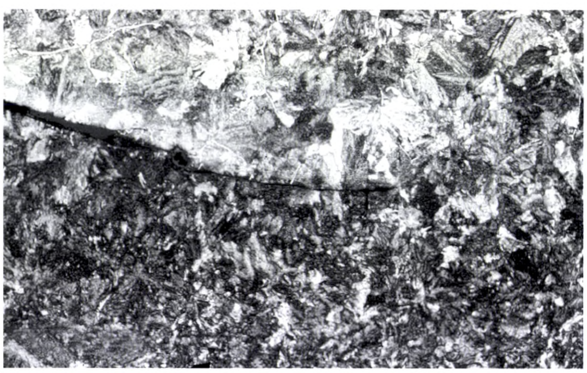


Fig. 244. The end of a defect, a crack, from forging. Pearlite, HV 260-310. A 2.2 kg steel wedge from Sylte, Ringebu, Oppland. C 23 007. PES. Side length 1 mm. Courtesy Struers.

The Haugtun, Follebu, Oppland, wedge, C 26259, has a pearlitic edge, 0.4-0.7%C, with glassy inclusions; and a ferritic-pearlitic cross section, 0.1-0.5%C, with fayalite-glass slags. The slag inclusions are rich in TiO_2, and the total analysis is somewhat related to the Sylte wedge, C 23007.

The five wedges, which are typical of the Norwegian wedges in the 0.6-2.1 kg weight class, are well forged from steel of medium to high carbon content, 0.4-0.8%C. The usual heterogeneity implies that soft ferritic zones do occur, but when present they are usually to be found in the shaft and the neck, while the edges are pearlitic. This is a clever way of producing a

Fig. 245. Another detail of the steel wedge, Fig. 244. Pearlite and grain boundary ferrite. PES. Side length 0.5 mm. Courtesy Struers.

wedge for forest work, pearlitic hard and wear-resistant along the edge, and ferritic (-pearlitic) tough in shaft and neck. In the present, somewhat corroded condition, signs of cold deformation from work were difficult to see, but the general impression was that the wedges here examined were new and unused. From the relatively few datings available it appears that the steel bars were common between 300 and 500 A.D., while the steel wedges are mainly from 300 to 650 A.D.

Comparing the analytical data for the wedges, Table 10.4, with those for the steel bars, Table 10.3, it is seen that they overlap in all components. Of particular interest are the significant presence of manganese, barium and titanium, and the general absence of phosphorus. All the objects are heterogeneous, but they may properly be termed steel, since more than 2/3 of the material has more than 0.4%C. The steel bars have relatively more steely material than the wedges, which makes sense if the steel bars are merchandise for further working by the blacksmiths, while the wedges are finished tools for the forest industry.

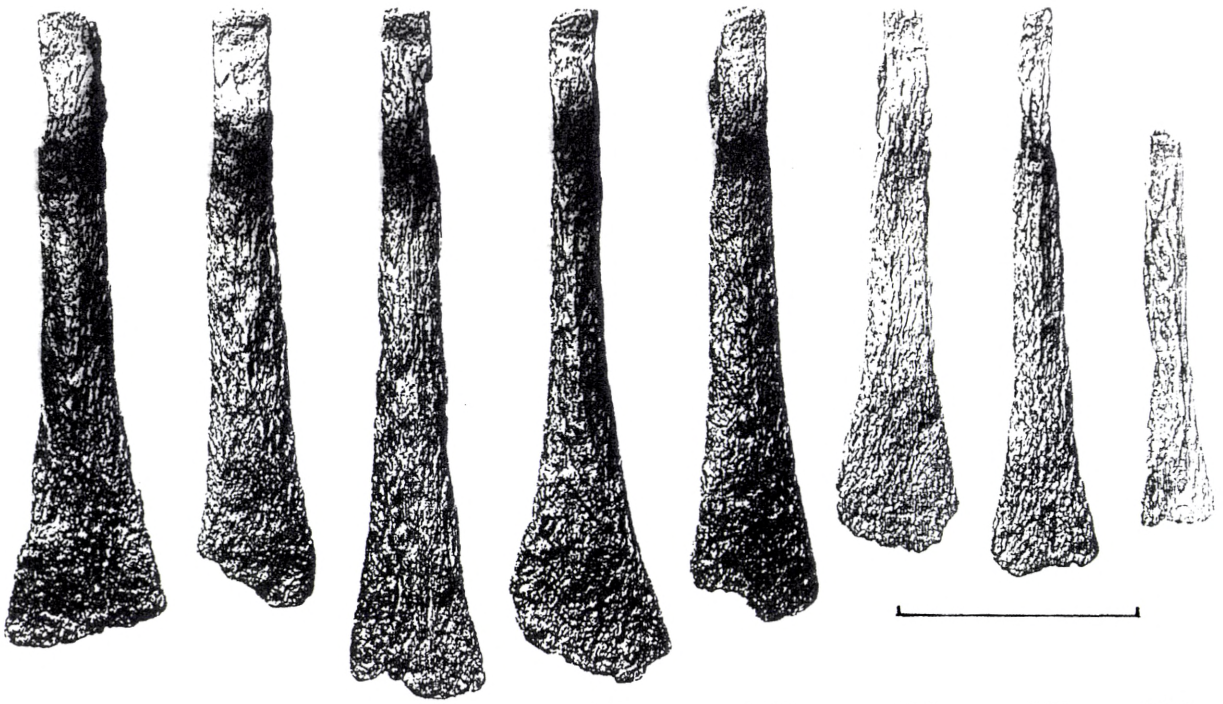
The steel wedges have rarely been found outside Norway, but a few cases are known. In 1848 a hoard of 8 wedges and one celt was found in a gravel-pit in Understed, 11 km NW of Sæby, Vendsyssel, Denmark. The dimensions of the wedges are the following: 1260 g (26 cm long), 1170 g (24.6 cm), 1150 g (28.4 cm), 1070 g (27.6 cm), 975 g (25.0 cm), 730 g (22.5 cm), 680 g (23.5 cm), and 230 g (fragmented,16.5 cm). The material is in the National Museum, Copenhagen, where a cursory examination of the 1150 and 975 g objects showed them to be heterogeneous, but chiefly pearlitic steel with up to 0.9%C. They were rather free of slag inclusions and phosphorus, so they are in shape, structure and composition of exactly the same nature as the Norwegian wedges and were, no doubt, imported from Valdres in ancient times, Fig. 246.

The Engelhardt publication on the Nydam boat find (1865, plate 15[11]) illustrates an axe-shaped wedge with a preserved shaft, kept in place by an inserted iron split. It seems to be one of the Norwegian wedges,

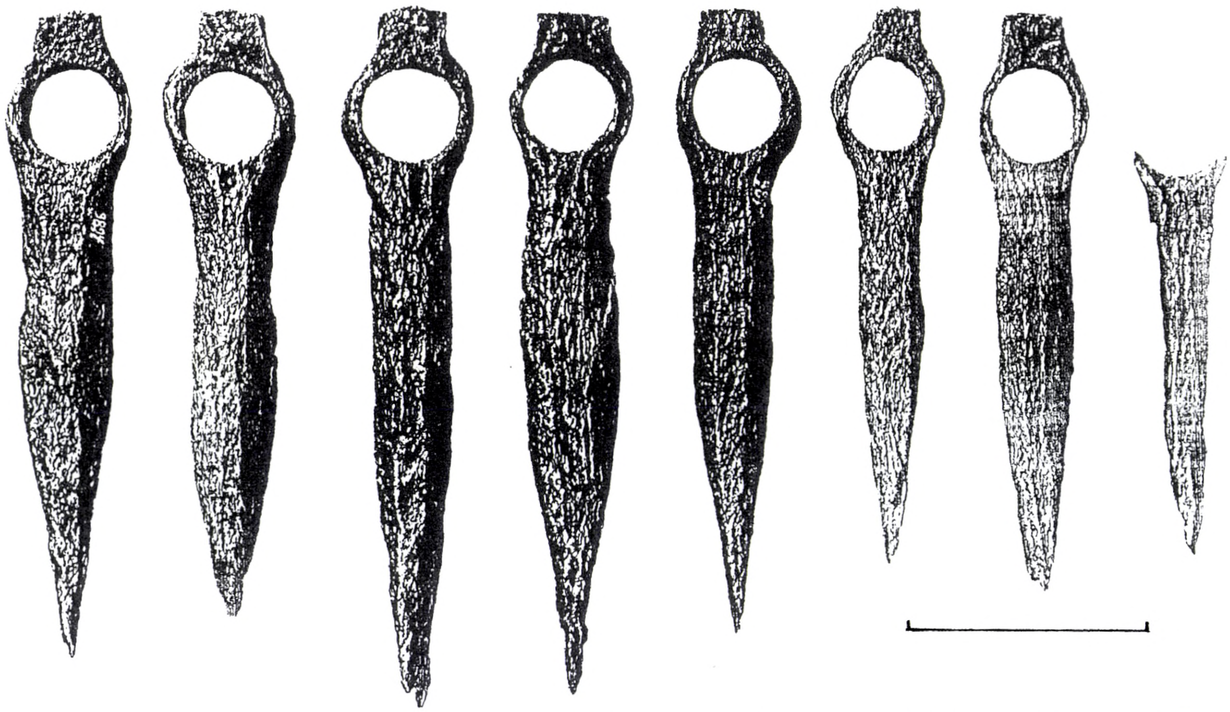
Table 10.4. SEM-EDAX analyses and hardnesses of Norwegian steel wedges

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	29.6	6.3	36.9	2.0	0	3.0	18.6	2.0	0.7	0.7	0.2	100	1.59	54.4
2	33.8	20.3	19.0	1.5	0	3.5	17.4	2.6	0.9	0.8	0.2	100	1.94	59.8
3	52.3	8.6	12.5	0.4	0	4.5	14.9	3.8	1.5	1.2	0.3	100	3.51	115
4	57.7	10.2	5.9	0.3	0	8.7	11.7	2.8	2.1	0.6	0	100	4.93	154
5	56.8	12.2	3.7	tr.	0	8.2	13.3	2.8	2.3	0.7	0	100	4.27	167
6	38.6	23.8	16.6	1.0	0.2	2.8	12.9	2.2	1.5	0.4	0	100	2.99	46.6
7	30.7	43.0	10.8	0.2	0.3	1.6	9.8	1.9	0.9	0.5	0.3	100	3.13	26.2
8	49.4	20.3	4.8	0.2	0	4.7	14.8	2.3	2.4	1.0	0.1	100	3.34	95.6

1. Nørdstevold, Ø.Gausdal, Oppland. 930 g steel wedge, C 10776 a. The edge. Phosphorferrite.
   HV: 111-137-137
2. ibid. transverse section through 30 mm shaft. Widmanstätten ferrite-pearlite.
   HV: 113-134-208-219.
3. Sylte, Ringebu, Oppland. 2.2 kg steel wedge. C 23007. The edge. Pearlite.
   HV: 204-232-261-269-311.
4. Holm, Gausdal, Oppland. 2.0 kg steel wedge. C 27975. The edge. Spheroidised Pearlite.
   HV: 167-194-213.
5. ibid. transverse section through 20 mm neck. Ternary Fe-C-P structure.
   HV: 132-155-160-198.
6. Skjelle, Sel, Oppland. 2.1 kg steel wedge. C 28600. The edge. Pearlite-ferrite.
   HV: 116-205-235.
7. ibid. transverse section through 32 mm eight-sided shaft. Widm.ferrite-pearlite.
   HV: 110-129-175.
8. Haugtun, Follebu, Ø.Gausdal, Oppland. 1.6 kg steel wedge. C 26259. Shaft. Pearlite-ferrite.
   HV: 101-131-152-176-204.



1260 1170 1150 1070 975 730 680 230



1260 1170 1150 1070 975 730 680 230

but if so a very early one. It requires further examination.

A wedge-shaped object from Vimose (National Museum 21188 M 1-1) seems to be another one of the Norwegian steel wedges. If this can be confirmed, these two Danish finds support the very early occurrence of this tool type, available already about 300 A.D.

Also interesting are two wedges illustrated by Serning (1966, plates 98[35] and 106[1]). The wedges were found in Dalarna, Sweden, and are from the Migration Age. They are, respectively, 20 cm long (no weight given) and 24 cm long (1575 g), and they show heavy deformation in the neck, proving that, at least these objects, were used as wedges, and not as axes.

I would like to express my best thanks to Hege Svane and Professor Irmelin Martens, Oslo, for discussions and the long-term loan of samples of steel bars and wedges from Oldsaksamlingen, Oslo.

Sweden

We saw in Chapter 8 that bloomery iron production was well established in many places in Sweden at least by 500 B.C. The furnace sites were in general in the forests, near the bog iron ores and the red soils, and away from the settlements, as in Vestmanland and Uppland. In the next period, 0-600 A.D., the iron production expanded and new districts became involved. Significant bloomery sites have been detected in Väster Götland (Key 1982), Småland (Karlsson 2001), Scania (Stjernquist 1970), Halland (Nihlén 1939), and Gästrikland and Jämtland (Magnusson 1986). Samples of production slags and iron objects from some of these sites will now be examined.

At Trösken, Sörby, 8 km south of Åresunda Church, an Iron Age production site has been excavated and C-14 dated to 332 ± 103 A.D. (Englund 2002: 57, and pers.comm.). A 190 g slag of stalactite type has been analysed, Table 10.5, line 1. The slag is relatively poor in FeO and consequently contains no wüstite, but only few manganofayalite laths (25 μm wide, -4% MnO), and a complex matrix of various skeleton crystals in glass.

Fig. 246. Eight steel wedges from Understed, Denmark. No doubt imported from Valdres in the Roman Iron Age. Seen from two sides. The cross sections are approximately octagonal. Weight in grams. Scale bar 10 cm. Courtesy The National Museum, Copenhagen.

At Hemlingby, 2 km south of Gävle, several boat nails from the younger Iron Age were discovered, however, in severely rusted condition. The best preserved, of 14.4 g, was examined, Table 10.5, line 2. It may have been produced just 6 km further west at a bloomery site on the banks of Gävle Å in Valbo (Ljung 1990). The nail is heterogeneous, but mainly ferritic, with streaks of phosphorferrite, with 0-0.3% P in the metal. Arrhenius (1959: 42) analysed two boat nails from the same find and found 0.12 and 0.22% P in the metal, in excellent accord with the present results. The slag inclusions are extremely fine-grained fayalite-glass complexes with high phosphorus content.

In lines 3-4 are entered two analyses of the same production slag from Fornlämning 39, Myssjöen, 30 km SW of Östersund, Jämtland. On the site, which is on the lake shore, there are a stone-built furnace, a slag heap, an anvil stone, and traces of roasted bog iron ore. It has been C-14 dated to 355-561 A.D. (Magnusson 1986: 152, 362; 1997: 32). The two analyses, performed by different analysts with a year in between (but using the same equipment) are in perfect agreement. The slag consists of 65% manganofayalite (6% MnO, 0.1 mm wide laths), 20% manganowüstite (2% MnO) and 15% polyphased matrix. A number of 1μm fine, white sparks in the matrix turned out to be iron sulphides.

Table 10. 5. SEM-EDAX analyses of slags and slag inclusions in iron objects from Sweden

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	39.8	37.4	2.6	-	0.5	1.8	14.4	2.4	0.5	0.6	-	100	2.76	47.2
2	28.1	54.2	1.3	-	3.8	1.1	8.7	1.4	1.2	0.2	-	100	3.23	20.9
3	26.0	60.0	4.3	0.4	0.2	1.9	5.3	1.1	0.2	0.2	0.4	100	4.91	13.1
4	25.6	60.5	4.3	0.2	0.2	1.9	5.3	1.1	0.3	0.2	0.4	100	4.83	13.2
5	36.1	45.2	1.0	-	0.6	5.4	6.6	2.4	2.7	-	-	100	(5.47)	(36.5)
6	23.9	62.6	0.4	-	1.4	3.5	5.3	1.5	1.4	-	-	100	4.53	18.2
7	24.5	59.8	0.7	-	5.4	1.6	5.3	2.1	0.6	-	tr.	100	4.62	14.6
8	29.0	51.8	3.1	0.4	0.8	1.8	10.6	2.2	0.1	0.2	tr.	100	2.74	29.4

1. Trösken, Sörby, Årsunda 59, Gästrikland. Production slag, stalactite type. 190 g. 330 A.D.
2. Hemlingby, Valbo sogn, Gästrikland. SHM 19807: 6a. 14.4 g nail. 200-500 A.D. HV: 111-121-122-136-188.
3. Myssjöen, Jämtland. Fornlämning 39. Production slag, 772 g, No. 76: 3. 355-561 A.D. Analyst VFB, 31.08.94.
4. ibid. The same, another section. Analyst Helle Wivel, 24.08.95.
5. Jämtland, unspecified locality. Spade-shaped iron bar, 627 g. SHM xx. HV: 85-88-92-102-(175)
6. Inaberg, Söderala sogn, Helsingland. Spade-shaped iron bar, 239 g. SHM 22994. HV: 122-130-144-150.
7. Husbyberget, Askersund sogn, Närke. 5.6 g nail, SHM 15774-4. 200-500 A.D. HV: 102-127-143-148-157.
8. Västra Varpet 92, Karlslunda sogn, Småland. Production slag, 466 g, No. 92. 200-1200 A.D.

The two next lines in Table 10.5 concern the spade-shaped iron bars, Figure 250. These bars were common semiproducts from the fifth to the eleventh century. They consist of soft wrought iron with little carbon and phosphorus. They are thus of an entirely different character than the Norwegian steel bars and wedges, and have been in demand for, e.g. agricultural spades, nails and boat nails, domestic kettles and salt pans, and for the backbone of tools that need to have steel inlays.

Fig. 247. Section through a 190 g stalactitic production slag from Trösken, Årsunda No. 59. Primary fayalie laths and secondary duplex matrix of fayalite and glass. PS. SEM. Scale bar 0.1 mm.

Fig. 248. Production slag No. 76:3 from Myssjöen, Jämtland. Fayalite (grey), wüstite (white) with fayalitic rims, glass and sparks of iron sulphide (white). PS. SEM. Scale bar 0.01 mm.

Fig. 249. Bloomery. Furnace 2, Myssjö RAÄ 40. The furnace is viewed from the top. An outer circle of stones is lined on the inside with clay. On the right side is the pit for the bellows. The white stone is 50 cm long. Magnusson 1986: 93.

The spade-shaped iron bars have been found in hoards in particularly four Swedish- Norwegian provinces, Jämtland, Medelpad, Hälsingland and Gästrikland, Table 10.6.

The spade-shaped bars may be described as four-sided iron sheets with one corner doubled over to form an often carelessly made socket (Hallinder & Haglund 1978). The bars from Hälsingland are generally 20-28 cm long and weigh 150-350 g. The bars from Jämtland, Medelpad and Ångermanland are 28-34 cm long and weigh 350-1000 g. A third heavier group, 34-44 cm long and weighing 1000-1650 g, comes exclusively from Gästrikland.

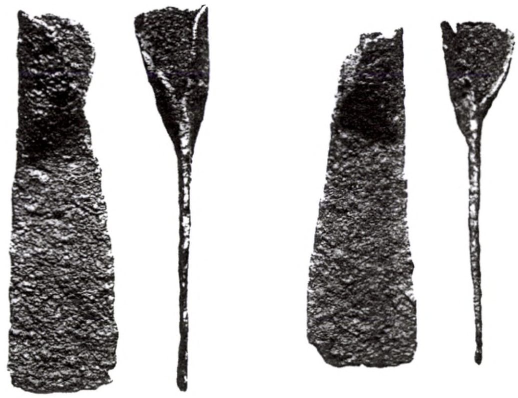


Fig. 250. The spade-shaped iron bars are typical for the Storsjö-region in Jämtland. They are found in hoards here and in Medelpad, Hälsingland and Gästrikland. They were the raw material for much manufacture in, e.g., Helgö, but they have also been traded far away, e.g., to Bornholm and to Norway, as these two, that were found at Vingelen, Tolga, Hedmark. About 25 cm long and of 0.6 kg weight. Hauge 1946.

Table 10.6. The distribution of spade-shaped iron bars (from Hallinder & Haglund 1978)

Region	Number of finds	Minimum original number of spade-shaped bars	Number extant
Medelpad	24	425	279
Jämtland	23	412	293
Hälsingland	22	478	97
Gästrikland	5	104	52
Uppland	5	28	22
Ångermanland	5	18	14
Gotland	3	15	3
Dalarna	2	5	5
Västmanland	2	5	4
Södermanland	1	1	1

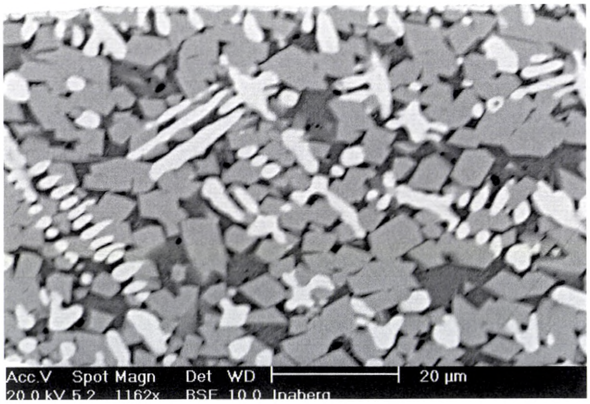


Fig. 251. Section through a spade-shaped iron bar of 239 g from Inaberg, Hälsingland, SHM 22994. The slag inclusion displays wüstite dendrites, blocky fayalite and a glassy matrix. PS. SEM. Scale bar 0.02 mm.

Many bars from Hälsingland, Gotland and Helgö have been studied by Hansson & Modin (1973) and Thålin (1973), who in particular were interested in the presence of cobalt and nickel in solid solution in the metal. While it has been suggested that the presence of nickel could be due to the incorporation of meteoritic iron, Hansson & Modin (1973) concluded that nickel and cobalt were due to some special ores, enriched in these elements. The present author fully supports this viewpoint. Two unusually long (55 cm) spade-shaped bars from Torsåker, Gästrikland, were studied in some detail by Grandin (2000). The metal phase was dominantly ferritic without phosphorus (generally less than 0.05% P), but the bars were heterogeneous with ferritic-pearlitic and a few pearlitic patches, and locally 0.15% P. Cobalt, nickel and copper were all in the range 0.01 to 0.08% and thus of no structural significance.

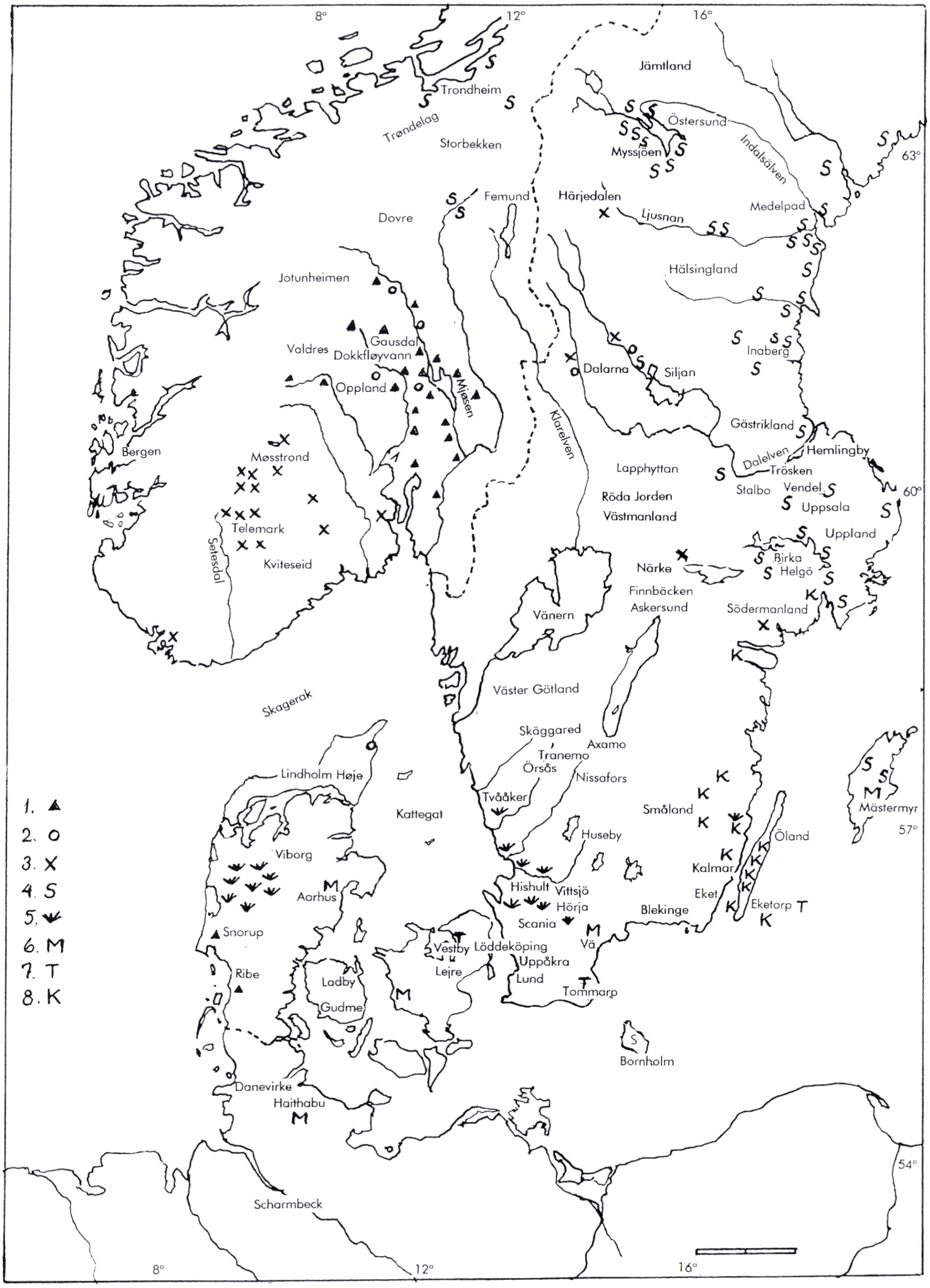
While the production sites for the spade-shaped bars almost certainly have to be found in Hälsingland, Jämtland and Gästrikland (Magnusson 1986: 272), many finds are tied to the ancient trading routes, both across the mountain ridge, Kølen, to Trondheim, Norway, and southwards to Uppland, Åland, Gotland and even Bornholm, where three bars were found at Tingsted, 3 km NE of Vester Marie (Watt 1979).

The biggest hoard on record of spade-shaped bars contained 126 pieces and came from a bog near Månsta, Näs, 23 km SSW of Östersund, Jämtland. This find is probably near to one of the important production sites, which could very well have been the above-mentioned Myssjö.

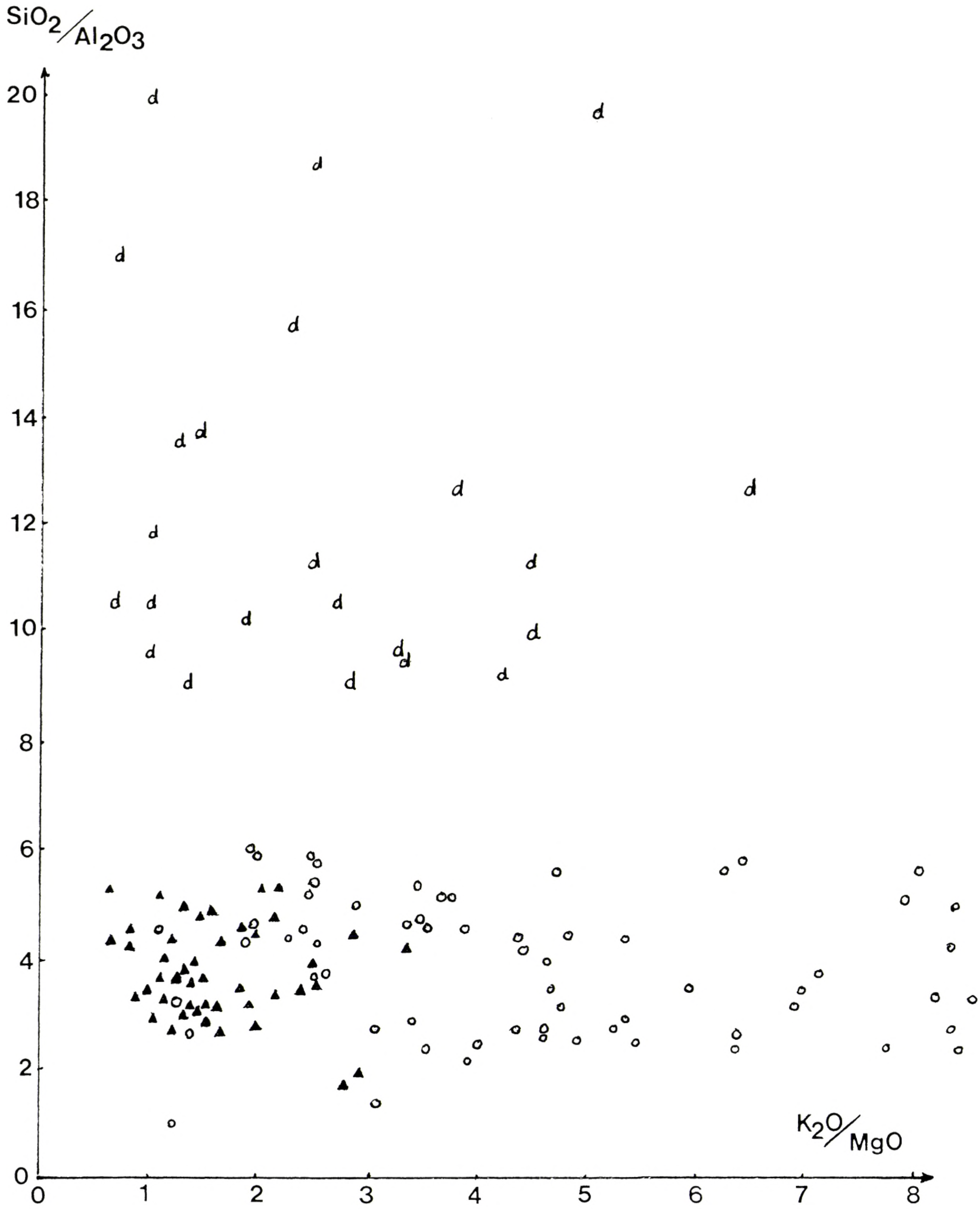
The spade-shaped bar from an unknown locality in Jämtland, Table 10.5, line 5, falls in terms of length and weight within the Jämtland category II of Hallinder & Haglund (1978). It is 30 cm long, 11 cm wide at its maximum, 0.5 cm thick (max.) and weighs 627 g. A section through the socket shows a pure and very soft ferrite without carbon and phosphorus. The slag inclusions are mainly small rounded wüstite blebs (no manganese) with so few ordinary slag inclusions that a meaningful analysis could not be performed. Locally unintended surface carburization from the forging process has increased the hardness from the general low level of about 90 HV to 175 HV. No sections could be prepared from other parts of the bar, but the general shape and corrosion aspect suggested that all was of soft, wrought iron.

The spade-shaped bar from Inaberg, Hälsingland, is 24.5 cm long, 7 cm wide at its maximum, has a 1-2 mm thick plate and weighs 239 g. It falls nicely within the Hälsingland group I of Hallinder & Haglund (1978). A section from the socket showed a phosphorus-free ferritic-pearlitic structure with 0-0.2%C and a hardness range of 121-150 HV. The same bar has already been examined by Arrhenius (1959: 42), who also found only a little phosphorus in the metal, 0.06%. The slag inclusions are fine-grained wüstite-fayalite glasses. The socket has acquired its 5 mm thickness by folding the sheet back on itself, followed by forge-welding. The welding seam appears as a yel-

Fig. 252. Iron and steel in Scandinavia, about 400-1200 A.D. Locations of furnaces and finds as mentioned in the text. **1,** Norwegian spoon-shaped steel bars. **2,** Norwegian steel wedges. **3**, Fellujern, or cleft-blooms. **4**, Spade-shaped iron bars. **5**, Kloder, or blooms cleft into four fingers. **6**, Mästermyr iron bars. **7**, Tommarp phosphorus tongues. **8**, "Lieformade ämnen", or Kalmar steel bars. Scale bar 100 km.



8°
12°
16°
Jämtland
Trondheim
Trøndelag
Storbekken
Östersund
Myssjöen
Indalsälven
63°
Femund
Härjedalen
Dovre
Ljusnan
Medelpad
Hälsingland
Jotunheimen
Gausdal
Valdres
Dokkfløyvann
Oppland
Mjøsen
Inaberg
Dalarna
Siljan
Klarelven
Gästrikland
Bergen
Møsstrond
Lapphyttan
Dalelven
Hemlingby
Trösken
Stalbo
Vendel
Uppsala
60°
Röda Jorden
Västmanland
Telemark
Uppland
Setesdal
Kviteseid
Närke
Birka
Helgö
Finnbäcken
Askersund
Vänern
Södermanland
Skagerak
Väster Götland
Skäggared
Axamo
Tranemo
Örsås
Nissafors
Lindholm Høje
Tvååker
Kattegat
Småland
Mästermyr
57°
Huseby
Öland
Viborg
Kalmar
Aarhus
Hishult
Vittsjö
Eket
Hörja
Eketorp
Blekinge
Scania
Snorup
Vä
Vestby
Löddeköping
Lejre
Uppåkra
Ribe
Ladby
Lund
Tommarp
Gudme
Bornholm
Danevirke
Haithabu
54°
Scharmbeck
1.
2.
3. X
4. S
5.
6. M
7. T
8. K


SiO2/Al2O3
20
18
16
14
12
10
8
6
4
2
0
K2O/MgO
0
1
2
3
4
5
6
7
8

lowish band of high hardness, 290-330 HV. It is probably a nickel-enriched austenitic alloy with minute carbide inclusions, compare the many nickel-enriched spade-shaped bars from Hälsingland (Thålin 1973, Table 1).

Analytically, the two spade-shaped iron bars, Nos.5 and 6 in Table 10.5, are interesting. The slag inclusions have K_2O/MgO ratios close to one, deviating from that of most other Swedish iron objects that have ratios (much) larger than two, Fig. 253. The two spade-shaped objects studied by Grandin (2000) have K_2O/MgO ratios of 1.58 and 1.40. Apparently the ores from which the spade-shaped bars were made in Jämtland and Hälsingland, were slightly different from what was common in the rest of Sweden and approached in composition those of the Norwegian Telemarken. Perhaps the same is true of Dalarna, where I have analysed slags from Gryvelsjö with K_2O/MgO 1.13, while Serning (1973:37) found 1.17 and 2.0 in two production slags from Gryssen, Dalarna. The decomposition products of the geological formations in the Dalarna-Härjedalen-Jämtland mountain range may thus be somewhat similar to the Telemarken deposits, in SiO_2/Al_2O_3 as well as in the K_2O/MgO ratios. Unfortunately the standard work on Jämtland's ores and slags (Magnusson 1986) does not include K_2O in the analytical tables.

Husbyberget is a 5.6 g nail from the younger Iron Age. The structure consists of 0.05-0.3 mm large grains of phosphorferrite, locally with beautiful phosphorus ghost structures. The phosphorus content ranges in the heterogeneous material from 0.16 to about 0.4%, with correspondingly high hardnesses. The slag inclusions are glassy with an average content of 5.4% P_2O_5, the highest recorded in any ancient Swedish iron object.

Fig. 253. Provenance of Scandinavian artifacts illustrated by slag composition. The ratio SiO_2/Al_2O_3 against K_2O/MgO divides the plane in areas where Danish artifacts are entirely separated from Norwegian and Swedish material. These, however, show some overlap and require further discussion. Δ Norwegian, **d** Danish, **O** Swedish. All data from this publication.

Fig. 254. Bronze and gilded bronze objects with almandine garnets from the Uppåkra settlement, 500-900 A.D. Lunds Universitets Historiska Museum.

Västra Varpet is a 466 g production slag from Karlslunda, Småland. Its precise locality and age are unknown, but it is estimated to be from the Iron Age or Viking Age (L.E.Englund, pers.comm.). Nihlén (1932: 181) identified several bloomery sites in Karlslunda sogn, but it is uncertain where Västra Varpet belongs. The slag is coarse-grained and rusty, because it is rich in free iron, occurring as lace work and coral islands. It consists of 30% wüstite dendrites, 50% manganofayalite laths (-6% MnO) and 20% polyphased matrix. Small hercynite crystals with 0.8% TiO_2, 0.4% V_2O_5 and 1.8% MnO are common. The matrix contains 1.6% BaO. It appears that the bloomery site was dependent on local Småland lake ore.

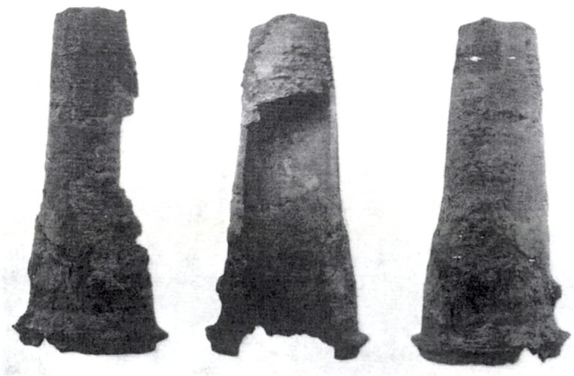


Fig. 255. The Scharmbeck furnace, seen from three directions. About 105 cm high and 50 cm in exterior diameter at the lower part. Wegewitz 1957.

At Uppåkra, 5 km SW of Lund, Skåne, a very rich settlement was excavated in the late 1990s. It was apparently an important trading centre, existing from the Roman Iron Age till the Viking Age, when all activities moved to Lund. On the Uppåkra site many craftsmen were present, and copper- and bronze as well as iron was worked. Bars, slags and crucibles have been found, and the studies continue (Larsson & Hårdh 1998).

Another important centre was Helgö, a 5 km long, narrow island in Lake Mälaren, about 20 km west of Stockholm. From 200 to 800 A.D., with maximum activities 400-600 A.D., the centre comprised a number of (seasonal) workshops for the casting of silver and bronze jewellery and forging of iron. Numerous spade-shaped iron bars, arrowheads, knives (B.Arrhenius 1970), purification slags (Hallinder et al.1986) and other debris have been detected. Witnesses of the extensive trading relations are finds of 68 Roman gold solidi, of 26 guldgubber, a Coptic bronze sieve, an Irish bishop's staff from the 7th century, and an oriental Buddha statuette from the 8th century (Holmqvist 1961; 1963; 1972; 1976). In the late 9th century the activities were moved to Birka on the island of Björkö, about 10 km NW of Helgö (Ambrosiani & Eriksson 1991). The Uppåkra and Helgö centres were similar to the Danish Lundeborg and Hørup centres.

South of the Baltic Sea

In the Gory Swietokrzyskje (Holy Cross Mountains), east of Kielce, 150 km south of Warsaw, extended iron production sites have been found (Bielenin 1973; 1976; 1999). The furnaces are a variation on the theme shaft-pit furnaces, where the furnace was used only once, Fig. 184[9]. The pit accommodated a 50-250 kg elephant's foot slag, and the shaft was about 1 m high (Bielenin 1977; 1983). The furnaces were often arranged in rows of three or four, and they have been dated from late La Tène to the end of the Roman empire (50 B.C.- 450 A.D.) In the lower part of the shaft were 2-4 air intakes, but since no tuyeres have been found, it has been assumed that the furnaces were operated on natural draught. At least 4000 furnace sites had been identified by 1983. The ore was in the Roman Iron Age mined in up to 18 m deep shafts, where the iron gossans of siderite deposits were utilized. The weathered ore was easily accessible and so soft that it was termed smetana, i.e. soft cheese or cream. In the mine galleries coins from the time of the Emperors Vespasian and Trajan have been found (Bielenin 1973).

Shaft-pit, or slag-pit furnaces have also been recorded from Czechoslovakia (Pleiner 1977), Burgenland in Austria (Bielenin 1977), the Netherlands (Nie 1995; 1997), northwestern Germany (Nikulka 2003), and Slesvig-Holsten (Jöns 1992). The lucky find of large fragments of two slag-pit furnaces at Scharmbeck, 10 km south of Hamburg (Wegewitz 1957) made it possible to make a plausible reconstruction of a 1 m high shaft with four air intakes, and an inner diameter at the holes of 34 cm. The Scharmbeck furnace is on display in the Helms Museum in Harburg.

Fig. 256. Excavations in progress 1978, Biskupice, Mazovia, Poland. The top soil has been removed so that the massive elephant's foot slags have become visible.

About 1970 another large bloomery site was discovered at Biskupice, near Pruszkow, 20 km SW of Warsaw (Bielenin 1999). About 7000 slag-pit furnaces have been detected and dated to the same period as the sites near Kielce. Over 300 km^2 around Pruszkow, smithing hearths, houses, wells, roasting sites, and other evidence of permanent settlements have been examined, and it appears that the importance is equivalent to that of the Holy Cross Mountains.

In Table 10.7, lines 1-5, are entered the analyses of five different elephant's foot slags, each of about 100 kg from the Biskupice production site. The average, line 6, shows that the bog iron ore was manganese and phosphorus-rich, and not much different from the Danish ores of the calcium-rich variety, e.g.Table 9.4, lines 11-12. However, the ratios CaO/K_2O and K_2O/MgO clearly put the slag compositions outside(to the right of) the Danish zones, Fig. 253, and the reason

Fig. 257. Close up of an elephant's foot slag. Biskupice 1978. Scale bar 20 cm.

is probably that the geology of the moraine deposits west of Warsaw is slightly different from that of eastern Denmark. (It would be interesting to analyse production slags from the Holy Cross Mountains, which may be different in composition because of an entirely different ore type.)

The Biskupice slags consist of 80% coarse-grained manganofayalite (-6% MnO,-1% P_2O_5), 10% manganowüstite (-2% MnO), and 10% of a matrix of calcium-iron-phosphate and glass. The fayalite laths and – blocks reach sizes of 0.1-0.2 mm in accordance with a relatively slow cooling of the large production slags. No iron objects were available from the site, but it must be assumed that they would be rather similar in composition and structure to the bloom and lancehead from Snorup, Table 9.3.

A 95 g fragment of a production slag from Drangstedt, ENE of Bremerhaven, Germany, was given to me by Patrice de Rijk. It came from excavations of a bloomery site, dated to 0-200 A.D. (Rijk 1997). The slightly corroded fragment consists of 70% rather pure fayalite blocks, 0.10-0.25 mm in size, 10% fine wüstite dendrites, and 20% matrix with fine fayalite skeleton crystals. In chemical composition, line 7, it is poorer in manganese, but richer in aluminium than the Biskupice slags.

Fig. 258. Five elephant's foot slags, all turned upside down. Biskupice 1978. Scale bar 50 cm.

From the Joldelund bloomery site, only 25 km south of the present-day Danish-German border, two production slags have been examined, Table 10.7, lines 8-

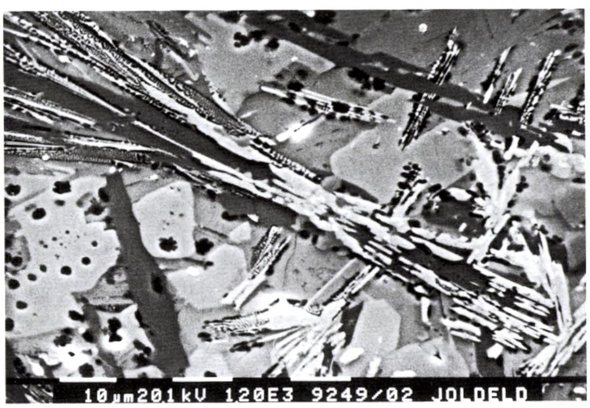


Fig. 259. Section through a stalactitic slag from Joldelund, furnace No. 180. Phosphorus-fayalite, rod shaped iron oxides (?), two shades of very phosphorus-rich matrix, and small silicon-rich palmate droplets. PS. SEM. Scale bar 0.01 mm.

9. They come from two of the more than 500 furnace sites that were examined around Kammberg in the 1990s (Jöns 1992). The furnaces which were dated to 200-400 A.D. were of the slag-pit type and were run on local bog iron ores. Line 8 is a 100 g stalactite slag from the underside of a 100 kg elephant's foot slag block. Line 9 is an individual slag of palm size. The two slags are rather similar in structure and composition, consisting of 60-65% coarse phosphorus-fayalite (-2% P_2O_5), 20-25% wüstite dendrites and about 15% matrix in two shades. One is a calcium-iron-phosphate glass, the other an iron-silicon-phosphate glass with some barium (-3% BaO). Locally there are pockets of leucite with fine wüstite particles. The bulk composition is similar to the western Jutland Snorup slags, Table 9.3, but Joldelund is richer in phosphorus. The resulting iron objects must indeed have been phosphorus-rich, wrought irons.

Gera-Tinz, the last line in Table 10.7, is a fragment of a 100 kg elephant's foot slag from a bloomery site in Thüringen, Germany (Dusek 1967). The slag-pit

Table 10.7. SEM-EDAX analyses of production slags (elephant's foot type) from Poland and Germany

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	25.2	55.5	2.6	tr.	6.2	6.2	2.4	1.1	0.2	0.4	0.2	100	10.5	15.4
2	24.3	58.8	3.0	0.3	4.6	4.9	2.7	0.9	0.2	0.1	0.2	100	9.0	13.0
3	25.7	57.6	4.8	tr.	4.6	4.1	1.6	0.9	0.1	0.3	0.3	100	16.1	10.0
4	23.8	59.9	3.4	0.2	5.2	4.7	1.7	0.5	0.1	0.3	0.2	100	14.0	10.2
5	25.5	57.6	4.7	tr.	4.4	4.0	2.5	0.6	0.1	0.3	0.3	100	10.2	9.7
6	24.9	57.9	3.7	0.1	5.0	4.8	2.2	0.8	0.1	0.3	0.2	100	11.3	11.8
7	27.9	55.8	0.3	-	4.7	4.2	5.5	0.9	0.3	0.1	0.3	100	5.1	17.9
8	20.7	67.2	0.7	-	6.5	1.7	2.3	0.4	0.5	tr.	tr.	100	9.0	6.6
9	20.0	66.2	2.4	0.2	5.6	2.4	1.8	1.0	0.4	tr.	tr.	100	11.1	7.5
10	34.7	43.0	2.2	-	0.5	1.0	12.2	4.6	1.2	0.6	tr.	100	2.8	41.6

1. Biskupice, Warsaw, Poland. 95 g fragment of an elephant's foot. SB 1.
2. ibid. 100 g fragment of another. SB 2.
3. ibid. 120 g fragment of a third. SB 3.
4. ibid. 150 g fragment of a fourth. SB 5, HW.
5. ibid. 50 g fragment of a fifth. SB 6.
6. Average of lines 1-5.
7. Drangstedt, Bremerhaven, Germany. 95 g production slag.
8. Joldelund, Husum amt, Slesvig, 100 g stalactite slag from 100 kg slag block, furnace No. 180. 350-450 A.D.
9. ibid. 450 g slag plate.
10. Gera-Tinz, Thüringen, Germany. 65 g fragment of 100 kg elephant's foot slag block. Iron Age.

Fig. 260. Elephant's foot slag of 100 kg from Gera-Tinz; Thuringia. No wüstite, only fayalite laths and corroded matrix. PS. SEM. Scale bar 0.1 mm.

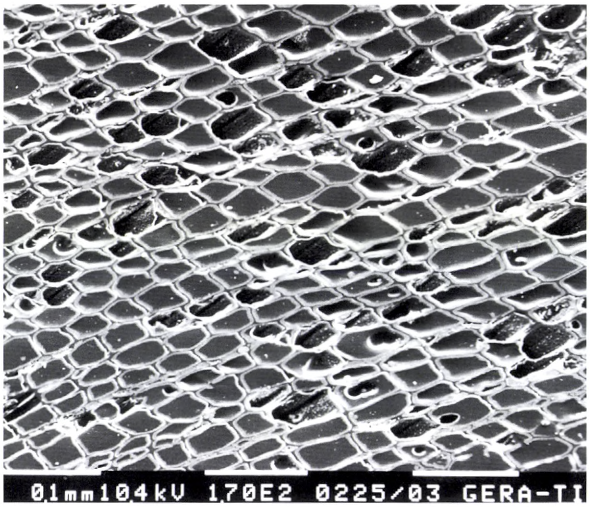


Fig. 261. Fossilized inclusion of charcoal in the slag block, Fig. 260. The cell walls have become replaced by goethite. PS. SEM. Scale bar 0.1 mm.

furnace is dated to 100-200 A.D. The slag contains cm-sized inclusions of charcoal, now converted to cellular aggregates of goethite. Evidently, the pit had been filled with wooden sticks before the shaft was charged with crushed ore and charcoal. When, later during the smelting operation, slag poured down in the pit, the supporting wood sticks became enveloped. They later decayed, becoming impregnated and fossilized by goethite. The slag consists of about 60% mangano-magnesia-fayalite (-3% MnO,- 2% MgO) and 40% glass matrix in which there are pockets of leucite with wüstite particles. The chemical composition fits well with the ore type described by Dusek (1967), an oxidized, dense clay-ironstone from the lower Zechstein formation, with 51.8% Fe, 2.8% MnO, 1.2% CaO and 0.5% MgO.

Iron objects from Iron Age Germany were not available for this study, but many have been treated in earlier publications, among which the reader may be referred to Schürmann (1958), who examined everyday objects from the Roman villa "Am Hostert" near Waldesheim, and Daeves (1940) who summarized a number of older examinations of slags and iron objects.

Great Britain

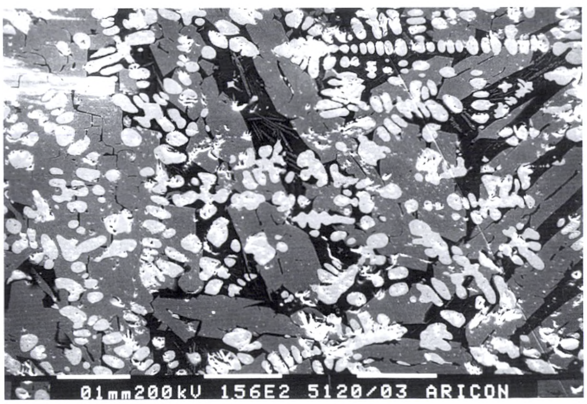


Fig. 262. Tap slag from Ariconium, 136 g. Wüstite dendrites (white), fayalite laths and duplex matrix. PS. SEM. Scale bar 0.1 mm.

A Romano-British iron-working site from 100-350 A.D. has been excavated at Ariconium, south Herefordshire (Schubert 1957; Cleere & Bridgewater 1966). Ariconium is 17 km NE of Monmouth, near Ross-on-Wye, and located north of the Forest of Dean in an area characterised by black soil and slag fragments, witnessing the vivid activity in the Roman Iron Age. A Roman road, metalled with iron slag, leads from a mine at Wigpool towards Weston-under-Penyard, the ancient Ariconium (Bridgewater 1968). During the excavation of a trench for the Welsh Water supply, a number of slags and other metalworking debris were studied and analysed (Starley 1994). Remains of six furnaces were identified, and tentatively classified as slag-pit types. Apparently they were operated by forced draught from bellows supported over the slag-pit.

A section through a flat tapslag was examined, Table 10.8, line 1. In the topside leucite pockets with wüstite particles are common, Figs. 262-263, in the

Fig. 263. Detail of the Ariconium tap slag, Fig. 262. Wüstite, fayalite, and leucite (black) with wüstite particles. PS. SEM. Scale bar 0.1 mm.

Table 10.8. SEM-EDAX analyses of Iron Age slags from Great Britain

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F	G
1	25.1	60.4	0.2	0.2	1.9	8.9	2.5	0.6	0.1	-	0.1	100	2.82	22.9
2	25.9	60.6	0.6	0.2	2.6	7.9	0.9	0.4	0.6	tr.	0.3	100	3.28	19.2
3	28.3	44.3	10.9[a]	1.2	1.7	9.4	1.6	<0.1	1.1	-	0.4	100	3.01	22.1
4	22.5	68.7	0.5	1.2	1.1	3.8	1.2	0.4	0.2	-	0.4	100	5.92	9.23
5	50.5	31.3	2.7	0.7	1.9	8.6	2.9	0.8	0.5	0.1	tr.	100	5.87	40.9
6	26.0	54.6	3.1	0.5	1.0	12.2	1.4	0.3	0.5	0.1	0.3	100	2.13	25.6
7	23.4	56.3	4.9	0.3	1.1	11.0	1.6	0.5	0.5	0.1	0.3	100	2.13	23.1
8	29.5	62.1	0.6	0.9	1.4	3.9	0.5	0.5	0.2	tr.	0.4	100	7.56	9.91

1. Ariconium, Hereford, Worcester. 136 g production slag. Tapslag. 100-300 A.D.
2. Creeton Quarry, Stamford, Lincolnshire. 50 g production slag. Tapslag. 100-300 A.D.
3. Ribchester, Lancashire. 42 g production slag. Tapslag. 100-300 A.D. [a] also 1.1% BaO.
4. Dartmoor, National Park, Devon. 105 g production slag. Tapslag. Roman Iron Age.
5. Crawcwellt, Gwynedd, Wales. 25 g purification slag. Pre-Roman Iron Age.
6. Llwyn Du, Gwynedd, Wales. 56 g production slag. Tapslag. Roman Iron Age?
7. ibid. 400 g production slag. Tapslag. Roman Iron Age?
8. Welhambridge, East Yorkshire. 26 g production slag. Pre-Roman Iron Age.

underside many quartz particles from the tapping channel are embedded. The average structure consists of 50% pure fayalite laths, 0.1 mm wide, 25% wüstite dendrites and 25% glassy matrix. Locally are dispersed 15-50 μm iron particles, angular or globular. The slag composition suggests a rather pure ore type which can hardly have been bog iron ore, but rather a hematite type. The Ariconium slag is very similar to the Portoferraio and Baratti slags which were the result of smelting hematite ores from Elba, Table 4.8. In England hematite often forms large irregular masses, in-filling cavities in the limestone of Furness, West Cumbria, and the Forest of Dean. Allen (1988) has published a number of bloomery slag analyses of samples where the ore came from the Forest of Dean. My Ariconium analysis fits well into his analytical scheme, except that my Al_2O_3- and K_2O-values are at the high end. The transportation of ore from the Forest of Dean, a distance of about 5 km, does not seem to have presented a serious hindrance.

In 1993 a Romano-British iron smelting site was discovered at Creeton Quarry, 12 km north of Stamford, Lincolnshire (Cowgill 1995). The presence of the Creeton site was a surprise as it had always been held that iron smelting did not extend to Lincolnshire in the Roman period. The slag is a tapslag which in section shows four consecutive runs, each about 4 mm thick.

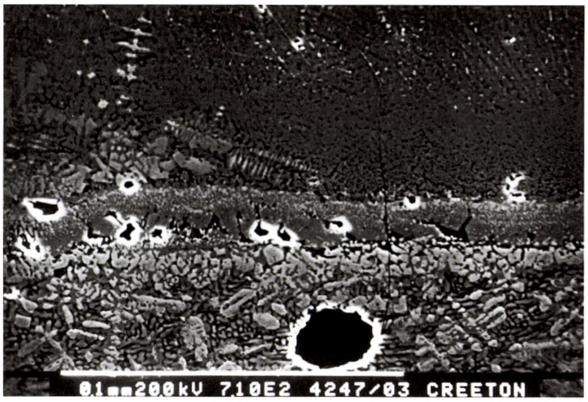


Fig. 264. Section through a 50 g tap slag from Creeton. First layer, below, with magnetite skeleton crystals in the free surface. Second layer shock-cooled and fine grained. PS. SEM. Scale bar 0.1 mm.

Fig. 265. A 42 g tap slag from Ribchester. Facetted fayalite, a little wüstite, and a duplex matrix. Black skeleton crystals of hercynite in the fayalite. PS. SEM. Scale bar 0.1 mm.

The upper part of each layer, which for a short time was exposed to the air, displays many small magnetite skeleton crystals. The interior is fine-grained and composed of 60% pure fayalite (10-15 μm wide laths), 20% wüstite dendrites and 20% glassy matrix. The average slag composition is not much different from that of Ariconium, but the ore was different, probably a sedimentary ironstone, which forms workable beds in the Middle Lias formation and, until recently, has been quarried to support the steel works at Corby, 25 km SW of Stamford (see e.g. Percy 1864:226, Table IV, analysis C.T.11).

The Ribchester slag, Table 10. 8, line 3, is a tapslag, associated with a settlement outside a Roman fort at the Roman road going north from Blackburn, Lancashire. A survey-in-depth of the ironworking slags and debris was undertaken by Starley (1995), who found that the settlement had been the seat of large-scale crafts/industries. Together with the working of leather, iron metallurgy, and, in particular, smithing had been important occupations.The upper crust of the slag here examined is rich in magnetite skeleton crystals. The inner parts consist of 60% manganofayalite blocks (50 μm wide with 16% MnO), 5% wüstite dendrites, and 35% polyphased matrix. Locally there are hercynite crystals with 5% MnO. The slag is unusually rich in manganese. Perhaps some unusual bog iron ore was exploited?

The Dartmoor tapslag is from a furnace site in the National Park in South Devon. It consists of 60% pure fayalite (20-50 μm thick laths), 25% wüstite dendrites, and 15% glassy matrix. Locally there are 5-30 μm iron particles. The slag is relatively low in aluminium (high F-value). The high ratio FeO/SiO_2 suggests that the bloomery process had a relatively low yield of iron, this being a soft, phosphorferritic wrought iron. Perhaps the ore was a magnetic oxide of iron, known to occur in Dartmoor (Percy 1864: 224).

Since 1986 excavations have been carried out each year at the Pre-Roman Iron Age ironworking settlement at Crawcwellt on the wild moorland, about 10 km east of Harlech Castle (Crew 1999: Crew & Crew 1995; Crew & Musson 1996). Some ten tons of waste slag dated to 300-1 B.C. have been found, considerably more than at any other prehistoric site in Britain. The slag here examined is low in manganese and phosphorus, and is probably from the purification step. The structure is unusual for a slag, being about 40% magnetite crystals and 60% glassy matrix. The ironsmelting was based upon bog iron ores, which here are rich in manganese and phosphorus, and some

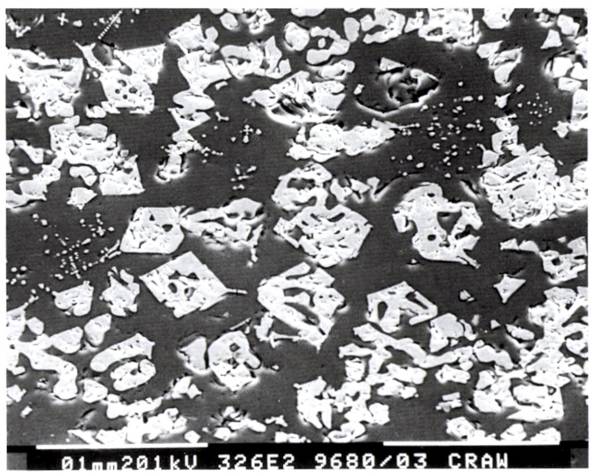


Fig. 266. Section through a 25 g magnetic purification slag from Crawcwellt. The cubic magnetite crystals contain a few percent Al_2O_3. Glassy matrix. PS. SEM. Scale bar 0.1 mm.

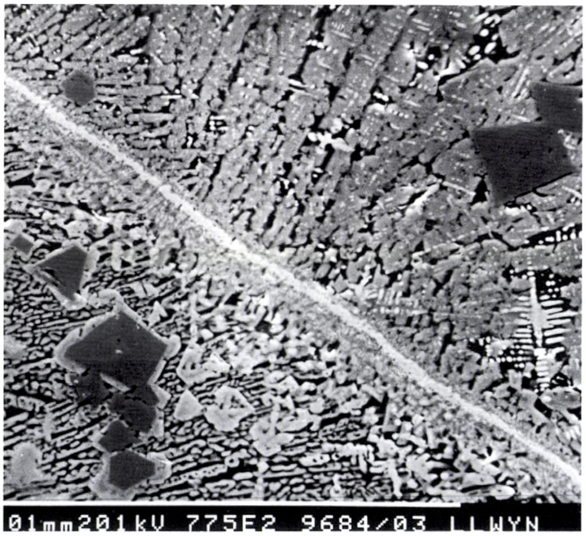


Fig. 267. Section through a 400 g platy tap slag with tubular channels, from Llwyn Du. The first run, below, the second above. Cubic hercynite crystals with exterior zone of aluminium-enriched magnetite. PS. SEM. Scale bar 0.1 mm.

20 furnaces, all found within buildings, have been excavated. The furnaces were small, about 25 to 30 cm in internal diameter and were not tapped.

Also in Wales, only 4 km SE of Crawcwellt, five other bloomery sites have been detected in the 1990s (Crew 1999; Crew & Crew 1995). At Llwyn Du a large, well-preserved furnace structure, some 2 x 1.5 m in overall diameter, was revealed, and nearby a possible smithing hearth has been observed. The site is included here in a Romano-British context, but more thorough examination may result in a dating as late as the 14th century (Crew 1997). The two slags here examined are layered tapslags, coming from a manganese-enriched bog iron ore. The structure consists of 65-80% manganofayalite, 10% manganowüstite dendrites (-1.5% MnO), and a polyphased matrix. Locally there appear 5-10 μm iron particles. Zoned hercynite crystals, 10-20 μm across, are common. The nuclei are apparently relatively pure hercynite (with 1% MgO and 3% MnO), while the exteriors are rather aluminium-enriched iron oxide, Fig. 267.

Welhambridge is one of several bloomery sites located along a creek system near Holme-on-Spalding-Moor, 25 km SE of York (Halkon 1995). C-14 datings on charcoal from the slag heaps give 450-250 B.C., older than was originally anticipated. Thick deposits of bog iron ore occur in the vicinity. The presence of some 5400 kg of slags and other ironworking debris attests to vivid activity in the Pre-Roman Iron Age. Both ore and products may have been shipped along the dendritic creek and river systems that are connected to the River Humber. The slag is a typical ancient production slag, but low in Al_2O_3 relative to many other British slags. It consists of 80% coarse-grained pure fayalite (>0.1 mm across), 10% wüstite dendrites, and 10% polyphased matrix. Locally there appear 5-10 μm iron particles. Micron-sized iron sulfide particles are segregated in the matrix. Their weathering has caused significant degradation and rust-colouring of the slags.

Iron and steel objects from Great Britain were not available for the present study, but readers may be referred to Coghlan (1956), Schubert (1957), Tylecote (1976; 1987), Cleere & Crossley (1995), and references therein. Manning & Hurrell (1976) explained and illustrated a large number of Romano-British objects from the Museum of Antiquities in Newcastle upon Tyne, and Brown (1964) examined a Roman bloom from Cranbrook, Kent.

Nails are far and away the most common metal finds on any Roman site, but one find, in particular, the massive hoard from Inchtuthill, Perthshire, Scotland, has aroused much interest (Angus et.al. 1962). The nails were found buried in a $3^1/_2$ m deep pit, specially dug for the purpose. The total number was over 875,000. The nails were probably buried when the Roman legion about 87 A.D. abandoned the unfinished fortress, for which the nails had been intended. The desire was to prevent this large quantity of iron from falling into the hands of the Scottish tribes, who prized iron more than silver and gold.

The nails in the middle of the hoard have survived very well, the exterior ones having reacted with oxygen and water to form a protective barrier. After having discarded about 2 tons of corroded, protecting nails, the remaining nails were sorted into five classes:

225-256 g (28 pieces), 92-416 g (1344 pieces), 13-75 g (25,088 pieces), 5-17 g (85,128 pieces), and 2-6 g (763,840 pieces). They were, as usual for ancient iron objects, very heterogeneous, with carbon ranging from nil to 0.9%. Phosphorus was practically absent, below 0.06%, except in the smallest nails, where 0.16% P was reported. Copper was below 0.02% and nickel below 0.05%. The hardness range was from 86 to 325 HV (100 g). Two of the nails were included in the comprehensive analytical work by Henger (1970). The bloomery sites or smithies where the nails were made have not been identified, and the ore types are unknown. A variety of Roman nails are exhibited in the Museum of Antiquities in Newcastle.

Spain

The pyrite deposits of the famous Rio Tinto district, which stretches from north of Seville and 100 km west, even into Portugal, have been mined for 3000 years, first for gold and silver, then for copper, iron and sulphur. They are the largest pyritic copper deposits of the world, having produced over 200 million tons of pyrite and 5 million tons of copper, with as much still in the ground. Some 50 ore bodies have

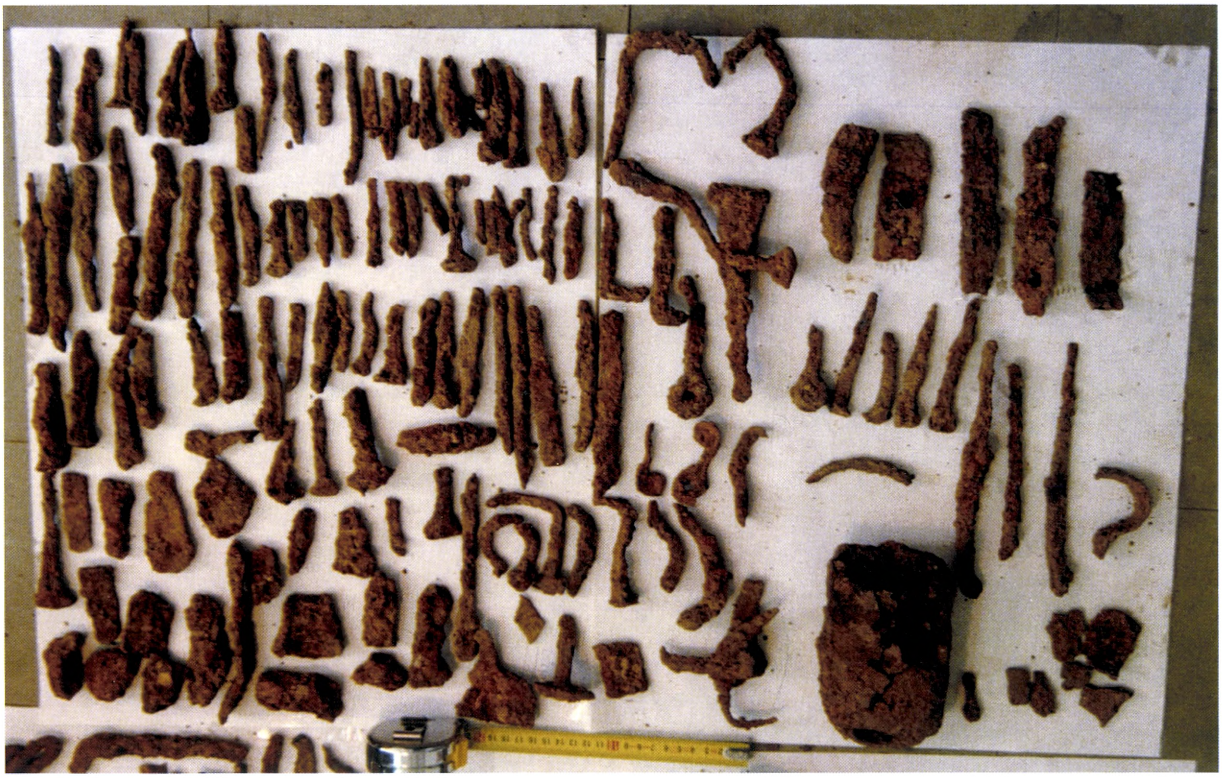


Fig. 268. A collection of rusted iron objects from the Aznalcollar excavation, northwest of Seville, Spain. Scale in cm. Courtesy Mark A. Hunt Ortiz, 1995.

Table 10.9. SEM-EDAX analyses of slag inclusions in iron and steel from Aznalcollar, Seville, Roman Spain, about 350 A.D.

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	54.6	9.7	6.1	tr.	0	12.3	10.7	3.4	2.3	0.6	0.3	100	5.10	182
2	29.5	7.3	27.1	6.6	0	3.0	12.4	6.7	1.7	3.1	2.6	100	2.38	58
3	39.1	8.1	30.8	1.0	0	2.6	13.0	2.5	0.9	0.8	1.2	100	3.00	48
4	38.8	9.3	26.8	3.9	0	1.5	10.5	2.3	1.0	2.3	3.6	100	3.70	38
5	30.9	50.0	3.3	tr.	3.6	1.9	6.4	1.4	1.9	0.4	0.2	100	4.83	20.4
6	29.7	54.5	0.9	0	2.4	2.2	7.1	1.8	0.8	0.2	0.4	100	4.18	20.6
7	20.1	69.7	0.5	0	0.1	1.0	6.7	1.1	0.2	0.3	0.3	100	3.00	12.8

1. 44 g steel nail, AZ-94, square 81, bag 9. HV: 227-233-238-255-286.
2. Head of 30 g steel nail, AZ-94, square 81, bag 5. HV: 166-289-345-360-396.
3. Head of 34 g steel nail, AZ-94, square 90, bag 3. HV: 321-367-369-396-404.
4. 38 g steel bar, AZ-94, square 81, bag 9. HV: 222-238-238-253-254.
5. 56 g iron bar, AZ-94, square 81, bag 9. HV: 157-172-188-196-203.
6. 107 g iron bar, AZ-94, square 81, bag 9. HV: 100-120-126-138-(264)
7. 375 g purification slag. AZ-94, square 65, bag 168.

been worked, mostly in huge open pits. The mines were for centuries little used, but when a British company took over in 1873, a new era began. The ore is pyrite, FeS_2, with 48% sulphur and 0.5-2% copper, and the present annual production is about 2 million tons of ore.

The Book of the Prophet Ezekiel (27: 12, 25) mentions the ships that bring silver and iron, tin and lead from Tarshish. Modern research identifies this with the lower part of the river Guadalquivir and the city of Seville (Domerque 1990). Tartessos, or Tarsis, was according to Herodotus (1: 163; 4: 152) an important trading centre, dominated by Phoenician merchants from Gades (Cadiz).

The Romans became firmly established in Spain in 19 B.C., and they developed the already existing silver, lead and iron mines. While the location of many silver and lead mines is well known, the location of the iron mines is, so far, little known. One possible mine seems to be at Sotiel Coronado, 20 km SW of Rio Tinto, where there are huge slag heaps, estimated at millions of tons (Allan 1968; 1970), Tylecote (1987: 300), and Ortiz (1988). Perhaps, however, they are mainly due to copper- and silver smelting (Rothenberg & Palomero 1986). An overview of present-day Spanish mineral industry may be found in Guzman (1983). The mineral industry and its importance for the Span-

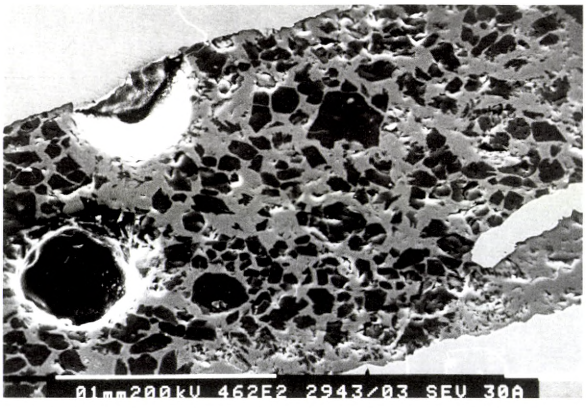


Fig. 269. A massive steel nail head of 30 g, Aznalcollar. 81:5, 30. Unusual slag inclusion, displaying two immiscible glass phases. **1**, 37% SiO_2-5% FeO-30% Al_2O_3-25% K_2O (black) and **2**, 31% SiO_2-5% FeO-19% MnO-12% BaO-6% CaO-10% Al_2O_3-2% K_2O-5% MgO-7% TiO_2 (light). PS. SEM. Scale bar 0.1 mm.

Fig. 270. Section through a 34 g steel nail, Aznalcollar 90: 3,34. Fine grained pearlite of extreme hardness, 321-404 HV, perhaps caused by some copper in solid solution. PES. Side length 0.12 mm. Courtesy FORCE Technology.

ish economy in Roman times have been treated by Blazquez (1978).

The iron ores for the ancient bloomeries may have come from the gossans, or iron hats, of goethite and limonite (Ortiz 1988). These have now been used up, but they must have contained some copper and sulphur, which may explain some of the results presented below.

In 1992 the mining company Boliden Apicsa, S.L. opened new activities at Aznalcollar, 28 km NW of Seville. In the course of the work it became necessary to excavate the monastery of Nuestra Senora del Buen Suceso del Retamal, which had been abandoned in the early 19th century. On the premises of the monastery, archaeologists discovered the remains of a Roman Iron Age settlement and cemetery which could be dated to about 350 A.D. (Ortiz, pers.comm.). The numerous iron objects found in square 81, a portion of which has been here examined, were apparently a hoard or a deposit, intended to be reused later.

The first, Table 10.9, line 1, is a 44 g bent nail, 13 cm long and 9x9 mm square at its thickest part. The structure is ferritic-pearlitic, often in a Widmanstätten development. The carbon content is 0.2-0.5% and there is no phosphorus. There is 1.5-2% (!) copper in solid solution in the metal, which may explain the unexpectedly high hardness for a ferritic-pearlitic structure. In the corrosion crust some copper has been precipitated. There is no copper in the glassy slag inclusions, but these are rich in manganese and calcium.

The 30 g nail head, line 2, is massive, 20x20 mm square. All slag inclusions are manganese- and barium-rich glasses without phosphorus, some of them severely crushed from smithing operations. Some few wüstite dendrites have up to 9% MnO. There are apparently two immiscible glass phases, one rich in K_2O and Al_2O_3, the other rich in MnO, TiO_2, BaO and SO_3. Copper is not present. The metal is fine-grained pearlite with about 0.7% C, 0 P, and of high hardness.

The 34 g nail head, line 3, is 15x15 mm square. The slag inclusions consist of crushed glass, very rich in manganese and sulphur. The metal is fine grained eutectoid steel with 0.7% C, and even some hypereutectoid parts. It is extremely hard, probably due to some copper in solid solution.

The 38 g iron bar, line 4, measures 45x12x12 mm. The forging has created crushed manganese-sulphur-enriched glass slags. Copper and phosphorus were not detected. The metal displays heterogeneous pearlitic-ferritic structures of medium hardness.

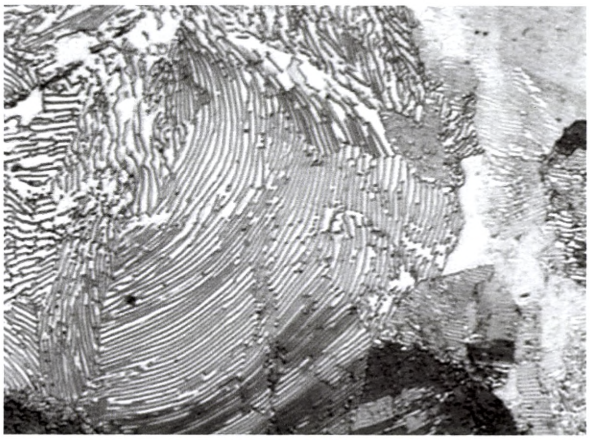


Fig. 271. A steel bar from Aznalcollar, 38 g, 81: 9, 38. Normal, lamellar fine pearlite, HV 222-254. PES. Side length 0.05 mm. Courtesy FORCE Technology.

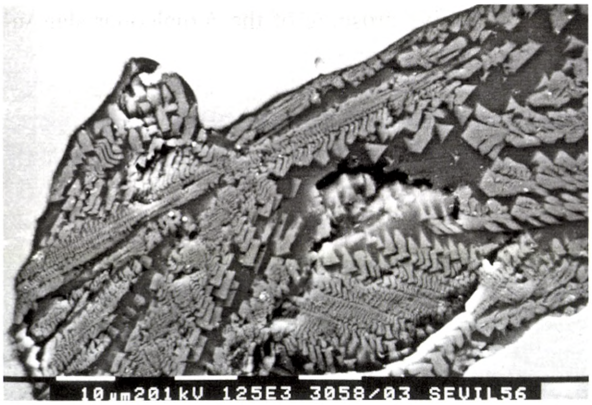


Fig. 272. A 56 g steel bar from Aznalcollar, 81: 9,56. The slag inclusion displays serrated fayalite crystals in a glassy matrix. PS. SEM. Scale bar 0.01 mm.

The 56 g iron bar, line 5, measures 55x20x20 mm (max.). The crushed slags are mainly two-phased fayalite-glass slags with much phosphorus and little sulphur, evidently much different from the preceding ones. The metal is ferritic-pearlitic and phosphorferritic with a relatively low hardness. Zones with up to 0.5% P in the ferrite occur. Copper was not detected.

The 107 g iron bar, line 6, is related to the previous bar, but it is complex as if it was once a composite of an iron plate and a copper plate. Severe corrosion has blurred the picture. What is left are some copper foil and a rather soft ferritic-pearlitic iron with less than 0.2% C and a little phosphorus (<0.2%). The slag inclusions consist of 50% fine-grained wüstite and 50% matrix. On the site was found a well-preserved Roman bell made of three iron foils and two copper foils (Ortiz, pers.comm.). Perhaps the 107 g iron bar was stock metal for a similar bell?

The 375 g purification slag, last line, is from another part of the excavation site, the settlement, where blooms were purified to bars and plates. As is usually the case, manganese and phosphorus are much lower in the purification slag than in the slag inclusions of the finished objects. No production slags were identified on the site, so the settlement must have received its blooms from the neighbourhood, probably from at least two different bloomeries.

One operated on an ore, rich in manganese, barium, aluminium, potassium, titanium and sulphur, which gave rise to perfect steely objects, such as lines 1-4. The other operated on a"normal" ore, with much less manganese and aluminium, but with some phosphorus. This resulted in phosphorferritic, soft iron objects. It appears that we are here dealing with the two gossan types, discussed by Ortiz (1988: 603), the first sitting in its original position, the other having been dissolved and sedimented at some distance, thereby having been depleted of manganese and sulphur, but enriched in phosphorus.

Fig. 273. Corroded iron-copper composite, Aznalcollar, 81: 9, 107. Metallic copper in corroded iron grain boundaries. Above, as polished. Below, photograph with CuKα radiation. SEM. Scale bar 0.1 mm.

The significant presence of sulphur in the first four objects suggests that the producing iron master omitted, or did not know, the practice of roasting. The sulphur did not, however, hinder the production of eminent steel objects, the high manganese and low phosphorus being a guarantee of the issue of the bloomery process.

The extensive crushing of the Aznalcollar slag inclusions is rarely met with. It was very common in the Celtic forgings (Chapter 5) and in the cold-worked Inuit objects (Chapter 1), and must, in general, be conceived as a sign of incompetency, or with respect to the Inuit, to the lack of fuel.

The Delhi Iron Pillar

To conclude this chapter on iron in the period 0-600 A.D., the author begs permission to move outside his general European scene in order to present a remarkable metallurgical monument, the iron pillar at Delhi, India. It is located in the southern part of the city in the temple complex of Qutb Minar, and it is encircled by Muslim ruins from the 13th century. Its fame rests upon its impressive size and its excellent state of preservation. Hindu tradition maintains that its resistance to corrosion is due to its construction from seven different metals, seven being a sacred number (Beck 1891: 217).

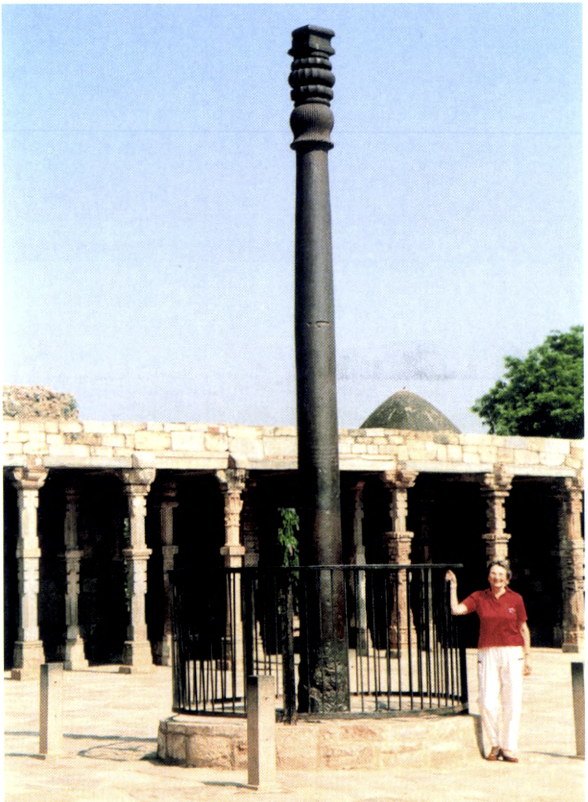


Fig. 274. The Delhi iron pillar, photos October 18, 1997. An iron grid to protect the pillar was put up in 1996.

The pillar has a total length of 720 cm, of which presently about 50 cm lies below ground. It is massive and has an estimated mass of about 6 tons. The diameter near the top is 30 cm, but in the buried, lowest part 62 cm. This is anchored in a massive lead plate, which again is supported by a heavy stone frame (Wranglén 1970). It was moved to its present position about 1100 A.D., but it was made some 700 years earlier, since an ancient inscription honours a certain King Chandra, who was probably the influential Chandragupta II (375-413 A.D.).

It has, of course, not been easy to acquire study material from a sacred monument. Nevertheless, the small flakes that from time to time have been removed and analysed, show that the iron is an unalloyed, low carbon and medium phosphorus wrought iron of the usual heterogeneous composition. According to Hadfield (1925), Bardgett & Stanners (1963) and Wranglén (1970), the carbon range is 0.08-0.28%, and the phosphorus range 0.11-0.48%.

Sulphur is everywhere below 0.008%, and copper and nickel are both below 0.05%. This composition is quite common in ancient iron objects, objects which under other conditions are known to corrode livelily.

Fig. 275. The Delhi iron pillar. On its foot, an ancient inscription in Sanskrit reports the victories of King Chandragupta, 375-413 A.D.

In fact, the lowest part of the pillar, which on an earlier occasion for centuries was underground, is severely attacked, as would be expected.

The pillar was forged from a number of 20-30 kg heavy blooms, which in itself is quite an achievement for those days. "Indeed, it is only within the last century or so that any European iron master could have undertaken to produce such a forging" (Hadfield 1925: 42). Only after the advent of the steam hammer and heavy crane machinery in the 19th century did such forgings become possible in Europe.

There is general agreement now, as in particular expressed by Wranglén (1970), that the near to perfect state of preservation is due to i) a rather dry Indian atmosphere which in the important initial phase was probably slightly ammonia-containing, promoting a superficial protective oxide film, ii) a favourable iron composition with some phosphorus and no sulphur, iii) a large, dark mass, which heated well during the daytime (max.40°C), makes any rain evaporate rapidly and prevents the formation of dew during the nighttime, and iv) the rain, 700 mm annually, was from the beginning clean and free of chlorides, which in coast-near locations elsewhere present a hazard.The present-day industrial atmosphere may be more aggressive, but the protective oxide-film appears to be rather effective.

To these important features may perhaps be added the protection from casual, ritual smearing with butter on seasonal, festive occasions.

In 1996 an iron fence was erected around the pillar to prevent pilgrims and tourists from touching the bare iron. It is a rather unpopular measure, for people used to visit the place and embrace the pillar in order to secure long life and prosperity. The pillar has for centuries stood up to and even profited from these embraces, so the measure seems to be entirely superfluous.

Chapter 11

The spoils of victory, and pattern-welding, 0-600 A.D.

The brehon handed him a hilted weapon,
a rare and ancient sword named Hrunting.
The iron blade with its ill-boding patterns
had been tempered in blood. It had never failed
the hand of anyone who hefted it in battle.

Beowulf, v.1457-61, translated by Seamus Heaney 1999.

The countries on both sides of the Baltic Sea were at the beginning of the new millennium still outside the consciousness of the Roman world, or, rather, very little information or chronicles from that time have survived to our times. Tacitus published "Germania" in 98 A.D., and Jordanes provided glimpses of migration routes and aristocratic family ties of his day, in the fifth and sixth centuries. Tacitus had respect for the tribes around the Baltic Sea, the Charudes, Gotones, Rugii, Sviones, Æstii, and, in particular, the Cimbri (Chapter 37), who had previously been a threat to the Roman world. Tacitus' description of the Nordic ship, a large rowing boat without sail (Chapter 14), has been fully confirmed by the discovery of the Nydam boat.

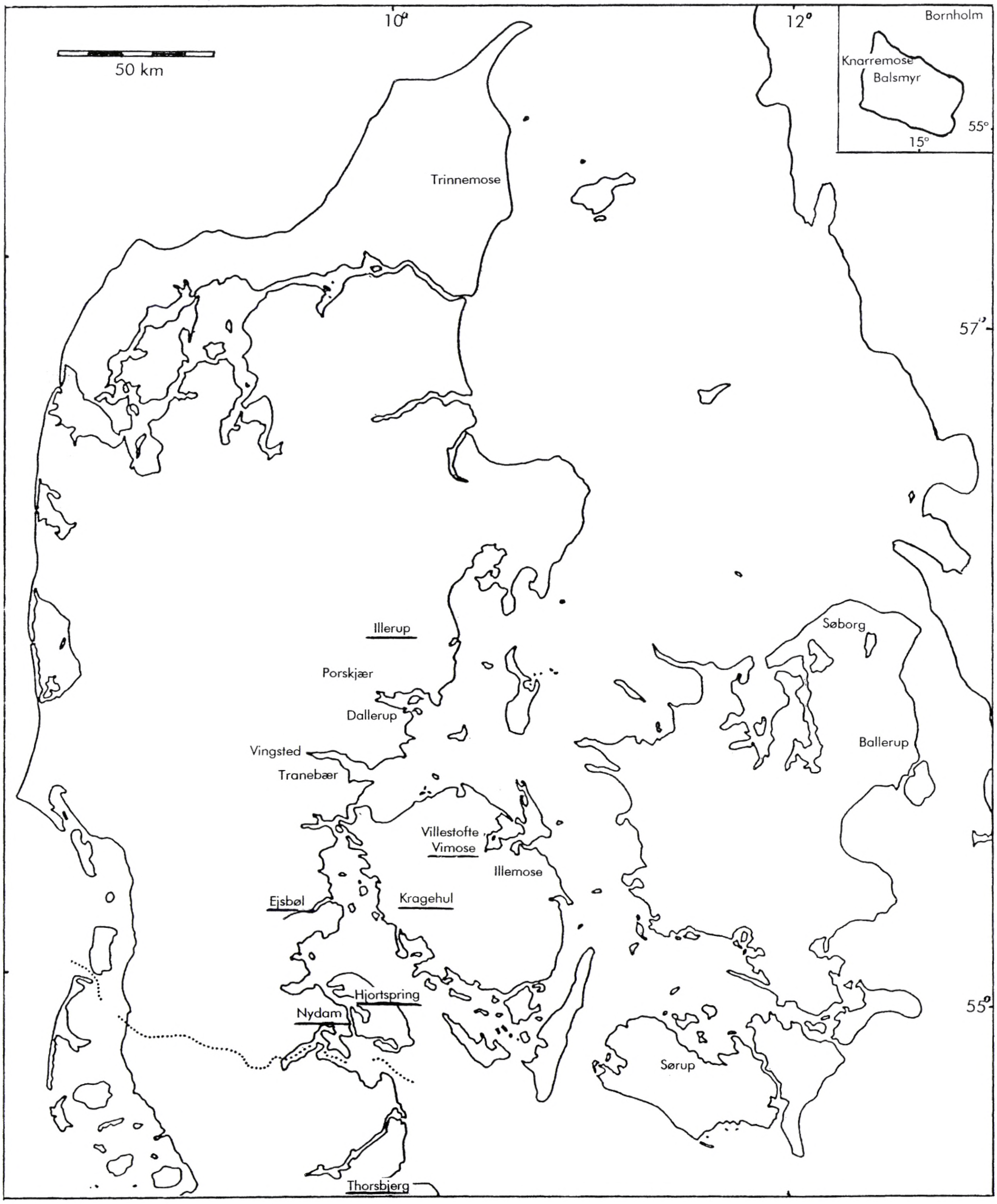
The period may be called the formative period in Scandinavia, where competition between the tribal elites led to numerous raids and minor wars in order to define principalities or "states". In 24 bogs in southern Scandinavia, war booty sacrifices have been found from these centuries. The Hjortspring boat, Chapter 8, is the only large weapon-offering find from the Pre-Roman Iron Age.

A number of the sites cover several individual deposits, so overall there may have been as many as 50 different sacrifices of chiefly army equipment, from shields and lances, to horse trappings, Roman coins, combs and fire-setting equipment, and, in three cases, entire ships. Judging from the number of war booty offerings, the period of conflict reached its peak in the third century A.D. The number declined and faded out by the end of the fifth century (Jensen 2003).

The interpretation of the sacrifices has gone in chiefly two directions. Do the sacrifices represent a victorious defence by a "home guard" over an aggressor, coming by sea? Or do they represent the spoils of victory, achieved somewhere "overseas", and carried back home in a Roman triumphant way, finally to be sacrificed in the local, sacred forest lake? (Jørgensen et al. 2001).

It has always been a source of some surprise that human skeletons or graves have not been found in association with the war booty offerings. Only the remains of severely molested and dismembered horses and dogs have been identified. If the weapon offerings were booty brought home, it is perhaps understandable that there would be no human skeletons among the material (U.L.Hansen 2003). On the other hand, if the fight had taken place near the place of sacrifice, the fallen enemies might have been hanged in the trees as food for the ravens in honour of the supreme god Odin. Centuries later we hear about ritual offerings

Fig. 276. The war booty sacrifices in Denmark. Hjortspring is from about 300 B.C., the others from about 100-450 A.D. The most important ones are underlined.



50 km
10°
12°
Bornholm
Knarremose
Balsmyr
55°
15°
57°
55°
Trinnemose
Illerup
Porskjær
Dallerup
Vingsted
Tranebær
Villestofte
Vimose
Illemose
Ejsbøl
Kragehul
Hjortspring
Nydam
Thorsbjerg
Søborg
Ballerup
Sørup

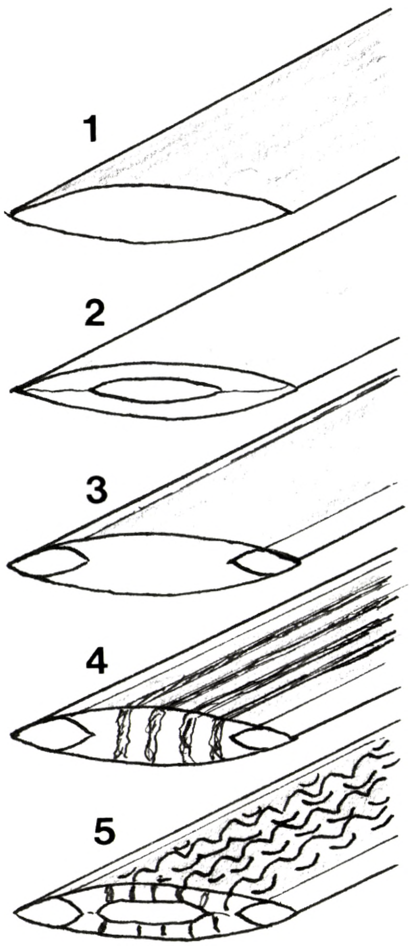


Fig. 277. Five sword types. **1**, common type with the usual heterogeneities, but no attempt of piling or pattern-ing. **2**, A central core of ferritic material, no pattern on the surface. **3**, Common type, but with forge-welded edges of another material, often steel. The edges may appear different. **4**, Pattern-welded material, with inlaid edges. The polished and etched sides display intricate patterns, but the edges stand apart. **5**, As 4, but with a central core of a different material, often steel. Edges stand apart. A rather rare type.

where men, horses and dogs were hanged in the trees of the sacred forest (Adam of Bremen, Book 4: 27, about 1070 A.D.).

While the discussion is currently on the issue of offensive versus defensive armies, we do have some knowledge of which regions were involved in the conflicts. The new knowledge comes from a close study of the types of ornament and, in particular, personal belongings such as combs and fire-setting equipment (Ilkjær 1990; 2000; 2003).

The war booty with a total of about 40,000 objects provides a fascinating insight into an ancient, warring world. Silver, gold and bronze are richly represented, e.g. as decorations on shields and as status symbols. But what here is of interest is the weaponry. The state of preservation of the iron objects is generally good and sometimes excellent, due to the permanent cover of water-logged mud, and later embedding in anaerobic basic lake and turf deposits (Christensen 2003). On the other hand, most metallographic work has, unfortunately, been restricted to second quality, rusted fragments, which could be sacrificed because they were of little exhibition value.

Vimose, which lies a few kilometers NW of Odense, contains one of the most extensive war booty sacrifices known, with about 4000 objects (Engelhardt 1869; X.P.Jensen 2003). The finds are concentrated within an area 35 m in diameter, and it is assumed that they were thrown out into a shallow lake on three occasions. The first occurred between 70 and 150 A.D., the second about 150 A.D., and the third and largest between 210 and 260 A.D.

From this last deposit a broken fragment of a 6 mm thick and 25 mm wide, double-edged sword has been examined. The sword was so hard that it could only be cut with a rotating carborundum-impregnated cutting disk. The macrostructure of the section and the general absence of any patterns on the deeply corroded surface indicate that the sword was a rather simple product, type 3 in Fig. 277, consisting of a steel blade with

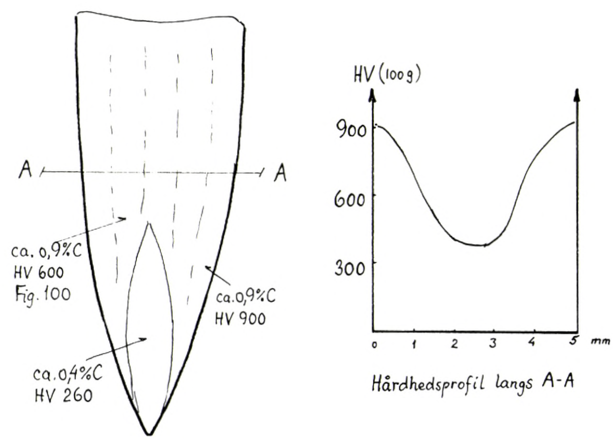


Fig. 278. Cross section of a sword from Vimose, Fyn. Left, an inferior edge has been hammer-welded to a steel backing. Right, Vickers hardness (100 g load) across the section.

inlaid edges along both sides.The bulk of the sword is of the usual, heterogeneous type, with no less than 0.5-0.7% carbon and no phosphorus. The slag inclusions are few, and all are glassy and mostly only 100 x 10 μm in size, Table 11.1. Their composition is in harmony with the high-carbon metal structure. Their significant manganese and titanium content, and the low phosphorus and F-value suggest a production site for the sword blade in Norway or near the Rhine.

The very edge is formed by a 4 mm deep, wedge-shaped inlay, which the ironmaster had selected for this purpose. Unfortunately he failed, because the edge is low-quality, low carbon steel (0.2-0.3% C), not fit for the quenching operation.

The very complex microstructure of the sword is due to an unsuccessful hardening procedure. The austenitic temperature, 750-800°C, was held for too short a time, so the preexisting pearlite of the bulk of the sword was not completely transformed into austenite. On water-quenching, the rapidly cooled surface transformed 100% into fine-grained martensite of maximum hardness, but further in the surviving, small spheroidized, pearlitic grains nucleated haloes of extremely fine-grained hard pearlite, while finally the remaining austenite transformed into martensite. In the central core of the sword the cooling rate only sufficed to form pearlite, compare Fig. 157.

The Vimose sword is thus a rather mediocre weapon, because the weapon smith did not fully understand his business. i) The inlaid edges should have been of steel, ii) the bulk was already a fine-quality steel and did not require extra steel edges, iii) the austenitizing temperature was rather low, and the holding time too short, iv) no final tempering took place. With respect to the last point, tempering, i.e.a brief reheating to 100-300°C, the blacksmith should not be blamed, because it appears that tempering of hardened objects was used very rarely in ancient times.

The Vimose find (3rd deposition) comprised at least 200 lanceheads and more than 155 spearheads, most of them with ash tree stakes. A lancehead of the Norwegian Skiolum type bears the runic inscription *wagnijo*, which is probably the name, modern Vagn, English Vaughan, of the smith who made the weapon (X.P.Jensen 2003; J.Jensen 2003: 497, 529). The presence of combs, produced from antlers of reindeer and elk, also points to a Norwegian connection, whether the Vimose tribe attacked southern Norway and brought the spoils of war back to their sacred lake, or the tribe successfully pushed back attacking boats from southern Norway.

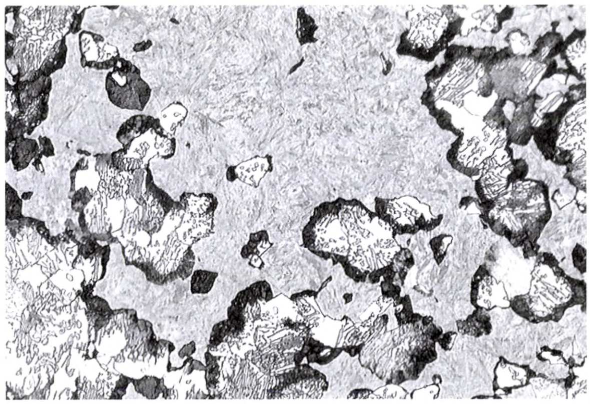


Fig. 279. The Vimose sword did not acquire an equilibrated austenitic structure throughout, because the time at 750-800°C was insufficient. On quenching the undissolved, but spheroidized pearlite islands formed nuclei for new, fine grained pearlite (black rims). At about 200°C the remaining austenite transformed to 0.7% C martensite (fine, grey needles). PES. Side length 0.15 mm. Courtesy FORCE Technology.

Illerup Ådal is the largest and archaeologically best documented war booty offering site in Scandinavia (Ilkjær 1990; 2000; 2003). Through the west-east oriented valley, 2 km north of Skanderborg and 20 km SW of Aarhus, there ran an ancient rivulet that locally widened into a series of small lakes. In one of these, with an area of about 100,000 m^2, the Illerup find was made. Through the years 1950-1956 and 1975-1986 systematic excavations of 40% of the area yielded about 15,000 objects, most of which are now housed in the Moesgård Museum, where an instructive exhibition elucidates the archaeological achievement.

It is assumed that there are a great many antiquities left in the remaining 60% of the bog, but these are not under immediate threat, since after the interruption of the digging campaigns the groundwater level was allowed to come back to its original level. Already now it is, however, clear that the collection of Roman swords, half of them with stamps or inlays, is the largest and most important ever found in Europe. Some of the warriors were craftsmen and they brought along their tools on the expedition. A beautiful, small soldering iron belonging to a goldsmith is a surprising find.

The scientific results are being published in a series of books by Jysk Arkæologisk Selskab (Volume XXV). So far "Lances and spears", "Belts and accessories", "Magnificent harnesses", "Excavation reports", and "The shields" have appeared. A few metallographic examinations of swords, lanceheads, spears and knives have been published in the 1990s by Thomsen (1992) and Ilkjær et al. (1994).

By the kind cooperation of J.Ilkjær seven lanceheads from the first and largest of three deposits could be examined, Table 11.1, lines 2-4. The deposit presumably took place about 200 A.D. Four of the lanceheads are of the Vennolum type, of which some 300 are known (Ilkjær 1990). Vennolum is a weapon grave in Oppland, north of Oslo, where the type specimen was first described. Two of the lanceheads are of the Skiaker type, while the last one is loosely called a southern Norway type. The best preserved weapons have been found in basic parts of the moor where pH is larger than 8.5, while the poorly preserved ones have been found in the topmost layers where pH is less than 7.0. In four of the seven objects the corrosive attack has unfortunately dissolved some of the glassy

Fig. 280. Three lanceheads from Illerup Ådal, 1880.YTL, 1880.VUD, and 1.BLX. Scale bars 8 cm.

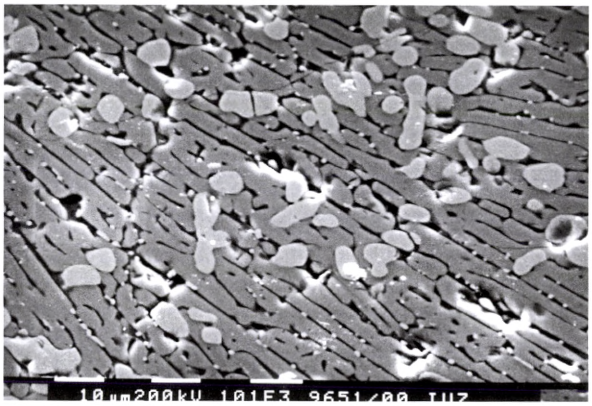


Fig. 281. Corroded slag inclusion in the Illerup lancehead 1880.IUZ. Especially the matrix between the fayalite laths have been eaten away. PS. SEM. Scale bar 0.01 mm.

microconstituents of the slag inclusions, so chemical analyses of the slags become meaningless.

The lancehead 1880 YTL weighs 214 g, has a rather short socket (80 mm), and is totally 410 mm long (Ilkjær 1990, Plate 97). A section from the transition socket-blade shows a structure of spheroidized, fine-grained pearlite with about 0.6%C and no phosphorus. The hardness is medium to high, 186-213 HV. The metal was tough enough to stand up to a bending of 75° when molested during deposition in the lake. In the edge are three deep cuts, either from a fight, or more likely from the ritual deposition. The slag inclusions are few, but usually occur as 100x10 μm glass stringers. In composition they are similar to the steel bars of Valdres, Table 10.3.

The lancehead 1880 VUD weighs 160 g, has a severely corroded socket, and is 345 mm long (Ilkjær 1990, Plate 88). A small section from the transition socket-blade was examined. The structure is slightly spheroidized fine pearlite with about 0.6%C and no phosphorus. The hardness is 186-224 HV and similar to the preceding one. A yellowish light line through the etched structure reveals where the socket was folded over and hammer-welded. The slag inclusions are chiefly small glasses, one, however, reaching the dimensions 300x30 μm. Their composition with respect to the important elements, manganese, phosphorus and titanium, and the F-value is similar to the preceding one.

The two lanceheads are so similar in shape, structure, hardness and slag inclusions that in all probability they were produced in Valdres, or from steel bars coming from Valdres. They were not quench-hardened, but they were sufficiently hard and tough to have served as excellent weapons.

The lancehead 1.BLX weighs 100 g and is of the Skiaker type (Ilkjær 1990, Plate 47). It has a length of 270 mm, of which the socket constitutes one third. A section from the transition socket-blade shows ferritic structures, where some zones display very large ferrite grains, 0.5, even 1 mm across. In the grains and also in some grain boundaries there are fine precipitates of phosphides, Fe_3P. The phosphorus content is estimated at 0.4-0.8%, which explains the anomalous grain growth of the ferrite at forging temperatures of 900-1000°C, and the appreciable hardness.

The slag inclusions are three-phased wüstite (15%), fayalite (70%) and glass (15%), and they are rich in phosphorus, but poor in manganese, aluminium and titanium. Locally, the slags contain iron-phosphate-glass pockets. The composition of the metal and the slags is widely different from the preceding lance-

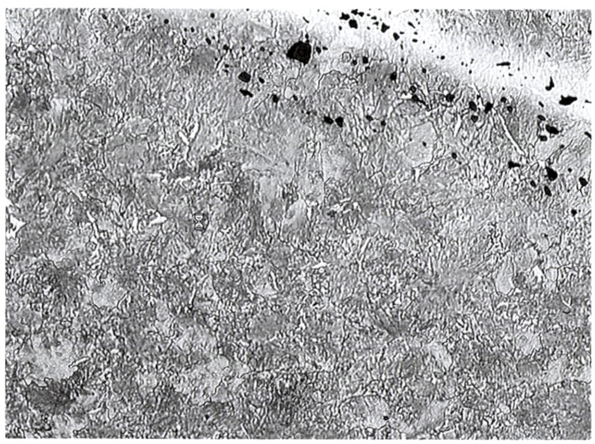


Fig. 282. The hammer-welded joint between two parts of the Illerup lancehead is seen as a yellowish line, associated with slags above. Illerup 1880.VUD. PES. Side length 1.2 mm. Courtesy FORCE Technology.

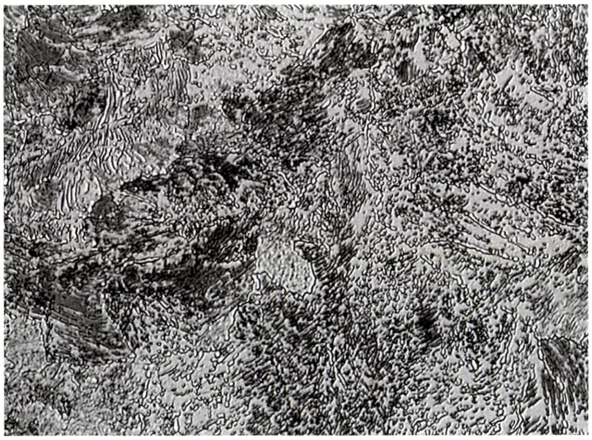


Fig. 283. Detail of Fig. 282. The bulk structure is excellent, slightly spheroidized pearlitic steel with a hardness of 186-224. PES. Side length 0.12 mm. Courtesy FORCE Technology.

heads of Valdres steel, and rather points to Danish iron bars of the western Jutland type, as presented in Table 9.3, last four lines, and Table 9.1, lines 1-2.

The lancehead 1.KB is a 135 mm long socket fragment of the Skiaker type (Ilkjær 1990, Plate 42), and only weighs 75 g. Imprints of a cloth in which the object has been wrapped are visible in the corroded surface deposits. The section shows a very coarse-grained ferrite, 0.2-0.6 mm grains, with phosphide precipitates. There are numerous Neumann bands from some violent cold deformation, perhaps from when the weapon was broken asunder. The hardness range is 135-192 HV, similar to the preceding one. The slag inclusions are also similar, but they are too corroded for a meaningful analysis. The lancehead was most likely made by the same smith from the same Danish material as lancehead 1.BLX.

The lancehead 1.BQY is of the rather uncommon type 14, from southern Norway (Ilkjær 1990, Plate 9). The socket being lost, the remaining blade weighs 64 g and is 180 mm long. A section through the blade displays coarse ferrite, 0.1-0.2 mm across, with Neumann bands, alternating with fine-grained phosphorferrite with 0.2-0.4% P. The hardness is 180-186-209 HV due to the combined effect of an appreciable phosphorus content and some cold deformation. The slag inclusions are mostly three-phased with wüstite (0-15%), fayalite (70-75%) and glass (10-20%). They were too corroded for measurements to be taken.

The lancehead 1880.IUZ is of the Vennolum type (Ilkjær 1990, Plate 60). It is broken into two pieces, a 176 g socket with part of the blade, and a 32 g point, with a total length of 352 mm, of which 1/5 falls on the socket. On the blade is an imprint of some textile fixed

Table 11.1. SEM-EDAX analyses of material from the war booty offerings in Denmark

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F	G
1	60.5	5.4	3.2	0	6.6	16.0	5.3	2.1	0.9	-	100	3.78	349
2	51.1	4.8	10.8	0	13.3	13.7	3.0	2.3	1.0	-	100	3.73	207
3	52.6	8.2	9.2	0	3.2	21.2	3.8	0.9	0.9	-	100	2.48	167
4	19.6	64.0	0.9	11.6	1.6	1.7	0.6	-	-	-	100	11.5	5.1
5	28.7	53.9	2.4	8.2	2.5	2.7	0.8	0.3	0.3	0.2	100	10.6	9.8
6	58.1	23.5	4.1	1.5	4.7	5.2	1.8	0.4	0.5	0.2	100	11.2	41.6

1. Vimose, Odense, Fyn. 100 g sword fragment, quench-hardened. HV: 226=322-429-787-933.
2. Illerup Ådal, Skanderborg, Jutland. 410 mm long lancehead. 1880 YTL. HV: 186-192-195-200-213.
3. ibid. 345 mm long lancehead. 1880 VUD. Vennolum type. HV: 186-197-197-214-224.
4. ibid. 270 mm long lancehead. 1.BLX. Skiaker type. HV: 135-138-146-160-192.
5. Anchor from the Nydam boat. Section 3421 B. HV: 158-165-201.
6. ibid. Section 3421 A. HV: 160-182-202-206-222.

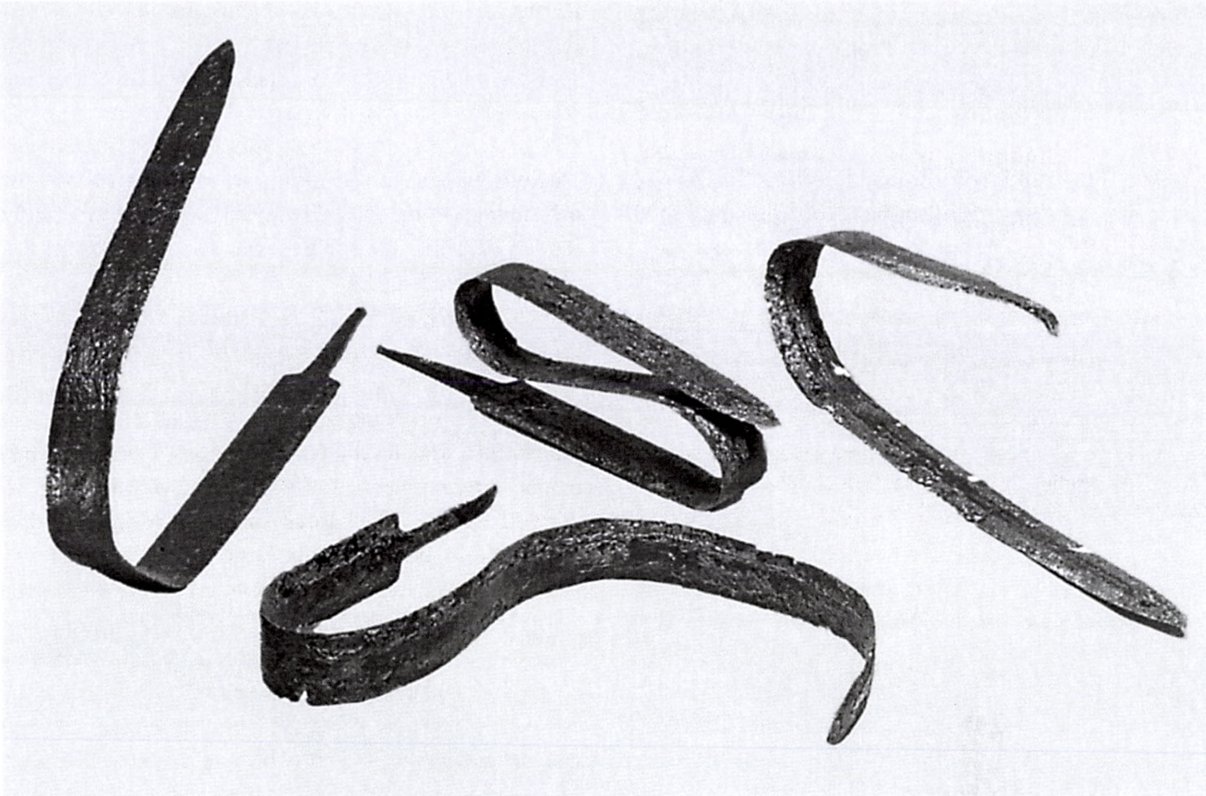


Fig. 284. Four Illerup swords, destroyed by bending (hot!) before being deposited as a sacrifice. Courtesy Jørgen Ilkjær, Moesgård.

in the rusty coating. A section from the transition socket-blade shows alternating zones of coarse ferrite (-0.3 mm grains) with fine phosphide precipitates, fine-grained ferrite (-0.03 mm grains), and some spheroidized, ternary Fe-P-C structures with about 0.2% P and 0.2% C. The hardness is low, 112-120 HV, corresponding to annealed wrought iron. The slag inclusions are three-phased with wüstite (60-70%), fayalite (0-15%) and glass (10-15%). They are unfortunately too corroded for a meaningful analysis. The metallic structure and the slag inclusions are widely different from the two first Vennolum lanceheads, Table 11.1, lines 2-3, so 1880.IUZ must have been made from a different ore, even if being of the same shape.

The last lancehead 1880.QLN is also of the Vennolum type (Ilkjær 1990, Plate 77), but rather small, weighing 112 g and only 252 mm long, of which 1/5 falls on the socket. A section from the transition socket-blade displays 100% ferritic zones with grain sizes of 0.02-0.2 mm, alternating with ternary Fe-P-C structures with about 0.2% C and 0.2% P. The hardness is 118-131 HV, corresponding to ferrite with a little phosphorus in solid solution. The slag inclusions are three-phased with wüstite (15-25%), fayalite (65-75%), and glass (about 10%). They are, however, selectively corroded and unsuited for quantitative analyses. Qualitatively, the slags and the metal are quite similar to the previous 1880.IUZ, and they may have come from the same stock.

Summarizing the results of these seven lanceheads from Illerup Ådal, about 200 A.D., it may be stated that they were not burned on a funeral pyre, but some were deliberately bent or broken before they were thrown into the lake. On two of them were fossil im-

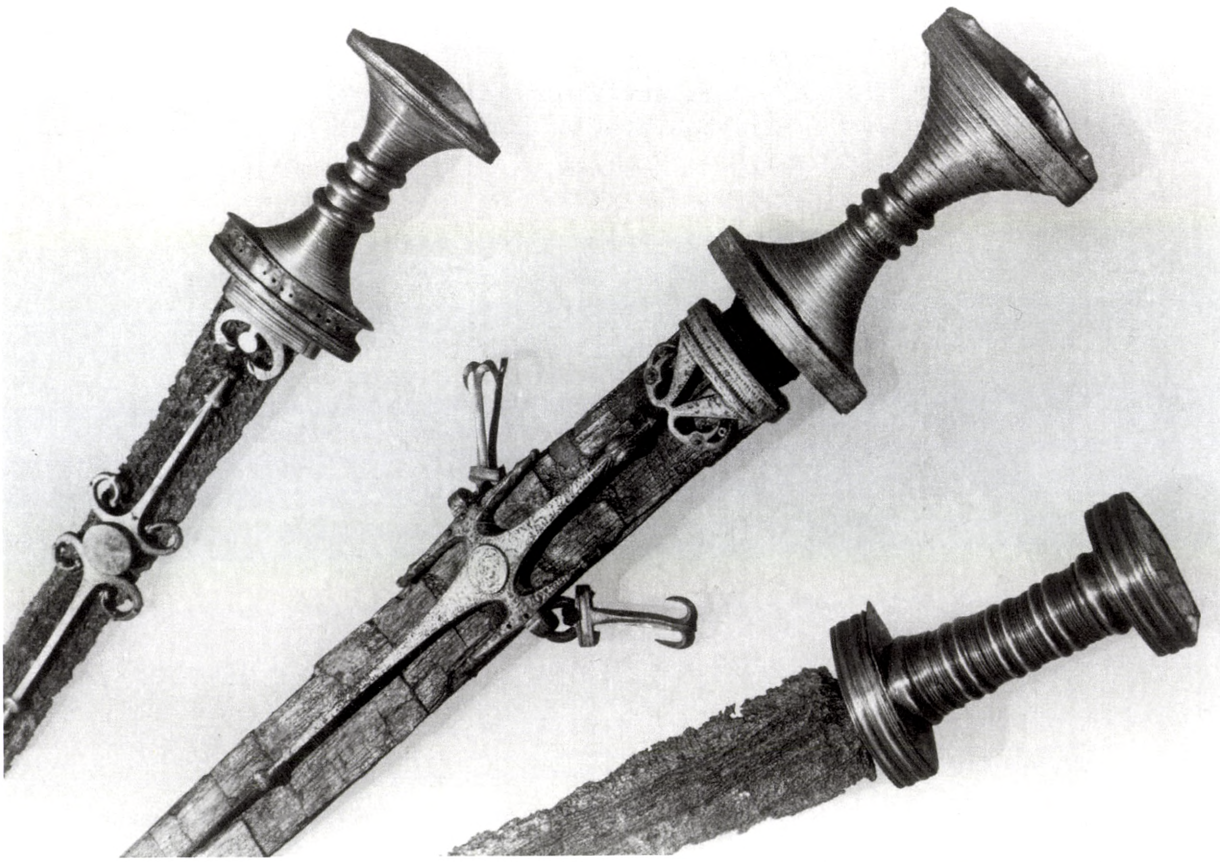


Fig. 285. Three swords with parts of the decorations for the scabbards. Deposited about 450 A.D. in Kragehul bog, Fyn. The National Museum, København.

prints of some textile, probably from a cloth wound around the heads. None of the lances had been quench-hardened, although two, 1880.YTL and 1880.VUD of the Vennolum type, were made of excellent steel suitable for hardening. Swords and knives might be quench-hardened, but spears, lances and arrowheads were not. These two lanceheads were the hardest, but at the same time they were tough and must have been outstanding weapons. The other two Vennolum types, 1880.IUZ and 1880.QLN, were made of soft, ferritic iron, while the two Skiaker lanceheads, 1.BLX and 1:KB, were made of phosphorus-rich ferrite with a medium to high hardness. The two outstanding lanceheads were undoubtedly produced in Valdres from the region's special ores, well suited for steel production (Chapter 10), while the two Skiaker lanceheads may have been made from western Jutland's iron bars (Chapter 9). The corrosive attack on three lanceheads unfortunately prevented any decision with respect to origin.

The Thorsbjerg war booty offering was found in a forest moor near Sønder Brarup in Angel, 18 km NE of Slesvig. It was, from 1858 to 1861, the first to be excavated by competent archaeological personnel (Engelhardt 1863). Thorsbjerg bog is the only one of the sacrificial bogs that is acidic and poor in nutrients because of the surrounding sandy moraine deposits. This has had the effect that very few iron objects have survived. In return, the find is rich in circular shields, leather belts and sandals, and many textiles, cloths and garments have been preserved. There are also some silver and bronze objects, and the famous protecting silver mask for a chieftain comes from Thorsbjerg. Roman coins date the booty-deposit to have happened between the 1st and 4th centuries. It is the general opinion that the Thorsbjerg find has more associations to northern Germany than to Scandinavia (Jensen 2003: 540). Most of the finds had to be surrendered to Bismarck's new Germany, as stipulated in the Peace-treaty that concluded the German-Danish war in 1864. A modern war booty offering! They are now on display in the Museum at Schloss Gottorp, Schleswig.

The Kragehul war booty offersite had been known since 1751, when in 1865 the find was excavated and published (Engelhardt 1867). The small kettle-moor 600 m NW of Flemløse Church, and 26 km SW of Odense, Fyn, housed a number of two-edged swords, scabbards, lances, spears, shields, arrows and some fire-setting steels and stones. Some of the stakes had tracery ornamentation. It appears that three or four events were celebrated by the sacrificial rites, the first occurring about 200 A.D., the last about 450 A.D. (Ilkjær 2003: 56; J.Jensen 2003: 556).

The Ejsbøl war booty offersite is located about 2 km NW of Haderslev Cathedral, south Jutland. Weapons and other military equipment were discovered in 1955 during drainage work, and the systematic excavations, covering 1700 m^2, took place in the following years (Ørsnes 1968; J.Jensen 2003: 562). The bog had been used for ritual purposes for centuries before the first war booty was sacrificed about 300 A.D., the so-called Ejsbøl-Nord deposit. A second, smaller deposit, Ejsbøl-Syd, took place about 450 A.D. The Ejsbøl-Nord deposit constitutes 90% of the total objects and may be interpreted as the remains of a force comprising 9 mounted warriors (horsetrappings, saddles, pairs of spurs), 60 warriors armed with swords (two-edged swords, belt-buckles, and knives), and 200 warriors, each carrying a lance, a spear and a shield. Most objects had been severely damaged by fire before being thrown into the ancient lake. The find is exhibited in Haderslev Amts Museum. Fascinating new investigations in Ejsbøl in the late 1990s have been described and an overview of the entire Ejsbøl location given by H.C.Andersen (2003).

The Nydam war booty offersite and the Nydam boat are located in a NW-SE trending bog, 4.5 km due north of Dybbøl Church, Sundeved. Before Engelhardt's systematic excavations (1865) for Flensborg Museum in the years 1859-1863, many weapon finds had been reported in connection with peat-cutting. Now a huge amount of weaponry and other military equipment was secured. The remains of a 23 m long oak boat and two smaller boats, built of pine, were also found. Most of the material was lost to Germany, under the Peace-treaty just mentioned. The Nydam-boat and the war booty are now on display at the Museum of Schloss Gottorp, Schleswig. In 2003-2004 the Nydam boat was loaned to the National Museum, Copenhagen, where it drew much attention (Rieck 2003). The transport alone from Slesvig to Copenhagen and the construction of a large air-conditioned tent to protect the boat were quite extraordinary feats.

Fragments of the pattern-welded swords from Nydam bog have from time to time been studied by metallurgists and craftsmen, who wanted to understand the complex textures and reproduce the pattern-weld-

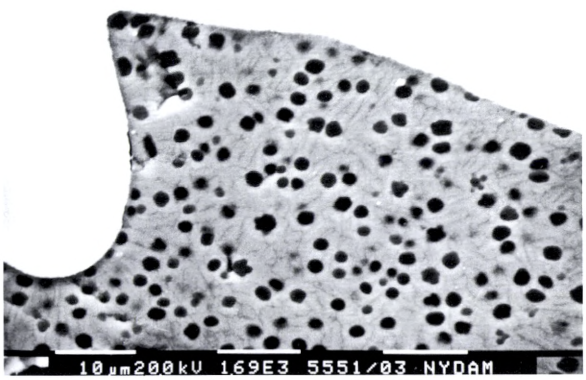


Fig. 286. Section through the anchor from the Nydam boat. The slag inclusion is typical for iron objects from western Jutland. Immiscible droplets (black glass) in a duplex, phosphorus-rich slag. PS. SEM. Scale bar 0.01 mm.

ed objects. Early reports are by Neumann (1927) and Schürmann (1959), while a comprehensive study was published by Thomsen (1992). An examination of eight Nydam swords concludes this chapter.

In 1989, the National Museum took the initiative in launching a major programme of new investigations in the bog that was to extend over ten years (Rieck 2003). Simultaneously the bog was mapped and monitored for acidity and aeration in order to improve the understanding of corrosion and decay in peat (Matthiesen 2003).

Among the new objects discovered in 1993 was an iron bar which apparently was the missing part of a ship's anchor, found in 1864 but later lost (Rieck 2003: 308). The anchor is estimated to have been 1.6 m high. The newly found rectangular midsection is 39 cm long, has at one end a cross section of 35x15 mm and at the opposite end a cross section of 40x17 mm. The weight of the midsection is 1.8 kg, the entire anchor can hardly have weighed more than 10-15 kg. Still, it was a major piece of iron for the time.

Two small sections were examined, Table 11.1, lines 5-6. The first section displays 25-200 μm ferrite grains with phosphide precipitates on the grain boundaries. The average phosphorus content is 0.29%, and the hardness range is 158-201 HV. The other section has more phosphorus, ranging from about 0.2 to 0.7%. The structure consists of phosphorferrite with distinct ghost structures and with locally coarse-grained ferrite with high (0.7%) phosphorus content, indistinct grain boundaries and etchpits. The highest hardness values are found in the phosphorus-rich ferrite grains. Carbon was not detected.

The slag inclusions are 50-200 μm in size and display a characteristic spotted glass texture, known from authentic western Jutland slags. Although the two analyses are apparently different in composition, they are in internal harmony as explained in Chapter 7. As SiO_2 increases, so do MnO, CaO, Al_2O_3, K_2O, MgO and TiO_2. But FeO and P_2O_5 decrease, and the F-value remains (almost) constant. The composition of the iron and slag inclusions is very similar to objects of western Jutland origin and, incidentally, also rather similar to the Illerup lancehead in line 4.

It is quite a surprise that an iron object with so heavy a cross section has been broken into pieces. Perhaps the breakage took place in the wintertime, since it is known that the high phosphorus content can induce cold-shortness. On the other hand, some heavy sledge hammer strokes may have had the same effect at normal temperatures.

While the anchor must be referred to the period 300 ± 50 A.D., it is uncertain to which of the three ships it belonged. It is the largest forged-iron object of the period, and it is the earliest example of the use of true stocked anchors in Scandinavia.

Hammer-welding (Danish, essesvejsning)

The art of hammer-welding is as old as the knowledge of iron-making. It disappeared and was (almost) forgotten in the early 20th century, when autogeneous welding and cheap electric welding transformers were introduced in the workshops everywhere.

In a 3000-year-long practice the smithy had been little changed, the tools had remained the same, the anvil perhaps being the only object which changed substantially, from a stone, through humble, small anvils stuck into a heavy oak block, to the heavyweight (80-220 kg) cast steel anvils of today (Beck 1891:463, 539; Manning 1976; Richardson 1978). The smithing hearth was mostly fired by charcoal, but in the last few centuries pit coal (nøddekul) has also been widely used. Today the blacksmith normally uses pit coal and can choose between hundreds of iron-based alloys. But the ancient smith, i.e.until about 1880, had only iron, phosphorus-enriched iron and unalloyed steel to choose from.

Two different main operations may be distinguished

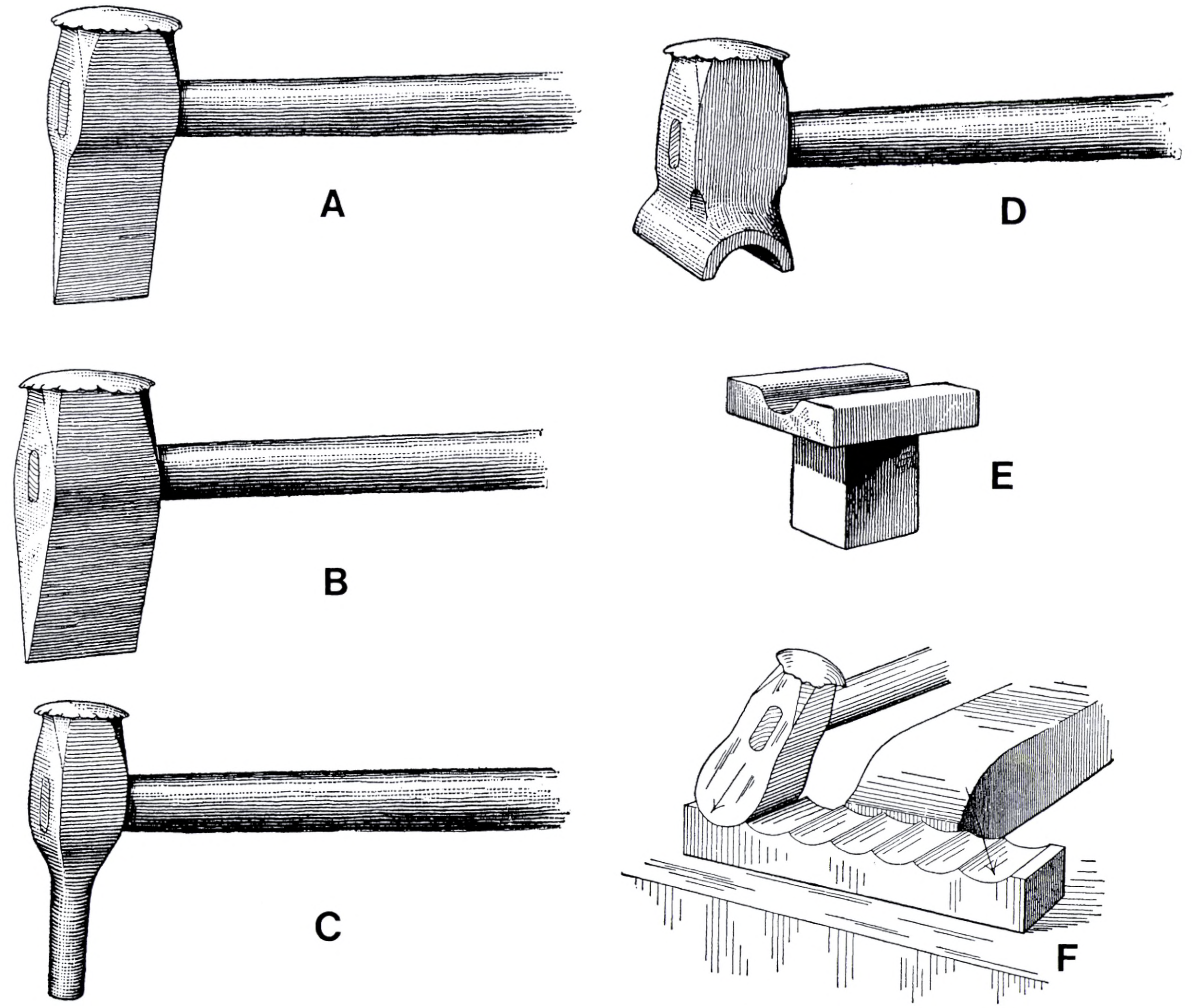


Fig. 287. Important tools of the blacksmith. **A,** Hot chisel. **B,** Cold chisel. **C**, Round punch. **D**, Top swage. **E**, Bottom swage. **F**, The fuller applied to drive the metal outward. The tool is held against the workpiece by a helper, while the blacksmith hits it hard with a heavy hammer. Richardson 1978.

in the smithy. First the shaping at 900-1100°C, where the workpiece is formed by the hammer, is drawn out, spread, upset, provided with holes, bent etc., often applying various helping tools, like the set hammer, the upsetting plate, various swages, and the hardie inserts into the anvil (Richardson 1978; Fleming 1980; Tobiassen 1981; Schmirler 1981). And secondly, the hammer-welding (Danish: essesvejsning), at 1100-1250°C, where two or more pieces are united to a larger composite, or a steel edge is inserted into a tool or a weapon. This operation is usually followed by further shaping operations.

The hot-forged objects would often require filing, grinding, and polishing, and in later times perhaps be provided with threaded ends or a drilled hole. The average smith was expected to be able to offer these

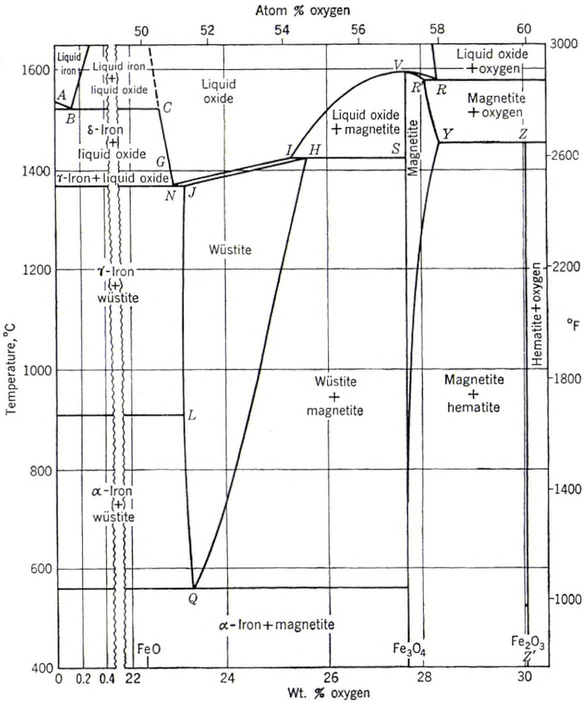


Fig. 288. The iron-oxygen equilibrium diagram. Wüstite forms and is stable above 570°C. It has a significant range of composition. Cooled from, e.g., 1000°C, it may precipitate magnetite, but otherwise it survives as a metastable compound at room temperature. J.Amer.Chem.Soc. 1946 **68**, 798.

services. Less common work was usually performed by a limited number of specialists. This included the hardening of tools (chisels, files, knives etc.), and in much later times, after 1600 A.D., the carburization of wrought iron (cementation) in order to make steel.

The shaping takes place while the object is in the austenitic state. The deformed austenite crystals continuously recrystallize and thus allow the new shapes to develop without the work- piece cracking or becoming harder and stiffer. When the hot-forging is finished, the austenite crystals transform into ferritic-pearlitic or phosphor-ferritic structures, according to the actual iron-carbon-phosphorus composition. In 99% of all cases this equilibrium structure is the final structure of the object. It is often called the normalized structure. Sometimes, however, the structure may be

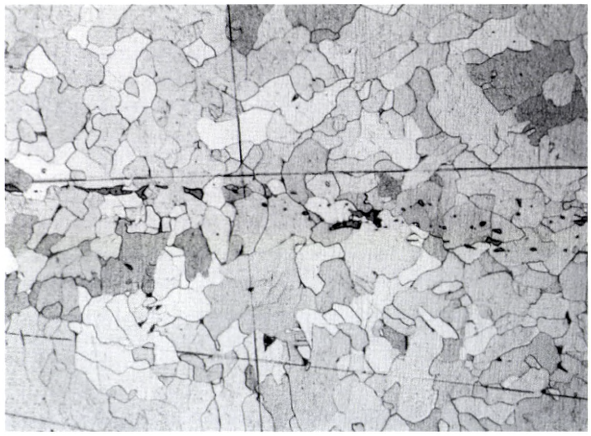


Fig. 289. Joint between two bars of pure iron (Armco iron), hammer-welded without flux. The joint is only visible by a line of minute wüstite inclusions. The metal is continuous across the joint. The original austenite has transformed to equiaxial ferrite grains. PES. Side length 1.3 mm.

altered by subsequent coldwork, recrystallization or hardening.

While this happens to the interior structure, the hot surface is exposed to the air and becomes oxidized. Under equilibrium conditions the surface becomes coated by FeO (wüstite, innermost layer), Fe_3O_4 (mag-

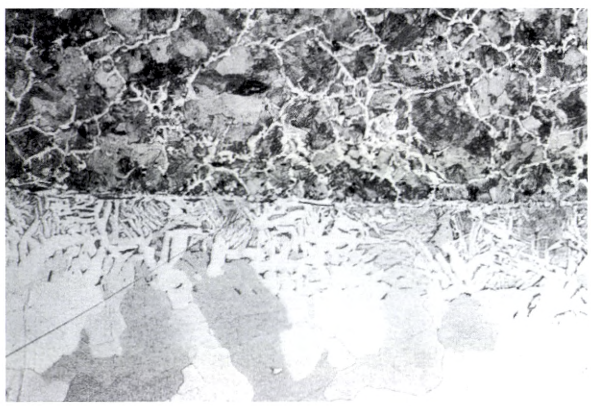


Fig. 290. Joint between Armco iron (below) and 0.55% C-steel (Uddeholm UHB 11). As flux, fine sand was added during the hammer-welding. The hearth was fired with pit coal (nøddekul). PES. Side length 1,3 mm.

Fig. 291. Detail of Fig. 290. Joint between Armco iron (99.8% Fe, <0.02% C, O, Si, Mn, Ni, N) and UHB 11. Tiny ironsilicate slags in the joint. The Armco iron has become slightly carburized to a depth of about 0.2 mm. PES. Side length 0.4 mm.

netite, intermediate layer), and Fe_2O_3 (hematite, exterior layer), the three layers exhibiting a parabolic growth rate. They easily reach a thickness of 0.2 mm in a matter of minutes at high temperature (Modin 1960). During forging, equilibrium conditions do, however, not prevail, so the oxidized layers continuously spall off and new ones start growing. Sometimes the smith will dip his workpiece into cold water in order to remove the oxides by a sudden temperature shock. Since iron is a bad conductor of heat, the workpiece itself is not cooled, provided the dip is short to only influence the surface layers.

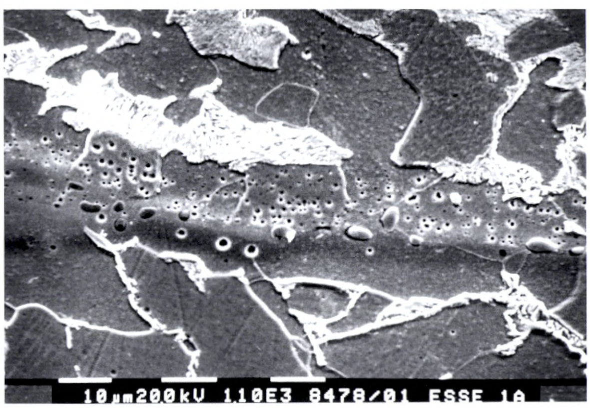


Fig. 292. Detail of the joint Fig. 290. The immediate surroundings of the joint are decarburized. The ferrite on the steel side is rich in etch pits. Further away lie normal pearlitic-ferritic structures. PES. SEM. Scale bar 0.01 mm.

If we assume, as very often was the case with ancient workpieces, that the object was an iron-carbon-phosphorus alloy, surficial iron would in the heat be converted into an oxidic crust, and carbon would burn away as gaseous carbon oxides. This would leave a carbon-depleted and phosphorus-enriched surface. The general feeling of many a modern craftsman, that ancient iron had better corrosion resistance than mod-

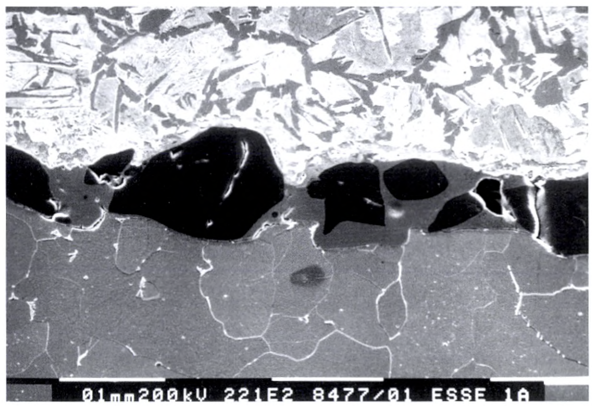


Fig. 293. Detail of the joint Fig. 290. In this part, the joint is imperfect. There is a surplus of quartz grains (black), and the slag (grey) has not been pressed away from the joint by hammering. PES. SEM. Scale bar 0.1 mm.

ern wrought iron and steel, is, no doubt, due to the improved corrosion resistance of this phosphorus-enriched surface. If a hole is drilled through the hot-forged object, the inner part of the hole is unprotected and will suffer from corrosion, relatively to the bulk piece. But if the same hole were punched through the hot workpiece while at forging temperature, the inside would be far better protected against corrosion.

Hammer-welding requires that the two surfaces to be joined are heated to about 1100ºC in a reducing environment, that is they must be properly placed in the charcoal-filled hearth. Under these conditions, most

Fig. 294. Hammer-welded joint from about 1800 A.D. between two iron bars of widely different composition. The joint has become visible due to long exposure to corrosion in the sea. Side length 8 cm.

oxygen is excluded and the surface of the workpiece becomes only covered by a thin layer of wüstite. If the shape of the workpieces allows a close physical contact in the hearth, the blacksmith can feel when the pieces stick together and can remove them and with gentle hammering make them adhere over the entire surface. It is no problem to make a good hammer-welding in this way. The wüstite film becomes shattered and the austenite grains grow around the oxide remains and secure a solid weld. A metallographical examination of an etched cross section of the weld will show metallic continuity of the ferrite grains across the weld. The weld is marked by scattered oxides and often characterized by a diffuse, yellowish, 10-30 μm wide line, caused by an elevated phosphorus content, originating from the phosphorus-enriched two surfaces to be joined.

In European bloomery practice where copper-, nickel-, cobalt-, or arsenic-enriched ores were sometimes used in the iron production, the characteristic diffuse zones along the joints may also be enriched in copper, nickel, cobalt and arsenic. It requires an elec-

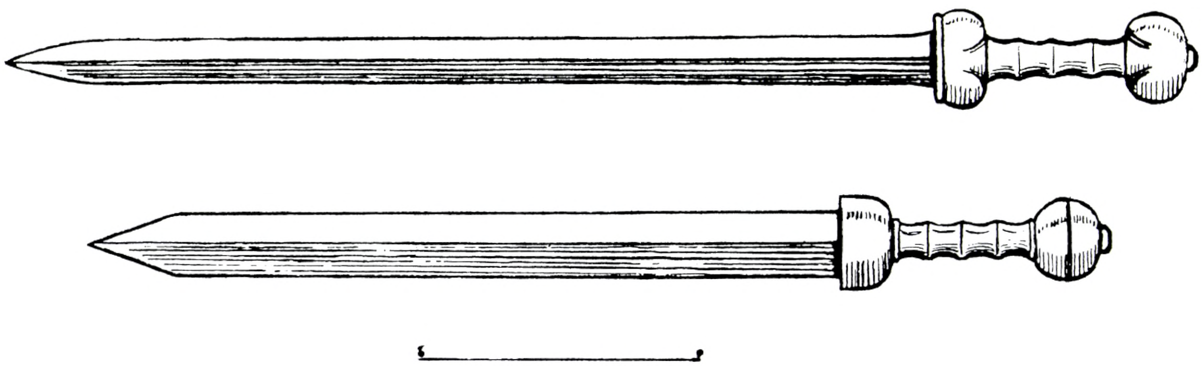


Fig. 295. Roman swords. Top, auxiliary cavalry spatha, reconstructed with a blade from Newstead (on Hadrian's Wall) and a bone hilt from Nijmegen. Bottom, the infantry gladius. Both late 1st or early 2nd centuries. Scale bar 20 cm.

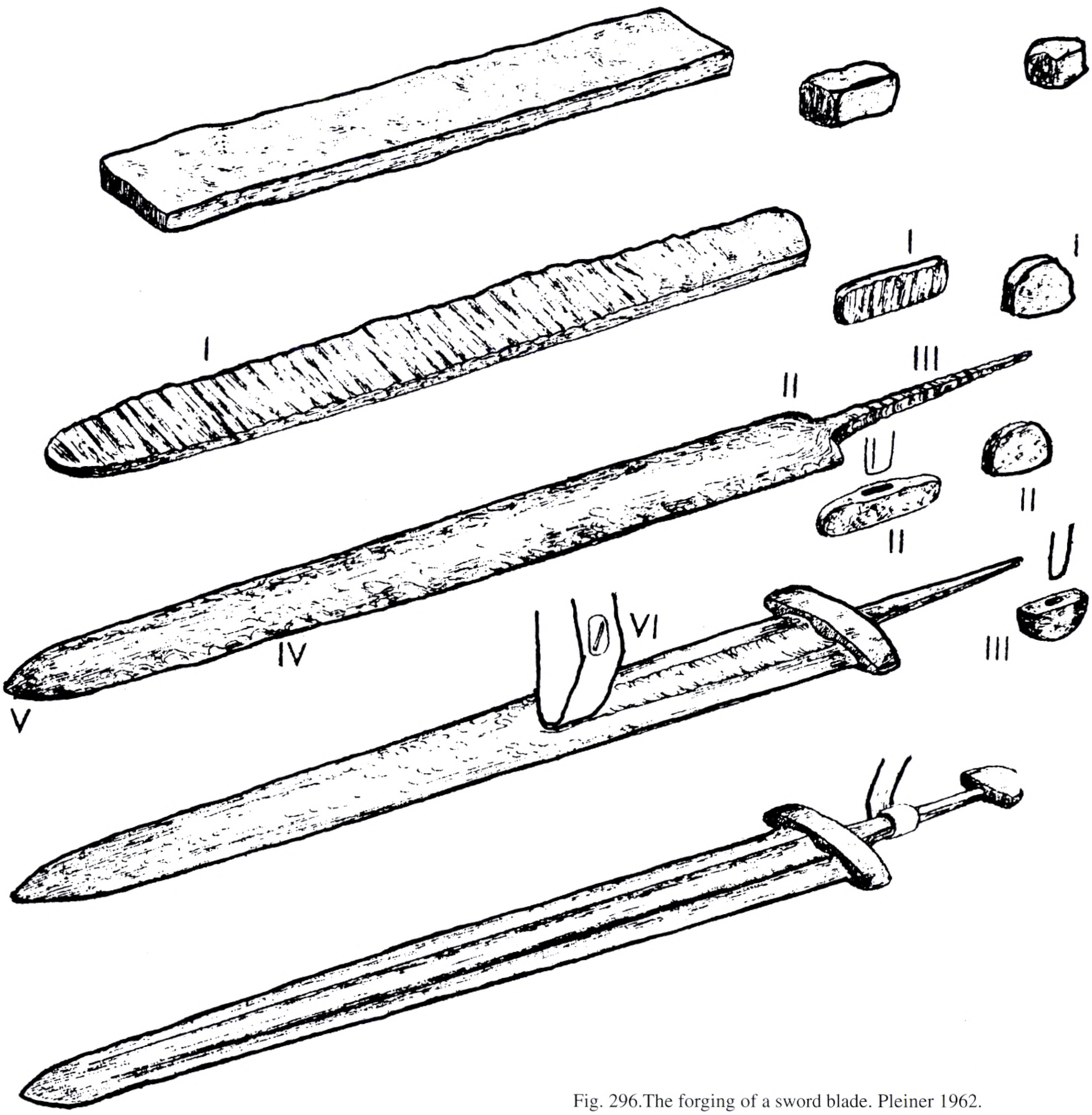


Fig. 296.The forging of a sword blade. Pleiner 1962.

tronmicroprobe examination to set things straight. In most Scandinavian cases the yellow line is, probably, due to phosphorus-enrichment.

The smith will usually improve his chances to establish a sound hammer-weld by throwing fine-grained sand onto his workpieces. Thrown into the charcoal fire towards the objects to be welded, at an early time when they are still relatively cold (900ºC), the sand will react with the surficial wüstite film: $3\ FeO + SiO_2 \rightarrow Fe_2SiO_4 + FeO$, and form a fluid slag (right side of the equation), which in composition is close to the eutectic minimum temperature, 1170ºC.

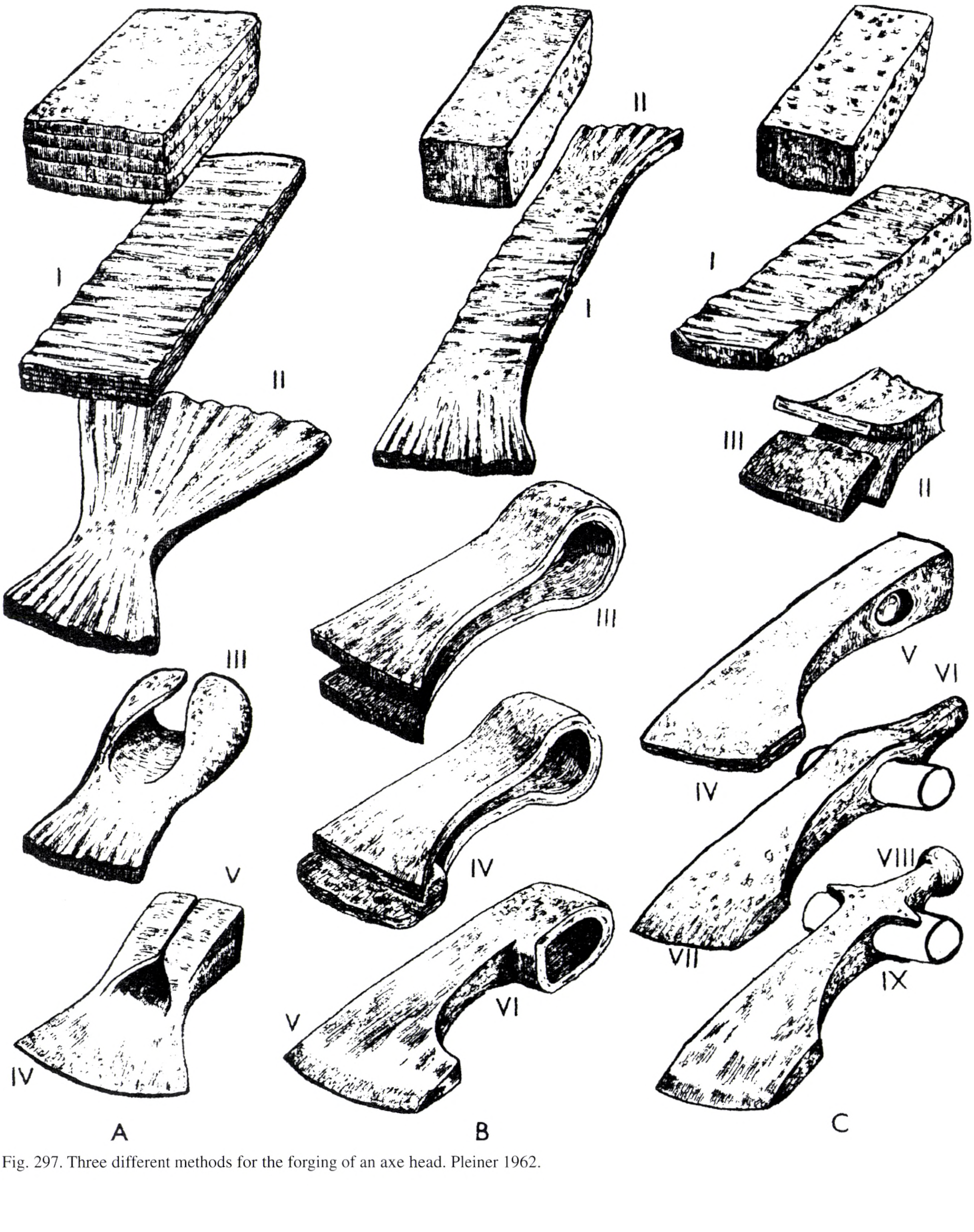


Fig. 297. Three different methods for the forging of an axe head. Pleiner 1962.

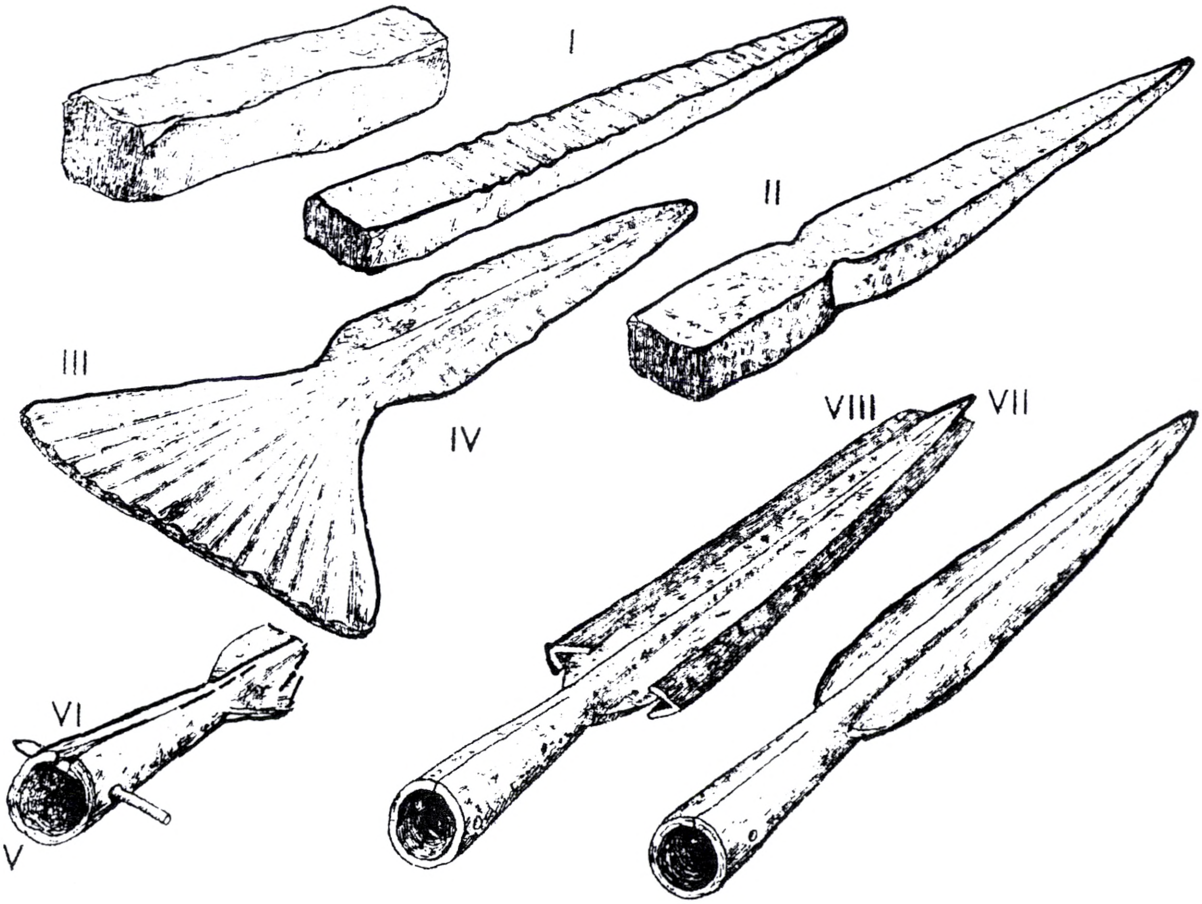


Fig. 298. The forging of a spearhead. Pleiner 1962.

The slag will protect the workpiece against further oxidation, while it is being heated to the correct welding temperature, just above 1200°C. Withdrawing the objects from the hearth, they are first gently tapped against the anvil whereby significant portions of the fluid surface slag run away, and then the two clean surfaces are hammer-welded. According to the routine of the smith and the type and relative size of the workpieces, the welded joint may be 100% sound, or retain more or less of the molten slag, or even display as yet undissolved quartz grains from the sand additions.

In present-day experimental work with the ancient hammer-welding technique, the blacksmith usually applies borax instead of sand to clean the surfaces (Bergland 1990: 140).

As a curiosity, attention may be drawn to the fact that sand/quartz will not react with the surface oxides on hot-forged iron, unless the iron is surrounded by a reducing atmosphere, so that the surface oxide is FeO. In an experiment where a cavity was machined into an iron block and filled with sand, and then exposed to 1200°C in a muffle furnace, no reaction between sand and iron oxides occurred. The iron cavity instead became covered by massive oxide scales of the type FeO, Fe_3O_4 and Fe_2O_3.

It is often stated that hammer-welding is best performed when the iron is taking "Hitz", that is, is burning amid lively ejection of white-glowing sparks. If the workpieces are heated this far, to about 1300°C, the risk is great that part of the iron becomes lost by burning. Only experience will teach the smith the right procedure.

One thing which he must have learned very early in history is to distinguish between unalloyed iron (<0.1% C) and carbon-enriched iron (>0.4% C). When at forging temperature, the first feels soft to the hammer, while the second is harder, the more so as the carbon content increases. It is, in fact, difficult by hammering to reduce a composite of a central bar of carbon steel surrounded by two equally thick bars of iron to a bar where all three layers retain their relative thicknesses. On the contrary, the outermost low-carbon layers yield the most and will finally tend to envelop the hard central layer, which itself may have lost only little of its initial thickness.

The experienced blacksmith would also, inside his usually dimly lit smithy, be able to determine the approximate carbon-and phosphorus content from the forging colours and the tendency to throw sparks. He would use his file on the cold object to estimate the hardness and wear resistance, and he would from the appearance of a fractured surface evaluate the toughness and the grain size. But, of course, he would not have known that it was the elements carbon and phosphorus that were responsible for most of these complex behaviours.

Pattern-welding (Danish, mønstersvejsning)

"The second century A.D. saw the introduction of the pattern-welded long cavalry sword right across Europe and it is clear that this was a prestige weapon. It is debatable whether it was any more efficient than a homogeneous piece of low-carbon steel, but at least it showed its structure on its surface like a piece of hallmarked silver" (Tylecote 1987: 273).

Pattern-welding is a hammer-welding technique in which iron objects of different composition are physically distorted, joined together, forged, polished and etched in order to display characteristic and often beautiful patterns on the surface. On the polished surface little can be seen, but etching with acetic acid, copper sulphate solutions or similar agents causes differential attacks on the components. Phosphorferrite is least attacked and stands bright and silvery, while carbon steel is severely attacked and becomes bluish, brownish or even black, according to the smith's intentions. The ferritic zones display an intermediate attack.

The process has been well described already by Beck (1891: 556), who unfortunately used the word Damaszenerklingen (sword blades from Damascus). In most German literature this term has survived, and various patterns have been named Streifendamast, Winkeldamast, and Rosendamast (Neumann 1927). Since the production method is widely different from that of genuine Damascus swords (Belaiew 1918; Sherby & Wadsworth 1985; Verhoeven & Pendray 1992), the term pattern-welding should be reserved for the method here discussed.

The earliest beginnings of pattern-welding may be observed in a few Celtic swords, but the technique was first developed when it became practised along the Rhine and swept over Europe after 150 A.D.

Ancient references reveal the pride of possessing such costly weapons. One such source is due to the famous historian Cassiodorus (about 490-580 A.D.), who quoted a letter of thanks from the Ostrogothic King Theoderic the Great (456-526 A.D.) to the Vandal King Thrasamund (then in North Africa and Sicily): "You have shown genuine brotherly love in sending me swords, made of iron more costly than gold. The polished blade shines so bright that you can use it as a mirror – In the middle of the blade are beautiful incisions like winding worms, and there are shadows numberless so you believe that the bright metal has been interwoven with many different colours" (Olaus Magnus 1555, Book 7, Chapter 3).

Fig. 299. A cast from a pottery mould, showing a bearded Roman blacksmith with hammer, tongs, and anvil, inserted in an oak block. Housesteads Fort, Hadrian's Wall.

The patterns were, however, not made by incisions or incrustations as believed by Theoderic the Great, and, later, by Engelhardt (1865). The blades were complex twisted structures made by joining rods of different composition, the individual rods themselves being heterogeneous iron-carbon or iron-phosphorus alloys. If the composite were made by the juxtapposition of rods twisted right and left, or from twisted rods afterwards split lengthwise, the most intricate patterns might develop, as one may imagine by imitating the process with coloured plasticine. Several experimental archaeologists and blacksmiths fond of ancient weaponry have experimented with pattern-welding and successfully recreated many old patterns and also created imaginative new ones (Liestøl 1951; Böhne 1963; 1969; Anteins 1968; Denig 1985; Bergland 1990; Andersen & Andersen 1991; Thomsen 1992).

Scandinavian, British and German smiths compete in the manufacturing of pattern-welded knives and swords, and the products are displayed (and sold) on annual markets in, e.g., Dortmund, York, Elverum, Seljord and Hamar. The author is the proud owner of a unique hammer-welded knife, forged from two layers of the iron meteorite Agpalilik from Greenland (Chapter 1) and a central layer of a modern steel. When hardened, polished and etched, the distorted Widmanstätten structure stands in beautiful contrast to the martensite hardened steel edge. The author cooperated with the professional and enthusiastic blacksmith Poul Strange, Viby Sjælland, in producing this and several other experimental knife- and dagger blades in the late 1980s.

The ancient swords had ornamental hilts, often of silver-clad wood, or horn with silver inlays.The head of the sword was provided with a pommel of iron, niello-inlaid bronze, cast and gilt silver, or ivory, and the scabbards were highly decorated (Jørgensen & Petersen 2003). It has been estimated that it must have taken at least 70 hours of smithing work to forge the blade and make the ornamented hilt (Anstee & Biek 1961).

Many blades were hall-marked or stamped, usually with names in Roman capital letters, such as CRISSIM MA, manufactured by Crissim. In the Roman Iron Age the insignia of Mars and Victory were often seen as incrustations in bronze, brass or gold (Rosenqvist 1968). The inscriptions and decorations on the sword blades are a main indication that the blades were manufactured under Roman control, probably mainly in the northern parts of the Limes. The blades may have been exported to Norway and Swe-

Fig. 300. Reconstruction of a Roman iron helmet, about 100 A.D. Based upon the Augsburg helmet and Colchester fragments. Robinson & Embleton 1985.

den where they were provided with hilts, scabbards and bandoleers of Nordic types (Ilkjær 2000).

The manufactures, fabricae, were often part of the legionary camps, situated at the side of the praetorium. Known fabricae were located in the camps of Wiesbaden, Mainz, Trier, Lorch, Niederbieber, Köln and Neuss; and in England, at Benwell and Housesteads (MacMullen 1960).

Corstopitum on Hadrian's Wall, 25 km west of Newcastle, the modern Corbridge, was a town which grew up to supply the neighbouring Roman fort. It developed into a supply base with a large civilian population with their furnaces and hearths and smithies, serving

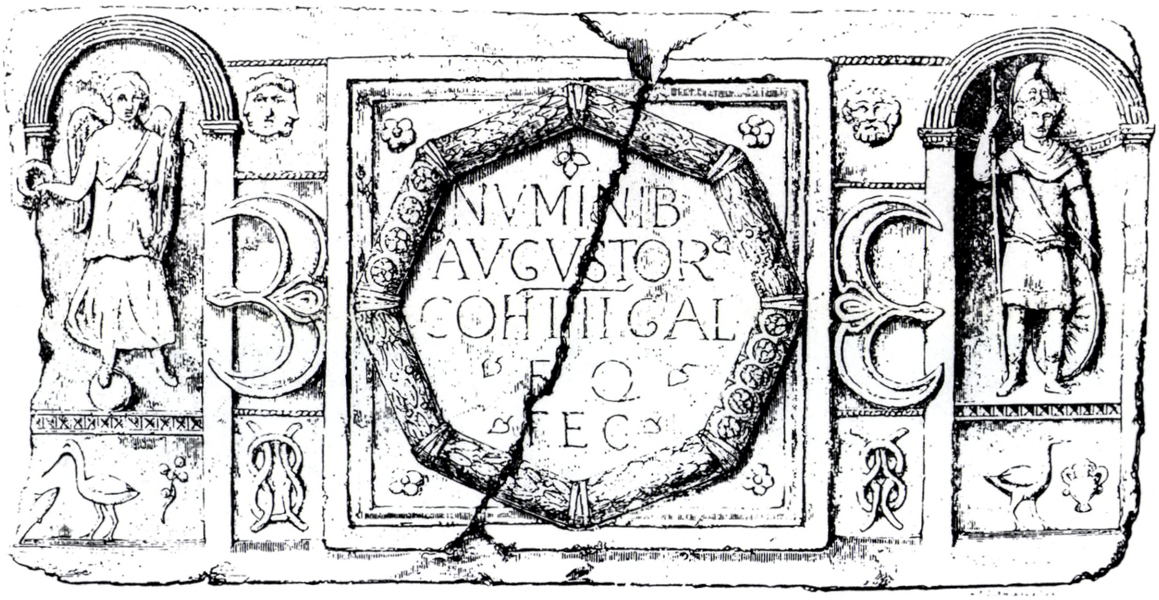


Fig. 301. The typical insignia of the Roman army on a sculptured memorial slab from Hadrian's Wall. Left, Victory flying through space on a globe, and right, the war god Mars in panoply. Size 140x70 cm. Graham 1979: 194.

Fig. 302. Section through Nydam sword 4154. Phosphorus-rich (7% P_2O_5) slag inclusion in the phosphorus-rich part of the sword, analysis 4154 P. Immiscible drops (black) in the slag, caused by the high P-content. PS. SEM. Scale bar 0.01 mm.

the army's needs. Corbridge was also the centre of a rich agricultural area, and nearby mines of coal, lead and iron were exploited (Graham 1979). In one house of the west Compound there were several hearths, iron slags, scalings, twenty-three javelinheads, a spearhead, seventeen arrowheads, and knives, nails, spikes and cramps, some unfinished. The small museum at Corbridge has a remarkable collection of civilian and military material and a fine series of sculptured and inscribed stones, including the famous Corbridge Lion. Just north of Corbridge was found a memorial stone to the Fourth Cohort of Gaul, displaying the typical insignia of the Roman army, Victoria and Mars, Fig. 301.

The iron bars for the fabricae along the Rhine may have come from bloomeries in Siegerland and Sauerland. It is also possible that a major part of the simpler iron came from the "Polish" Biskupice and Holy Cross Mountains and from the "Danish" western Jutland districts. These simpler iron qualities were unfit for steel production, but excellent for numberless utilitarian things. It would be interesting to study the slag inclusions in contemporary artefacts and compare the results to what has been here discussed.

In the Siegerland and Ruhr districts there are reports of manganese-copper-enriched ores, which are depleted of phosphorus. These ores have been used in bloomeries since 500 B.C. (Gilles 1936), and the manufacture would be characterized by slag inclusions which are much different from the above-mentioned Polish-Danish objects. Right up to the 19th century the high- grade steel blades from Solingen and Remscheid were famous. It is highly probable that the ancient weapons of good-quality steel were produced on the basis of these ores. If from Roman officials there were a ban on export of these fine sword blades, it was of little avail. The blades were so highly appreciated that they somehow found their way to the peoples outside the Roman Limes, not least to Scandinavia.

The war booty of Nydam contained 106 swords, of which some 90 were pattern-welded. Most of these are today in the Gottorp Museum, Slesvig, from where Schürman (1959) borrowed three sword fragments. Sword C was a rather simple blade with about 0.5% C, and it was well-hardened to values from 575 to 937 HV. Sword B apparently had a central pattern-welded section (Fig. 277, Type 4), but the simultaneous presence of 0.4% C and 0.2% P had prevented any hardening, and resulted in phosphorferritic and pearlitic structures of moderate hardness, 156-235 HV.

Sword A, of Type 5, was rather complex, and displayed hardnesses, irregularly going from 186 to 937. Evidently a water quench had been performed, but

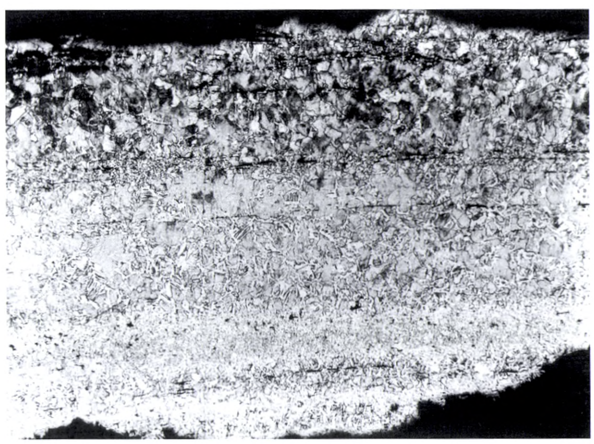


Fig. 303. Full section through the corroded Nydam sword No. 62. Top and center, carbon-rich steel, 146-195 HV. Below, ternary Fe-C-P structure. PES. Side length 1.5 mm.

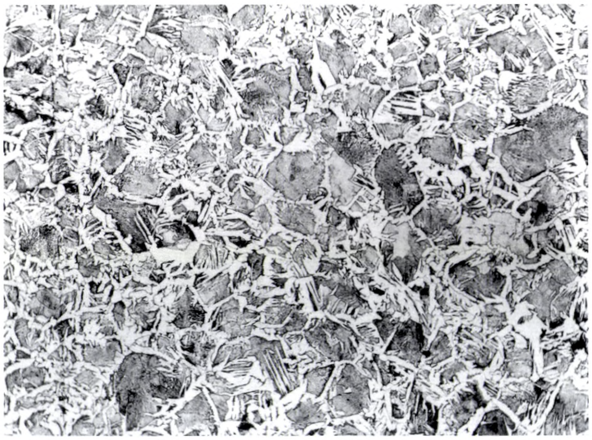


Fig. 304. Detail of Fig. 303, showing phosphorus-free ferritic-pearlitic Widmanstätten structure, HV 146-195. PES. Side length 1.0 mm.

with unpredictable results. These studies allowed Schürmann & Schroer (1959) to calculate several sections through the ternary iron-carbon-phosphorus equilibrium diagram, and they showed that phosphorus-rich iron crystals were much depleted of carbon, and vice versa, carbon-enriched crystals in equilibrium were much depleted of phosphorus. These results have later been confirmed and refined in the thermodynamically calculated ternary Fe-C-P diagrams, Thermocalc.

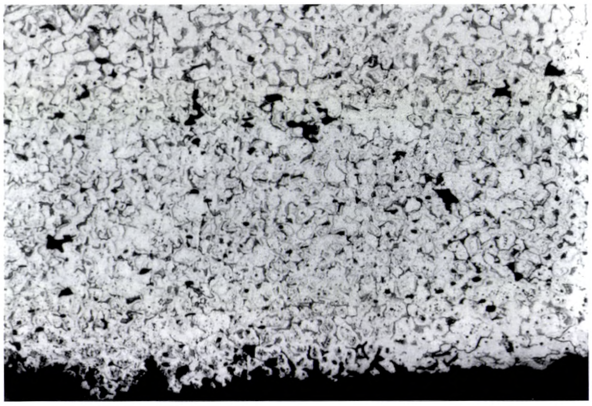


Fig. 305. Detail of Fig. 303, showing ternary iron-carbon (0.2%) – phosphorus (0.6%) structure. HV 192-237. PES. Side length 0.7 mm.

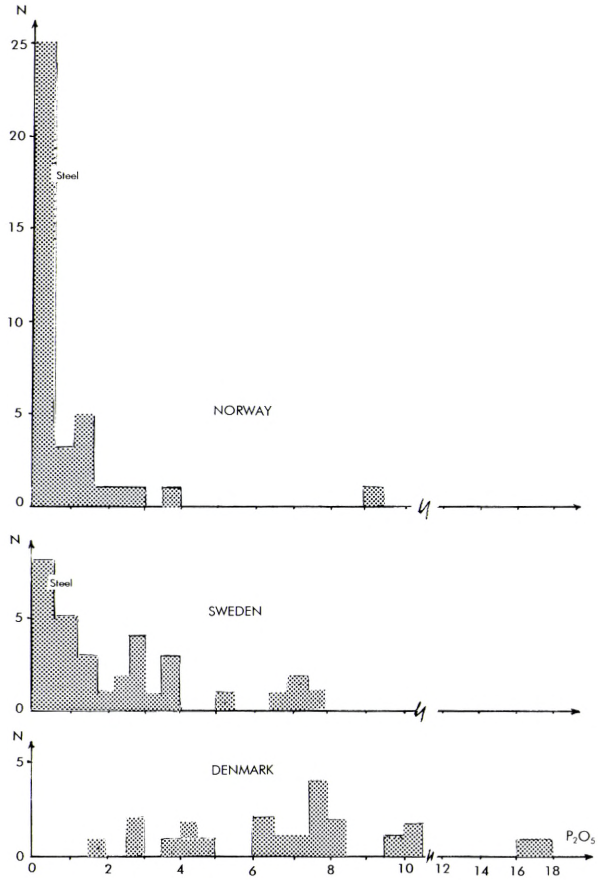


Fig. 306. The P_2O_5-content of slag inclusions in iron-manufacture from Norway, Sweden and Denmark. There is a very low P_2O_5-content in the Norwegian and Swedish steel objects. Certain unique Tommarp objects (Sweden) are phosphorus-rich, otherwise a high phosphorus content is characteristic of Denmark. The phosphorus content of the metal phase is generally below 10% of the P_2O_5-content of the slag inclusions.

Thomsen (1992) borrowed a number of other Nydam sword fragments for metallographic studies. By the kind cooperation of Robert Thomsen (1920-1995), the present author had the opportunity to reexamine some of these swords, in order to analyse the slag inclusions and determine the Vickers hardness (200 g load). All the examined eight blades are fragments, so the full length is undetermined. The width varied from 32 to 55 mm, and the maximum preserved thickness from 1.3 to 4.7 mm.

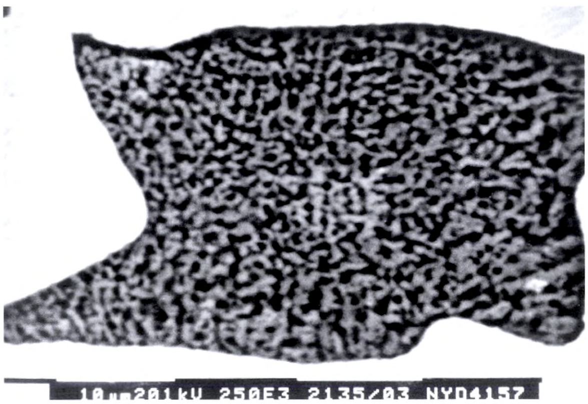


Fig. 307. Section throughh the Nydam sword 4157. The slag inclusion contains two immiscible phases, caused by a high P_2O_5-content, analysis 4157 P. Phosphorus is mainly located in the bright phase. PS. SEM. Scale bar 0.01 mm.

Nydam No. 43. The 36 mm wide blade is severely corroded. It is apparently of Type 4 (Fig. 277), manufactured from twisted rods of ferritic-pearlitic steel and of phosphorferritic (0.2% P) material. The edges are ferritic-pearlitic with Widmanstätten structure and 0.4-0.6% C, without phosphorus, and with excellent hardnesses of 206-255 HV. Martensite quenching has not been attempted. All slag inclusions are small and glassy. They display a very high manganese content and have some chromium oxide in solid solution.

Nydam No. 4154. The cross section is 40 mm wide and shows a beautiful pattern-welded structure of Type 4, where the central portion is manufactured from rods with 0.4-0.6% C and softer rods with up to 0.5% P and less than 0.1% C. The 10 mm wide edges on both sides are rather homogeneous carbon steel that etches to a smooth, pattern-less surface. They display extremely fine-grained ferritic-martensitic structures, up to 435 HV, proving that edge-hardening has been attempted. Exactly how is not easy to explain. One possibility is that the austenite-heated edge was rapidly cooled by being drawn through wet clay. The slag inclusions are glassy, but of two compositions. In the pearlitic-ferritic zones they have the analysis 4154 C, in the phosphorferritic zones the analysis 4154 P, Table 11.2.

Nydam, National Museum, No. 62. The 40 mm wide and only 1.3 mm thick blade has lost significant thickness by corrosion and is difficult to assign to type. It is irregularly laminated, but ferritic-pearlitic

Table 11.2. SEM-EDAX analyses of slag inclusions in eight swords from Nydam

No.	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	Cr_2O_3	SO_3	Σ	F	K
43 C	45.1	4.3	21.8	0	11.2	10.7	3.0	2.3	0.4	0.1	1.1	100	4.21	1.30
4154 C	55.9	5.3	8.2	0	10.5	12.4	3.5	3.4	0.6	0.1	0.1	100	4.51	1.04
4154 P	38.6	37.1	0.8	6.9	5.3	7.4	1.6	0.9	0.5	-	0.9	100	5.21	1.78
62 C	58.2	10.2	1.5	0	10.8	13.2	3.3	2.1	0.7	-	-	100	4.41	1.57
62 P	36.7	42.7	2.7	3.1	5.1	6.8	0.4	2.2	0.3	-	-	100	5.40	0.18
4157 C	56.0	3.8	4.1	0	5.4	20.2	5.0	4.5	1.0	-	-	100	2.77	1.10
4157 P	31.7	55.2	0.4	3.3	2.0	4.9	1.0	0.6	0.3	-	0.5	100	6.47	1.67
5409 C	63.5	8.8	2.1	0	7.9	11.6	4.2	1.3	0.5	-	0.1	100	5.47	3.23
5409 P	31.0	54.9	0.1	6.2	1.8	4.5	0.5	0.5	0.2	-	0.3	100	6.89	1.00
41 C	64.6	8.2	2.5	0	10.0	8.9	3.1	2.1	0.5	-	0.1	100	7.26	1.48
41 P	29.0	44.3	8.8	3.3	5.5	5.7	1.4	1.3	0.3	-	0.4	100	5.09	1.08
40 P	39.4	38.3	0.9	1.7	10.1	5.5	2.8	0.9	0.3	-	0.1	100	7.16	3.11
21	29.2	59.2	0.4	1.3	4.4	3.6	0.8	0.9	0.2	-	-	100	8.11	0.89

K = K_2O/MgO

structures in Widmanstätten-pattern constitute a major part, HV 146-183-185-195. Ternary Fe-C-P zones with 0.3-1.0% P and 0.2% C also occur, HV 192-199-202-209-237. The hard, ternary zones are mainly to be found along the edges. The slag inclusions are glassy. Inside the ternary zones the slags contain up to 10% P_2O_5, analysis 62 P.

Nydam No. 4157 is in cross section very similar to No. 4154, of Type 4, but the blade fragment is only 32 mm wide. In the central part, ferritic-pearlitic mixtures in Widmanstätten development (0.4-0.5% C, HV 196-229) alternate with fine-grained ternary Fe-C-P structures (0.3-0.4% P, 0.2% C, HV 196-257). The 5 mm wide edges consist of extremely fine-grained (10-20 µm) pearlitic and martensitic structures with hardnesses up to 676 HV. Evidently an edge- quenching similar to that observed on No. 4154 has taken place, with good results.

Thomsen (1992: 292) suggested that Nos. 4157 and 4154 were fragments of the same sword. A comparison of the slag analyses and of the blade dimensions does not support this suggestion.

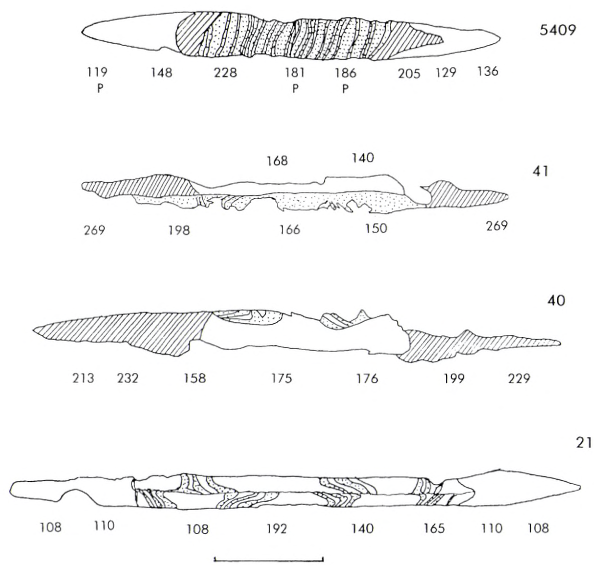


Fig. 309. Cross sections of four swords from Nydam, Nos. 5409, 41, 40, and 21. Vickers hardness at 200 g load. Adapted from Thomsen 1992. Scale bar 10 mm.

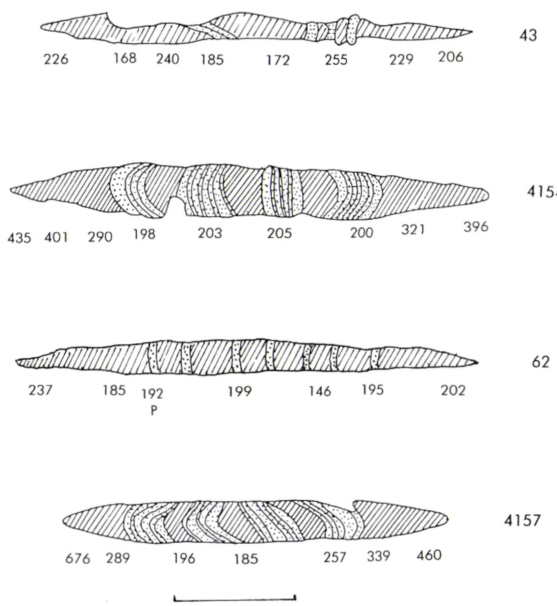


Fig. 308. Cross sections of four swords from Nydam, Nos. 43, 4154, 62, and 4157. Vickers hardness at 200 g load. Hatched, carbon-rich parts. Dotted, phosphorus-rich parts. White, ferritic parts. Scale bar 10 mm. Adapted from Thomsen 1992.

Nydam No. 5409. The blade is 40 mm wide and displays a pattern-welded texture of Type 4, not much different from the preceding one. However, the big difference lies in the edges, which here consist of phosphorferrite (0.2-0.3% P) with rather low hardness, 119-148 HV. The central part is manufactured from rods with alternating high phosphorus content (0.5-0.6% P) and medium carbon steel (0.4-0.5% C), resulting in indistinct, but bright phosphorferrite and well-resolved, but dull Widmanstätten ferrite-pearlite. The macroetched section, Fig. 310, discloses the important step in manufacturing when the forged, laminated blanket was doubled back on itself and further forged. The fayalite-glass inclusions in the phosphorus-rich zones contain up to 10% P_2O_5, and average out at 6.2%. In the Widmanstätten areas the slags are homogeneous glass without phosphorus.

Nydam No. 41 is a severely corroded blade, 42 mm wide, and now reduced to a thickness of 2-3 mm. It is apparently of Type 5, where the central parts are asymmetric, i.e. the blade has two sides which show different patterns. The homogeneous edges have very fine-grained (about 5 μm) 30% ferritic-70% pearlitic structures of high hardness, 255-270 HV. The slag inclusions, No. 41 C, are phosphorus-free, but contain some manganese, allowing for a fine steel structure in the edges. The central parts display various zones of ternary Fe-C-P alloys, where the ratio of carbon to phosphorus ranges from 0.1 to 1. There is up to 4.5% P_2O_5 in the slag inclusions and up to 0.4% P in the adjacent metal. Even if the average manganese content of the slag is as high as 8.8%, the presence of much phosphorus has prevented the formation of a steel structure. The hardness range,

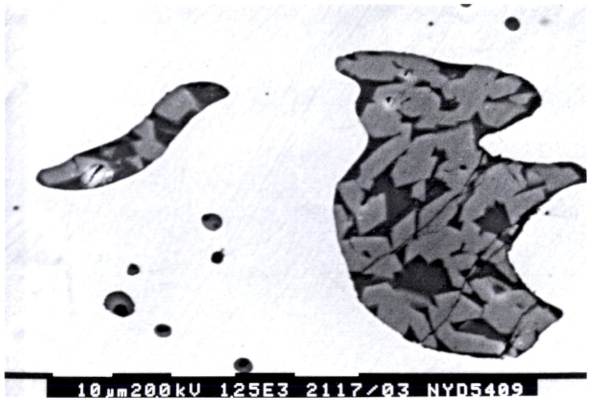


Fig. 311. Slag inclusions in the phosphorus-rich zones in the middle part of Nydam sword 5409, analysis 5409 P. Fragmented fayalite laths in phosphorus-rich glass. PS. SEM. Scale bar 0.01 mm.

Fig. 310. Ground, polished and etched 40 mm wide sword blade, Nydam 5409. The rods of the central portion have been bent and folded back on themselves. The edges have been welded on later. Thomsen 1992.

140-168 HV, is therefore much lower here than in the edges.

Nydam No. 40 is a severely corroded blade, 49 mm wide, and now reduced to a thickness of 3-4 mm. It resembles No. 41 pretty much and is apparently of the asymmetric Type 5. The homogeneous edges display fine-grained pearlitic-ferritic structures of moderate hardness, 199-232 HV, while the central parts are ferritic-pearlitic and have lower hardness, 158-176 HV. There are indications of a little phosphorus in solid solution locally (-0.15%P), but the P_2O_5- and MnO-content of the slag inclusions is generally rather low. Thomsen (1992: 297) suggested that Nos. 40 and 41 were parts of the same sword. This can hardly be the case, since the slag inclusions and the dimensions are incommensurable.

Nydam No. 21. The very wide blade, 55 mm, is not of high quality, either in manufacturing, or in hardness. It is probably an attempt at making a Type 5 sword, but the pattern is very irregular. The edges are almost pure ferritic grains of medium size (50-100 μm) and low hardness, 108-110 HV. The central parts display alternating zones of rather pure ferrite (108 HV) and heterogeneous phosphorferrite with up to 0.3% P in solid solution (140-192HV). Locally there are precipitates of phosphide needles. The slag inclusions are mostly three-phased wüstite-fayalite-glasses

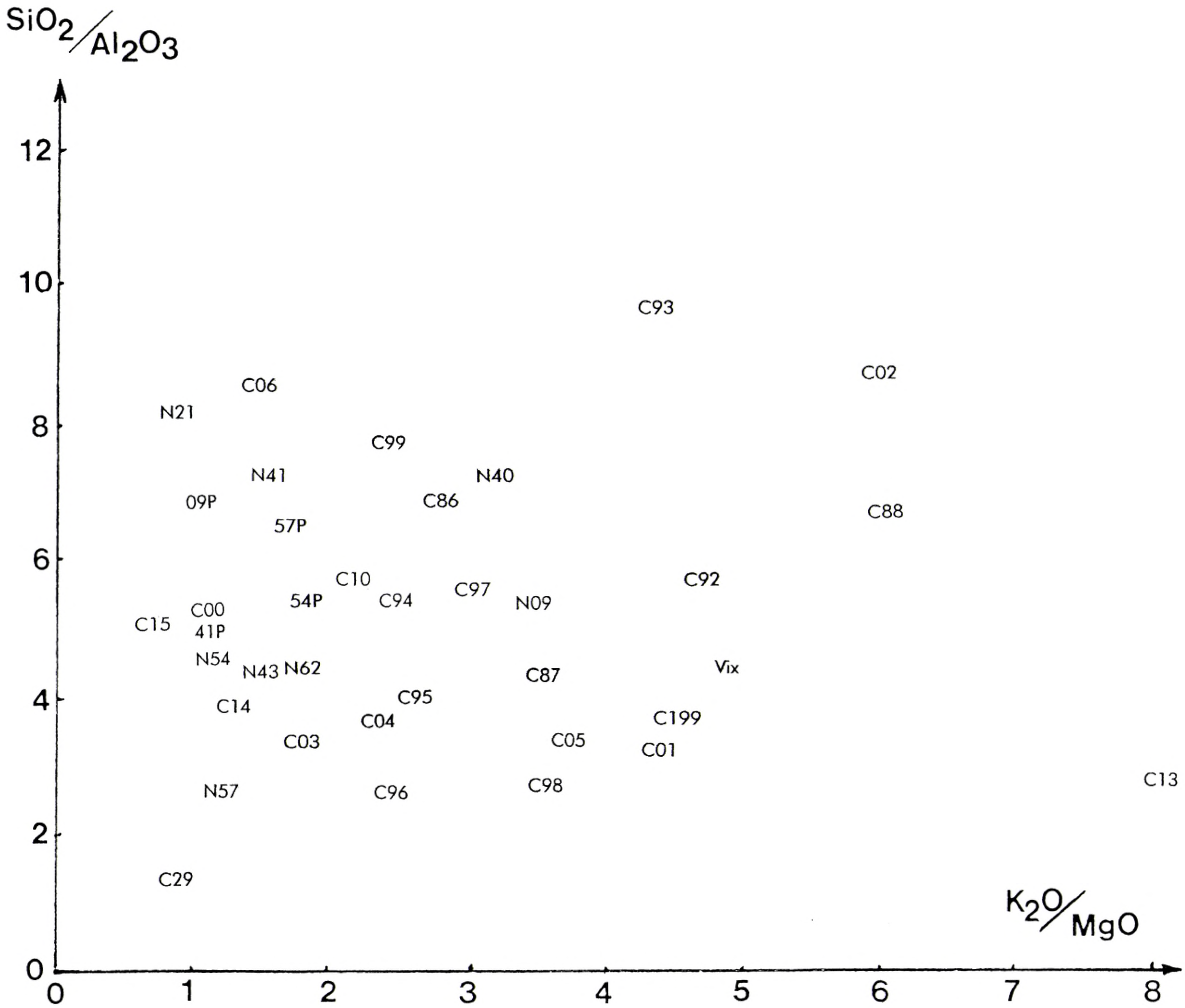


Fig. 312. Plot of slag inclusions in Celtic swords, marked **C**, and Nydam swords, marked **N** and **P**. The numbers refer to the Tables 5.1 and 11.2. Compare also Figs. 253 and 366.

(analysis 21, Table 11.2). The fayalite has 3% CaO in the molecule, while the glass phase is much richer, with up to 15%. No. 21 has the softest cutting edge of all the swords examined.

In summary, the eight pattern-welded swords from Nydam present a great variety in terms of manufacturing, width and quality. All are surprisingly free of slag inclusions and display successful joining of the various phosphorus-and carbon alloyed rods. The 5-10 mm wide edges are hammer-welded to the bulk of the sword and stand out as rather smooth and patternless rims. Two of the eight swords, 4154 and 4157, have excellent martensite-hardened edges with HV_{max} 676, while four others have acceptable hardnesses due to unhardened pearlitic-ferritic structures (206-269 HV). The last two, Nos.5409 and 21, were rather miserable, displaying ferritic edges of very low hardness, 108-129 HV. They were no better iron than an average nail.

While the macrostructure of the pattern-welded swords is conspicuous, the microstructure is utterly complex and sometimes very difficult to interpret, because several different materials have been kneaded together and repeatedly heated to forging temperatures, without reaching equilibrium at any time. Also the slag inclusion analytical method must here stand its ultimate test, partly because the slags are few and small, and partly because it is necessary to distinguish between the important remains of the production slags, and the later introduced inclusions of forge-welding slags. These last ones are, however, usually recognizable by being rich in SiO_2 (>66%) and low in CaO.

It is difficult to maintain that the pattern-welded sword was just a prestige weapon (Tylecote 1987:273). The examination shows that it was indeed of high coherence and quality and sometimes was hardened (the Vimose sword) or had martensite-hardened edges over a tough nucleus. It would be difficult to understand that a company of warriors, in casu Nydam, would enter serious combat, armed with 90 pattern-welded and 16 average swords, if they didn't appreciate the combat-value of their pattern-welded swords.

On the other hand it is somewhat surprising that these clever sword smiths never introduced the method of a correct water-quench followed by tempering at a few hundred degrees. This procedure would have removed any brittleness, and have resulted in weapons of sufficient hardness and ductility for combat purposes.

Pattern-welding was apparently exclusively applied to sword and lancehead production (Thomsen 1971d). Pattern-welded lanceheads from Norway were already reported by Rygh (1885, Figs. 517, 522). Knives and daggers have not been reported. The pattern-welded weapons have mainly been found in Germany, England and Scandinavia, while Italy and the Mediterranean countries are notably poor in them. By far the largest concentration happens to be in Denmark in association with the war booty sacrifices. Almost all are of the spatha type, the cavalry sword, being usually 70-80 cm long, including the hilt. Weights are rarely reported, but the author had the opportunity to weigh 11 whole swords, shortly after they had been excavated during the Illerup Ådal campaign. They weighed 830, 810 (broken into two), 800, 760 (with Mars figure), 740, 670. 670, 640, 560, 540 and 530 grams. The newest survey of the war booty sacrifices has been presented by Ilkjær (2003).

Chapter 12
Iron and Steel in Scandinavia 600-1200 A.D.

The weapon must the man
in the field not forget,
not move from it a foot.
Nobody knows
where on his way
he will be wanting his spear.

Havamal, v.38

Denmark

The formation of the state we today call Denmark was a cultural and military process which took centuries. In the history books presently used in the Danish school system the kingdom starts with King Gorm and his son Harald Bluetooth, who about 975 inaugurated the decorated Jelling stone in memory of his father Gorm and his mother Thyra. The proud signature of the runic inscription boasts: "That Harald who won all Denmark and Norway and christened the Danes".

But the Danes and a rudimentary Danish realm had at that time already existed about 500 years. Glimpses of the early days come from Jordanes (551 A.D., §23), who says that the Danes (about 500 A.D.) conquered the Herules and took their territory in possession. And from Procopius (555 A.D.), who tells about a group of Herules who were returning to their ancient home in the North now occupied by the Danes. This ancient "state" may be interpreted to have included Jutland and the islands of Fyn and Sjælland, and probably Halland and Scania east of Øresund (Markvad 2004).

The Danes and the Saxons were early in close contact, as we learn from the poem of the French bishop Venantius Fortunatus (died 609 A.D. in Poitiers), who mentions their combined raid on Friesland in about 565 A.D.

The Danes and the Frisians play significant roles in the Anglo-Saxon poem Beowulf, the backbone of which may refer to historic events in the 5th and 6th centuries (Klaeber 1950; Haarder 1975; Heaney 1999). One event, in particular, seems fixed, namely the defeat and fall of the Geatic King Hygelac when raiding the Frankish coast in about 515 A.D. (Grundtvig 1820; Klaeber 1950). This daring raid, from Vester Götland to northern France, was undertaken in open rowing boats, like the Nydam boat or the Sutton Hoo boat (Bruce-Mitford 1979), and testifies to the long range from where war booty might be carried.

Land defence against Saxons and Franks was established in the 7th and 8th centuries, when earthen walls and wooden ramparts were built across the root of Jutland. Dendrochronological examinations of the ancient timber of Danevirke provide us with the date 737 A.D. for early parts of the ten-kilometer-long fortification west of Slesvig (H.H.Andersen 1977; 2004). In 726 A.D. a channel across the island of Samsø, The Kanhavekanal, was constructed in order to control in-

Fig. 313. Six situations from the Vølsunge saga. Bottom right, Regin's first attempt at forging a sword for Sigurd. A helper operates the double bellows for the hearth in the background. Middle, Sigurd tests the sword, but it breaks into two pieces when he tries to cleave the anvil. Top, Sigurd, in his pit, stabs the dragon Fafner with his new sword, Gram. The swords are apparently marked as pattern-welded. Bottom left, heart-blood from the slain Fafner makes Sigurd understand the song of the bird in the tree. Above, his horse Grane. At the top the deceitful Regin is killed by Sigurd. Wood carving on the 12th century portal of Hylestad Church, Setesdal, Aust-Agder. Courtesy Oldsakmuseet, Oslo.

ternal Danish waters. To organize such impressive works there must have been an undisputed central power already at this time. In 782 A.D. the Saxon King Widukind sought asylum in Denmark during his resistance to the Frankish Emperor Charles the Great. Somewhat later the Danish King Hemming, in 811 A.D., signed a peace treaty with the Emperor. The meeting took place at the river Ejder, which for a long time to come was to be respected as the southern limit of the Danish realm.

The interest in the pattern-welded sword continued through the 6th and 7th centuries when Visigoths, Longobards and Franks were at the height of their powers after occupying the ruins of the Roman empire. In Swedish aristocratic graves from Vendel and Valsgärde, as well as in numerous Gotlandic graves, the swords are of the pattern-welded types. These were probably still manufactured in workshops along the Rhine and possibly also in the Walloonian provinces, Liège and Namur.

In the Viking Age the patterns became simpler, except perhaps in the manufacture of lance- and spearheads, where the old technique survived for a long time (Lorange 1889). In the new technique the sword was an untwisted laminate, consisting of a carbon-steel squeezed between two softer layers. After final forging, filing and grinding the carbon-steel would constitute the edges of the double-edged sword, and the flat sides would display no patterns, and there was no reason for an etch. On the Bayeux tapestry, celebrating the Normannic invasion of England in 1066 A.D., the attacking Normans are mainly armed with double-edged swords – some of the weapons appear broken in the margins – while the Angli are shown fighting with lances and long axes, after the Norwegian fashion.

The swords appear in the saga literature and in ancient lays under a wealth of names (Falk 1914; Drachmann 1967). It is remarkable that almost none of the famous, named swords are said to have been forged in Iceland, Norway, Denmark or Sweden. Apparently they came from abroad, but precise information has not survived. An element of secrecy and well-guarded recipes, and perhaps even deceitful misleading information, protected the cunning blacksmiths.

If you wanted a perfect weapon you somehow had to get into contact with the dwarfs. King Svaferlame commanded the dwarfs, Dylin and Dvalin, to manufacture the sword Tyrfing, and other dwarfs produced the sword Gunnlogi for Sigurd the Silent. Sometimes the swords were precious heirlooms of known descendence, or they had to be unearthed from the graves of famous warriors, as when Midfjords-Skegge opened Rolf Krake's tomb at Lejre to get into possession of his sword Skøvning (Drachmann 1967). Uffe, in his decisive fight with Saxon opponents, attributed his victory to the sword Skrep, long buried in the earth by his father Vermund. The blind Vermund recognized his precious sword from its clang when Uffe hit his enemies (Saxo, Book 4).

The only thing we can learn from the ancient texts is that the good weapons were not manufactured in Denmark or even Scandinavia, but had to be acquired elsewhere. Perhaps the dwarfs, including the most famous of all, Vølund, were located along the lower Rhine and in the forests of Siegerland (iron-and steel bars) and Walloonia (phosphorus-rich ores). This is more or less the same area where the main events in the mediaeval Nibelungenlied took place (e.g. Stodte 1956; Hatto 1970; Mejdahl 2004). The hero Sigurd/Siegfried had his sword Gram/Balmung manufactured by his fosterfather, the dwarf Regin/Mimer. However, Mimer's workshop was by the Austrian poet placed as far away as in impenetrable forests (!) in distant Iceland.

Surprisingly enough, there is in the period 700-1200, and in fact up to about 1300 A.D., very little evidence of iron production in Jutland or on the Danish islands (Buchwald & Voss 1992). It has been assumed that the furnaces were small, without slag pits, and therefore impossible to identify in the Danish cultivated landscape. But another explanation now seems more plausible. The iron production took place elsewhere, in Germany, Norway, Halland, Scania, Småland, and central Sweden. From these areas with their excellent ores and extensive forests, iron and steel bars, and finished objects were imported into Denmark. The following analyses of iron objects excavated from Danish graves, forts and settlements will bring home this viewpoint.

Excavations since 1970 have shown that Ribe not only is the oldest city in Denmark, but the oldest in Scandinavia (Olsen 1975 b). The market place on the northern side of Ribe Å was founded between 700 and 710 A.D. and soon developed into an important all-year city (Stig Jensen 1991 a, b; 1992). In about 860 A.D. the missionary Ansgar visited the city, and about 948 A.D. it became a bishop's seat. The present cathedral was built in the second half of the 13^{th} century from ashlars of volcanic tuff, sailed on the Rhine from the quarries near Andernach, in the Cologne district.

From excavations in the smithies of Ribe, dated to about 750 A.D., a number of iron objects have been recovered. An irregular part of an iron bloom, D 13908, 13.5x5x4 cm (max.), has a specific gravity of 3.5 g/cm^3 and, in section, diplays large production slag inclusions with 60% wüstite, 35% fayalite and 5% glass. The metal is phosphorferrite with 0.4-0.6%P in solid solution. A similar, irregular bloom, D 13909, 9.5x4x4 cm (max.) also displays a phosphorus-rich metal, with well-developed ghost structures, etch pits and precipitates of fine phosphide needles. The third, irregular bloom, D 13910, 11x5x4 cm (max.) has, with a spec.grav. of 5.3 g/cm^3, more iron than the first two. The metal is rich in phosphorus, 0.6-1.0% P, and the ferrite is coarse- grained with indistinct grain boundaries. Neumann bands from some coldwork are not uncommon. The slag inclusions are of the spotted glass type which often occurs in western Jutland's phosphorus-rich material, Fig. 314. The three blooms were probably brought to Ribe from one of the last bloomery sites near Varde, about 40 km to the north. Their composition is very similar to, e.g. the Snorup bar, Table 9.3, line 14.

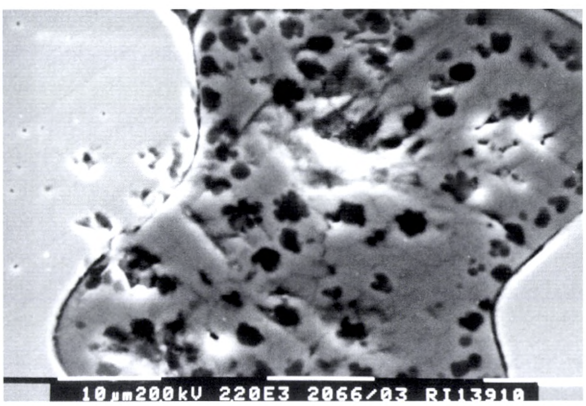


Fig. 314. Slag inclusion in the phosphorus-rich iron bloom, Ribe 13 910. The slag consists of two glasses, one high in phosphorus, iron and manganese (light), and one high in silicon and aluminium (black). PS. SEM. Scale bar 0.01 mm.

A number of purification slags of the planoconvex type was also found in Ribe. The planoconvex kalotslags have been thoroughly examined and compared to similar slags from Helgö and Haithabu (Madsen 2004). In Table 12.1, line 4 is entered the analytical result for a 500 g kalot slag, D 6215 B, which may derive from purifying blooms of the above composition. The F-value is in the same range as it should be, while manganese, phosphorus and sulphur have been significantly reduced. The slag is composed of 25% wüstite, 65% fayalite (ab. 30 µm thick laths) and 10% glassy matrix.

15 km south of Ribe, in Brøns, the author found two planoconvex slags of 346 and 401 g, Table 12.1 lines 5-6. They were embedded among ordinary stones of the same size in the pavement around the church. The 346 g kalotslag is grey and heterogeneous, and displays wüstite-rich enclaves, while it is rather clean of charcoal and stony matter. It has about 10% wüstite, 40% fayalite (10-50 µm thick laths), and 50% polyphased matrix. The 401 g kalot slag is rusty brown from corrosion, which is due to the inclusions of 10-30 µm iron particles. The structure is heterogeneous, rather clean and generally with 30% wüstite, 50% fayalite (10-30 µm thick laths), and 20% glass phase.

The presence in the Ribe district of blooms and planoconvex slags shows conclusively that about 700-750 A.D. there still was some iron production going on in the Snorup-Varde area, and that Ribe already was becoming an important crafts centre, an early city, like Haithabu and Birka. The occurrence of planoconvex slags and iron bars in Haithabu (Hedeby) has been studied by Thomsen (1971), Müller-Wille (1980), Piaskowski (1983) and Westphalen

Table 12.1. SEM-EDAX analyses of material from southwestern Jutland, and from Ladby, Odense amt.

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	29.0	52.8	3.2	-	6.8	1.8	2.9	0.9	0.2	0.3	2.1	100	10.0
2	36.0	47.9	1.6	-	2.9	4.0	3.9	2.1	0.5	0.2	0.9	100	9.23
3	34.7	42.2	5.9	-	7.7	3.0	2.7	1.3	0.2	0.2	2.1	100	12.9
4	23.0	70.6	1.3	-	0.1	1.3	2.0	0.9	0.5	0.1	0.2	100	11.5
5	30.2	57.0	0.3	-	1.2	5.8	2.8	2.0	0.4	0.2	0.1	100	10.8
6	23.0	65.8	0.8	-	2.0	3.6	2.3	1.6	0.4	0.2	0.3	100	10.0
7	31.6	47.2	3.0	-	1.0	4.2	9.4	1.6	1.1	0.4	0.5	100	3.36
8	29.8	39.1	14.8	1.2	0.5	4.0	7.0	1.7	1.0	0.4	0.5	100	4.26
9	60.1	13.2	3.3	0.5	0	3.2	13.4	3.5	2.0	0.8	0	100	4.49

1. Ribe,Tvedgade 10 M76, layer BS, Ribe. D 13908. 679 g part bloom. HV: 140-145-156-162-216.
2. ibid. D 13909. 250 g part bloom. HV: 123-128-131-140-205.
3. ibid. D 13910. 657 g part bloom. HV: 254-291-293-293-325.
4. Ribe, Dommerkontorets Have 5 M 74, square DD, layer Z. 500 g planoconvex slag. 719-730 A.D.
5. Brøns Church. Stray find 1996. 346 g planoconvex slag.
6. ibid. Stray find 1996. 401 g planoconvex slag.
7. Dommerkontorets Have, Ribe. Found 1974. 27.5 kg ship's anchor. The shank. HV: 81-129-140-169-229.
8. The Ladby ship, Karlstrup sogn, Odense amt. Ship's anchor, arm. HV: 82-87-115-134-168.
9. ibid. The shank of the anchor. HV: 82-87-114.

(1989). An overview of the studies centred around Haithabu has been presented by Jankuhn (1976) and Elsner (1992).

Also in Ribe, a ship's anchor was found in 1974/1975 (Bencard & Aistrup 1979; Rieck 2004). It is 1.5 m long, weighs 27.5 kg, and is archaeologically dated to 750-800 A.D. Sections through the shank and the arms show a heterogeneous, phosphorus-free metal, with a wide variation in structures, from almost pure ferrite (0%C), over Widmanstätten ferrite-pearlite (0.25-0.45% C), to pearlite (0.6-0.8% C). The hardness shows a similar range, 81-229 HV. Many hammer-welded zones are apparent as narrow, yellowish bands with a few slags. The arms, in one, single piece, had a central, punched hole, through which the shank had been forced. But the forge-welding of shank to the arms had not been very successful, for the joint is an almost continuous seam of thick layers of smithing slags.

A metal analysis performed at Korrosionscentralen (now FORCE Technology) in 1979 showed 0.03% Si, 0.01% Mn, 0.05% P and 0.007% S, typical of ancient wrought iron of the phosphorus-poor variety. The slag inclusions are quite variable, but one common type consists of about 50% fayalite, finely disseminated in a glass matrix. The metal and the slag composition point to a production site outside Denmark, most probably in southern Norway, Table 12.1, line 7.

The Ladby viking ship was excavated from its burial mound in 1935, and was later thoroughly described by Thorvildsen (1957). Further excavations in 1984 (Madsen & Thrane 1985) revealed a palisade, 30 m in diameter, around the mound. An extensive description (A.C.Sørensen 2001) rounded the picture off with computer visualization of the find and discussion of the preservation problems.

The chieftain's grave had been in the foremost third of the ship, but it had been plundered long ago. Enough remained, however, for a dating to about 950 A.D. Aft there were skeletons of eleven horses and

Fig. 315. Ship's anchor from Ribe, originally of 27.5 kg. Sections for examination are marked.

several dogs, and in the prow there was a rather well-preserved iron anchor, 136 cm high and of about 37 kg weight. The weight here quoted is that of an exact copy forged in 1990 for the Skuldelev 5 ship, "Helge Ask" (Vadstrup 1993: 152). To the anchor, a unique 10 m long iron chain continuing in a three-stranded bast rope was attached (Sølver 1946). The oak ship had been 20.6 m long, and iron rings along the railing showed where the mast-ropes had been secured. In the soil there were imprints of the numerous iron nails from the riveted boat.

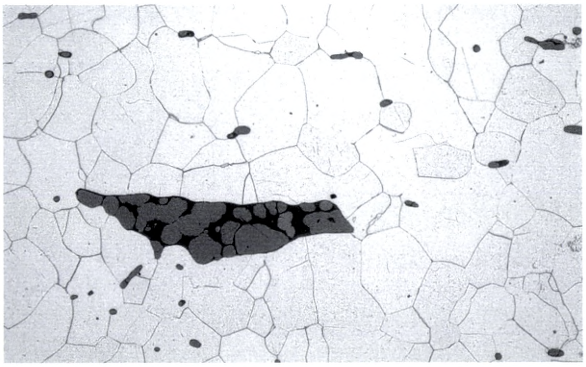


Fig. 316. Phosphorus-free ferritic part of the Ladby ship's anchor with a slag inclusion. PES. Side length 0.25 mm. Courtesy Struers.

In Table 12.1, lines 8-9 there are analyses of slag inclusions in the anchor's arm and its shank. The two analyses are fine examples of the harmony within one and the same, large object, produced from common bloomery stock. Increased SiO_2 is followed by increases in Al, K, Mg and Ti, and decreases in phosphorus and sulphur. The metal is phosphorus-free, equiaxed ferrite-pearlite with 0-0.3% C with a hardness range of 82-168 HV. The anchor's composition is similar to that of the Ribe anchor, and it was almost certainly manufactured in Norway.

Four rivets from the Ladby ship, which were analysed by Rasmussen (1992), turned out to have a significant cobalt content. Nails and rivets from Norway are known to be rather rich in cobalt (Rosenqvist 1979), again pointing to a Norwegian origin for (the iron of) the ship. The Ladby boat grave is so far the only one of its kind in Denmark.

In 1957-1962 excavations in Peberrenden, Roskilde Fjord, resulted in the recovery of five viking ships, which had been sunk deliberately in the eleventh century as a protective barrier for the city of Roskilde

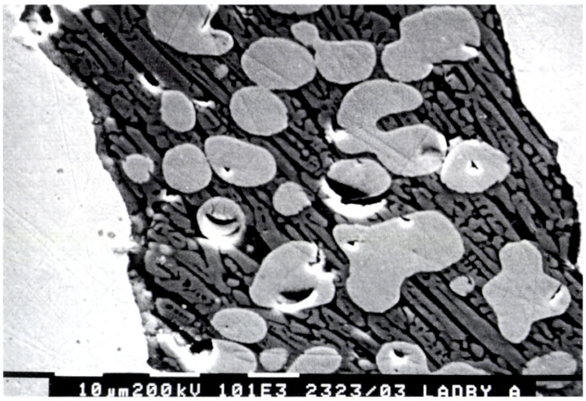


Fig. 317. Slag inclusion in the ferritic part of the Ladby ship's anchor. Globular wüstite and fayalite-glass matrix. PS. SEM. Scale bar 0.01 mm.

(Olsen & Crumlin-Pedersen 1969). As the ships were restored and exhibited in a new museum building in Roskilde, experimental archaeologists and shipwrights started several projects to rebuild the old ships and test their sailing abilities (Vadstrup 1993). An unexpected problem was the procurement of suitable nails and rivets. The normal mild steel qualities St37 and St42 proved unsatisfactory, because they were too hard and had insufficient ductility to be forged to flat-headed rivets and corresponding square rivet-plates. Armco-iron was tried, but was difficult to acquire in the right dimensions, and it also proved rather expensive.

Experiments at the Department of Metallurgy, The Technical University of Denmark, led in the spring of 1983 to the production of the first satisfactory rivets, which were then used in "Roar Ege", a copy of the Skuldelev 3 merchant ship. About 2000 rivets plus as many rivet plates were used for the 14.2 m long oak-built ship. The material for the rivets arrived as coils of 9.5 mm round Siemens-Martin steel from Daval, France, after DIN 17140, Class 3, D8-2. It is a rimmed quality with the following charge analysis: 0.05%C-0.35% Mn – 0 Si – 0.02%P – 0.02% S and 0.005% N. The coils were cut to about 100 mm length and forged to a 6.5-7 mm thick shank with a flat, round head, 2.5 mm thick at most, and 25 mm in diameter. The rivet

Fig. 318. Rock carving from Ramsundberget, Södermanland, illustrating the same story as Fig. 313. Sigurd licks blood from the killed dragon and understands the bird's warning. He slays Regin. The double bellows are protected by a clay- or soapstone plate. Anvil, tongs and hammer complete the blacksmith's tools. In the center are the horse Grane and a scene depicting Sigurd killing the dragon with Gram. The runes are inscribed on the dragon. 4,7 m long carving from about 1000 AD.

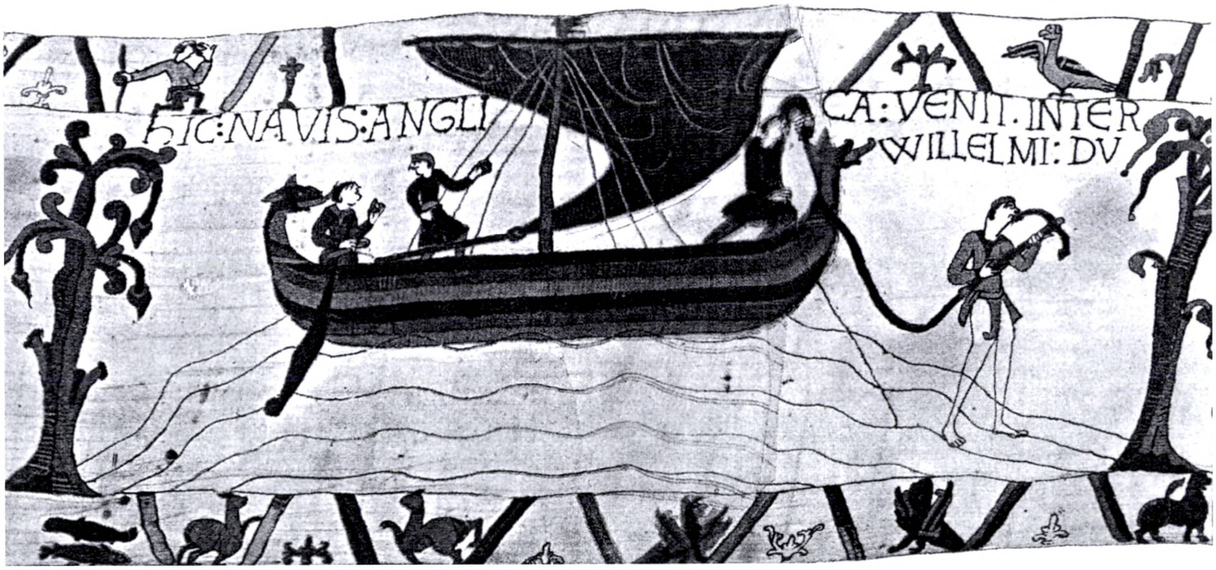


Fig. 319. Some men arrive from England and tell Duke William of King Edward's death and at the same time of Harold's coronation. The anchor is laid out. The Bayeux Tapestry, the embroidery probably begun soon after the Battle of Hastings, 1066 A.D.

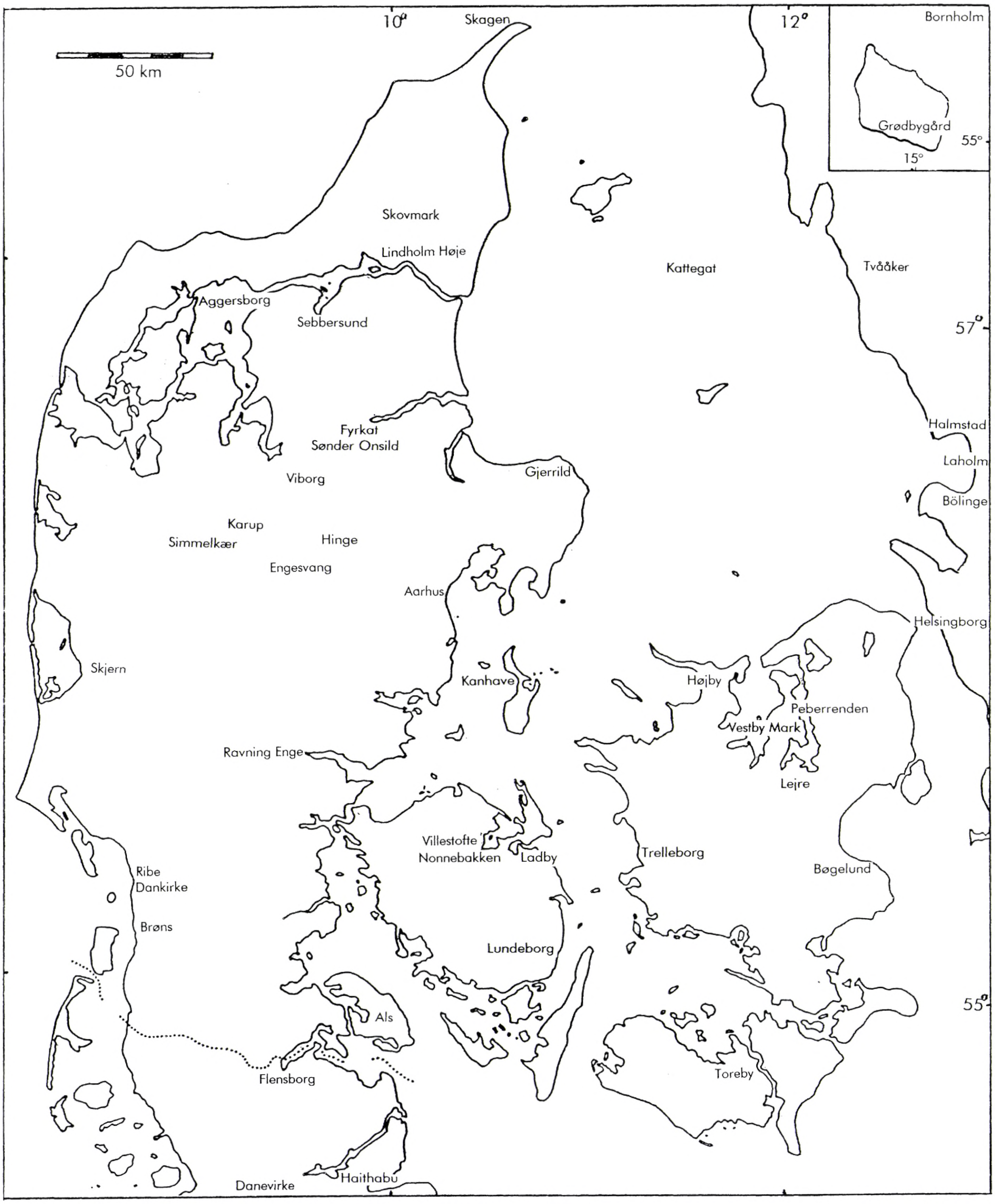
plates were 25 mm square and about 2 mm thick. All rivet dimensions had been copied from a study of the corroded rivets in the Skuldelev 3 ship. The rivets had a circular cross section. It appears that rivets of square cross sections first became common in the Middle Ages, and, e.g., became the general choice for the building of the German Kogge-ships.

The blacksmiths who worked with this material praised it and were much surprised to experience the difference from the modern material they were used to.

The rivet plates can, e.g. be produced in the following way (Richardson 1978). First heat: The 9-10 mm round bar is heated in the charcoal-fired hearth to a yellow colour, and a 100 mm length is forged flat to 2 mm thickness and 20-22 mm width. In the second heat, again to a yellow colour, holes are punched with 20-22 mm distance along the middle of the flat section. In the third heat, the individual rivet plates are cut from each other, either with a hot-chisel, or on the hardy inserted in the hardy-hole on the anvil. The finished plates and rivets are, while still hot, dipped in wood-tar for some initial corrosion protection.

The rimmed Siemens-Martin steel here chosen is, however, still not the same and not as easy to work as the ancient iron. First, the SM steel contains 10 times as much manganese as the old material. Manganese is a primary hardener of the ferrite- as well as the austenite phase, and the more manganese, the more force is required. Secondly, ancient iron objects often contain 10 times as much phosphorus as the SM steel. The presence of phosphorus improves the corrosion resistance somewhat, and also improves the hammer-welding capacity. And thirdly, in the SM steel there are no silicate-slag inclusions, but there may be some (Fe, Mn) sulphide slags. The ancient slag inclusions were apparently quite helpful during forging and hammer-welding.

In the late 1980s a copy of the Skuldelev 5 warship was built (Vadstrup 1993:142). For this ship a similar modern steel was used, but it had first been oil-drawn about 50% to a bright, hard quality, 10 mm in diameter. Also this material was praised by the blacksmiths. The two qualities are, by the way, often used for modern wire production, and for the fine (black) nails with large heads, required by the upholsterers.


10°
Skagen
12°
Bornholm
Grødbygård
55°
15°
50 km
Skovmark
Lindholm Høje
Kattegat
Tvååker
Aggersborg
Sebbersund
57°
Halmstad
Fyrkat
Sønder Onsild
Gjerrild
Laholm
Viborg
Bölinge
Karup
Simmelkær
Hinge
Engesvang
Aarhus
Helsingborg
Skjern
Kanhave
Højby
Peberrenden
Vestby Mark
Ravning Enge
Lejre
Villestofte
Nonnebakken
Ladby
Trelleborg
Bøgelund
Ribe
Dankirke
Brøns
Lundeborg
55°
Als
Toreby
Flensborg
Danevirke
Haithabu

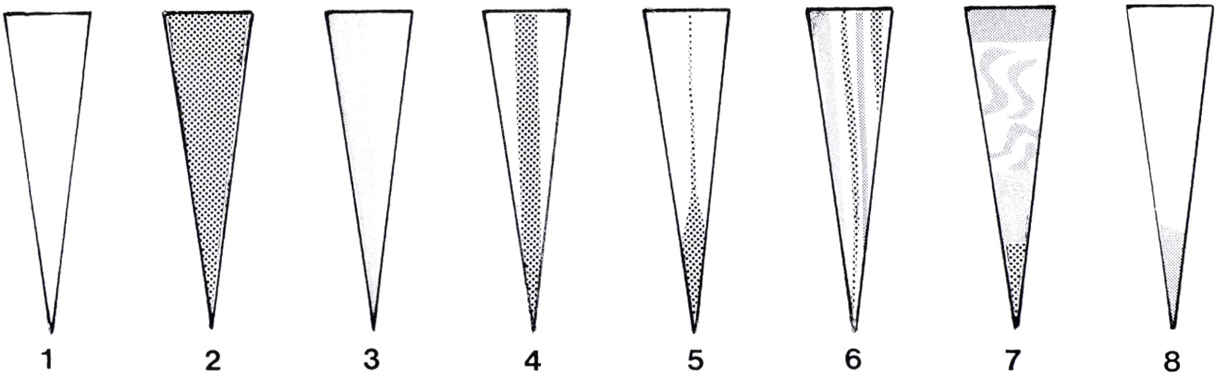


Fig. 321. Sketch of eight textural types of knives. Cross sections of blades. **1**, mainly ferritic iron. **2,** mainly pearlitic steel. **3**, Two-layered ferrite-pearlite. **4,** Pearlite between two layers of ferrite. **5,**Pearlitic edge.**6,** many-layered composite. **7,** steel edge, complex back. **8,** steel edge, homogeneous back.

Lindholm Høje was a settlement with a graveyard opposite Aalborg at the Limfjord, Jutland. After a long existence, from about 400 A.D., it had to be abandoned due to severe western sandstorms in the eleventh century. The settlement and the graveyard were entirely buried. In 1889 and 1895 preliminary excavations revealed the presence of stone-set graves, and in 1898 the treasure was secured for later archaeological examinations. These took place from 1952 to 1958, which led to the discovery of 589 graves, of which more than 90% were cremation graves inside circular or triangular stone-settings, mainly from 700-800 A.D. Those interred had regularly been provided with fibulae, knives and whetstones (Ramskou 1976; 1981; Marseen 1992). In the present study 16 knives were examined. Some were unfortunately too corroded for a meaningful analysis, and others, from the cremation graves, had transformation structures from their sojourn on the funeral pyre. These could, in the sections, be recognized on the scale of wüstite, magnetite and hematite, which displayed thicknesses from 30 to 250 µm.

In Table 12.2 are the results of 9 knives which escaped the funeral reheating. They were found inside the settlement and may be dated to 800-900 A.D. Common to the knives is the F-value of 3-5, the generally low phosphorus content, and the high magnesium- and titanium content. These facts point definitively away from a Danish manufacture and towards Norway, or perhaps Scania-Småland. The carbon content is surprisingly low, 0.1-0.4% generally, for knife production, and the knives are of low quality. The first three are little else than soft wrought iron with some phosphorferrite (-0.2%P) and ferrite-pearlite. No attempt at quench-hardening has been observed. The

Fig. 320. Finds and furnaces in Denmark from the late Iron Age to the Viking Age and early Medieval Age. Locations according to the text.

Fig. 322. Slag inclusions, extended and broken, in the ferritic part of knife 2122 from Lindholm Høje. Wüstite, fayalite and glass. PS. SEM. Scale bar 0.01 mm.

Table 12.2. SEM-EDAX analyses of knives from Lindholm Høje, northern Jutland.
Material from Historisk Museum, Aalborg

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	36.1	45.1	0.4	0.2	3.2	10.0	3.1	1.0	0.7	0.2	100	3.61
2	30.3	45.6	1.0	1.7	6.3	8.4	4.2	1.2	0.3	1.0	100	3.61
3	54.1	20.8	0.4	1.1	3.2	14.0	3.8	2.0	0.6	tr.	100	3.86
4	51.4	27.3	0.7	0.7	3.6	11.7	3.8	0.3	0.4	0.1	100	4.39
5	52.5	17.0	0.8	0	6.0	13.0	8.8	1.0	0.9	tr.	100	4.04
6	40.5	32.6	1.6	0.8	9.0	10.3	2.3	2.0	0.5	0.4	100	3.93
7	29.6	43.0	1.2	5.5	4.6	9.4	4.3	1.4	0.3	0.7	100	3.15
8	55.6	8.1	3.2	0	12.5	11.7	6.1	2.4	0.3	0.1	100	4.75
9	33.1	40.2	10.3	2.7	2.5	6.7	1.5	0.9	0.4	0.6	100	4.94

1. Corroded knife 8.5 cm long. No. 2122. Phosphorferrite, pearlite-ferrite. HV: 93-108=220-261=112-112.
2. Knife fragment. No. 2077. 25-100 µm ferrite. HV: 94-100-103-114-117.
3. 5.6 g fragment.House ruin. No. 2228. 50-800 µm phosphorferrite, P-ghost HV: 112-163-181-182-191.
4. Knife fragment from a house ruin. No. 2319a. 0.2%C-martensite, <0.1%P. HV: 91-103-160=212-217.
5. 11 g knife blade. House ruin. No. 2015. Widm.ferrite-pearlite, martensite. HV: 111-116=158-188-190.
6. 13 g knife blade. House ruin. No. 2068. Ferrite and low-carbon martensite. HV: 90-124=187-203-231.
7. 3.7 g fragment. 0.16% Ni. No. 1939. Phosphorferrite; 0.3%C martensite. HV: 158-176-181=228-310-381.
8. 7.5 g knife. House ruin. No. 2319 b. Ferrite and 0.6%C martensite. HV: 175-258-=286-483-634-743.
9. 17 g knife. Ruin. 1.1% BaO.No. 2680. Phosphorferrite; 0.4%C martensite. HV: 171=312-327-396-412.

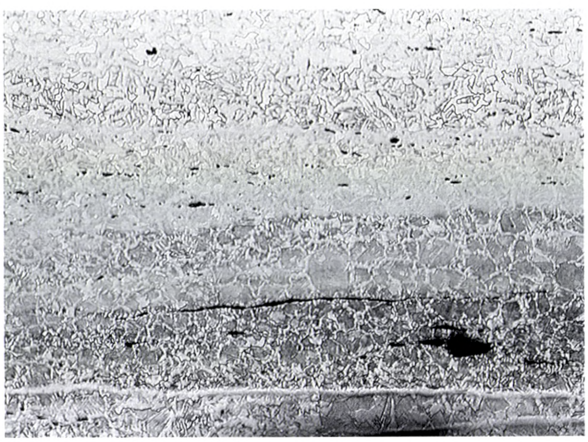


Fig. 323. Heterogeneous structure in knife 2015 from Lindholm Høje. Widmanstätten ferrite-pearlite and yellow lines from forging joints. PES. Side length 2.4 mm. Courtesy FORCE Technology.

knives are no better than ordinary nails. The following six have been subjected to water-quenching, but since the carbon content rarely increases above 0.4%, the resulting hardness is low. Furthermore, the martensitic hard zones often occur in the wrong places, distant from the cutting edge. Also, the correct hardening temperature was rarely obtained. In short, the hardening attempts generally failed.

In five of the knives the sections allowed some insight into the production methods. They can all be referred to the common Type 4 in Fig. 321. Nos.2122, 2015, 1939, 2319 b and 2096 (not included in Table 12.2) displayed a systematic attempt at hammer-welding different qualities. Between two soft ferritic layers a somewhat carbon-enriched layer had been inserted. In No. 2122 the middle 2 mm thick layer had

Fig. 324. Slag inclusion in the knife Fig. 323 Fragmented fayalite laths in glass. PS. SEM. Scale bar 0.01 mm.

about 0.4% C, but the knife had not been quench-hardened. In No. 2015 the middle layer had up to 0.5% C, but the preheating before quenching had been insufficient (perhaps 800°C), so the result was mediocre. In No. 1939 a 0.4% carbon midsection was squeezed between two phosphorferritic layers (-0.3%P). Upon quenching the outer layers were unaffected, but the midsection transformed into martensite. This knife had up to 0.16% nickel in solid solution in the metal phase, which is often observed in Norwegian material.

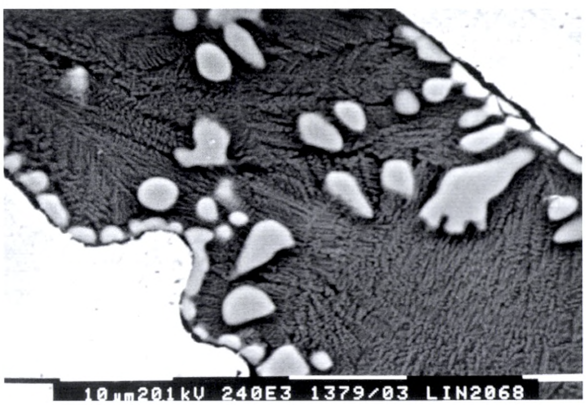


Fig. 325. Slag inclusion in the ferritic part of knife 2068 from Lindholm Høje.Wüstite nucleated on the austenitic walls and inside the slag. Fine grained fayalite-glass matrix. PS. SEM. Scale bar 0.01 mm.

In knife 2319 b the central section with up to 0.6% carbon had acquired adequate martensite hardness, but the small ferritic islands in the martensite suggest that the correct austenitic start temperature for hardening had not been achieved. Finally, knife No. 2096 had, in cross section, hardnesses of 110-120=350-709-372=118. The central section had acquired martensite hardness by a correctly performed hardening procedure. This was the only one of 16 knives which may deserve the predicate excellent.

A fire-steel, No. 2090, from a house ruin was also examined. Far from being a steel, it consisted of phosphorferrite with 0.3-0.4% P, no carbon, and hardnesses of about 200 HV. The author has no experience with the metallography of fire-steels from other sources, but perhaps the composition and hardness were good enough for the purpose.

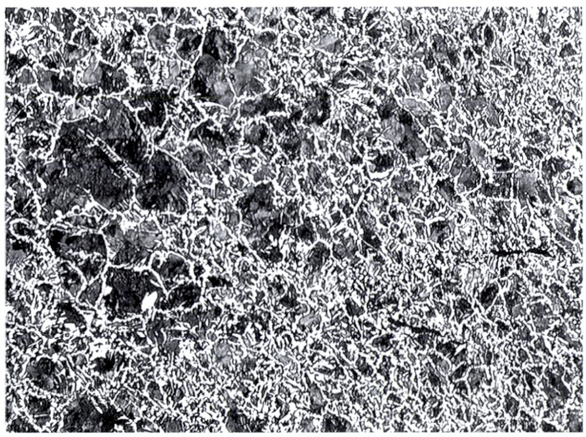


Fig. 326. Heterogeneous structure in the knife 1939 from Lindholm Høje. Fine-grained ferrite-pearlite. PES. Side length 0.6 mm. Courtesy FORCE Technology.

From the composition of the metal and, in particular, the slag inclusions, it must be concluded that all the Lindholm Høje material here examined is of Norwegian origin. Since smithies and purification slags have not been reported at Lindholm Høje, it is plausible that the knives were finished in Norway for export.

Fig. 327. Quench-hardened structure in knife 2680 from Lindholm Høje. Colony martensite with about 0.4% C. PES. Side length 0.2 mm.

At Selsø, 25 km WNW of Roskilde Cathedral, a small settlement, Vestby Mark, was excavated 1992-1994 (Sørensen & Ulriksen 1995). 36 small pit-houses from 700 to 1000 A.D. were identified along the stony beach of a protected inlet. The site may have served as a natural harbour, where local craftsmen in the sailing season were ready for ship repairs. In the pit-houses were found iron nails, boat rivets and iron scrap. The remains of metal casting and weaving were also identified. Off-season the inhabitants may have retired to Lejre or, later, to Roskilde.

Twenty objects, mainly nails and rivets, have been examined, Table 12.3 and 12.4. The oldest ones from 700-900 A.D. are in Table 12.3, the younger ones from 900-1200 A.D. are in Table 12.4. The metal is quite variable, but equally heterogeneous over the entire time span. Soft ferrite, HV < 120, occurs in seven of the nails and rivets, while phosphorus-enriched ferrite

Table 12.3. SEM-EDAX analyses of iron objects from Vestby Mark, 700-900 A.D.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	53.8	7.6	10.4	0	7.1	12.7	4.4	2.8	0.8	-	0.4	100	4.24
2	11.8	76.8	1.6	4.2	1.3	2.5	0.4	0.8	0.2	-	0.4	100	4.72
3	10.6	68.3	2.2	3.2	0.5	13.6	0.4	0.3	0.3	0.3	0.3	100	0.78
4	11.1	72.8	8.5	0.5	1.2	4.4	0.7	0.4	0.3	-	0.1	100	2.52
5	17.4	70.2	0.3	1.6	7.0	2.2	0.6	0.2	0	-	0.5	100	7.91
6	21.9	60.6	0.5	4.9	1.3	7.1	2.8	0.5	0.2	-	0.2	100	3.08
7	12.9	78.2	0.3	1.9	0.8	2.8	1.0	0.8	0.3	-	1.0	100	4.61
8	15.6	67.1	6.1	0.2	2.3	5.9	1.1	1.0	0.3	0.1	0.3	100	2.64
9	22.6	42.9	18.8	4.4	1.1	8.0	1.0	0.7	0.5	-	-	100	2.83
10	29.7	58.0	0.4	0.7	1.9	6.3	2.3	0.3	0.2	-	0.2	100	4.71

1. BAR x 66. 8th century. 9 g steel bar, 5.5x0.5x0.5 cm. Pearlite-ferrite. HV: 189-215-244-264-285.
2. BAR x 117. 8th century. 7 g bent nail. Phosphorferrite. HV: 101-105-108-115-118.
3. BAR x 217. 8th century. 4.7 g iron eye. Phosphorferrite, Cr-V-hercynite. HV: 130-158-160-205-229.
4. BAR x 299. 8th century. 6.6 g iron. Ferrite. (Fe,Mn)O. HV: 85-89-98-104-125.
5. BAR x 218. 8th century. 2.6 g iron pin. Ferrite, <0.1% P. HV: 102-104-104-104-112.
6. IÅ x 225. 9th century. 5 g bent nail. Ferrite. HV: 84-87-89-92-101.
7. IÅ x 147. 9th century. 14 g tinned iron pin. Phosphorferrite, coldworked. HV: 186-192-234-264-271.
8. IÅ x 43. 9th century. 3 g rivet plate. Ferrite, slightly coldworked. HV: 102-104-116-128-128.
9. IÅ x 146. 9th century. 5 g nail head. Ferrite. HV: 96-98-102-103-109.
10. PO x 4. 9th century. 105 g fragment of purification slag.

Fig. 328. Five boat rivets, Vestby Mark, 700-900 A.D.Scale bar 8 cm.

Fig. 329. Section through tinned iron pin, Vestby Mark IÅ x147. A corroded iron layer separates the tinned surface (white) from uncorroded iron. PS. SEM. Scale bar 0.1 mm.

occurs in seven others. These attain hardnesses up to 268 on account of the hardening effect of phosphorus, and some cold deformation. One, BAR x 66, is a fine-quality steel bar, in composition very similar to the Norwegian steel bars of Table 10.3. Two boat rivets, AFD x 515 and AFD x 517, which were found in the same pit-house, are identical in composition and hardness and must have been produced from the same stock, probably on the site. The knife, ABW x 34, is again an example of a very poor-quality tool, that is no better than an ordinary nail. The presence of purification slags, such as PO x 4 in Table 12.3, proves that Norwegian iron bars were imported and worked into various objects at Vestby Mark. Whether the tinning of IÅ x 147 was also performed here is not clear, but it is probable, given the presence of bronze workers. The F-values and the generally high magnesium and titani-

Table 12.4. SEM-EDAX analyses of iron objects from Vestby Mark, 800-1200 A.D.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	24.5	41.4	19.5	0.1	4.0	7.4	1.3	1.1	0.5	-	0.2	100	3.31
2	47.2	15.8	2.6	0	6.4	19.6	7.2	0.9	0.3	-	-	100	2.41
3	7.5	83.5	0.4	1.4	1.8	2.6	1.0	0.9	0.1	-	0.8	100	2.88
4	12.0	76.5	0.3	1.3	2.3	4.2	1.2	1.3	0.2	-	0.7	100	2.86
5	18.4	65.3	0.2	1.1	4.8	6.0	1.9	1.7	0.4	-	0.2	100	3.07
6	23.5	59.3	0.2	4.2	2.2	8.1	1.3	0.8	0.2	0.1	0.1	100	2.90
7	48.4	27.9	0.7	0.5	5.3	12.0	3.9	0.8	0.3	-	0.2	100	4.03
8	17.8	62.7	2.1	2.9	6.4	3.6	1.2	2.2	-	-	1.1	100	4.94
9	17.5	69.3	0.1	4.9	3.9	2.7	0.8	0.3	-	-	0.5	100	6.48
10	38.0	41.0	1.0	5.1	2.0	8.9	2.4	1.0	0.3	-	0.3	100	4.27

1. A x 23. 9th century. 20 g nail. Pearlite-ferrite.	HV: 128-136-177-202-232.
2. A x 34. 9th century. 16 g iron. Ferrite-pearlite.	HV: 151-162-185-192-194.
3. AFD x 515. 9th century. 14 g boat rivet. Phosphorferrite.	HV: 101-104-104-105-115.
4. AFD x 517. 9th century. 9 g boat rivet. Phosphorferrite.	HV: 101-109-110-111-116.
5. DL x 223. 10th century. 6 g nail. Ferrite.	HV: 81-86-89-90-94.
6. DL x 256. 10th century. 6 g bent nail. Phosphorferrite.	HV: 123-141-156-163-194.
7. DL x 341. 10th century. 3 g bent nail. Ternary Fe-C-P structures.	HV: 164-164-186-209-223.
8. ACA x 165. 10th century. 6 g nail. Phosphorferrite.	HV: 127-140-141-167-181.
9. ABW x 34. 10th century. 16 g knife fragment. Phosphorferrite.	HV: 105-116-120-135-137.
10. WI x 45. 12-13th century. 11 g phosphor tongue-bar. Phosphorferrite.	HV: 189-207-238-255-268.

um values point to a Norwegian origin for 18 of the 20 objects. The exceptions are BAR x 218, which may come from Denmark's southern neighbours, and the late WI x 45, last line of Table 12.4, which undoubtedly comes from Tommarp, Scania. Its characteristic shape and colour as well as its composition makes it rather unique, see Table 12.13.

At Sebbersund, 5 km west of Nibe, Limfjorden, a trading settlement of about the same age as Vestby Mark, 700-1100 A.D., was excavated in 1990-1991 (Christensen & Johansen 1992). Rather many well-preserved bronze objects were found, but iron objects were utterly few. From coffins in the 11th-century cemetery two iron nails were retrieved. While one crumbled away, it was possible to make metallographic sections through the other, No. 2863 x 1026, Table 12.5, line 1. The structure is heterogeneous, but generally carbon-free, and it has 0.2-0.6% P in solid solution. The phosphorferritic grains attain sizes of 0.5 mm (!), and some grains are rich in Neumann bands from cold hammering. The slag inclusions are spotted glass with tiny particles of iron sulphide. The nail was produced in a Danish bloomery, probably in western Jutland.

Ravning Enge, Table 12.5, line 2, is a 75 g fragment of an ancient horseshoe dated to 1000-1100 A.D.. It was found 12 km WSW of Vejle near the famous wooden bridge which King Harald Bluetooth about 980 A.D had built across Vejle Ådal. The horseshoe had unfortunately been conserved by annealing by the Rosenberg method in the National Museum. The metal now displays ternary Fe-C-P structures with about 0.1% P and 0.3% C. The slag inclusions are glassy with 5-10% wüstite, and have a composition rather

Table 12.5. SEM-EDAX analyses of Viking Age objects from Denmark

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	34.0	52.0	2.5	-	2.8	2.0	3.7	1.4	0.5	0.3	0.8	100	9.19
2	27.9	56.7	1.5	-	4.2	3.9	3.1	1.2	0.9	0.1	0.5	100	9.00
3	31.3	60.0	0.2	-	0.2	2.9	2.7	2.1	0.5	-	0.1	100	11.6
4	49.8	21.0	1.3	-	0.1	10.9	10.8	2.3	3.0	0.7	0.1	100	4.61
5	43.4	12.2	14.9	0.3	0.2	12.0	11.4	2.6	2.0	0.6	0.4	100	3.81
6	35.2	31.0	19.3	-	1.1	2.9	6.6	2.2	1.0	0.5	0.2	100	5.33
7	27.6	59.9	0.1	-	0.3	2.9	5.8	3.0	0.4	-	-	100	4.76
8	25.0	54.4	0.2	-	7.3	2.6	5.9	1.6	1.9	0.5	0.6	100	4.24
9	19.3	62.1	2.0	-	8.9	1.2	4.6	1.0	0.6	0.3	-	100	4.20
10	30.1	51.3	2.2	-	3.8	3.8	5.2	1.6	1.0	0.2	0.4	100	5.79

1. Sebbersund, Limfjorden. No. 2863x1026. 9 g coffin nail. Phosphorferrite. HV: 151-154-166-169-171.
2. Ravning Enge, Vejle Å. D 805/74. 75 g worn horseshoe. Phosphorferrite. HV: 103-111-144-178-182.
3. Villestofte, Pårup sogn, Odense. Stray find of purification slag. 63 g.
4. Sønder Onsild, Hobro. Grave VI. 750 g steel axe. Pearlite-ferrite. HV: 125-147-193-254-303.
5. Højby Sø, Odsherred. D 82/1984. 703 g steel axe. Widm.ferrite-pearlite. HV: 137-143-169-174-185.
6. Højby Sø, Odsherred. D 183/1989. 618 g steel axe. Widm.ferrite-pearlite. HV: 136-142-156-218-224.
7. Bøgelund, Varpelev sogn, Stevns. 497 g purification slag.
8. Toreby sogn, Maribo. FMN 1107x5. 12 g knife. Phosphorferrite; martensite. HV: 141-183-188=409-505.
9. Trelleborg, K.Stillinge sogn. Q 1423. 12 g arrowhead. 0.4% $V_2 0_5$. Phosphorferrite. HV: 117-144-145-148-166.
10. ibid. D 9952. 60 g horseshoe fragment. Phosphorferrite. HV: 139-156-162-173-183.

similar to the previous coffin nail, thus suggesting a Danish origin.

In the cultivated fields of Vestergård, Villestofte, 7 km west of Odense, several slags were found in 1988 by Peter Mortensen, who estimated them to belong to the Viking Age. Two slags of 153 and 63 g were examined. They are planoconvex slags of the purification type, Table 12.5, line 3. They are rather porous and heterogeneous. The structure is mostly 5% wüstite, 90% calciumfayalite (-4% CaO) and 5% matrix. They come from purification of blooms of Danish origin.

The presence of nails, horseshoes, and purification slags in the late Viking Age proves that a very modest iron production still occurred in Denmark. The actual bloomery sites have so far not been found.

From a Viking Age cemetery, about 950 A.D., at Sønder Onsild, 6 km SW of Hobro, a 750 g axe was examined (Roesdahl 1978; Buchwald 1978). The axe is of a common Norwegian type (Rygh 1885, Fig. 561). It was cut in longitudinal and transverse directions in order to reveal the steps in its construction. It consisted of pearlitic steel, enveloping a rather small nucleus of soft ferritic iron. The axe had not been quench-hardened, but displayed the natural hardness range from ferritic 125 HV to fully pearlitic material, 300 HV, along the edge.The carbon content was generally high, 0.5-0.7%, locally even 0.9%, resulting in hypereutectoid structures. Phosphorus was absent. The slag inclusions were typically 60% magnesiafayalite (-7% MgO) and 40% glass. The slags were often broken, and even the primary fayalite crystals had been broken by continued reheating and forging. The composition of the slag and the F-value correspond so

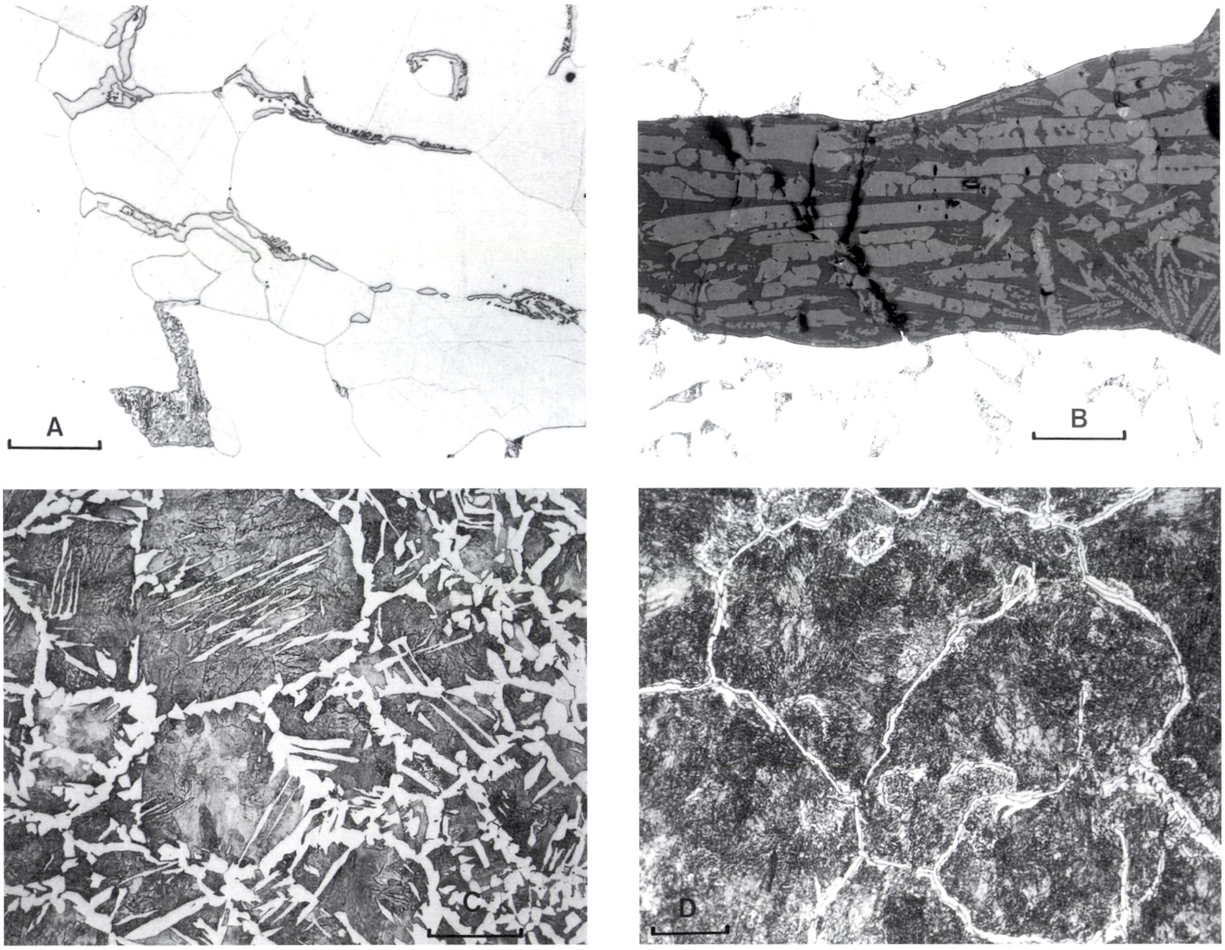


Fig. 330. Four views of the heterogeneous structure in the 750 g axe from Sønder Onsild. Imported from Norway. A, ferrite, cementite and a little pearlite. B, ferrite and pearlite with a fayalite-glass inclusion. C, Widmanstätten ferrite-pearlite. D, hypereutectoid structure of pearlite and grain boundary cementite. PES. Scale bar, A, 0.02mm, B, 0.05 mm, C, 0.15 mm, D, 0.05 mm. Buchwald 1978.

closely to the Norwegian steel bars of Table 10.3, that there is no doubt that the steel axe was imported from southern Norway, and probably from the Valdres district.

Two other axes, which also turn out to be of Norwegian origin, are perhaps 200 years younger, 1150-1200 A.D. They come from Højby Sø, Odsherred, where they were found in the 1980s. The first, National Museum D 82/1984, weighs 703 g and measures 18 cm from edge to neck. A wedge-shaped section was removed from the blade and examined. The structure is pearlitic-ferritic with 0.3-0.5% carbon and no phosphorus. The slag inclusions consist of about 50% fayalite (5-10 μm laths) and 50% glass. The manganese content of the slags is extremely variable, from 4% to 29% MnO, for no obvious reason. MnO appears to be anticorrelated with the CaO content.

The other Højby Sø axe, D 183/1989 weighs 618 g and measures 16.5 cm from edge to neck. The structure is pearlitic-ferritic with 0.3-0.6% carbon and no phosphorus. The slag inclusions are about 50% manganofayalite (-22% MnO) and 50% glass, but the

Fig. 331. A 703 g steel axe, found in Højby Sø (D 82/1984), but imported from Norway. Scale bar 4 cm.

manganese content is harmonious and not wildly variable as in the previous axe. Both axes have a composition that reveals a Norwegian manufacture. Perhaps this is the proper place to remember a passage from Olav den Hellige's Saga (Heimskringla) that refers to events that took place about 1025 A.D.

"Einar Tambeskelve and Kalf Arneson had this winter meetings and consultations between themselves in the merchant town of Kaupang. Then there came a messenger from King Canute to Kalf Arneson, with a message to send him three dozen axes, which must be chosen and good. Kalf replied, "I will send no axes to King Canute. Tell him I will bring his son Svend so many, that he shall not think he is in want of any"." (Heimskringla, translated by Samuel Laing, Everyman's Library, Vol. 722, 1964, p. 395).

From this excerpt and from the archaeological results here presented, it is evident that the Danes mostly acquired their (good) axes from Norway and often through the trading centre at Kaupang. In 1949 an unusual find was reported from Gjerrild Strand on the northeastern coast of Djursland. Twelve axes were "threaded" tightly on a sturdy rod of spruce. The examination concluded that the axes had been on board a ship from Norway that was wrecked on the Danish coast some time in the Viking Age (Thorvildsen 1951). Unfortunately the axes had been thoroughly annealed at 800°C, before the metallographic examina-

Fig. 332. Slag inclusion in Fig. 331, displaying fayalite laths in a glass matrix, inside a pearlitic-ferritic steel structure. PS. SEM. Scale bar 0.1 mm.

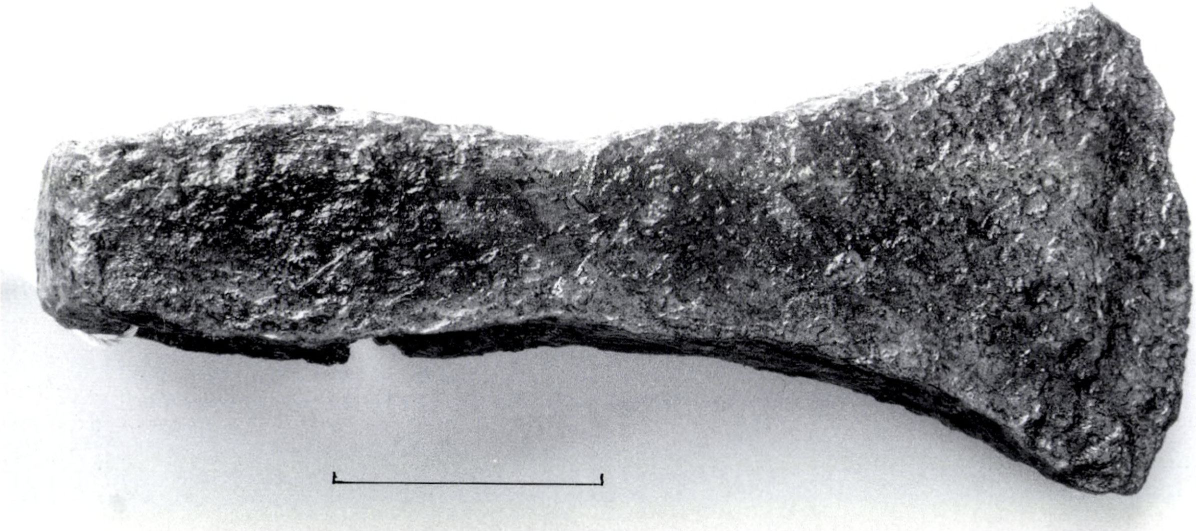


Fig. 333. A 618 g steel axe, found in Højby Sø (D 183/1989), but imported from Norway. Scale bar 4 cm.

tion appended to Thorvildsen's paper, and so the structural observations are of little value (Knud Holm, pers.comm.) The value of the find lies primarily in the confirmation of the extensive trade in iron and steel out of Norway in ancient times. Sizes and weights of ancient and modern Scandinavian axes and adzes may be found in Brånby (2002).

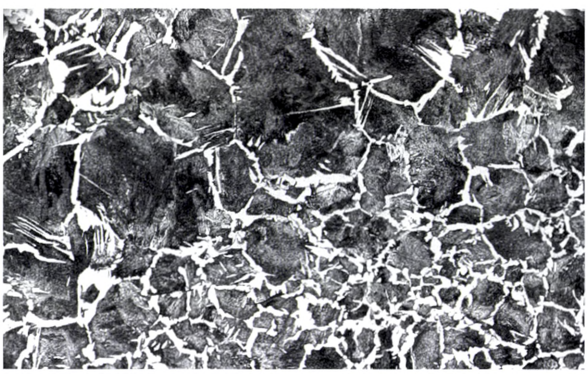


Fig. 334. Pearlitic-ferritic structure of the axe, Fig. 333. The austenite grains were about 0.1 mm at the top, but only about 0.03 mm at the bottom. PES. Side length 0.5 mm. Courtesy Struers.

At Bøgelund, 1 km south of Varpelev Church, Stevns, a Viking Age settlement was excavated in the early 1990s by Svend Aage Thornbjerg, Køge Museum. About 30 planoconvex slags bear witness to some purification work of blooms in the period 900-1000 A.D. However, no bloomery site or production slags are known from the region. Three planoconvex slags of 822, 636 and 497 g were sectioned, but the first two proved too corroded for meaningful work. The third is entered in Table 12.5, line 7. The slag has no magnetic parts, is free of the otherwise common, minute iron particles (and so it has survived), has no stones, but does contain some charcoal. The structure is 20% dendritic wüstite, 45% magnesiafayalite (-1.7% MgO), and 35% matrix with leucite. The average composition and the F-value suggest that the slag is the result of purifying imported blooms, most likely from Norway.

A knife fragment from Toreby, 5 km west of Nykøbing Falster, was examined for Mindestuerne, Nykøbing Falster Museum. It was dated to the 12$^{\text{th}}$ century. The section showed that the knife was a composite of a phosphorferritic part with 0.2-0.5% P and a hardness range of 141-188 HV, and a carbon-rich part

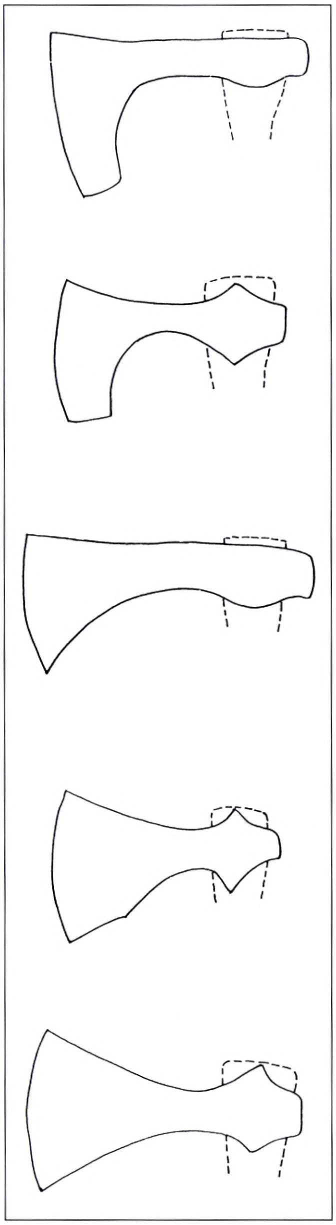


Fig. 335. Five Norwegian axes from the Viking age. The top two are typical "skægøkser" (bearded axes), the bottom one an all-round working axe. From "SPOR" No. 1, 1988. Trondheim.

with 0.4-0.5% C. Upon quenching this part acquired martensitic hardnesses of up to 505 HV. The slag inclusions are not from a Danish bog iron ore, but either from an ore in Scania or a Norwegian one.

The eminent Viking Age fort Trelleborg is located on the headland which is formed at the confluence of Vårby Å and Tude Å, 6 km west of Slagelse. The comprehensive excavations 1934-1942 (Nørlund 1948) were followed up by reconstructions of a longhouse. Various dendrochronological studies agree that the fort had a very short life, from 980 to 986 A.D., when it was destroyed and abandoned (Christensen & Bonde 1992). On the fort site a large number of iron objects have been found, such as knives, fire-steels, chains, spurs, axes, lance- and spearheads, and arrowheads. Tools were also present, such as chisels, swages, hammers, tongs, drills, tweezers, and scissors. An imported iron bar of the Mästermyr type is illustrated on Plate 46[10] (Nørlund 1948).

From Trelleborg an arrowhead, Q 1423, was examined, Table 12.5, line 9. It has been preserved by museum annealing. The structure now consists of 60-200 μm ferrite grains with etch pits and phosphor ghost patterns, due to 0.2-0.5% P in solid solution. The slags

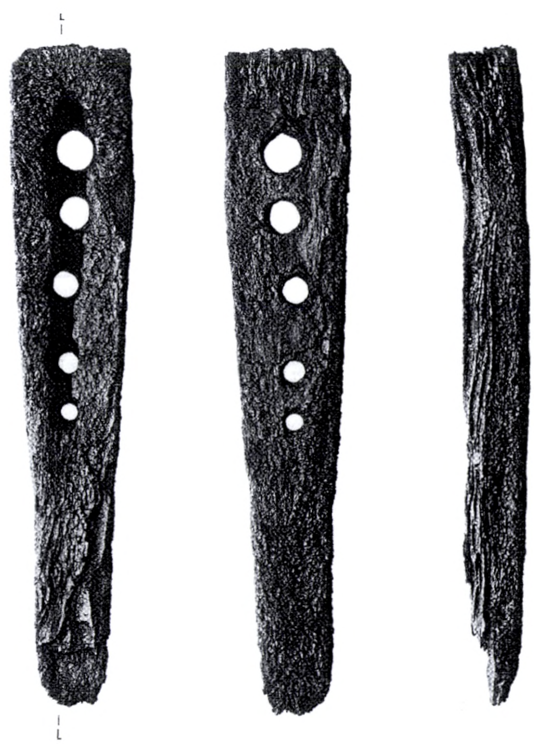


Fig. 336. Drawing die from 9th century Haithabu. Seen from three sides. Length 16 cm. Nauman 1971.

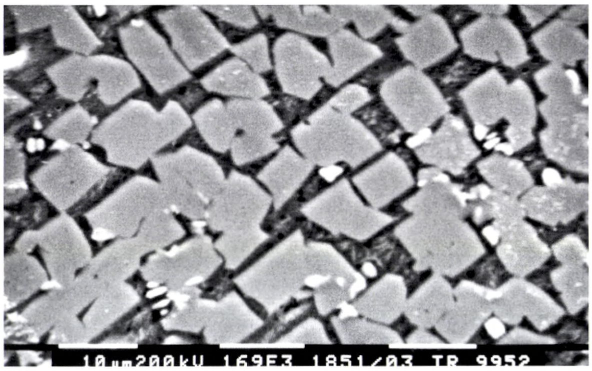


Fig. 337. Slag inclusion in an 11th century horseshoe, Trelleborg 9952. Square fayalite crystals and vanadium-rich iron oxide particles (white) in the glass matrix. PS. SEM. Scale bar 0.01 mm.

are chiefly glassy, but some contain a little wüstite. The slag composition points away from Denmark to some undetermined, southern origin.

The horseshoe fragment D 9952 was found on the Trelleborg site, but belongs to a farm about one hundred years younger which was built on the ruins of the fort. The structure is heterogeneous, with alternating zones of 10-50 µm ferrite with 0.2% P and 0.2% C, and 0.1-0.3 mm phosphorferrite with etch pits and P-ghost patterns. The slag inclusions are typically 5% wüstite, 50% fayalite(-3% MnO, -3% MgO) and 45% matrix. Many slags are crushed and the fayalite laths have been fractured, Fig. 337. The wüstite contains up to 2% V_2O_5 and there are also many micron-sized vanadium-rich parti-

Table 12.6. SEM-EDAX analyses of nails and tools from Aggersborg, about 985 A.D.

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	53.1	4.1	12.9	1.4	0	3.9	17.2	3.9	1.6	1.0	0.9	100	3.09
2	42.2	4.4	23.9	0.3	0	11.1	12.0	1.6	2.3	0.7	1.5	100	3.52
3	26.1	39.0	22.1	-	0.5	3.2	5.7	1.8	0.5	0.3	0.8	100	4.58
4	23.8	54.7	7.3	-	0.9	3.8	6.8	1.6	0.5	0.3	0.3	100	3.50
5	29.7	43.8	15.8	0.9	0.9	1.9	4.2	1.2	0.5	0.6	0.5	100	7.07
6	32.9	33.6	3.7	-	0.1	11.0	13.0	3.2	1.9	0.4	0.2	100	2.53
7	35.6	31.8	2.0	-	0.2	4.4	14.8	9.3	1.3	0.6	-	100	2.41
8	27.4	58.7	0.9	-	0.4	1.1	7.7	2.0	0.5	0.6	0.7	100	3.56
9	50.2	11.4	2.9	1.4	0	10.2	14.6	3.4	4.2	1.6	0.1	100	3.44
10	33.2	40.6	1.2	-	0.3	12.0	6.4	3.1	2.8	0.2	0.2	100	5.19
11	30.1	36.7	21.4	0.4	2.2	3.7	3.0	0.8	0.9	0.4	0.4	100	10.0
12	22.6	62.1	0.4	-	4.6	1.4	6.2	1.2	0.5	0.2	0.8	100	3.65

1. A 1. 10 g steel nail. P-free ferrite-pearlite and pearlite. HV: 172-205-215-226-246.
2. 12 a. 14 g nail with 5 mm thick contra-plate. P-free ferrite & spheroidized pearlite HV: 108-117-122-158-183
3. 15 a. 18 g nail. P-free ferrite, some Neumann bands.Variable MnO. HV: 85-87-92-95-99.
4. A3-440-C. 315 g hoe, 151 mm long. P-free ferrite-pearlite. HV: 102-129-137-138-147.
5. A3-69 E. 27 g sickle, 130 mm long. Ferrite-pearlite. 0.03% nickel. HV: 168-169-182-183-203.
6. A3-502 A-q1. 12 g knife fragment.111 mm long. P-free pearlitic steel. HV: 147-169-202-224-241.
7. A3-504. 6 g knife fragment. 101 mm long. Central martensitic layer. HV: 104-126-195-223=383.
8. A3-725-E2. 16 g knife fragment 116 mm long. Central martensitic layer. HV: 105-111=391-404-509.
9. A3-836-D. 16,7 g knife fragment. 123 mm long. P-free pearlitic steel. HV: 186-186-207-218-237.
10. A3-700-I. 8.8 g arrowhead. 108 mm long. P-free ferrite-pearlite. HV: 117-124-129-134-143.
11. A3-760-D1. 7.7 g arrowhead. 120 mm long. Ternary Fe-C-P, P-ghost. HV: 139-163-166-175-231.
12. A3-765-B. 6.2 g arrowhead. 83 mm long. Ferrite with 0.3-0.4% P. HV: 207-231-234-252-269

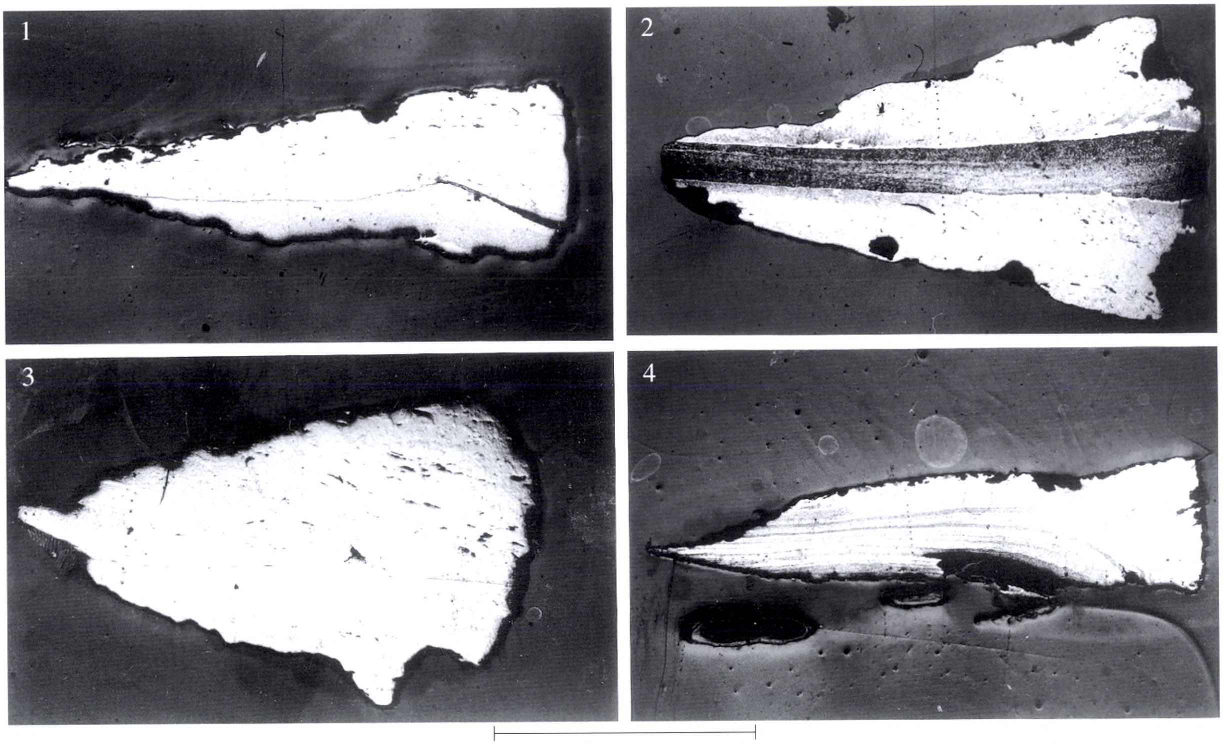


Fig. 338. Sections through four knives from Aggersborg. **1,** A3-760-D2, Type 2. **2,** A3-725-E2, Type 4. **3,**A3-1508, Type 5, **4,** A3-199, Type 6. Scale bar 4 mm.

cles in the slag inclusions. The average V_2O_5 content of the slag inclusions is 0.4%. This points away from Denmark, and towards Scania and Halland, which from about 1050 A.D. became iron-producing provinces.

The circular Trelleborg fort had a diameter of 136 m, but the contemporaneous fort at Aggersborg, with its 240 m diameter, was significantly larger. Aggersborg was located on the northern side of Limfjorden, 40 km west of Aalborg, where it was in control of the narrow Aggersund (Olsen 1975; Roesdahl 1981). Parts of the fort were excavated 1945-51, 1970 and 1976 (Nørgaard et al. 1986).

By the kind assistance of Jørgen Nordquist and Aalborg Historiske Museum it was possible to examine three nails, two tools, four knife fragments and three arrowheads excavated on Aggersborg and thus dated rather precisely to 980-990 A.D. The three nails, Table 12.6, lines 1-3, are rather different from each other. The first is a steel nail, mainly pearlitic, the third is an ultra-soft, ferritic nail. Common is a low phosphorus level, and a very high and variable manganese level in the slag inclusions.

From the 315 g hoe, sections were taken from the edge and the socket. The structure is heterogeneous, phosphorus-free ferrite and pearlite, with a range from 0.05 to about 0.4% C. The slag inclusions are mainly 40% wüstite and 60% matrix, decomposed on a submicroscopic level. The sickle, A3-69E, has been forge-welded from two almost identical iron pieces; or perhaps just folded over on itself to build up the body. The structure is heterogeneous, ferrite-pearlite with a trifle of phosphorus which is concentrated (0.21% P) along the yellowish welding band. The metal contains a little nickel, 0.03%. The hardness is relatively high, because the sickle is slightly coldworked. Near the edge the hardness increases to 237-310 HV. The slag

Fig. 339. Ferrite and spheroidized pearlite in the Aggersborg knife A3-520-Aq1. PES. Side length 0.15 mm Courtesy FORCE Technology.

inclusions are mainly fayalite-glass, but the fayalite laths have been thoroughly broken and "spheroidized" during the forging operations.

All knives at Aggersborg had been much used and had often been ground, when finally placed in the graves. A3-502A-q1 (Fig. 321, Type 4) has a curved back which is up to 3.5 mm thick.The knife has been forged from three pieces with 0.2-0.7% C. The structure consists of spheroidized pearlite without phosphorus, and hardening has not been attempted. The slag inclusions are 100% glass. A3-504 has a straight back, up to 3 mm thick. It has also been forged from three pieces, Type 4. The 0.5 mm thick central zone has 0.2-0.4% carbon, nil phosphorus, and stands in sharp contrast to the two covering parts which are ferritic with 0.05-0.1% C. Quench-hardening has been attempted, but since the carbon content was low, the martensite in the central zone has insufficient hardness, max. 383HV.

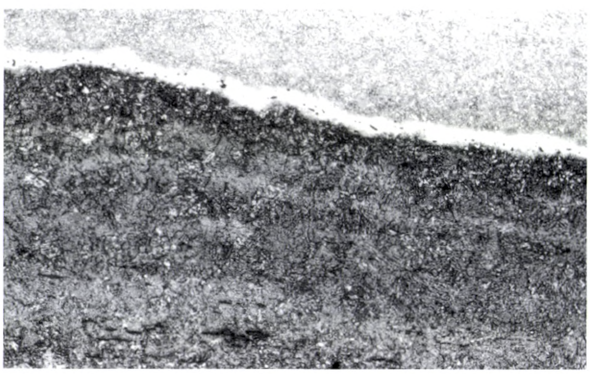


Fig. 340. The martensitic central layer is separated from the exterior ferritic layer by a light, yellow forging line. Compare Fig. 338-2. Aggersborg knife A3-725-E2, PES. Side length 1 mm, Courtesy Struers,

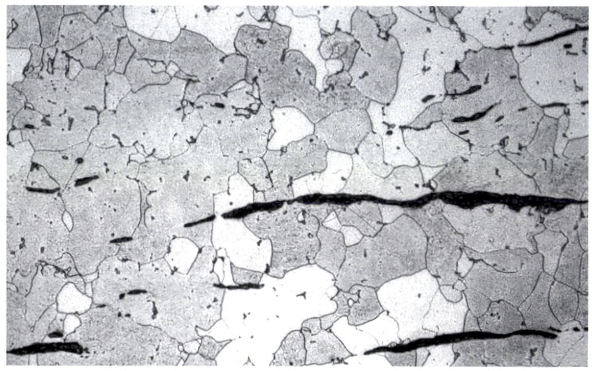


Fig. 341. Ferritic part with wüstite-glass slag inclusions in the Aggersborg arrowhead A3-700-1. PES. Side length 0.25 mm. Courtesy Struers.

A3-725-E2 has a straight back which is up to 4.5 mm thick. Also this knife has a 0.8 mm thick, carbon-enriched central zone (0.3-0.4% C), surrounded by low-carbon ferritic zones, Type 4. Quench-hardening has led to hardnesses of 404-509HV (max.), which must have been present also in the cutting edge, now corroded away. The slag inclusions are mainly 5% wüstite-60% fayalite and 35% glassy matrix. A3-836-D has a curved back up to 3.5 mm thick. The knife has been forged from only one carbon-rich steel plate which has been bent back on itself to give body in the forging process, Type 2. The structure is rather homogeneous, consisting of fine-grained pearlite-ferrite with 0.6-0.7% C of typical steel hardness. Quench-hardening has not been attempted. The few slag inclusions are glassy and they are crushed.

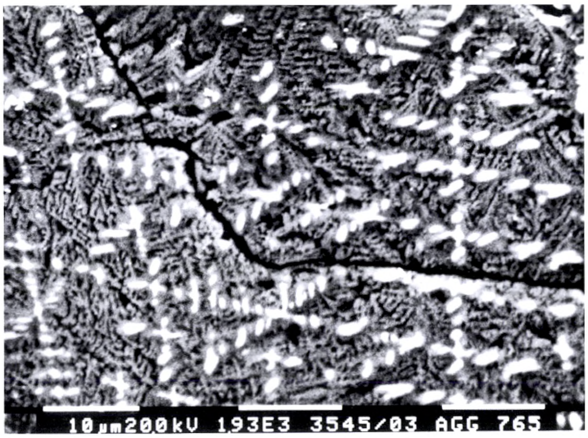


Fig. 342. Slag inclusion in an arrowhead A3-765-B from Aggersborg. The diffuse appearance of the wüstite dendrites and matrix is caused by a high P_2O_5-content. PS. SEM. Scale bar 0.01 mm.

The two knives A3-760-D2 and A3-836-D are similar in shape, metallic structure, hardness and slag composition. Perhaps they were made by the same Norwegian blacksmith.

Three arrowheads have been examined : The first A3-700-I is heterogeneous with a carbon range of 0.1-0.3% and with ferritic-pearlitic structures. The slag inclusions consist of fine- grained wüstite and glass. The arrowhead A3-760-D1 displays ternary Fe-C-P structures (about 0.2% C, 0.2% P), with zones of ghost ferrite, and zones with Widmanstätten ferrite-pearlite. The structures are somewhat coldworked, which is the reason for the relatively high hardnesses. The slag inclusions are chiefly glassy, and they have been severely crushed; the manganese content is unusually high. The arrowhead A3-765-B is an iron phosphorus alloy

Table 12.7. SEM-EDAX analyses of ten nails from Nordre Grødbygård, Bornholm. BMR 1399.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	13.7	76.0	0.3	2.3	1.1	3.4	0.9	0.4	0.1	1.8	100	4.03
2	16.6	74.9	0.3	0.3	1.2	4.3	1.3	0.4	0.4	0.3	100	3.86
3	20.2	69.9	0.4	0.4	1.4	5.1	1.5	0.2	0.4	0.5	100	3.96
4	21.6	68.0	0.4	0.5	1.6	5.2	1.6	0.4	0.4	0.3	100	4.15
5	23.5	64.8	0.4	0.7	1.5	6.1	1.6	0.4	0.4	0.6	100	3.85
6	24.8	60.7	0.6	1.1	2.6	6.8	2.1	0.9	0.1	0.3	100	3.65
7	20.5	60.1	1.5	5.5	2.4	7.2	1.3	0.9	0.2	0.4	100	2.85
8	29.8	55.6	0.7	0.6	2.1	7.5	2.2	0.6	0.5	0.4	100	3.97
9	25.6	54.1	2.1	3.4	2.8	8.7	1.6	1.1	0.4	0.2	100	2.94
10	24.5	52.1	2.0	7.1	2.3	8.1	1.3	1.6	0.4	0.6	100	3.02

1. 24 F. 8.2 g nail. Phosphorferrite. HV: 126-127-132-147-172.
2. 24 D. 9.4 g nail. Ferrite, Widmanstätten structure. HV: 157-158-159-179-202.
3. 24 A. 10.2 g nail. Ferrite, Widmanstätten structure. HV: 118-122-124-146-150.
4. 24 E. 14.6 g nail. Ferrite, Widmanstätten structure. HV: 137-142-182-183-215.
5. 24 I. 14.9 g nail. Ferrite, Widmanstätten structure. HV: 120-132-148-192-231.
6. 24 X. 9.0 g nail. Phosphorferrite. HV: 137-138-142-144-160.
7. 24 L. 12.3 g nail. Phosphorferrite, P-ghost structures. HV: 170-170-177-179-202.
8. 24 J. 12.9 g nail. Ferrite, Widmanstätten structure. HV: 138-151-158-211-245.
9. 24 C. 11.0 g nail. Phosphorferrite. Widmanstätten structure. HV: 152-176-187-199-201.
10. 24 G. 9.3 g nail. Phosphorferrite. Widmanstätten structure. HV: 118-120-138-168-223.

with up to 0.4% P in solid solution. The ferrite forms 0.1-0.3 mm large grains with etch pits, fine phosphide precipitates and frost ghost patterns. On top of this is some coldwork, which explains the high hardness. The slags are fine-grained, blurred wüstite-fayalite-glass inclusions with a high proportion of P_2O_5.

Of the twelve iron objects from Aggersborg, ten have metal structures and slag compositions that point towards a Norwegian origin. The sickle, A3-69 E, has an F-value of 7.0, which is higher than usual for Norwegian material, and the metal phase contains some nickel.

Also the arrowhead A3-760-D1 has a metal structure and a slag composition that make it difficult to place within either a Danish or a Norwegian reference frame. These two objects have apparently a southern origin, from some Frankish workshop in the Rhine area?

In the summer of 1988 a cemetery from 1050-1100 A.D. at Nordre Grødbygård, Åker sogn, Bornholm, was partly excavated. Ten coffin nails from grave 24 were sectioned and analysed, Table 12.7. The analyses are arranged according to falling average FeO-content of the slag inclusions. It appears that all nails belong to one and the same lot of common stock, heterogeneous as always, but with internal slag harmony with respect to Al_2O_3, MnO, CaO etc, compare Chapter 7. The sections display a range of rather rapidly cooled ferrite, phosphorferrite and Widmanstätten structures, some of them slightly coldworked. The phosphorus ranges from 0 to 0.5% in solid solution, and carbon from 0 to 0.4%. The variation is natural and comes from the same bog iron ore, in which manganese and phosphorus occur irregularly within a limited area. The slag inclusions are mainly wüstite-glass mixtures, but occasionally magnesium-rich fayalite laths (-4% MgO) occur.

The suite of nails is interesting in showing the variation in metallic structures, hardness and slag inclusions that may be expected from one and the same bloomery site. This was presumably in southern Norway or in Scania.

Norway

In the period 600-1200 A.D. many bloomeries existed in Norway, both in Trøndelag (Stenvik 1991), Valdres (Narmo 1996), Hallingdal (Bloch-Nakkerud 1992), Oppland (Larsen 1991; 1992), Telemark (Martens & Rosenqvist 1988) and Østerdalen-Gråfjellet (Narmo 1997; Stene 2004). Slags and iron objects from a few of these sites have been available for the present study.

In Table 12.8 production slags from well-examined bloomery sites in Telemark, Oppland and Trøndelag are presented. The first five entries are from Hovden, a small island in Lake Møsvatn, Telemark, situated about 950 m a.s.l. (above sea level). The next two are from bloomeries ½ to 1 km inland from the coastline of the same lake, while Hardingbukti is located at Holvik at the lake's eastern end (Martens & Rosenqvist 1988). In their paper are extensive analyses of slags, also for trace elements, and of the bog iron ores around the lake. These were found to be low in manganese, magnesium and phosphorus (ibid:165-168).

The slag analyses lines 1-8 represent a period of about 600 years. The first slag is from an oval "hellegryte", a flag-stone-lined bowl furnace Fig. 182[1]. The next four are from a much later shaft furnace built inside a three-walled house. The fourth side of the house was open to the slag heap. The Erlandsgård slag is from a a shaft furnace with tapping facility, while the Vestre Langhaugen slag is a tapslag from a well-preserved "hellegryte", a bowl furnace. The structure of the slags from the two "hellegryte" occurrences is different from the normal slags from the shaft furnaces. They have a very high proportion of FeO and, in addition, they contain minute grains of free iron, which points to a special process. The "hellegryte" furnace type should be further studied.

Table 12.8. SEM-EDAX analyses of production slags from Norway

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	14.6	76.3	1.8	0.1	0.2	1.4	4.4	0.6	0.2	0.1	0.3	100	3.32
2	18.5	68.6	0.3	-	0.2	1.2	9.1	1.2	0.4	0.2	0.3	100	2.03
3	24.2	59.3	1.2	-	0.3	1.8	9.9	1.9	0.7	0.3	0.4	100	2.44
4	26.5	58.4	1.4	0.1	0.3	1.4	8.9	2.0	0.5	0.2	0.3	100	2.98
5	29.6	57.5	0.2	-	0.2	1.3	8.1	2.4	0.3	0.2	0.2	100	3.65
6	32.6	52.1	0.9	-	0.2	1.6	9.5	2.1	0.3	0.4	0.3	100	3.43
7	14.3	76.6	0.3	-	0.2	1.6	5.5	0.8	0.3	tr.	0.4	100	2.60
8	28.6	59.5	0.7	-	0.2	1.9	6.2	1.8	0.6	0.2	0.3	100	4.61
9	22.9	61.7	5.9	1.3	0.2	1.9	4.3	0.7	0.1	0.4	0.6	100	5.33
10	27.5	50.8	4.4	-	0.5	2.6	10.7	2.2	0.5	0.5	0.3	100	2.57
11	28.4	48.1	7.3	0.5	0.2	2.3	10.1	1.9	0.3	0.7	0.2	100	2.81
12	29.7	50.2	2.0	-	0.2	2.7	11.7	2.0	0.7	0.6	0.2	100	2.54
13	37.6	43.7	5.2	-	0.1	1.6	8.3	2.1	0.5	0.7	0.2	100	4.53
14	36.0	47.0	4.7	-	0.1	1.5	7.4	2.0	0.5	0.6	0.2	100	4.86
15	28.9	58.4	1.7	-	0.1	1.3	6.7	0.9	0.6	0.4	1.0	100	4.31
16	29.7	49.1	0.3	-	0.7	5.2	7.5	3.0	2.3	0.3	0.1	100	3.96
17	28.8	45.1	0.4	-	3.0	4.9	10.0	5.0	2.2	0.4	0.2	100	2.88

1. Søndre Hovden, Møsstrond. 47/35 No. 14. C 34526. 250 g slag from "hellegryte". 500-600 A.D.
2. ibid. 47/35 No. 5. C 34524 d 2. 96 g production slag from shaft furnace. 1000-1100 A.D.
3. ibid 47/35 No. 5. C 34524 d 3. 80 g production slag from the same furnace.
4. ibid. 47/35 No. 5. C 34524 d 1. 120 g production slag from the same furnace.
5. ibid. 47/35 no.5. C 34524 d 4. 45 g part of imperfect bloom from the same furnace.
6. Erlandsgård, Møsstrond. 56/32 No. 3. C 33971 k. 80 g tapslag from a shaft furnace. 900-1100 A.D.
7. Vestre Langhaugen, Møsstrond. 50/30 No. 6. C 32692. 222 g slag from "hellegryte". 700-900 A.D.
8. Hardingbukti, Holvik, Møsstrond. C 33241. 12.4 kg iron bloom. 800-1200 A.D. HV: 102-107-109-114-133.
9. Dokkfløyvann, Oppland. DR 222. C 37476. 65 g production slag. 400-600 A.D.
10. ibid. DR 59. C 37462 h. 154 g production slag. 1000-1300 A.D.
11. ibid. DR 44. C 37453. 106 g production slag, tapslag. 1000-1200 A.D.
12. ibid. DR 187. C 37471 å. 13 g tapslag. 1000-1200 A.D.
13. ibid. DR 36. C 37449 t'. 21 g tapslag.1260-1290 A.D.
14. ibid. DR 36. C 37449 t''. 12 g tapslag. 1260-1290 A.D.
15. Storbekken, Budal, Sør Trøndelag. 450 g production slag, IV. Tapslag. About 1000 A.D.
16. Bergens Museum, BM 245x1497. 725 g planoconvex purification slag. 1000-1200 A.D.
17. ibid. BM 245x2189. 328 g planoconvex purification slag. 1000-1200 A.D.

Slag C 34524 d 4 is much more rusty and crumbling than the other slags. It is because it is rich in free iron, displaying the initial stages of bloom formation, Fig. 103. The slags are in general wüstite-rich, fayalite-glass mixtures. The fayalite is rather pure, but does contain up to 4% MnO in C 34526.

Fig. 343. Section through an imperfect bloom, Søndre Hovden, C 34 524, d4. Wüstite particles have nucleated upon major iron nodules (white). The rest of the slag is fayalite laths in glass. PS. SEM. Scale bar 0.1 mm.

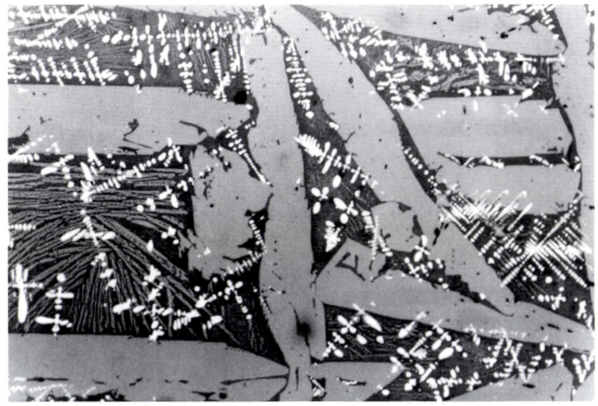


Fig. 344. Section through a 80 g tap slag from Erlandsgård, C 33 971 k. Fayalite laths and fine-grained matrix of fayalite, wüstite and glass. PS. Side length 0.6 mm.

In Telemark a number of characteristic, massive iron blooms, weighing from 2.8 to 13.5 kg, have been found. They often occur in hoards, and since they lack datable objects they have been very difficult to place in an archaeological context (Hauge 1946). According to Martens (1979) they are soft wrought iron

Table 12.9. Norwegian cleft blooms, so-called Fellujern
From Hauge 1946, Martens 1979 and own observations

Mus.No.	Find-spot	Dimensions cm	Wedge opening, cm	Weight kg	Specific gravity	Notes
C 33241	Hardingbukti, Møsstrond, Telemark	26x23x12	4-5	12.45	6	Marks of tongs
C 25340-I	Edland, Grungedal, Telemark	25x18x10		11.6	7	
C25340-II	ibid	24x17x11	8	10.0	7	H.p.149
C 25340-III	ibid.	23x17x11		9.8	6.8	Marks of tongs
C 25340-IV	ibid.	21x16x11	4	9.4	6.5	
C 33586-I	Løyningbukti, Borse, Telemark	23x18x9		9.85	7	Marks of tongs
C 33586-II	ibid.	22x16x11		9.75	6.5	Marks of tongs
C33586-III	ibid.	28x22x8	4	13.45	6.5	Marks of tongs
C 33586-IV	ibid.	23x21x12	6	13.35	6.5	Marks of tongs
Berg.Museu	Fyresdal Kommune, Telemark	20x17x12	5	8.5		
C 34847	Øyane, Fyresdal, Telemark	19x15x11		6.7	7	Marks of tongs
C 34850	Unknown	17x13x8	3-4	6.85		M. p. 193
?	Olesrud, Nyland, Tinn, Telemark	24x16x3½	6	6		H.p.154
C 28282	Nordstrand, Lunde, Nome, Telemark	20x15x6½	7	5.1	7	Slightly hammered
C 34846	Li, Gransherad, Notodden, Telemark	19x12½x5	5-6	2.83		H.p153, M.194
C 22615	Skeibrok, Lista, Farsund, Vest Agder	18x13x5	4	4.0	7	M.p.194
?	Søndre Oreberg, Sande, Vestfold	15x11x7½		5?		Lost, M.p.191

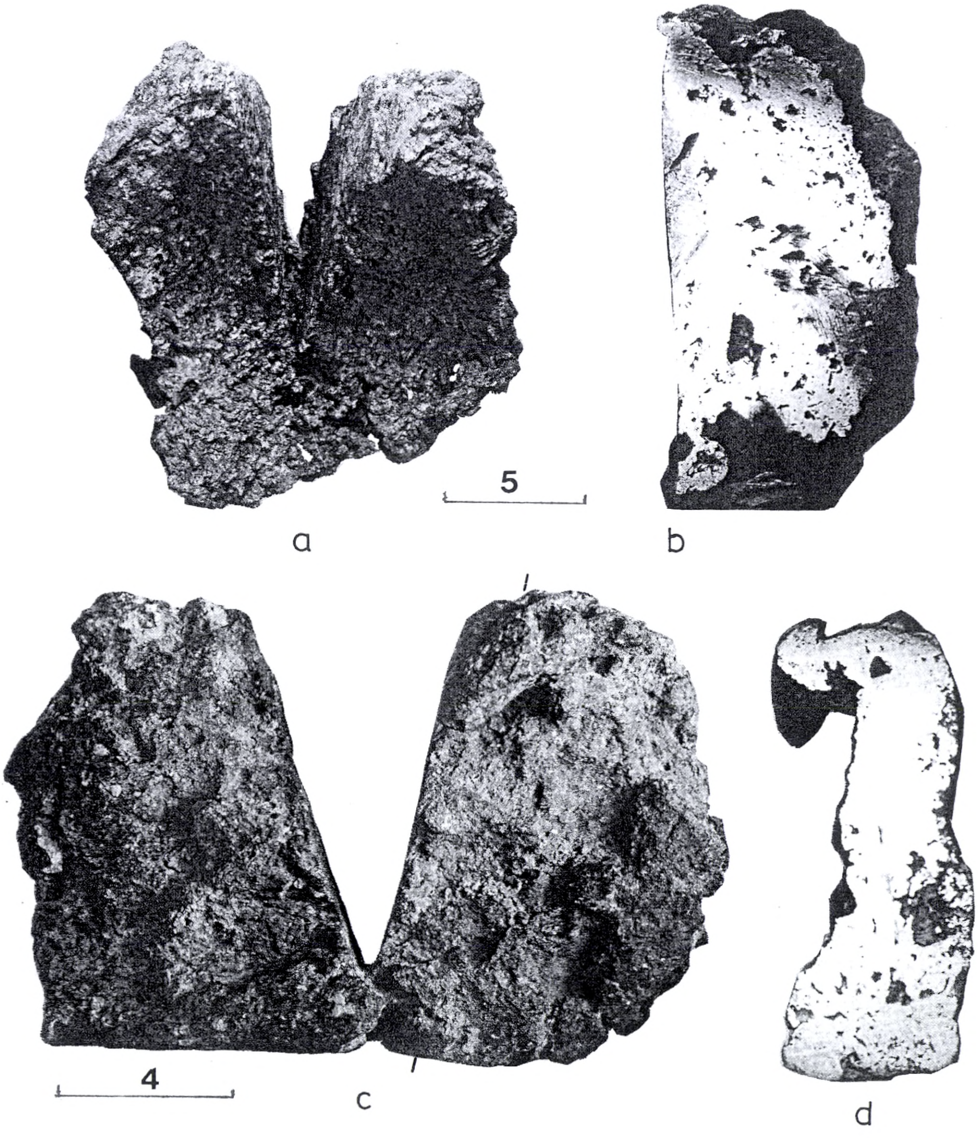


Fig. 345. Two Norwegian cleft blooms, or Fellujern. **a, b,** the 12.45 kg Hardingbukti, C 33 241. **c, d,** the 2.8 kg Li, C 34 846. The figures to the right are cut and polished sections. Scale in cm. Adapted from Martens 1979.

types, with local surficial carbon-enrichment. They have a convex underside and may have been a product of the shaft furnaces at Møsstrond, since their diameter, 15-25 cm, fits well with the bottom shape of these shaft furnaces. A list of known blooms is presented in Table 12.9.

Hardingbukti, Table 12.8, line 8, and Table 12.9, line 1, is one of these blooms, Fig. 345[a-b]. It weighs

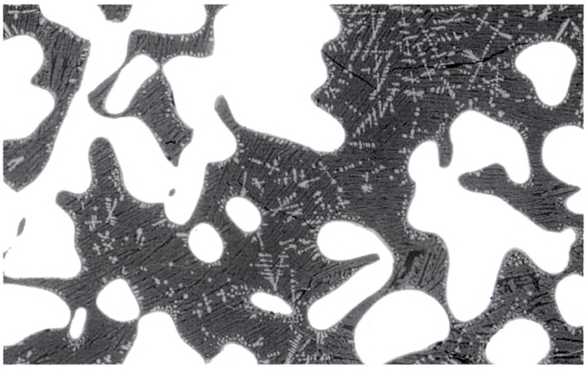


Fig. 346. Section through the 12.45 kg bloom from Hardingbukti, C 33 241. Ferritic, phosphor-free iron surrounded by wüstite-fayalite-glass slag. PS. Side length 0.25 mm. Courtesy Struers.

12.45 kg and has like the others a characteristic axe cut which nearly splits the bloom into two halves. Its maximum dimensions are 26x23x12 cm, and the specific gravity is about 6.0 g/cm^3. The relatively low value is due to several internal holes and some slag inclusions, which could be seen when the bloom was sectioned into 2.8, 2.6 and 7.0 kg part specimens. The bloom is bowl-shaped with a convex underside and a concave topside, as if the iron master had compressed and stamped on it when it was still on the bottom of the furnace and was plastic. On opposite sides there are indistinct marks of the tongs with which the bloom was held when a helper cleft the glowing hot massive iron with an axe.

The slag inclusions in the bloom consist of 25% wüstite dendrites in a submicroscopically duplex matrix. When the slag solidified, numerous wüstite crystals nucleated on the iron walls. The metal phase is partly coherent, partly occurring as islands and lace- and networks in the typical initial phases of bloom building, Fig. 103. The metal is rather pure ferrite, with less than 0.05% C and P, and with grain sizes from 25 to 500 μm. The hardness is correspondingly low.

The slag composition of the Hardingbukti bloom and the structure is so similar to the slags from the shaft furnaces at Hovden and Erlandsgård, that it must be concluded that the iron was produced in one of these bloomeries, as was already proposed by Martens (1979: 195; 1988:110). Since many of the shaft furnaces have by now been well dated by the C-14 method to about 800-1200 A.D., the uncertainty as to the dating of these cleft blooms has disappeared. They belong to the Viking Age and the two following centuries. It is highly likely that the other cleft blooms of Table 12.9 were also produced around Møsvatn, and on their way to the trading centres for some unknown reason were left in hoards or depots in Telemark, south and east of the production sites, see the map Fig. 252.

On inspecting the cleft blooms indistinct marks of tongs can be seen on some of them, as noted in Table 12.9. If we assume that the bloomery cake was first manipulated on the bottom of the furnace with a massive wooden stake, in order to expel some of the slags, it would achieve a slightly hollowed, concave top side as is in fact observed on many of them. Then the helper would grip the cake with tongs and hold it upright on an anvil or stone while the iron master immediately would cleave the glowing mass with a heavy axe. If the mass was lifted up and was left to itself without cleaving, it was called a blæsterjern, if it was also cleft it was called a fellujern and commanded a slightly higher price (+20%) (Jonsbok, Grágás). The Norwegian and Icelandic (Vigfusson 1882) practice was to open the bloom with only one axe cut. We shall later see that the Danish practice required three cuts, so the bloom would acquire four fingers, The Danish four-fingered version was called a klode (Buchwald 1991), and the individual fingers were called klimpjern. They were in use as late as the 16th century.

Dokkfløyvann is about 180 km NE of Møsvatn in the Oppland Fylke (province), and lies in a different geological setting of metamorphic Cambro-Silurian rocks (Holtedahl 1960: 151). The bog iron ores give rise to furnace slags which are rich in manganese and titanium and thus rather different from the Møsstrond slags, see Table 12.8. The slags are from five different bloomery sites, representing a time frame of about 700 years (Larsen 1991). But the time and the furnace type have not influenced the slag compositions, which are chiefly governed by the ore. The slag block, line 9, is a repetition of the slag already discussed in Chapter 10 (Table10.1, line 2), but it is included again here to show the continuity over time in slag compositions.

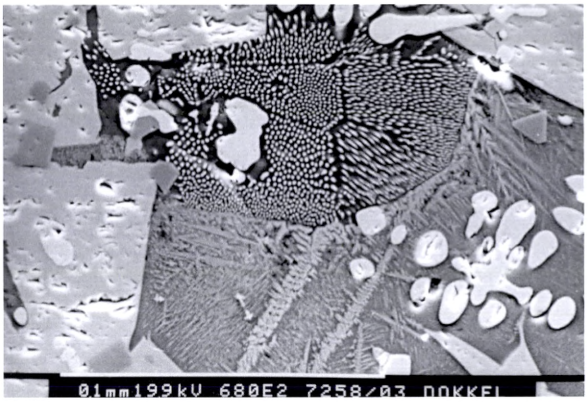


Fig. 347. Section through a tap slag from Dokkfløyvann, C 37 453. A central leucite-wüstite pocket, surrounded by wüstite-dendrites, edgy hercynite crystals, large fayalite blocks and fine-grained, matte matrix. PS. SEM. Scale bar 0.1 mm.

C 37462 h is from a shaft furnace with slag tapping. This particular slag had adhering parts of the furnace wall, the composition of which was presented in Table 9.7. The slag is 15% wüstite, 70% fayalite and 15% matrix in which there are occasional hercynite crystals.

C 37453 is a slag from the typical Dokkfløyvann-furnace, type III (Larsen 1991: 97). On the top of a gentle slope, 2 or 3 coal pits are located, followed lower down by a flagstone-covered working floor, inside which 2 or 3 shaft furnaces have been dug parallel with the coal pits. The slag heaps are found on either side of the furnaces, and a house is situated below the site. The tapslag from here is 10% wüstite, 50% fayalite (25 μm thick laths) and 40% duplex matrix with local leucite pockets. The leucite contains most of the barium.

C 37471 å is a 13 g tapslag from a shaft furnace with only one associated coal pit. The slag is divided into several zones because new runs have enveloped the initial streams. The slag is half fayalite, half duplex matrix with many 10-15 μm hercynite crystals. In these there is some chrome-, titanium- and vanadium substitution (-0.4% Cr_2O_3, -1% TiO_2, -0.9% V_2O_5).

C 37449 t' and t'' are two tapslags from the typical Dokkfløy arrangement, type III B, with three coal pits and three shaft furnaces. The furnaces are rather late, belonging to the last phase before (all) iron production around Dokkfløyvann came to a full stop due to the plague, which was very severe in Norway in the 1350s. The slags are wüstite-free, half fayalite, half duplex matrix. On the underside some mineral grains from the soil have been partially absorbed. The grains are feldspars and some ilmenite, $FeTiO_3$, which helps to explain the local rather titanium-rich iron ore.

The next slag in Table 12.8 comes from Storbekken, Trøndelagen, from a furnace geographically close to the furnace treated in Table 10.1, but much younger. The slag is a massive tapslag with a ropey surface, Fig. 138. It consists of 5% wüstite and equal amounts of fayalite (30 μm laths, -2% MnO, -2% MgO) and duplex matrix. The slag composition is similar to the contemporaneous Møsstrond slags, Table 12.8, lines 2-6, though perhaps with a little less phosphorus and more aluminium. Perhaps the Trøndelag ores belong to the most phosphorus-poor ores in Norway?

The two last slags of Table 12.8 are kalot slags from the early city of Bergen. They are purification slags of the typical planoconvex type and come from a large collection of similar slags in the Bergen Museum (Brinch Madsen, pers.comm.). They consist of about 20% wüstite dendrites, 30% magnesiafayalite laths (40-80 μm wide, -11% MgO!) and 50% duplex matrix, i.e. glass with feathery fayalite skeleton crys-

Fig. 348. Section through a tap slag from Dokkfløyvann, C 37 471 å. Numerous edgy hercynite crystals, bulky fayalite and duplex matrix. PS. SEM. Scale bar 0.1 mm.

tals. Some leucite pockets, $KAlSi_2O_6$, are also present. In the slags there are occasional 10-40 μm unconsumed iron particles. The presence of many kalot slags in Bergen indicates that numerous iron blooms from the Norwegian production sites in the inland seters have been transported to the city for purification and further processing to finished iron objects. This activity required much fuel in form of wood from the adjacent forests. It is unfortunately not yet possible from the purification slags to deduce the origin of the parent blooms, other than that they are of Norwegian origin.

It appears that similar workshops were also active in Trondheim about 1150-1350 A.D., since a number of planoconvex slags have been found here and have been examined (Espelund 1992). The iron blooms that were purified in Trondheim probably came from Storbekken, Table 12.8, line 15, and similar bloomeries.

Apart from the iron bloom from Hardingbukti, there are not many iron objects from the period that it has been possible to study. The nails and nail-like objects, which are entered in Table 12.10, all come from recent archaeological excavations, but even if many have been found on bloomery sites, it is not at all certain that they were produced there.

The first four objects are from a Viking Age boat grave (800-900 A.D.) from Valler, Eidanger Church, 5 km SE of Porsgrunn, on the coast. Two and two the boat nails are similar in slag composition and hardness. Two nails and a flat iron piece are from a house ruin at Søndre Hovden, Møsstrond, that may be dated to 1100-1300 A.D. (Martens & Rosenqvist 1988: 160). No. 8 is

Table 12.10. SEM-EDAX analyses of Norwegian nails

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	24.1	55.9	6.1	-	1.2	2.5	7.9	0.9	0.7	0.3	0.4	100	3.05
2	29.0	52.4	5.8	0.6	1.4	2.3	5.7	1.0	0.9	0.1	0.8	100	5.09
3	31.6	45.5	0.4	-	3.8	4.6	8.7	2.1	2.0	0.8	0.5	100	3.63
4	28.7	45.0	0.5	-	9.0	4.2	7.0	1.7	2.2	0.7	1.0	100	4.10
5	10.5	82.9	0.7	-	0.4	1.7	2.0	0.5	0.9	0.2	0.2	100	5.25
6	21.6	62.8	3.0	0.3	1.3	2.6	5.0	1.2	0.8	0.3	1.1	100	4.32
7	32.9	45.4	0.3	-	2.9	6.2	8.0	2.6	0.8	0.5	0.4	100	4.11
8	20.2	57.9	4.1	0.2	1.9	4.2	7.9	1.4	0.9	0.4	0.9	100	2.56
9	20.4	64.6	1.2	-	1.1	3.0	7.0	1.1	1.1	0.3	0.2	100	2.91
10	28.0	54.1	1.7	-	2.3	3.8	6.5	2.3	0.8	0.1	0.4	100	4.31
11	12.2	80.7	1.1	-	0.2	1.0	2.9	0.6	1.0	0.1	0.2	100	4.21

1. Valler, Porsgrunn. C 28429 h3. 7.6 g nail. Widmanstätten structure. 0.1-0.4%C. HV: 133-146-156-161-162.
2. ibid. C 28429 h1. 7 g boat nail. Phosphorferrite, Widmanstätten structure HV: 166-170-177-181-227.
3. ibid. C28429 h2. 5.7 g boat nail. Ternary Fe-C-P, 0-0.4%C, 0-0.3%P. HV: 172-176-186-223-274.
4. ibid. C 28429 h5. 4.9 g boat nail. Phosphorferrite. HV: 208-220-231-232-268.
5. Sdr. Hovden, Møsstr. C 31339 q3. 4.3 g nail. Ternary Fe-C-P, 0-0.2%C, 0-0.2%P. HV: 117-124-131-145-153.
6. ibid C 31339 q2. 5.8 g nail. Widmanstätten structure, 0-0.35%C. HV: 161-169-175-186-253.
7. ibid. C 31339 q1. 12.8 g iron piece. Ternary Fe-C-P, P-ghost. HV: 153-161-175-204-211.
8. Erlandsgård, Møsstrond. C 33971 da. 3 g rivet plate. Phosphorferrite, 0-0.2%P. HV: 121-138-140-153-159.
9. Dokkfløyvann, Oppland. C 37462 a. 8 g iron pin. Phosphorferrite, Neumann bands. HV: 131-138-140-147.
10. ibid. C 37471 a. 5 g horseshoe nail. Phosphorferrite. HV: 106-107-113-113-133.
11. ibid. C 37449 d. 4.8 g horseshoe nail. Coldworked ferrite-pearlite. HV: 116-137-160-216-257.

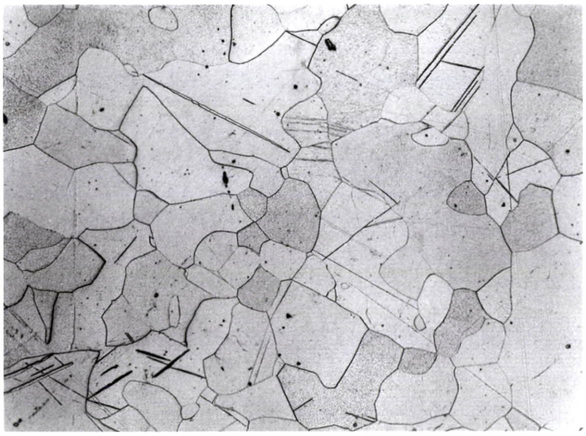


Fig. 349. A section through an 8 g iron pin from Dokkfløyvann, C 37 462 a. Ferritic grains with numerous Neumann bands from cold-hammering. PES. Side length 1 mm.

a rivet plate from Erlandsgård, dated 1000 A.D., but its slag composition has little to do with the furnace slag from the same place, Table 12.8, line 6. Nos.9-11 are three iron objects found on furnace sites at Dokkfløyvann and dated to1000-1300 A.D. Two horseshoe nails appear now for the first time in the material, although we met horseshoes already in Table 12.5.

It is difficult to relate the eleven objects to a particular iron production district, the more so because there are other Norwegian bloomery sites than the few ones here examined. Evaluating from the level of manganese. magnesium, calcium and aluminium in the slag inclusions it may be cautiously proposed that Nos. 1, 2, 6, 8, and 10 derive from the Dokkfløyvann – Beitostølen area, while Nos. 3, 4, 5, 7, 9, and 11 may come from the Møsvatn area.

Sweden

In central Sweden iron handling continued and was quite extensive in Dalarna (Serning 1973: 11), Närke (Hansson 1989), Västmanland (Löthman 1993), Hälsingland (Magnusson 1994), and Vester Götland (Magnusson & Millberg 1982; Englund 2002). North of these centres, important bloomery sites have been excavated in Jämtland (Magnusson 1986), which in these centuries and later was strongly oriented towards Trøndelagen in Norway. South of them there was much activity in Småland (Berglund 2000) and some limited production in the provinces of Halland (Strömberg 1995) and Scania (Thun 1967), both of which, like Jämtland, in the later part of the period became included in the Danish kingdom.

Hyenstrand (1979) has suggested that Sweden in the Younger Iron Age-Viking Age could be divided geographically into iron-producing districts and iron-consuming districts. Most agricultural tools were still based on wood, but the period saw a clear rise in the application of sickles, scythes, iron shares (ards), iron-clad spades, axes and knives. Myrdal (1982) has surveyed the development of farm implements and practices in Sweden up to 1000 A.D. and compared it to contemporary European practices.

When the churchyard in Vendel, 32 km north of Uppsala, was enlarged in 1881, a splendidly furnished boat grave was discovered. Continued investigations revealed a total of 14 boat graves within a narrow area, and a new name in Swedish archaeology was coined: The Vendel period, 550-800 A.D. In 1893 a similar gravefield was detected at Tuna in Alsike, and in 1928 another one at Valsgärde, Gamla Uppsala. The two new sites each comprised 14-15 boat graves. In the about 10 m long boats the deceased chieftain was surrounded by his weapons, daily utensils, horse, dog, and provisions for future travel. The lavish bronze, silver and gold objects were decorated in the specific Vendel style, rich in stylized animals.

It appears that the rich families living around Uppsala had based their life on iron handling and trade in iron. There are many iron slag heaps associated with the Vendel- and Valsgärde farms, and they have been C-14 dated to the Vendel period. A discussion of the Vendel period, including a comparison with the Sutton

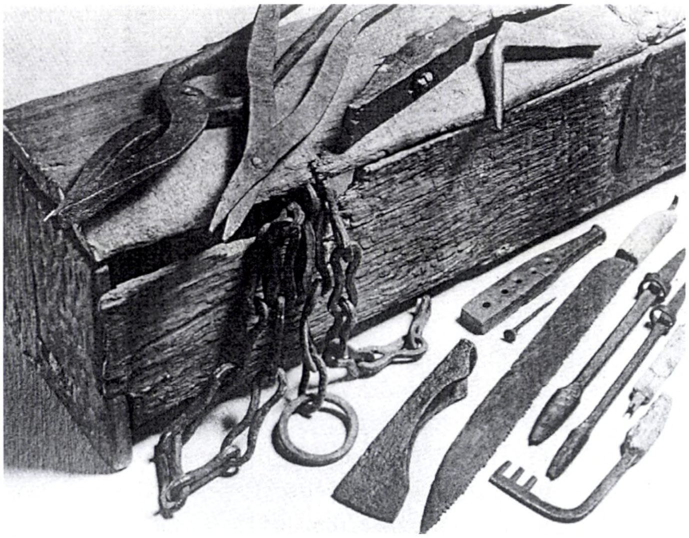


Fig. 350A. The Mästermyr find, Gotland. Oak chest, chain, axe, nail-iron, nail, saw, two augers (Danish, skebor), key, tong, scissors, hammer.

Fig. 350B. The Bygland find, Telemark. Hammers, tongs, chisels, an anvil and a draw plate.

Hoo boat grave in England, may, e.g., be found in Sandwall (1980).

Significant studies of iron objects from the period 600-1200 A.D. have been published on, e.g., knives from Helgö and Birka (B.Arrhenius 1970; Tomtlund 1973), lanceheads from Västmanland (Modin & Thålin 1969), and various objects from Scania (Thomsen 1971 a). The phosphorus content of a large number of objects was examined by O. Arrhenius (1959), and also iron bars, locks, keys and other objects from Helgö have been thoroughly examined (Lamm & Lundström 1978). Petersen (1951) examined and catalogued a large range of Norwegian tools from the Viking Age.

One of the most important finds of iron objects in Scandinavia took place in 1936, when an oak chest, full of tools, was excavated at Mästermyr, Gotland. Apparently the chest had been lost in the ancient lake about 1000 A.D., perhaps when the ice cover collapsed under a sledge. In the chest there were two large bronze kettles, a fire grid, bells, chains, a steel yard, padlocks, keys, and a variety of tools: Tongs, hammers, small anvils, saw blades, files, adzes, axes, augers, nails, nail irons, or draw plates (unfinished), scrapers, and chisels (Oldeberg 1966: 70; Thålin-Bergman 1981; Arwidsson & Berg 1983). The bells were too large to be bells for the cattle and may have been manufactured for liturgical purposes. They were made from hammered, folded and riveted iron plate, that finally had been copper-clad, compare the Aznalcollar bell, Chapter 10, p. 260.

In the chest there were also two elongated iron bars, type examples of the trading half product later called the Mästermyr bar (Hallinder 1978). They weighed 906 and 872 g and measured respectively 51x(4.6-2.8)x(1-0.5) cm and 48.5x(4.4-3.0)x (1-0.3) cm. Mästermyr bars have also been found in Haithabu, 16 full bars and two fragments having been studied by Thomsen (1971 b). They have further been found in Århus (Andersen et al.1971:123), at Trelleborg (Nørlund 1948, Plate 46[10]), and at Nosaby, Kristiansstad, Scania (Hallinder 1978:54). Thomsen (1971b), who examined three different bars, found that they were soft wrought iron, mainly ferritic, but of the usual heterogeneous nature. There was little phosphorus in the iron, <0.09%, and no attempt at quench-hardening was detected. The Mästermyr bars are apparently a half product of wrought iron, belonging to the Viking Age only, and geographically limited to Denmark and southern Sweden. They were, however, hardly produced in Denmark.

Other important finds of tools have been made in a Norwegian grave from the 10th century, the Bygland grave, Morgedal, Kviteseid, Telemark (Blindheim 1963) and at Veksø, Sjælland (Engberg & Buchwald 1995), the last one was difficult to date more precisely than to the 12th or 13th centuries.

In Table 12.11 there are a number of slags from Västmanland, Småland and Väster Götland. The Axamo slag is from an iron-handling site, 6 km west of Jönköping (Nordmann 1994). The preliminary date of the site was confirmed by an interesting new dendrochronological examination of charcoal (pine) from the twin furnaces, which showed that the furnaces had been in operation about 1120-1150 A.D. (Bergenblad 1998). The slag here examined is a typical purification slag, step 3 (Table 4.4), with about 30% wüstite, 60% calcic fayalite (-1.8% CaO) and 10% matrix. There are scattered iron particles, 10-50 μm across, inside the slag.

The Tranemo slags are from excavations carried out 1987-1989 by Englund (2002), 36 km SE of Borås. The clay-built shaft furnaces were small, only 25-35 cm in inner diameter, but the best preserved had up to 70 cm high shafts. They are like inverted cones, i.e.a few centimeters wider at the top than at the bottom, probably to facilitate the removal of the bloom from above.

The Tranemo furnaces usually occur in pairs, only 0.5-1m apart, and have openings for tapping. Each pair of furnaces is framed by a common stone wall. Not far from the furnaces there are several coal pits, in which surviving charcoal could be identified as pine. The ore was found within 100 m of the furnaces and

Table 12.11. SEM-EDAX analyses of slags from Sweden

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sun	F
1	44.1	36.8	1.1	0	1.3	13.7	2.1	0.4	0.3	0.2	100	3.22
2	19.3	71.7	0.4	0.8	2.3	3.7	0.9	0.4	0.1	0.4	100	5.21
3	25.5	63.4	0.6	0.3	2.9	4.6	1.5	0.7	0.1	0.4	100	5.54
4	25.5	62.5	0.9	0.3	2.8	5.2	1.7	0.5	0.1	0.5	100	4.90
5	27.8	59.2	0.6	0.4	3.3	5.7	1.8	0.6	0.1	0.5	100	4.88
6	24.4	49.5	1.5	0.2	2.6	8.3	2.4	0.5	0.3	0.3	100	4.14
7	27.5	59.4	1.9	0.6	1.3	7.1	1.3	0.5	0.1	0.3	100	3.87
8	28.7	58.6	1.2	0.2	2.1	6.2	1.8	0.5	0.3	0.4	100	4.63
9	31.4	55.7	1.6	0.3	2.2	5.9	1.7	0.5	0.1	0.6	100	5.32
10	33.7	50.6	1.7	0.1	2.9	7.5	2.4	0.5	0.4	0.2	100	4.49
11	25.5	64.4	0.6	0.3	1.6	5.6	1.4	0.4	0.1	0.1	100	4.55

1. Röda Jorden, Riddarhyttan, Västmanland. 337 g tapslag. 1000 A.D.
2. Axamo, Jönköping, Småland. 50 g purification slag. 1100-1150 A.D.
3. Tranemo, Väster Götland. RAÄ 266. I. 350 g production slag, furnace bottom. 900-1300 A.D.
4. ibid. IV. 90 g tapslag. Fine-grained.
5. ibid. III. 80 g tapslag. Fine-grained.
6. ibid. VI. 250 g production slag.
7. ibid. Englund experimental furnace No. 30. 250 g production slag.
8. ibid. 75 g tapslag. Fine-grained.
9. ibid. 125 g part bloom.
10. ibid. 25 g part bloom, "järnrusa".
11. Örsås, Väster Götland. RAÄ 27. No. 27:2. 1386 g multilayered tapslag. 1150-1280 A.D.

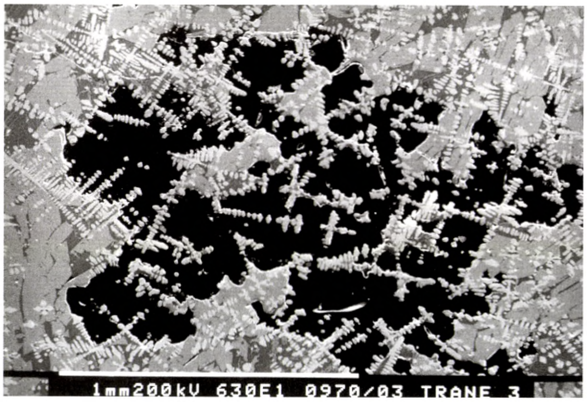


Fig. 351. Section through the top of a tap slag, No. III, from Tranemo. The primary wüstite dendrites protrude into a void that was drained from slag early in the solidification process. PS. SEM. Scale bar 1 mm.

consisted of an iron-rich (about 60% iron) rather pure red soil. This is also obvious from the slag analyses, Table 12.11, lines 3-6, where particularly the low manganese, titanium and phosphorus values are striking.

In order to improve the understanding of ancient bloomery iron production, a long-term experimental project was initiated in 1993 (Englund 2002: 206). From the experimental furnace No. 30 four slags have been examined, lines 7-10. The same red soil ore as had been used in ancient times was also used in the experimental runs, and it is seen, by comparison with lines 3-6, that the new slags correspond well with the old ones, except for the manganese content. Blooms weighing about 1.6 kg were forged into 0.4 kg bars. These were further transformed into nails and hooks, and some were drawn to a wire, 2mm in diameter. Apparently the iron was a soft wrought iron quality with less than 0.05% C.

The last line of Table 12.11 is an ancient slag from Örsås, 15 km west of Tranemo, where pairs of shaft furnaces were excavated (Englund 2002: 192). The slag is a multilayered tapslag with 25% wüstite, 50% fayalite and 25% duplex matrix. There are scattered 10-50 μm iron particles, occurring with about 5 per 10 mm^2. The furnaces and the slags are very similar to the Tranemo occurrence. Slags from secondary smithing such as hammer scales have not been detected in any of the excavated sites. Probably because the primary bloom was transported to the farm smithy, or to somebody else's smithy to be further processed.

The Tranemo furnace type was common in the Viking Age and the early Middle Ages. We will meet it again in Jernvirke, Halland, and it was also common in Väster Götland between Skara and Skövde (Magnusson & Millberg 1982) and at Axamo, Småland (Bergenblad 1998). Similar furnaces are found in isolated examples all the way up to Jämtland. Otherwise the furnaces seem to have had a mainly western distribution, with finds in western Germany, France and Switzerland (e.g.Sönnecken 1994).

Tommarp is a small church town in Scania at the southeastern extremity of Sweden, only 8 km from the Baltic Sea. In 1100-1300 A.D., when the iron objects of Tables 12.12 and 12.13 were produced, Skåne was a very important and rich part of the Danish kingdom. In 1959-1960 land belonging to the property Hemmet was excavated by Lund's University (Thun 1967). In the areas designated G and L quite a few finished and unfinished iron objects were found, apparently in the vicinity of smithing hearths and some anvil stones. By the kind cooperation of Anders Ödman, Historisk Museum at Lund, some of the finds could be examined.

Tommarp 191 II is a wedge-shaped, compact bar,

Fig. 352. Another view of the same slag, but deeper in from the surface. Wüstite dendrites (white), fayalite (grey) and the last solidified duplex matrix. PS. SEM. Scale bar 0.1 mm.

Table 12.12. SEM-EDAX analyses of slags and iron objects from Tommarp, Scania

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	28.1	56.7	3.7	2.3	1.6	4.8	1.9	0.3	0.3	-	0.3	100	5.85
2	28.2	48.4	0.9	2.9	9.8	5.5	2.6	1.1	0.3	-	0.3	100	5.13
3	23.6	47.4	1.7	3.9	4.0	10.1	4.8	1.2	0.6	0.1	2.6	100	2.34
4	22.5	69.1	0.2	0.2	1.3	4.4	1.6	0.2	0.3	-	0.2	100	5.11
5	30.5	59.6	0.3	0.6	1.5	5.3	1.4	0.3	0.3	-	0.2	100	5.75
6	34.1	52.7	0.1	1.6	2.5	5.8	2.4	0.3	0.4	-	0.1	100	5.88
7	30.1	50.3	0.7	0.8	3.0	11.6	1.5	1.1	0.5	0.2	0.2	100	2.59
8	34.5	43.7	3.3	0.6	4.3	10.0	2.4	0.4	0.5	0.2	0.1	100	3.45
9	32.3	43.0	1.3	2.1	5.4	10.7	3.7	0.3	0.7	0.2	0.3	100	3.02
10	29.5	35.6	5.5	2.0	10.1	12.6	2.7	0.9	0.7	0.1	0.3	100	2.34
11	30.1	53.9	0.3	0.7	4.3	7.1	1.8	1.0	0.4	-	0.4	100	4.24

1. Tommarp, Hemmet, Scania. 191 II, 7504. 1097 g wedge-shaped bar. HV: 123-143-153-178-244.
2. ibid. 23 II. 38 g end of bar. Phosphorferrite, P-ghost. HV: 123-126-126-134-143.
3. ibid. L 27-35. 76 g part of bar. Coarse phosphorferrite. HV: 97-115-130-145-143.
4. ibid. Purification slag. 142 g fragment of planoconvex slag. Corroded.
5. ibid. Purification slag. 99 g fragment.
6. ibid. 126 II. Purification slag. 250 g planoconvex slag.
7. ibid. 25396-1. 40.8 g nail. 15 100 μm ferrite. No phosphorus. HV: 85-93-99-111-123.
8. ibid. 25396-3. 14.7 g nail. Ferrite-pearlite. No phosphorus. HV: 148-156-169-193-209.
9. ibid. 25396-2. 21.8 g nail. Phosphorferrite, P-ghost. HV: 122-128-164-176-190.
10. ibid. 135 II. 66 g iron angle. Ferrite-pearlite. Phosphorferrite. HV: 123-124-130-134-148.
11. Vä, Skåne. 705 g planoconvex purification slag. 1150-1450 A.D.

measuring 17x6x1.5 cm, with a heterogeneous structure of alternating phosphorferrite (-0.6% P) and phosphorus-free ferrite-pearlite parts (0.3-0.7% C), Fig.

Fig. 353. Compact, heterogeneous, phosphorus-rich iron bar of 1097 g from Tommarp, 191 II-7504. Scale bar 8 cm.

Fig. 354. Section through a small, phosphorus-rich iron bar, Tommarp 23 II. The slag inclusions display imperfect wüstite dendrites in phosphorus-rich glass. PS. SEM. Scale bar 0.1 mm.

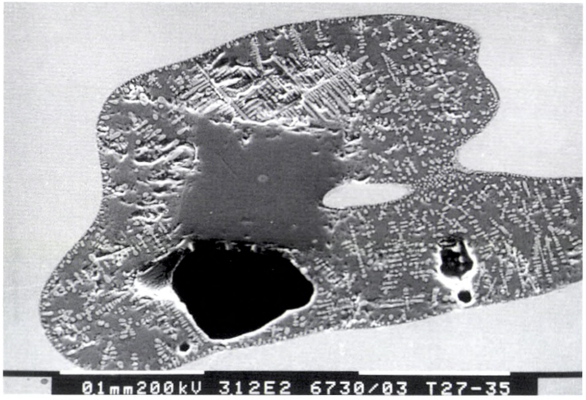


Fig. 355. Slag inclusion in another phosphorus-rich iron bar, Tommarp L 27-35. Wüstite dendrites in glass, and a 0.1 mm hercynite crystal $(Fe,Mg)(Fe,Al)_2O_4$ with chromium and vanadium. PS. SEM. Scale bar 0.1 mm.

353. The slags are all glassy, occasionally with a few wüstite dendrites. No. 23 II was in ancient times cut from a bar, perhaps in order to separate this phosphorus-rich part. The structure is rather homogeneous phosphorferrite with ghost-patterns, and about 0.4% P. No. L27-35 is a similar cut, with coarse phosphorferrite, appearing as 0.1-0.5 mm grains, with etch-pits and up to 0.6% P in solid solution. In the slag there are numerous whitish iron sulphide particles and scattered 50-100 µm hercynite crystals with 2.8% Cr_2O_3 and 0.4% V_2O_5. The three samples are the raw stock from which all the following iron objects have been forged. Interesting is the level of vanadium, which in a significant number of objects from Scania has been reported to lie above 0.1% V_2O_5.

Table 12.12, lines 4-6, displays three planoconvex purification slags found near smithing hearths. They have the characteristic structures of purification slags, and are relatively depleted of MnO and P_2O_5. They developed when blooms from elsewhere were purified to form bars of the type just mentioned in lines 1-3.

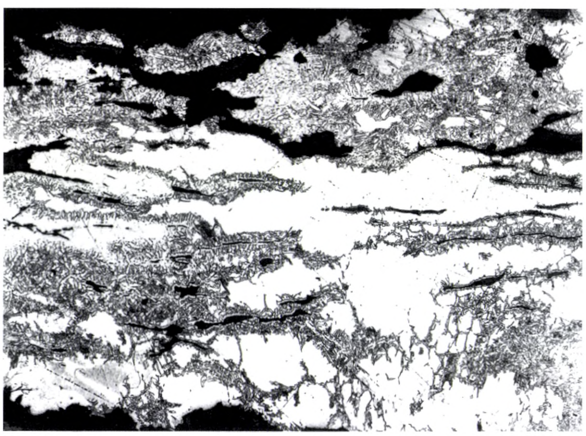


Fig. 356. Heterogeneous structure of the 15 g Tommarp tongue 774-1. Variations of phosphorus ghost structures with numerous glass slags. PES. Side length 0.45 mm.

Fig. 357. Wüstite dendrites in a slag inclusion in the Tommarp tongue 774-2. The glass matrix is under decomposition into a carpet of "feathery" imperfect fayalite crystals. PS. SEM. Scale bar 0.01 mm.

Table 12.12, lines 7-10, presents three nails and a fitting from the smithing activities on the site. The hardness of the nails ranges from 85 to no less than 209 HV, which must be considered high for a nail. The last line is a 0.7 kg planoconvex purification slag from the mediaeval trading centre and royal seat at Vä, 3 km south of Kristiansstad (Stjernquist 1951). Rather much of this slag type was found at the excavations in 1991. Also a piece of bar iron, measuring 25x6x3 cm was found (Ödman 1992). The slag is heterogeneous and has magnetic zones locally. The structure is about 30% fine wüstite, 40% fayalite and 30% matrix with

Table 12.13. SEM-EDAX analyses of slag inclusions in special phosphorus-rich minibars, the Tommarp tongues

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	26.3	56.9	1.4	2.7	2.1	7.1	2.0	0.8	0.4	-	0.3	100	3.70
2	26.1	55.1	4.7	1.0	2.8	5.8	2.3	1.0	1.0	-	0.2	100	4.50
3	23.0	54.5	5.2	6.8	1.6	5.0	2.3	0.6	0.5	0.1	0.4	100	4.60
4	24.5	50.8	5.0	7.5	2.1	5.6	3.0	0.7	0.4	-	0.4	100	4.38
5	32.9	48.8	1.0	1.4	5.8	5.6	2.5	1.0	0.5	0.2	0.3	100	5.87
6	38.9	33.4	9.7	1.6	3.8	7.7	3.3	0.9	0.4	-	0.3	100	5.05
7	29.0	44.9	2.8	7.0	5.0	4.8	3.5	1.8	0.4	-	0.8	100	6.04

1. 774-4. 15 g, 81 mm. Phosphorferrite, phosphide needles. HV: 86-91-93-118-118.
2. 774-5. 11.6 g. Phosphorferrite, P-ghost. HV: 134-135-136-139-139.
3. 774-2 C. 10.4 g. Phosphorferrite, P-ghost. HV: 137-166-190-191-205.
4. 774-2 B. the same, another section. HV: 149-166-185-200-209.
5. 774-3. 13.2 g. Phosphorferrite, P-ghost. HV: 139-145-159-169-178.
6. 774-1. 15.0 g. Phosphorferrite, P-ghost. HV: 198-210-234-238-249.
7. Eketorp's Borg, Öland. P 22-60. 16 g. Phosphorferrite. P-ghost. HV: 156-198-198-258-261.

scattered 10-20 μm iron particles. Inclusions of charcoal are not uncommon, Fig. 91.

The presence of purification slags and iron bars suggests that Vä was a site where blooms from northern Scania's bloomeries were purified and transformed into commercial items, which could be sailed down the Helgeå for delivery to distant parts of Denmark.

In Table 12.13 are assembled six tongue-shaped objects which already when found were considered rather unusual by Thun (1967: 13,42). According to the excavation report a total of 160 pieces were found. The average weight, before cleaning, was 20 g, and the dimensions were (7-9) x (2-2½) x (0.2-0.3) cm. Their shape reminds one of thin tongues, and with their unusual smooth chocolate brown colour they look like dark chocolate delicacies. Many, if not all, are bent at an angle, presumably done hot by the smith as a quality test, Fig. 176. The structure is phosphorferrite with 0.2-0.8% P and no carbon. Phosphor-ghost patterns are common, and etch-pits occur in the most P-enriched ferrite grains. The hardness is high, due to the significant phosphorus content, except for line 1, which instead is rich in precipitated phosphide needles. The hardness probably fell, because the super-saturated ferrite grains exsolved the superfluous phosphor atoms.

The phosphor tongues have been forged from bars such as lines 1-3 in Table 12.12 They were probably intended to be traded as a specific grade of iron which could be used as inlays in pattern-welded objects. When stacked with alternating soft iron and/or carbon steel, the forged composite, after polishing and etching, would develop intricate and attractive patterns, where the phosphorus-rich parts would stand unattacked and bright against the other, more easily etched parts. The carbon steel in particular would appear dark and dull (Buchwald & Wivel 1998).

An additional possibility is that the tongues might have served as inlays in difficult hammer-welding operations where the phosphorus-rich material might ease the work. A third possibility is that P-enriched iron was used for wire-drawing. However, it appears less plausible that the flat tongues should be a good starting point for wire fabrication.

That the phosphor tongues were an appreciated trader's item is proved by at least two finds elsewhere, on the islands of Öland and Sjælland. The first was

Table 12.14. SEM-EDAX analyses of slag inclusions in nails and rivets from Löddeköping, Scania

	SiO_2	FeO	MnO	BaO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	SO_3	Sum	F
1	20.8	56.2	0.7	-	3.1	3.2	7.0	3.5	0.9	0.6	4.0	100	2.97
2	27.1	47.6	0.8	-	2.1	4.4	9.8	4.7	1.4	0.9	1.2	100	2.77
3	21.7	64.0	4.9	0.6	0.4	1.7	4.3	0.9	0.9	0.4	0.2	100	5.05
4	46.5	11.6	2.2	-	0.5	20.4	9.1	6.3	2.6	0.7	0.1	100	5.11
5	15.2	74.1	0.6	-	0.7	3.3	3.5	1.0	0.9	0.3	0.4	100	4.34
6	15.4	73.1	0.6	-	0.9	3.3	3.5	1.5	1.0	0.3	0.4	100	4.40
7	27.7	43.0	11.4	-	3.0	1.7	8.9	2.7	0.8	0.5	0.3	100	3.11
8	29.8	35.0	0.7	-	0.8	18.9	9.9	2.4	1.7	0.6	0.2	100	3.01

1. Boatgrave 106. No. 1. 14 g boat-rivet. 0.1 mm phosphorferrite. -0.4% P. HV: 131-131-146-147-168.
2. ibid. No. 3. 10.2 g boat-rivet. 0.05 mm phosphorferrite, P-ghost. -0.4% P. HV: 132-156-163-164-169.
3. Boatgrave 108. No. 2. 12.9 g boat-rivet. 0.1-0.2 mm ferrite, Neumann bands. <0.1% P. HV: 88-90-93-105.
4. ibid. No. 1. 30.7 g boat-rivet. Ferrite-pearlite, 0.2-0.4% C, <0.1% P. HV: 103-121-139-139-212.
5. Grave 157. No. 2. 16.5 g coffin nail. 0.03-0.05 mm ferrite. <0.1% P. HV: 103-106-112-116-117.
6. ibid. No. 1. 25.4 g coffin nail. 0.05-0.1 mm ferrite. <0.1% P. HV: 121-122-126-139.
7. Grave 1251. No. 1. 25 g coffin nail. Phosphorferrite. Widmanstättenstructure. HV: 157-175-182-189-222.
8. ibid. No. 2. 19 g coffin nail. 0.03-0.05 mm ferrite. <0.1% P. HV: 110-117-127-134-144.

found in early mediaeval layers on the Eketorp's Borg, Öland (Stenberger 1966). In line 7 is entered the examination of the 16 g tongue from Statens Historiska Museum P 22-60. Its general shape, a 45° bend near one end, and a smooth chocolate-brown corrosion crust immediately suggest that the object is a Tommarp tongue. The structure, hardness and the slag composition fully confirm the proposition. The other find, from Vestby, Denmark, was already discussed in Table 12.4, line 10.

The unusual corrosion crust can be up to 1.5 mm thick and consists of an interior, thick P-poor crust (1-2% P_2O_5) and an only 0.05-0.1 mm thick exterior part with about 20% P_2O_5, 72% Fe_2O_3, and a little CaO, SO_3 and SiO_2. It is this P-enriched layer which constitutes the smooth chocolate-brown surface. There are no indications of a crystalline nature, or that the layer should be an iron-calcium-phosphate. It appears to be an amorphous phase.

From a number of graves and boat-graves at Löddeköping, near Barsebäck, 15 km NW of Lund, various nails and rivets were donated to this project from the Historiska Museet in Lund. The objects were dated to 950-1050 A.D., Table 12.14. The structures vary

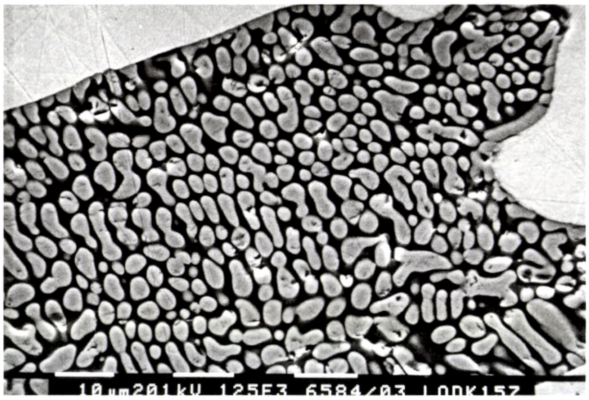


Fig. 358. Slag inclusion in ferrite in a 25 g coffin nail from Löddeköping, Grave 157. Wüstite in an unusual development, caused by homogeneous nucleation from very many nuclei. PS. SEM. Scale bar 0.01 mm.

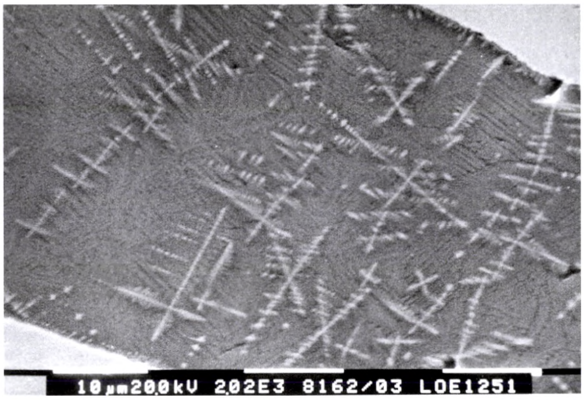


Fig. 359. Slag inclusion in Widmanstätten ferrite-pearlite in a 25 g coffin nail from Löddeköping, Grave 1251. Imperfect wüstite dendrites due to a high P_2O_5-content in a carpet-fayalite structure, compare Fig. 357. PS. SEM. Scale bar 0.01 mm.

from almost pure ferrite, over phosphorferrite with up to 0.4% P and ghost structures, to ferrite-pearlite in Widmanstätten development with 0.2-0.4% carbon. In the same nail several of these structures may appear together. Two boat-rivets, lines 1-2, are duplicates and must come from the same batch. The same is true of the two coffin-nails, lines 5-6, that are exact dupli-

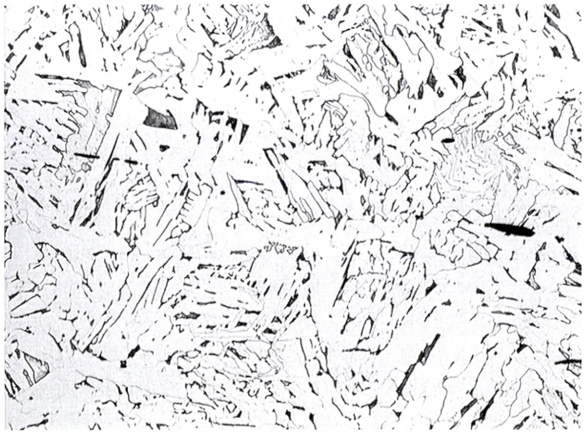


Fig. 360. Low carbon Widmanstätten ferrite-pearlite in the nail, Fig 360. PES. Side length 0.6 mm. Courtesy FORCE Technology.

Table 12.15. C-14 dated iron production sites in Sweden
Adapted from Hansson 1989

Province	Pre-Roman Iron Age	Roman Iron Age	Migration Period	Vendel Period	Viking Age	Middle Ages	Total
Blekinge						2	2
Dalarna		1	3	17	13	3	37
Gotland	1	1					2
Gästrikland		3	2		2	2	9
Halland						3	3
Hälsingland				8	4	1	13
Jämtland		9	6	1	5	32	53
Närke	2	2	2	7	5	1	19
Småland	2	3				30	35
Västergötland		1	2	1	5	13	22
Västmanland	2			3			5
Östergötland						1	1
Öland	1						1
Total	8	20	15	37	34	88	202
In percent	4.0	9.9	7.4	18.3	16.8	43.6	100

cates. The slag inclusions are chiefly glassy with fine wüstite dendrites. Many of them were crushed by the blacksmith when he worked "cold" at rather low temperatures, 700-600°C. Two coffin-nails, lines 7-8, have square sections, 5 x 5 mm, while the other six have circular cross sections. The nails are probably from Norwegian bloomery sites, compare Table 12.10. About 1000 A.D. there were, as far as is known, no bloomery sites in Scania and Halland.

The number of C-14 dated iron-production sites in Sweden has been estimated by Hansson (1989), Table 12.15. The C-14 dated furnaces are only a fraction of all known sites, but the study is interesting by its examination of the relative weight of the various provinces. The information is, of course, not a true picture of the intensity of ancient iron production and quantities of iron. It is rather a reflection of the present status of the inventory which is biased by the initiatives of individual archaeologists, and the financial support for C-14 analyses from various sources, e.g. the provincial boards. A similar analysis has so far not been worked out for Denmark and Norway.

Iceland

According to mediaeval literary sources, Iceland was first populated by Norsemen, who, in particular, emigrated from western Norway. Traditionally 874 A.D. is the date when the first permanent settlements were established. As we have seen above, ironmaking was widespread in Norway at that time, so the emigrants no doubt were ready for ironmaking in their new land, where the conditions were very favourable (Fridriksson & Hermanns-Audardóttir 1992). The basalt, the main rock type of Iceland, has a considerable iron content, 11-12% ($FeO + Fe_2O_3$), and relatively little phosphorus (Barth 1952). A rapid leaching out of iron compounds ensured that bog iron ore deposits were widespread and of good quality. The charcoal was made from birch which covered much of the island when the first settlers arrived. The slowly growing forests suffered, however, from the settlers' many activities, and after a few centuries fuel became a limiting factor.

Bloomeries are found in three regions, Thjórsárdalur, Fljótsdalhérad and Fnjóskadalur. On some sites the furnaces were apparently built inside the houses, a so-called raudasmidja. Ironmaking was appreciated and has often been mentioned in the Norse sagas. In Landnamabook you read: "Björn lived at Dalsmynni. He was the first to blow iron (rauδi) in Iceland, so he was called Rauδa-Björn". The information is interesting because it implies that the furnace was not dependent on natural draught, but was actively worked by hand-operated bellows. At the farm Borg, 50 km north of Reykjavik, the father of the famous viking and poet

Table 12.16. SEM-EDAX analyses of slags and an anvil from Iceland

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Sum	F
1	31.6	49.3	2.8	0.3	3.9	9.3	1.3	0.6	0.6	tr.	0.3	100	3.40
2	24.0	64.1	1.3	0.2	2.4	5.4	0.9	0.7	0.5	0.1	0.4	100	4.44
3	12.4	78.4	0.4	3.0	2.0	2.6	0.4	0.3	0.1	-	0.4	100	4.77

1. Belgsá, Fnjóskadalur. 86 g tapslag. About 1000 A.D.
2. Lundur, Fnjóskadalur. 143 g tapslag. About 1000 A.D.
3. Skogar, southern coast. 18 kg iron anvil. About 1000 A.D.Ferritic. HV: 96-117-117-120-124.

Fig. 361. Section through a tap slag from Belgsá, Iceland. Fayalite laths and duplex matrix. The 0.01 mm zoned hercynite crystals (dark grey) have a rather pure hercynitic nucleus with 3% TiO_2 and 0.6% V_2O_5. PS. SEM. Scale bar 0.1 mm.

Egil Skallagrimsson, had his smithy: "Skallagrim was a skilful smith and produced much iron during the wintertime. He built a bloomery at the sea not far from the farm, on a site which is now called Rauðanes". An appropriate anvil was secured from the bottom of the bay. Skallagrim dived and found a good stone for the smithy:".. and it is so large that four men today are not able to lift it" (Egil's Saga).

Fig. 362. Section through a massive tap slag from Lundur, Iceland. First tap, below, was followed by a second run, top, which solidified rapidly on top of the cold, first slag. The wüstite dendrites radiate away from the cooling surface. PS. SEM. Scale bar 0.1 mm.

Fnjóskadalur, near Akureyri, is in the centre of the most prosperous farming areas in northern Iceland. It had its trading centre at Gásir close by, and it was also an area with many iron- producing farms.

Production slags from two of these sites have been examined, Table 12.16. At the farm Belgsá a stone-lined bowl-furnace was described by Nielsen (1926). The tapslag, line 1, has a ropey surface and an underside with sintered mineral grains from the tapping channel. The structure is 50% fayalite laths (-4% MnO, -2% MgO) and 50% duplex matrix. Zoned hercynite crystals, 10-20 μm across, are common. The nuclei contain up to 3% TiO_2 and 0.8% V_2O_5 in solid solution. The rims are depleted of aluminium and enriched in silicon, and thus no longer of hercynite composition.

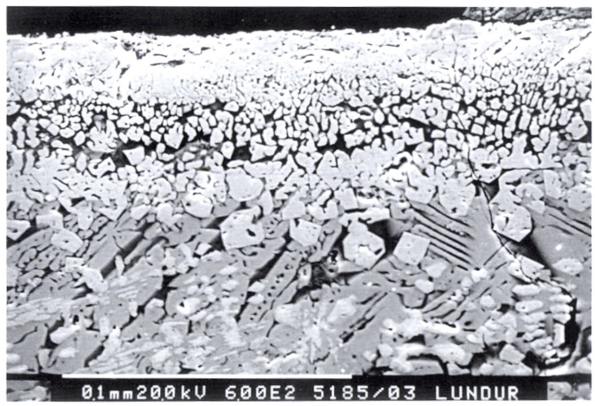


Fig. 363. The exposed top of the tap slag from Lundur, Fig. 362. Numerous magnetite skeleton crystals make the slag slightly magnetic. Below, fayalite laths and wüstite dendrites. PS. SEM. Scale bar 0.1 mm.

At the farm Lundur, also in Fnjóskadalur, a 2 m high slag heap was reported by Nielsen (1926). A massive tapslag from this find is entered in line 2. In the cross section four individual layers can be distinguished. The structure is 20% fine wüstite dendrites, 50% fayalite laths (-2% MnO, -1.2% MgO), and 30% duplex matrix. Scattered in the slag are 5-10 μm iron particles. The surface of the tapslag is oxidized and displays a 0.05-0.1 mm thick zone of skeleton iron oxide crystals (magnetite).

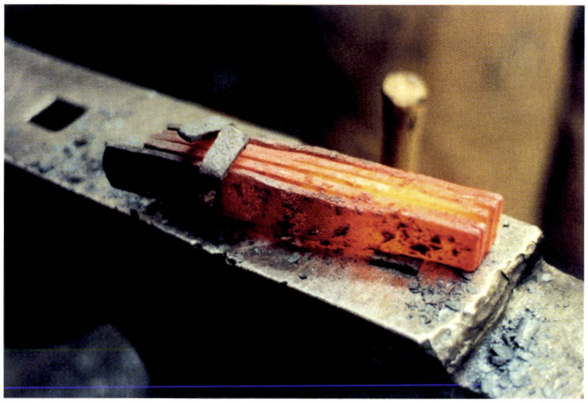


Fig. 364. The initial phase in hammer-welding a packet of three ferritic and two pearlitic bars. The five bars are in the beginning held together by a thin iron strip. This may later be removed with the hot chisel. Experimental work at DTU, Jens Fich, 1990.

In 1989 a 15-18 kg massive iron block, which in ancient times had served as an anvil block in Thjórsárdalur, was noticed by the curator of the small museum at Skógar, Rangarvellir syssla, in SW-Iceland. It was found at an abandoned farm called Holt undir Eyjafjöllum.The block was suspected of being an iron meteorite, so a small corner of 31g was hacksawed and sent to the author for examination. Unfortunately it was not a meteorite, but a massive piece of wrought iron, built up and forge-welded from many pieces. The structure was ferrite and phosphorferrite, with less than 0.05% carbon and up to 0.4% phosphorus, and with ferrite grain sizes of 30-300 μm. In the superficial ferrite grains some Neumann bands occur, probably from the time that the block served as an anvil.

There are rather few slag inclusions. Those in the forge-welding zones are simple iron oxides, while those surviving from the production furnace are 60% wüstite, 30% fayalite (-1% MnO, -1% MgO), and 10% duplex matrix, Table 12.16, line 3. These wüstite-rich slags are in harmony with the pure ferritic structure, see Chapter 7. The massive anvil is an impressive feat for its time.

The three Icelandic objects are a small sample, but it may be cautiously concluded that the basaltic geology gives rise to phosphorus-poor bog iron ores, and these in turn to phosphorus-poor ferritic irons.

According to letters of exchange in the autumn of 1991 with Inspector Thorkell Grimsson, The National Museum of Iceland, Reykjavik, there are on display in the museum two ancient iron lumps, which apparently are of the four-fingered Danish bloom variety. One, No. 2148 of 2.47 kg, was acquired for the museum in 1882. It was found in an ancient smithy on the farm of Saurar near Helgafjell, western Iceland. The other, No. 1965:139 of 8.6 kg, was found before 1965 on the farm Mynes at Eiðathinglá, eastern Iceland. The presence of four-fingered mediaeval blooms in Iceland is evidence of a bloomery practice which is more related to contemporary Danish than to Norwegian practice, which is surprising, considering that the major trading and cultural links to Mediaeval Iceland were with

Fig. 365. Iron helmet, with appended neck protection of hanging iron plates. Vendel-style decorative bronze ornamentation around the eyes and on the top. About 600 A.D. Valsgärde, Uppland. Uppsala University Museum.

Norway. Hopefully, local Icelandic archaeologists will examine this problem.

In the 1560s, just after the collapse of the Catholic church, there were still some bloomeries in use in the northern bishopric of Hólar, west of Fnjóskadalur, but soon thereafter references to iron-making disappear (Fridriksson & Hermanns-Audardóttir 1992). The situation was thus much the same as in Denmark.

Chapter 13
Epilogue

"Gold is for the mistress, silver for the maid,
copper for the craftsman cunning at his trade".
"Good", said the Baron, sitting in his hall,
"But iron, cold iron, is master of them all".

Rudyard Kipling, 1865-1936.

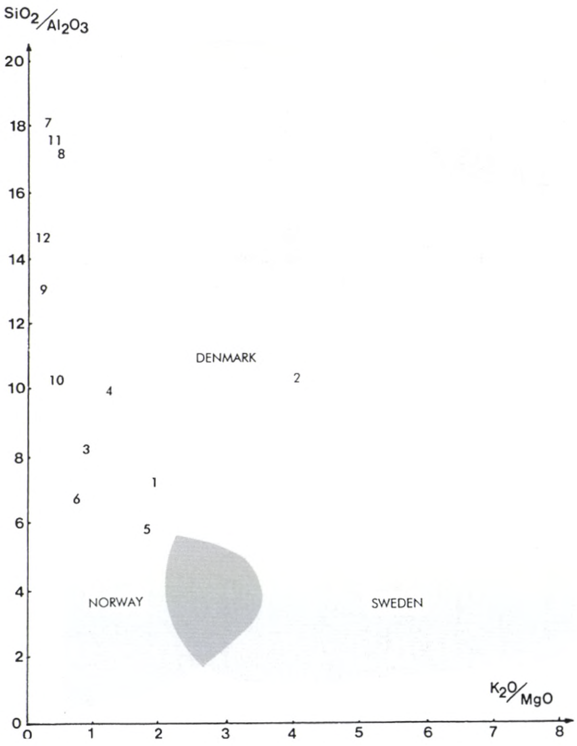


Fig. 366. Plot of slag inclusions in bloomery iron from Denmark, Norway and Sweden. Compare Figs.253 and 312. Inserted numbers 1-12, are from Table 13.1 and show how iron manufacture from the indirect processes plot outside the irons of the direct process. Of particular interest is that Swedish Osmund iron and stangjern plot well outside Swedish bloomery iron.

In the late 12[th] century an entirely new method of iron production appeared. In the blast furnace (Danish, højovn; Swedish, masugn) the iron ore was reduced to fluid slag and to fluid pig iron. The two liquids were allowed to separate, in accordance with the large difference in specific gravity, slag with about 3 g/cm^3, and pig iron with about 7.5 g/cm^3. The pig iron was tapped first, then the slag was tapped and discarded. In the first couple of centuries, the tapped iron consisted of white pig iron, because the blast furnaces were operated rather cold. The apple-sized, white iron nodules were then reheated and oxidized in the finery, whereby the desired soft wrought iron was produced. The pig iron was only used occasionally for castings, it was very hard and somewhat brittle and could not be worked. When the blast furnaces in the 15[th] century became higher and hotter, the tapped pig iron had been slightly altered in composition, and was what we today call grey cast iron. This is much softer than the white iron and can be sawed, filed and machined, and it gained ground as, e.g., fire plates in the finery hearths, as guns and cannon balls, weights and grid irons. After about 1550 A.D. it appeared as oven plates for indoor heating, and these were often finely decorated (Nygård-Nilssen 1944).

The new process has been called the indirect iron process, because the product from the blast furnace had to be treated in a second step, an oxidative remelting in a finery. Thereby it was converted into the desired soft, wrought iron.

The new small, wrought iron bar was in Sweden called osmund. 24 osmunds must weigh a lispound, about 6.7 kg, therefore the osmund bar had an average weight of 283 g. The osmunds were under strict control packed in barrels in the export harbours, mainly Stockholm, and each barrel must hold a skippound, about 137 kg. Each barrel contained 480 osmunds and had a value of 480 pence, or $2^1/_2$ marks. Later, infla-

Table 13.1. SEM-EDAX analyses of slag inclusions in 12 fined irons from 1300 to 1876 A.D.

	$Si0_2$	Fe0	Mn0	P_20_5	Ca0	Al_20_3	K_20	Mg0	$Ti0_2$	V_20_5	Cr_20_3	$S0_3$	Σ	F	K
1	38.6	47.3	1.5	0.1	3.5	5.4	1.7	0.9	0.2	-	-	0.8	100	7.15	1.89
2	31.0	58.8	1.2	0.2	3.6	3.0	1.6	0.4	0.1	-	-	0.1	100	10.3	4.00
3	49.2	23.0	3.3	0.4	9.1	6.0	2.1	2.6	2.7	1.3	-	0.3	100	8.20	0.81
4	28.1	56.4	2.3	1.8	5.4	2.8	1.3	1.0	0.3	0.3		0.3	100	10.0	1.30
5	27.0	54.8	1.2	2.2	6.7	4.8	1.6	0.9	0.4	0.2	-	0.2	100	5.63	1.78
6	32.9	41.5	3.9	1.9	9.9	4.8	1.5	2.1	0.7	0.7	-	0.1	100	6.85	0.71
7	16.5	62.5	1.4	9.1	6.5	0.9	0.1	0.6	0.2	0.2	-	2.0	100	18.3	0.17
8	20.9	65.1	1.5	7.1	0.6	1.2	0.1	0.2	0.2	0.3	0.2	2.6	100	17.4	0.50
9	21.1	63.1	0.5	9.3	2.4	1.6	0.2	1.2	0.1	0.3	-	0.2	100	13.2	0.17
10	17.5	69.7	4.0	4.7	0.3	1.7	0.1	0.2	0.3	0.2	-	1.4	100	10.3	0.50
11	22.8	63.6	3.7	4.6	1.1	1.3	0.1	0.3	0.5	0.3	0.1	1.6	100	17.5	0.33
12	20.4	58.5	4.5	9.2	2.1	1.4	0.2	1.1	0.2	0.2	0.1	2.1	100	14.6	0.18

K = K_2O/MgO

Swedish

1. Small, spindle-shaped bar, 22 g, Lapphyttan L 1614. Osmund iron, 1300 A.D. HV: 102-103-110-114-120.
2. Bar (stangjern). Pilestræde, Copenhagen. 1800 A.D. Brefvens Bruk-stamp. HV: 99-103-108-122-122.
3. Supporting iron. Roskilde Cathedral. !800 A.D. Nissafors Bruk-stamp. HV: 126-126-128-148-148.

Norwegian

4. Bar (stangjern) 951015, Odder Church. 1800 A.D. Ulefos-stamp. HV: 103-109-141-150-210.
5. Bar (stangjern) 4-37, Copenhagen. 1750 A.D. Bærum-stamp. HV: 100-105-113-151-196.
6. Bar (stangjern) SE 1, Jørlunde Church. 1750 A.D. Fritzøe-stamp. HV: 93-111-171-243-261.

Walloonian

7. Nail, 42 g. Val Saint Lambert Abbedy, Liège. 1650 A.D. HV: 103-105-112-141-169.
8. Nail, 8 g. Museum de Fer, Liège. 1650 A.D. HV: 191-200-201-207-211.
9. Horseshoe. National Museum, Copenhagen, D 1104. 1650 A.D. HV: 122-134-144-159-160.

Puddled irons

10. Supporting bar. Palmhouse, Kew Gardens, London. 1848 A.D. HV: 109-130-137-155-172.
11. Roof bolt, Saltaire, Yorkshire. 1850 A.D. HV: 156-182-191-202-224.
12. Bolt, Albert Memorial, London. 1876 A.D. HV: 124-130-148-153-173.

tion altered these initial conditions. The osmund question, in terms of weight, value and origin, has long been under discussion, but seems in the last two decades to have been solved (Björkenstam 1990). In about 500 years (1150-1650 A.D.) the "osmunds små stycker" were a backbone in Sweden's export. The osmunds were produced in several hundred small blast furnaces in Bergslagen. A few of the very early ones have in recent years been identified and excavated, e.g. Lapphyttan (Magnusson 1985; Björkenstam & Fornander 1985). The osmund raw material became very common in most of northern Europe. Mediaeval reports of imported osmund bars exist from at least the ports of London, Flensborg, Lübeck and Danzig. The osmund iron had a reputation for being particularly well suited for wire drawing.

The mediaeval blacksmith thus had iron of different origins at his disposal, osmund iron (and osmund steel) from Swedish Bergslagen, and "local" iron produced by the old direct process (Buchwald 2000). This situation would for example have been common in Norway, Denmark, Finland and Sweden.

In later times, additional iron qualities were introduced. First, some time before 1400 A.D., iron was exported from the Walloon districts (Liège, Namur, Charleroi). Later Spanish iron, Norwegian iron, Öregrunds iron, Lancaster iron, puddled iron, and more arrived on the markets.

In Table 13.1 it is shown how the slag-analytical method may be applied to characterize and classify the various iron types. In the Table are collected three fined irons from Sweden (1-3), three fined irons from Norway (4-6). three Walloon irons from the Liège district (7-9), and three puddled irons from England (10-12). When the ratios F = SiO_2/Al_2O_3 are plotted against the ratios K_2O/MgO, a pattern is developed which may help to sort the various iron qualities. Of particular interest is the fact that the Swedish and Norwegian fined irons plot well outside those fields where ancient Swedish and Norwegian irons, produced by the direct method, are plotted. The F-value, in particular, is well suited for the discrimination. Note also how heterogeneous the material is all the time, as expressed by the large span in hardnesses within the same object. This heterogeneity would only disappear with the introduction of the totally molten metal in massive batches in the Bessemer process and the following industrial furnaces.

It is planned to examine iron and steel up through the Middle Ages and the Renaissance until 1850 A.D. in a further volume, with particular emphasis on Scandinavia. The blast furnace, the finery and the chafery will be presented with slag-analytical data, on bulk slags as well as on slag inclusions in manufactured objects. It will be shown how the planoconvex slags (the kalot slags) disappear from the archaeological record with the coming of the blast furnace, because fined irons need no further purification. Alternatively, if planoconvex slags do appear in, e.g., a 17th century context, it is because some local direct furnace has survived in the area. The Walloon iron will be compared to contemporary fined irons from Sweden and Norway. Finally the puddled irons – which in many respects resemble the Walloon irons, see Table 13.1, but which came much later – will be treated in some detail. The data of more than 650 objects are already in the database, all that is needed is time for the presentation.

Much important information is to be gained from the unique books by Biringuccio (1540), Agricola (1556), Swedenborg (1734) and Rinman (1782), and they will be drawn upon repeatedly. Also, the law-enforced stamping of finished iron bars, effective in Sweden and Norway in the 17th, 18th and 19th centuries, will be discussed.

The treatise will end with the 19th -entury introduction of "Flusseisen", i.e.liquid iron and steel produced by the Bessemer-, Thomas- and Siemens-Martin methods.

In a final Table, 13.2, the author would like once more to illustrate the power of the slag-analytical method. During excavations at Vordingborg Castle, Sjælland, a rather large number of simple iron objects, such as nails, horseshoes and scrap from the castle smithy, were recovered. The archaeological dating has referred the finds to the period 1250-1400 A.D., which is a time when iron was available from many sources. Many of the excavated objects were severely corrod-

Table 13.2. SEM-EDAX analyses of slag inclusions in iron objects from Vordingborg Castle, about 1250-1400 A.D.

	SiO_2	FeO	MnO	P_2O_5	CaO	Al_2O_3	K_2O	MgO	TiO_2	V_2O_5	SO_3	Σ	F	K
1	12.3	60.7	0.6	16.3	6.5	0.9	1.0	0.7	0.1	0	0.9	100	13.7	1.42
2	27.0	58.2	1.6	3.8	3.8	2.8	1.6	0.5	0.2	tr.	0.5	100	9.64	3.20
3	17.9	39.7	21.8^x	10.0	3.7	1.4	1.9	0.5	1.0	0.1	0.5	100	12.8	3.80
4	21.9	52.5	0.5	1.9	1.9	17.8	1.8	0.6	0.4	0.2	0.5	100	1.23	3.00
5	29.4	47.8	2.1	6.1	2.9	6.3	3.6	1.1	0.4	-	0.3	100	4.67	3.27
6	28.4	50.1	3.4	0.5	2.3	12.4	1.9	0.3	0.3	0.1	0.3	100	2.29	6.33
7	63.7	12.0	1.1	0	7.6	10.7	2.8	1.6	0.4	-	0.1	100	5.95	1.75
8	29.3	58.7	1.2	0.2	3.2	4.5	1.3	1.1	0.2	-	0.3	100	6.51	1.18
9	28.3	56.1	0.7	0.2	6.9	4.6	1.1	1.7	0.2	-	0.2	100	6.15	0.65

K = K_2O/MgO x, also 1.5% BaO

Danish, direct bloomery method.
1. Nail, 115 g, D 354-4. 1250-1300 A.D. Phosphorferrite. HV: 132-151-155-162-164.
2. Horseshoe, 150 g fragment. D 49-4-1. 1300 A.D. Phosphorferrite. HV: 135-141-148-157-190.
3. Nail, 30 g, D 251-1. 1300-1400 A.D. Phosphorferrite. HV: 113-116-118-135-162.

Scanian, direct bloomery method.
4. Nail, 14.6 g. D 381-1. 1300-1350 A.D. Phosphorferrite. HV: 140-145-156-156-176.
5. Nail, 12.3 g. D 222-2. 1360-1400 A.D. Phosphoferrite. HV: 140-167-182-197-217.
6. Horseshoe, 32 g fragment. D 222-4. 1360-1400 A.D. Phosphoferrite, coldworked. HV: 121-141-192-201-201.

Osmund irons, indirect blast furnace plus finery.
7. Steel nail, 12 g. D 222-3. 1360-1400 A.D. Pearlite-ferrite. HV: 148-231-281-288-298.
8. Nail, 16 g. D 251-2. 1300-1400 A.D. Ferrite. HV: 98-113-125-140-(275).
9. Osmund bar, 221 g. D 301. 1300 A.D. Ferrite. HV: 82-88-92-110-125-(245).

ed, but nine rather sound objects could be selected at random from the many boxes stored in the magazine in the National Museum, Copenhagen. In Table 13.2 they have been analysed and divided into three groups, in accordance with the results of the slag-analytical method.

The iron of the objects Nos. 1-3 has apparently come from central Jutland, from furnace sites around Silkeborg, Vrads, Herning, Simmelkær, Karup and Kjellerup. This may be proved by the high F-values, the high phosphorus- and the rather high calciumoxide-content.

The second group, Nos.4-6, has been "imported" from the eastern part of Denmark, Scania. This is clear from the low F-values and from a comparison with the many Scanian iron objects which were discussed in Chapter 12.

The third group, Nos.7-9, has been imported from Bergslagen, Sweden. This is in itself not so peculiar, because there exist a number of records and receipts, according to which osmund barrels were purchased by Danish customers. In 1402 A.D. Queen Margrethe acquired no less than 200 "læster" of osmund iron, i.e. 2400 barrels, or about 325 tons. In 1406 she had her

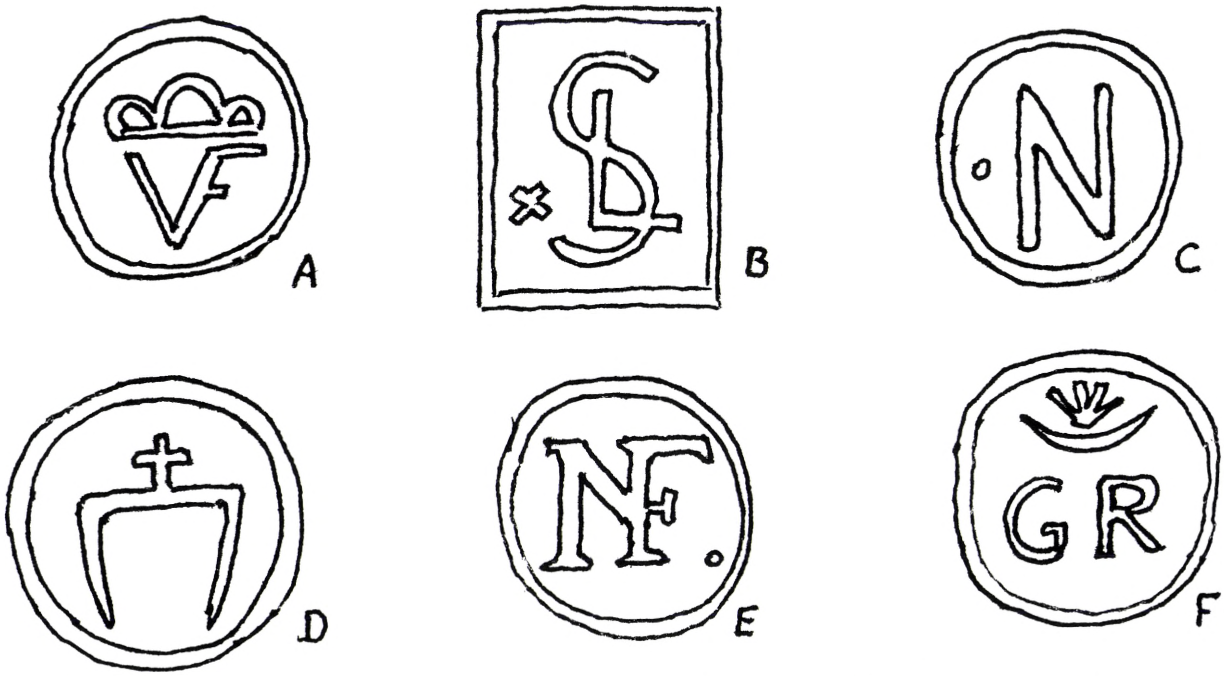


Fig. 367. Factory stamps on forged stangjern (iron bars) from the 18th and 19th century. Norway: **A**, Fritzø. **B**, Ulefos. **C**, Nes. **D**, Bærum. Sweden: **E**, Nissafors, Småland. **F**, Brefvens Bruk, Närke.

sheriff in Dalarna buy a further 127 "læster" (Buchwald 2000).

No. 9 is, in fact, 3/4 of an osmund bar, the trade product which was so common in mediaeval times. This particular bar is ferritic, and the nail, No. 8, could have been forged in Vordingborg from this bar or from a similar one. The steel nail, No. 7, was forged from an osmund steel bar, a quality which was also on the market. The early osmund bars are characterized by intermediate F-values (which incidentally are higher than those of Swedish material produced by the direct method), and by low phosphorus- and low sulphur contents. Manganese is low in these three examples, but may be much higher (up to 16% MnO) in osmund bars from other blast furnaces which were operated on manganese-rich hematite and magnetite ores (Buchwald 2000).

The Vordingborg castle smithy thus had access to at least three different iron sources in the 13th and 14th centuries. The presence of an osmund bar in the castle smithy proves that the castle imported osmund bars from Bergslagen at an early date, and that the smith worked it into, e.g., nails. It is likely that the Danish and Scanian iron also arrived at the castle as raw material, kloder and bars, and were manufactured into nails, horseshoes, trappings etc. in the castle smithy. – In about 1500 A.D. the test in Copenhagen to qualify as a master smith was to forge a horseshoe with matching nails from three osmund bars.

The slag-analytical method has been worked out on simple, unessential objects, like nails, bar iron (stangjern) and horseshoes. In the concluding story it has been shown how essential information may be gained about trading routes in about 1300 A.D. The method is now ready to be applied to important, even precious objects.

Appendix

A personal list of museums and open air facilities with good representation of the many-facetted history of iron. Furnaces and equipment are preserved to varying extent, and in some places working machinery is displayed. In other places, mines and workers' living-quarters, or even entire small town parts which have been laid out for the employees, may be visited. Some exhibits, especially in Scandinavia, are only open to the public from May 15 to August 31.

Denmark
Smedjen, Gamle Estrup
Moesgård, Aarhus
Godthaab Hammerværk, 9 km SW of Aalborg
Den Antikvariske Samling, Ribe Museum
Nationalmuseet, København
Tøjhusmuseet, København
Geologisk Museum (meteorites), København
Moseløkken Arbejdende Stenmuseum, Bornholm

Norway
Oldsaksamlingen med Vikingskipshuset, Frederiks Gate 3, Oslo
The Bloomery Iron Museum (Jernvinnemuseet), Hovden, Bykle, Aust Agder
Mostadmark Jernverk, Malvik, 25 km SE of Trondheim
Aust Agder Museet, Nes Jernverksmuseum, Arendal
Lesja Jernverksmuseum, Lesja
Kittilbu Utmarksmuseum, Vestre Gausdal
Fritzøe Jernverksmuseum, Larvik
Kongsberg Gruber og Sølvverk

Sweden
Dalarna
Ludvika Gammelgård Gruvmuseum
Flogbergets besöksgruva, Ludvika
Stora Kopparberget, mine and museum
Orsa Slipstensmuseum, Mässbacken
Polhemsmuseet, Stjärnsund
Siljansfors Järnbruksminne og Skogsmuseum, Mora.

Gästrikland
Bruksmuseet, Smedsgården, Sandviken
Gysinge Bruk, Smedsbostäder

Hälsingland
Bruksmuseet, Iggesund
Strömsbacka Stångjärnssmidja, Iggesund
The Axe Museum, Gränsfors Bruk AB, 10 km west of Gnarp

Jämtland
Fröå Gruva och gruvby, 100 km west of Östersund

Lappland
LKAB's Info-Mine, Kirunavaara Gruva
LKAB's Gruvmuseum, Poujtakvägen, Malmberget

Närke
Industrimuseet, Bruksgatan, Garphyttan
Brevens Bruks Museum, Kilsmo
Knallgruvan, Gruvmuseum, Zinkgruvan

Småland
Huseby Bruk
Husqvarna Fabriksmuseum
Industrimuseet, Norrahammar
Tabergsgruvan, Gruvgården, Öster Järnvägsgatan, Taberg
Bruksmuseet, Åminne

Stockholm
Tekniska Museet
Wira Bruk

Södermanland
Vapentekniska Museet, Faktoriholmerna, Eskilstuna
Åkers Bruks- och Hembygdsmuseum, Bruksområdet, Åker

Uppland
Vallonsmedjan, Österbybruk
Dannemora Gruva, Österbybruk
Bruksmuseet, Forsmark
Lancashiresmedjan, Karlholms Bruk
Bruksmiljöet, Söderfors

Värmland
Filipstads Bergsmuseum (Collection of ore minerals)
Gamla Bruket, Munkfors
Bessemerverket, Uddeholm Tooling, Hagfors
Minnenas Museum (Bofors bostäder), Korpkullsvägen, Gråbo
Museet, Borgviks Järnbruk, Borgvik

Västmanland
Engelsbergs Bruk, Fagersta (World Heritage)
Bruksmiljöet, Karmansbo
Löa Hytta, Kvarn och Såg, Löa
Konunga-Stollen, Klacka-Lerberg, Nora
Gruvmuseet og Nya Lapphyttan experimentalfelt, Norberg
Polhemshjulet, Norberg
Röda Jorden, Riddarhyttan
Bruksområdet, Ramnäs
Kvarnen, Herrgårdsalléen 1, Kolsva
Bruksmuseet, Surahammar (railroad wheels)

Östergötland
Bruksmuseet, Masugnsvägen, Boxholm
Bruksmuseet, Finspång
Hammarsmedjan, Hävla
Hults Bruk, Åby

Germany
Wikinger Museum Haithabu, Slesvig
Römisch-Germanisches Zentralmuseum, Mainz
Deutsches Bergbau-Museum, Bochum
Das Westfälische Freilichtmuseum, Hagen, 20 km south of Dortmund
Mineralogisches Institut (Meteoriten), Humboldt Universität, Invalidenstrasse 43, Berlin
Hammerschmiede Gröningen, 20 km south of Rothenburg a.d.Tauber
Deutsches Museum, München
Bergbau – und Industriemuseum Ostbayern, Schloss Theuern 92245 Kümmersbruck

France
Musée de l'Armée, Place des Invalides, Paris
Musée de ferronnerie, Le Secq des Tournelles (ancient church Saint-Laurent), Rouen

Belgium
Musée de Vie Wallone et Musée du Fer et Charbon, Liège
Le Fourneau Saint Michel, 6900 Saint-Hubert
Musée Royal de l'Armée et d'Histoire Militaire, Bruxelles

Great Britain
British Museum, Natural History (Meteorites), Cromwell Road, South Kensington, London
Victoria and Albert Museum, London
Science Museum, Exhibition Road, South Kensington, London
The Royal Armories, Clarence Dock, Leeds
Abbey House Museum of Nailmaking, Kirkstall, Leeds
National Mining Museum, Lound Hall, Haughton, Retford, Nottinghamshire
Museum of Antiquities, Newcastle-upon-Tyne
Derwentcote Steel Furnace, Newcastle-upon-Tyne
Allensford Blast Furnace, Newcastle-upon-Tyne
Corbridge Museum and Housesteads Fort, Hadrian's Wall, Newcastle-upon-Tyne

The Coalbrookdale Museum of Iron, Ironbridge Gorge Museum Trust, Telford
Blists Hill Ironworks and Museum, a few km east of Coalbrookdale, Shropshire
Sheffield City Museum
Abbeydale Industrial Hamlet, 7 km south of Sheffield
The Wortley Iron Works and Top Forge, 10 km north of Sheffield
The Black Country Museum, Tipton Road, Dudley, West Midlands
Backbarrow Blast Furnace, Windermere, Lancaster
Duddon Iron Furnace, Duddon Bridge, Nr Millom, Lake District
Blaenavon, Ironworks, Gwent, 35 km north of Cardiff, Wales
The Viking Museum, York
Bonawe Blast Furnace, Argyll, Scotland

Poland

Central Maritime Museum, Gdansk (Danzig)

Austria

Die Steirische Eisenstrasse, from Bruck a.d.Mur to Altenmarkt/St.Gallen
Lehrfrischhütte und Radwerk IV, Vordernberg
Erzbergbahn and Schaubergwerk, Eisenerz, Voest-Alpine Erzberg Gmbh
Die Schmiedemeile, from Ybbsitz (Bundesstrasse 22) to St.Georgen and St.Anton
Salzbergwerk Hallstatt
Die Eisenstrasse Oberösterreich, Sensenschmied Spital/Pyhrn; Nagelschmied, Losenstein; Schwert- und Harnischschmied, Molln
Grassmayr Glockenmuseum, Leopoldstrasse 53, 6010 Innsbruck
Mineralogisch-Petrographisches Abteilung, Naturhistorisches Museum, Burgring 7, Vienna (meteorites).

Switzerland

Das Eisenbibliothek, Georg Fischer AG, Schaffhausen, Paradise Estate

Italy

The Etruscan Museum, Villa Giulia, Rome
Armeria Reale di Torino
Fondazione Museo della Scienza e delle Tecnologia Leonardo da Vinci, Milano
Museo Archeologico (Etruscan art), 38 Via della Colonna, Firenze
The Museum, Portoferraio, Elba

Spain

Armeria del Palacio Real, Madrid
Museo Arqueologico Nacional, Madrid

Cyprus

Cyprus Museum (special hall of copper mining), Lefkosia (Nicosia)

USA

Cornwall Iron Furnace, 30 km east of Harrisburg, Pennsylvania
Hopewell Furnace and Village, National Historic Site, 40 km northwest of Philadelphia, Pennsylvania
Scranton Iron Furnaces, 150 km north of Philadelphia, Pennsylvania
Saugus Iron Works, 15 km north of Boston, Massachusetts
The Tremont Nail Company, 21 Elm Street, Wareham, Massachusetts

References

Abrahamsen, N. & Breiner, N. 1993: Archaeomagnetic investigations in Denmark, a Review. Archaeology and Natural Science **1**, 5-17.

Agricola, Georgius 1556: De Re Metallica. Translated from the first Latin edition of 1556 by Herbert Clark Hoover and Lou Henry Hoover (1912). Dover Publications, Inc. New York 1950, 638 pp.

Airola, Leena 1987: Mønstersmiing, en enestående teknikk i jernalderen. SPOR, Museet i Trondheim, No. 1, 18-21.

Aitchison, Leslie 1960: A history of metals. Macdonald & Evans Ltd. Vol. 1-2, 647 pp.

Albrectsen, Erling 1956: Nye bopladsgruber fra jernalderen (Holsegård, Fyn). Fynske Minder, Odense Bys Museer, p. 179-187.

Albrethsen, S.E. 1986: Starup Skole. Arkæologiske Undersøgelser i Danmark 1985: 130.

Alfsen, B.E. & Christie, O.H. 1972 Fra kulturhistorie til geokjemi. Om sjömalmen i Storsjöen i Odalen. Naturen **96,** 5-14.

Allan, J.C. 1968: The accumulation of ancient slag in the south-west of the Iberian Peninsula. Bulletin of the Historical Metallurgy Group, **1**, No. 1: 47-50.

Allan, J.C. 1970: Consideration of the antiquity of mining in the Iberian Peninsula. London.

Allen, D. 1967: Iron currency bars in Britain. Proceedings Prehistoric Society **33**: 307-35.

Allen, J.R.L. 1988: Chemical composition patterns in Romano-British bloomery slags from the wetlands of the Severn estuary. Journal of Historical Metallurgy **22**, No. 2: 81-86.

Ambrosiani, Bjørn & Erikson, B. G. 1991: Birka, Vikingastaden. Bra Böcker, Wiken, Helsingborg. 98 pp.

Andersen, Erik, Crumlin-Pedersen, Ole, Vadstrup, Søren & Vinner, Max 1997: Roar Ege. Vikinge- skibshallen i Roskilde. 274 pp.

Andersen, H.Chr. 2003: New investigations in Ejsbøl Bog, p. 246-257 in Jørgensen, L. et al (eds.). The spoils of victory. The National Museum, Copenhagen. 452 pp.

Andersen, H.Hellmuth. 1977: Jyllands vold. Wormianum. Aarhus. 76 pp.

Andersen, H.Hellmuth 2004: Til hele rigets værn. Danevirkes arkæologi og historie. Moesgård og Wormianum. Aarhus. 88 pp.

Andersen, H. Helmuth, Crabb, P.J. & Madsen, H.J. 1971: Århus Søndervold, en byarkæologisk undersøgelse. Jysk Arkæologisk Selskabs Skrifter, **9**, 337 pp.

Andersen, Lars & Andersen, Niels Møller 1991: Ældre jernalders mønstersvejsede sværd. 61-82 in Madsen, Bo (ed.) Eksperimentel arkæologi. Historisk-Arkæologisk Forsøgscenter, Lejre.

Andersson, Hans (ed.) 2004: Jernmøllen i Halland. Arkæologiske Undersøgelser 1993-1995. Hikuin **31**, 1-227. Moesgård.

Aner, E. & Kersten, K. 1973-88: Die Funde der älteren Bronzezeit des nordischen Kreises in Dänemark, Schleswig-Holstein und Niedersachsen. Band I-VIII. Kopenhagen, Neumünster.

Angus, N-S, Brown, G.T. & Cleere, H.F. 1962: The iron nails from the Roman legionary fortress at Inchtuthil, Perthshire. Journal of the Iron and Steel Institute, **200,** 956-968.

Anstee, J.W. & Biek, L. 1961: A study in pattern welding. Medieval Archeology (London) **5**, 71-93.

Anteins, A.K. 1968: Structure and manufacturing techniques of pattern-welded objects found in the Baltic states. Journal of the Iron and Steel Institute, **206**, 563-571.

Appel, Liv. 1986: Jernudvindingsanlæg ved Maglegaard, Østermarie. Fra Bornholms Museum, p. 88-92.

Arrhenius, Birgit. 1970: Knivar från Helgö och Birka. Fornvännen, p. 40-51.

Arrhenius, Otto. 1959: Die Grundlagen unserer älteren Eisenherstellung. Antikvarisk Arkiv, **13,** 1-46.

Arrhenius, Olof. 1967: Ore, iron, artefacts and corrosion. Sveriges Geologiske Undersökning. Serie C 626, 1-39.

Arrhenius, Otto. 1968: Smålands malmtrakt och järnframställning. Daedalus. Tekniska Museets Årsbok, p. 67-90.

Arwidsson, Greta & Berg, Gösta. 1983: The Mästermyr Find. A Viking Age tool chest from Gotland. Kungl. Vitterhets Historie och Antikvitets Akademien. Stockholm. 96 pp.

AUD. Arkæologiske udgravninger i Danmark. Rigsantikvarens Arkeologiske Sekretariat (ed.). København.

Asschenfeldt – Frederiksen, C. 1952: Jernalderfundet ved Riis-Tebstrup skole i Ousted sogn. Østjysk Hjemstavn **17,** 39-46.

Bardgett, W.E. & Stanners, J.F. 1963: The Delhi pillar: A study of the corrosion aspect. Journal of the Iron and Steel Institute **201**, 3-10.

Barth, Tom F.W. 1952: Theoretical petrology. John Wiley, New York. 387 pp.

Bartoloni, Gilda 1991: Populonia: characteristic features of a port community in Italy during the first Iron Age, p. 101-115 in Herring, E. et al. (eds.) Papers of the fourth conference of Italian archeology. Accordia Research Center, University of London.

Beck, Ludwig 1891: Die Geschichte des Eisens, Vol. 1. Zweite Auflage. Braunschweig. 1068 pp.

Becker, C.J. 1948: Die zeitliche Stellung des Hjortspring-Fundes. Acta Archeologica **19**, 145-187.

Becker, C.J. 1961: Førromersk jernalder i Syd- og Midtjylland. Nationalmuseets Skrifter, Større Beretninger, VI. København. 292 pp. 127 plates.

Becker, C.J. 1968: Das zweite früheisenzeitliche Dorf bei Grøntoft, Westjütland. Acta Archeologica **39**, 235-255.

Belaiew, N. 1918: Damascene steel. Journal of the Iron and Steel Institute **97**, 417-439.

Bencard, Mogens & Aistrup, May Stief 1979: Jernankeret fra Ribe. Nationalmuseets Arbejdsmark, p. 156-161.

Bendinelli, Goffredo 1916: Tomba con vasi e bronzi del 5-secolo a.C.Monumenti Antichi Accademia Lincei (Milano) **24**: 841-914.

Benvenuti, M., Mascaro, I., Costagliola, P., Tanelli, G. & Romualdi, A. 2000: Iron, copper and tin at Baratti, Populonia: Smelting processes and metal provenances. Historical Metallurgy **34** No. 2: 67-76.

Bergenblad, Harry. 1998: Medeltida järnugn (Axamo) daterad med hjälp av årsringar hos kolningsvirke. Bergsmannen, nr. 6: 34-35.

Bergland, Håvard 1990: Knivsmeden. Knivmakerarbeid og smiing. Universitetsforlaget, Oslo. 229 pp.

Berglund, Bengt. 2000: Järn i Småland. Jernkontoret, Stockholm. Vol. 1, 158 pp.

Bergström, Hilding. 1947: Handbok för kolare. Uppsala. 4th edition I-II. 165 +139 pp.

Bergsøe, Paul. 1975: H.C. Ørsted p. 9-31 in V.F. Buchwald (ed.) Glimt af Metallurgiens Udvikling i Danmark. Dansk Metallurgisk Selskab, 223 pp.

Berlin, Agneta Å. 1997: Åminne Bruk. Jönköpings Läns Museum. 42 pp.

Bernus, Suzann & Echard, Nicole 1985: Metal working in the Agadez region, Niger. p. 71-80. in Craddock, P.T. & Hughes, M.J. (eds). Furnaces and smelting Technology in antiquity. British Museum Occ. Paper No. 48.

Bielenin, Kasimierz 1973: Frühgeschichtliches Eisenhüttenwesen in Swietokrzyskie-Gebirge in Klein-Polen. Antikvariskt Arkiv **53**, 7-16.

Bielenin, Kasimierz 1976: Tidlig järnframställning i Polen, p. 73-102 in När Järnet kom. Göteborgs Arkeologiske Museum, Göteborg.

Bielenin, Kasimierz 1977: Übersicht der Typen von altertümlichen Rennöfen auf dem Gebiet Polens. Wissenschaftliche Arbeiten aus dem Burgenland **59**, 127-145. Eisenstadt.

Bielenin, Kasimierz 1983: Der Rennfeuer Ofen mit eingetieftem Herd und seine Formen in Polen. Offa **40**, 47-68.

Bielenin, Kasimierz 1999: Frühgeschichtliche Eisenverhüttung auf den Gebiet Polens, p. 57-63 in Gömöri, Janos (ed.) Traditions and innovations in the early medieval iron production. Sopron Museum.

Bielenin, Kasimierz & Woyda, S. 1978: Zwei Eisenverhüttungszentren des Altertums in Swietokrzyskie-Gebirge. In Eisen + Archäologie, Veröffentlichungen Deutsche Bergbaumuseum, Bochum **14**, 8-23.

Biringuccio, Vannoccio 1540: Pirotechnia. The M.I.T. Press. Paperback edition, Cambridge, Massachusetts 1960, 477 pp.

Birkhan, Helmut 1970: Germanen und Kelten bis zum Ausgang der Römerzeit. Österreichische Akademie der Wissenschaften, Wien. 636 pp.

Birkhan, Helmut 1997: Kelten. Österreichische Akademie der Wissenschaften, Wien. 1270 pp.

Biswas, A.K. & Bashforth, G.R. 1962: The physical chemistry of metallurgical processes. Chapman & Hall. London. 336 pp.

Björkenstam, Nils 1985: Reaction processes in the production of iron in low shaft furnaces. Journal Historical Metallurgy Society **19**, 186-192.

Björkenstam, Nils 1990: Västeuropeisk järnframställning under medeltiden. Jernkontorets Bergshistoriska Skriftserie, Stockholm. No. 26, 191 pp.

Björkenstam, Nils & Fornander, Sven 1985: Metallurgy and technology at Lapphyttan. Jernkontorets Forskning, Stockholm, Heft 34, p. 184-225.

Blazquez, J.M. 1978: Economia de la Hispania Romana. Ediciones Najera. Bilbao. 725 pp.

Blindheim, C. 1963: Smedgraven fra Bygland i Morgedal. Viking **26**, Oslo.

Bloch-Nakkerud, Tom 1992: Iron production in Hallingdal, p. 89-92 in Espelund, A. (ed.) Bloomery ironmaking during 2000 years, Vol. 2, Trondheim.

Blomgren, Stig 1980: The possibilities of producing iron nickel alloys in prehistoric times. Journal Historical Metallurgy Society **14**, No. 2, 103-104.

Bodey, Hugh 1983: Nailmaking. Shire Publications Ltd. 32 pp.

Bridgewater, N.P. 1968: Iron mining and working sites in and around the Forest of Dean. Bulletin of the Historical Metallurgy Group **2**, No. 1, 27-32.

Brizio, E. 1899: Il sepolcreto gallico di Montefortino presso Arceria. Monumenta Antichi Lincei (Milano) **9**, 617-791.

Broholm, H.C. 1960: Kulturforbindelser mellem Danmark og Syden i ældre jernalder. København. 312 pp.

Broholm, H.C. 1962: Et lurfund fra Hallenslev Mose, Vestsjælland. Aarbøger for Nordisk Oldkyndighed og Historie. 1961: 147-159.

Bronson, Bennet 1987: Terrestrial and meteoritic nickel in the Indonesian kris. Historical Metallurgy **21**, No. 1, 8-15.

Brown, G.T. 1964: Roman bloom from Cranbrook, Kent. Journal of the Iron and Steel Institute **202**, 502-504.

Bruce-Mitford, Rupert 1979: The Sutton Hoo ship burial. A handbook. Third edition. British Museum Publications Ltd, London. 134 pp.

Brånby, Lovisa 2002: Ancient northern European axes. Gränsfors Bruk AB, Hälsingland, Sweden. 28 pp.

Brøgger, A.W. 1940: Jernet og Norges eldste økonomiske historie. Det norske Videnskapsakademi, Historisk-Filologisk Klasse No. 1. Oslo.

Brøndsted, Johannes 1939: Danmarks Oldtid. Vol. 2, Bronzealderen. København.

Buchwald, V.F. 1964 a: A new Cape York meteorite discovered. Geochimica and Cocmochimica Acta **28**, 125-126.

Buchwald, V.F. 1964 b: Meteorit- og jernfund i Grønland, fra John Ross' rejse for at opsøge Nordvest-passagen i 1818 til vore dage. Naturens Verden, February, p 33-64.

Buchwald, V.F. 1975: Handbook of iron meteorites. University of California Press. Vol. 1-3, 1418 pp.

Buchwald, V.F. 1978: En metallografisk undersøgelse af en vikingetidsøkse fra Sønder Onsild. Aarbøger for Nordisk Oldkyndighed og Historie 1976: 96-122.

Buchwald, V.F. 1989: Mineralogi og reaktionsmodeller ved korrosion af jordfundne jerngenstande (meteoritter og oldsager). Dansk Metallurgisk Selskab, Årbog, p. 41-71. Copenhagen.

Buchwald, V.F. 1990: On the recognition of meteoritic iron in ancient samples.PACT **30**, No. 2, 53-61.

Buchwald, V.F. 1991: Jernfremstilling i Danmark i Middelalderen. Årbøger for Nordisk Oldkyndighed og Historie, p. 265-286.

Buchwald, V.F. 1992 a. Meteoritter, Nøglen til Jordens fortid. Gyldendal, København. 247 pp.

Buchwald, V.F. 1992 b: On the use of iron by the Eskimos in Greenland. Materials Characterization **29**, 139-176.

Buchwald, V.F. 1995: Om proveniensbestemmelse, med særligt henblik på de hallandske kloder, p. 108-126 in Olsson, S-E (ed.) Medeltida danskt järn. Högskolan i Halmstad. 178 pp.

Buchwald, V.F. 1998: Myremalm. Geologisk Tidsskrift, Hæfte 1, 1-26. København.

Buchwald, V.F. 1999a: Blæsterjern, kloder og klimpjern. Osmundjern, stangjern og puddeljern, p. 28-62 in Jensen, P.H. (ed.) Klimp og kloder. Blicheregnens Museum, Thorning.

Buchwald, V.F. 1999b: On a method to determine the provenance and character of ancient iron objects, in Crew, P. & S. (eds.) Early ironworking in Europe. Plas Tan w Blwch. Abstract.

Buchwald, V.F. 2000: Osmundjern og blæsterjern karakteriseret ved slaggeanalysemetoden, p. 65-68 in Ödman, Anders (ed.) Järn. Wittsjöskogkonferensen 1999. Inst.of Archeology, Lund, Report Series No. 75.

Buchwald, V.F. 2001: Ancient iron and slags in Greenland. Meddelelser om Grønland, Man & Society **26**, 1-92.

Buchwald, V.F. 2002: Jern og stål i Skandinavien før 1600 belyst ved slaggeanalysemetoden. Dansk Metallurgisk Selskabs Årbog, Vintermødet 2002, 45 pp.

Buchwald, V.F. 2004a: A note concerning three ancient anchors from Nydam, Ladby and Ribe, p. 183-186 in Bencard, M. et al. (eds) Ribe Excavations 1970-76. Jutland Archaeological Society.

Buchwald, V.F. 2004b: Om jernfremstillingspladserne nær Tvååker, Halland, p. 175-204 in Andersson, H. (ed.) Jernmøllen i Halland. Hikuin **31**, Moesgård.

Buchwald, V.F. & Clarke, R.S. 1989: Corrosion of Fe-Ni-alloys by Cl-containing akaganeite, β-FeOOH. American Mineralogist **74**, 657-667.

Buchwald, V.F. & Graff-Petersen, P. 1976: Catalogue of Meteorites. Analecta Geologica **4**, 1-87. Geological Museum, Copenhagen.

Buchwald, V.F. & Leisner, P. 1990: A metallurgical study of 12 prehistoric bronze objects from Denmark. Journal of Danish Archeology **9**, 64-102.

Buchwald, V.F. & Mosdal, Gert 1985: Meteoritic iron, telluric iron and wrought iron in Greenland. Meddelelser om Grønland, Man & Society **9**, 1-49, Copenhagen.

Buchwald, V.F. & Munck, Sole 1965: Catalogue of Meteorites. Analecta Geologica **1**, 1-81. Geological Museum, Copenhagen.

Buchwald, V.F. & Voss, Olfert 1992: Iron production in Denmark in Viking and Medieval times, p. 31-43 in Espelund, A. (ed.) Bloomery ironmaking during 2000 years. Vol. 2. Trondheim.

Buchwald, V.F. & Wivel, Helle 1998: Slag analysis as a method for the characterization and provenancing of ancient iron objects. Materials Characterization **40**, 73-96.

Buddhue, J.D. 1957: The oxidation and weathering of meteorites. University of New Mexico. Albuquerque. 161 pp.

Bulliot, N. 1899: Fouilles du Mont Beuvrai 1867 à 95. Paris.

Burke, J.G. 1986: Cosmic debris. Meteorites in History. University of California Press, Berkeley. 445 pp.

Bühler, R.W. 1988: Meteorite. Urmaterie aus dem interplanetaren Raum. Birkhäuser Verlag, Basel. 192 pp

Böhne, Clemens 1963: Die Technik der damaszierten Schwerter. Archiv für das Eisenhüttenwesen, **34**, 227-234.

Böhne, Clemens 1969: Vom Damaststahl zum Scharsachstahl. Archiv für das Eisenhüttenwesen, **40**, 661-665.

Bågenholm, Gösta 1999: Arkeologi och språk i norra Östersjöområdet. Disputats. Gotarc No. 12. Göteborg. 325 pp.

Caesars' Gallic War. Commentariorum Caii Julii Caesaris de Gallico Bello. Interlinear translation. David McKay, New York. 1952.

Carlberg, J.O. 1879: Historiskt sammandrag om svenska bergverkens uppkomst och utveckling. Beckmans Förlag, Stockholm. 663 pp.

Carpenter, H.C.H. & Robertson, J.M. 1930: The metallography of some ancient Egyptian implements. Journal of the Iron and Steel Institute **121**, 417-454.

Carter, Howard 1927-1933: The tomb of Tut-Ankh-Amun. London. Vol. 1-3.

Charles, J.A. 1980: The coming of copper and copper-base alloys and iron: A metallurgical sequence, p. 151-181 in Wertime & Muhly (eds.) The coming of the age of iron. Yale University Press.

Charles, J.A. 1985: Determinative mineralogy and the origins of metallurgy, p. 21-28 in Craddock, P.T. & Hughes, M.J. (eds.) Furnaces and smelting technology in Antiquity. Brit. Museum Occ.Paper No. 48.

Chladni, E.F.F. 1819: Über Feuer-Meteore und über die mit denselben herabgefallenen Massen. Wien, 434 pp.

Christensen, Charlie 2003: The sacrificial bogs of the Iron age,p. 346-354 in Jørgensen, L. et al. (eds.) The spoils of victory. Catalogue. The National Museum, Copenhagen. 452 pp.

Christensen, Kjeld & Bonde, Niels 1992: Dateringen af Trelleborg – en kommentar. Årbøger for Nordisk Oldkyndighed og Historie 1991: 231-233.

Christensen, P.B. & Johansen, Erik 1992: En handelsplads fra yngre jernalder og vikingetid ved Sebbersund. Årbøger for Nordisk Oldkyndighed og Historie 1991:199-229.

Clarke, Helen (ed.) 1979: Iron and man in prehistoric Sweden. Jernkontoret, Stockholm. 180 pp.

Cleere, H. F. & Bridgewater, N.P. 1966: The iron industry in the Roman period. Bulletin of the Historical Metallurgy Group, **1**, No. 6: 1-7.

Cleere, Henry & Crossley, David. 1995: The iron industry of the Weald. 2nd edition. Merton Priory Press. 425 pp.

Coghlan, H. H. 1956: Notes on prehistoric and early iron in the Old World. Pitt Rivers Museum. Oxford University Press. 220 pp. (2nd edition 1977.)

Coghlan, H.H. 1967: A metallurgical examination of eleven palstaves. Historical Metallurgy **1**: 7-21.

Coghlan, H.H. 1975: Notes on the prehistoric metallurgy of copper and bronze in the Old World. Pitt Rivers Museum. Oxford University Press.

Cowgill, Jane 1995: Evidence for iron smelting from South Lincolnshire. p. 11-12 in Crew, P & S (eds.) Iron for Archaeologists Workshop Plas Tan y Bwlch, Snowdonia National Park Study Center.

Craddock, P.T. 1977: The comparison of copper alloys used by the Greek, Etruscan and Roman civilisations. Journal of Archeological Science **4,** 103-124.

Craddock, P.T. 1995: Early mining and production. Edinburgh University Press. 363 pp.

Craddock, P. T. & Lang, Janet 1993. Gizeh iron revisited. Journal of Historical Metallurgy Society **27** no.2: 57-59.

Cresswell, R.G. 1992: The radiocarbon dating of iron artefacts using accelerator. Journal of the Historical Metallurgy Society **25**, 78-85.

Crew, Peter 1999: Magnetic surveys of ironworking sites in North- West Wales. p. 41-47 in Gömöri, Janos (eds.) Traditions and innovations in the early medieval iron production. Sopron Museum.

Crew, Peter & Crew, Susan 1995: Medieval bloomeries in northwest Wales. p. 43-50 in Magnusson, Gert (ed.) The importance of ironmaking. Jernkontorets Berghistoriska Utskott H 58. Stockholm.

Crew, Peter & Musson, Chris 1996: Snowdonia from the air. National Park Authority. Gwynedd. 56 pp.

Crew, Peter & Salter, Chris 1993: Currency bars with welded tips. p. 11-30 in Espelund, Arne (ed.) Bloomery iron making during 2000 years. **Vol. 3**. Trondheim.

Curtis, J. E., Wheeler, T.S., Muhly, J, D. & Maddin, R. 1979: Neoassyrian ironworking technology. Proceedings of the American Philosophical Society **123,** 369-390.

Dalhoff, N. 1915: Jørgen Balthasar Dalhoff. Gad. København **1,** 1915: 1-198. **2,** 1916: 201-431.

Daeves, Karl 1940: Untersuchung alter Eisenteile vom Kölner Dom. Stahl und Eisen **60,** 245-252.

Davidson, H. R. Ellis 1962: The sword in Anglo-Saxon England. Its archaeology and literature. Oxford University Press. 237 pp. + 16 plates.

Dechelette, Joseph. 1927: Manuel d' Archéologie Préhistorique Celtique et Gallo-Romaine. Tome 4, p. 417-1163.

Dehn-Nielsen, Henning 1999: Fortidsminder i Danmark. Sesam. Viborg. 355 pp.

Demurtas, Giuliana 1999: Copper and arsenical copper artefacts from pre-nuragic Sardinian cultures. Historical Metallurgy **33** no. 1: 1-12.

Denig, H. 1985: Alte Schmiedekunst-Damaszenerstahl. Heimatstelle-Pfalz.

Domergue, Claude 1990: Les mines de la Peninsula Ibérique dans l'antiquité romaine. Collection de l'Ècole Francaise de Rome. No. 127. Rome. 623 pp.

Drachmann, A.G. 1967: De navngivne sværd i saga, sagn og folkevise. Studier fra Sprog- og Oldtidsforskning, **77**, 5-73.

Durman, Alexandr 1997: Iron resources and production for the Roman frontier in Pannonia, p. 6-8 in Crew, P. and Crew, S. (eds.). Early Ironworking in Europe, Plas Tan y Bwlch (Abstracts).

Dusek, Sigrid 1967: Eisenschmelzöfen einer germanischen Siedlung bei Gera-Tinz. Alt-Thüringen **9,** 95-183.

Ehrenreich, Robert M. 1984: A study of iron technology in the Wessex (Pre Roman) Iron Age. p. 105-112 in Scott, B.G. & Cleere, H. (eds.). The crafts of the blacksmith. Belfast.

Elsner, Hildegard 1992: Wikinger Museum Haithabu. Et portræt af en tidlig by. Wachholtz Verlag. Neumünster.

Emmerling, J. 1971: Die metallographische Untersuchung der Schwertklingen aus Münsingen. Jahrbuch des Bernischen Historischen Museums in Bern 47/48 for 1967/68: 147-190.

Engberg, Nils & Buchwald, V.F. 1995: Værktøjskisten fra Veksø. Nationalmuseets Arbejdsmark, 62-75, København.

Engelhardt, Conrad 1863: Thorsbjerg Mosefund. København. 84 pp. 18 plates.

Engelhardt, Conrad 1865: Nydam Mosefund 1859-63. København. 66 pp. 15 plates.

Engelhardt, Conrad 1867: Kragehul Mosefund 1751-1865. Reprinted: Sønderjyske og fynske mosefund. With introduction by Mogens Ørsnes. Forlaget Zac. Copenhagen 1970. 30 pp. 4 pl.

Engelhardt, Conrad 1869: Sønderjyske og Fynske Mosefund. No. II. Vimosefundet. Reprinted with introduction by Mogens Ørsnes. Forlaget Zac. Copenhagen. 1970. 38 pp. 19 pl.

Englund, Lars Erik 2002: Blästbruk. Jernkontorets Bergshistoriska Skriftserie nr. 40. Stockholm. 423 pp.

Englund, L. E., Grandin, L., Hjärthner-Holdan E., Kresten, P. & Stilborg, O. 1999: Pre-Roman iron production in Söderåkra, Småland. Report nr. 9912. Riksantikvarieämbetet. GAL Uppsala.

Eriksen, Egon 1956: Frederiks-Værk, fra Kanoner til Kedler, 1756-1906-1956. De Forenede Jernstøberier A/S. 91 pp.

Espelund, Arne 1991: Bog iron ore for the bloomery process, p. 36-49 in Espelund, A. (ed.) Bloomery ironmaking during 2000 years.Trondheim.

Espelund, Arne 1992: The Mellager site in Trondheim, p. 93-114 in Espelund, A. (ed.) Bloomery ironmaking during 2000 years. Vol. 2. Trondheim.

Espelund, Arne 1993: The value of a tradition in ironmaking, p. 149-163, in Espelund, A. (ed.) Bloomery ironmaking during 2000 years. Vol. 3. Trondheim.

Espelund, Arne 1995: Iron production in Norway during two millenia. Arketype. Trondheim. 126 pp.

Espelund, Arne 2004: Jernet i Vest- Telemark. Iron in Western Telemark. Arketype Forlag, Trondheim. 200 pp.

Espelund, Arne, Mc Lees, Chris, Pagoldh, Monica & Sandvik, Paula U. 1987: Smedene på Ørene. Metallverksteder i middelalder-Trondheim. Arkeologiske Undersøgelser i Trondheim, Nr. 2, 254 pp.

Espelund, Arne & Stenvik, Lars F. 1993: The bloomery site Storbekken I in Budalen, p. 123-147, in Espelund, A. (ed.) Bloomery Ironmaking during 2000 years. Vol. 3. Trondheim.

Ethelberg, Per, Hardt, Nis, Poulsen, Bjørn & Sørensen, Anne Birgittte 2003: Det Sønderjyske Landbrugs Historie. Jernalder, Vikingetid og Middelalder. Haderslev Museum. 842 pp.

Evenstad, Ole 1782: Afhandling om jern-malm, som findes i myrer og moradser i Norge. Prisskrift, Kgl. Landhusholdnings-Selskabs 2den guldmedalje, p 387-449. Translated into German by J.G.L.Blumhof, Göttingen 1801.

Falk, Hjalmar 1914: Altnordische Waffenkunde. Videnskapsselskapets Skrifter. Historisk-Filosofisk Klasse, Oslo. No. 61: 1-209.

Farbregd, O., Gustafson, L. & Stenvik, Lars F. 1985: Tidlig jernproduktion i Trøndelag. Undersøkelserne på Heglesvollen. Viking **48,** 103-129.

Fell, Vanessa 2003: Metallographic examination of two (pre Roman) Iron Age hooked blocks from England, p. 129-133 in Nørbach, L.C. (ed.), Prehistoric and Medieval direct iron smelting in Scandinavia and Europe. Aarhus University Press.

Feugère, M. & Serneels, V. 1998: Recherches sur l'économie du fer en Méditerranée nord-occidentale. Monographies Instrumentun **4,** 263 pp. Éditions Monique Mergoil, Montagnac.

Flawn, Peter T. 1966: Mineral resources. Geology, engineering, economics, politics, law. John Wiley & Sons. New York. 406 pp.

Fleming, James Evans 1980: The blacksmith's source book. An annotated bibliography. Southern Illinois University Press, 204 pp.

Forbes, R. J. 1964-72: Studies in ancient technology. Second revised edition, 9 volumes, Leiden.

Forenius, Svante 1990: Stalbo, en tidlig järnframställningsplats i Uppland. Jernkontorets Bergshistoriska Utskott, H 46: 73-81. Stockholm.

Forrieres, C., Leroy, M. & Ploquin, A. 1989: La métallurgie du fer à Ludres en Lorraine. p. 253-276 in Pleiner, R. (ed.) Archaeometallurgy of iron. International Symposium in Liblice 1987. Prague. 495 pp. 34 pl.

Forshell, Helena 1984: Bronze cannon analysis. Alloy composition related to corrosion picture. Armémuseum, Stockholm, Rapport nr. 2, 28 pp.

Forshell, Helena 1992: The inception of copper mining in Falun. Theses and Papers in Archeology B 2, 189 pp. Archaeological Research Laboratory, Stockholm University.

Fossa-Mancini, Enrico 1922: L'arte minerarie e metallurgia al tempo degli Etruschi. La Miniera Italiana **6**: 225-231.

Fridriksson, Thorbjørn & Hermanns-Audardottir, Margret 1992: Ironmaking in Iceland, p. 5-15 in Espelund, A. (ed.) Bloomery ironmaking during 2000 years. Vol. 2. Trondheim.

Frydendal, H.C. 1931: (Fundene i Grimstrup) p. 699-713 in Aarbog for Ribe Amt.

Galliou, Patrick 1983: Iron in iron age and Roman Armorica. Offa **40,** 77-83.

Geer, Gerard de 1946: Sveriges naturrikedomar. Bonniers. Stockholm. 332 pp.

Gettens, R.J., Clarke, R.S. & Chase, W.T. 1971: Two early Chinese bronze weapons with meteoric iron blades. Freer Gallery of Art, Occasional Papers **4**, No. 1: 1-77.

Giardino, Claudio 1995: The west Mediterranean between the 14th and 8th centuries B.C. Mining and metallurgical spheres. BAR International Series **612,** 400 pp. and 10 pl.

Gilles, J.W. 1936: Die Grabungen auf vorgeschichtlichen Eisenhüttenplätzen des Siegerlandes. Stahl und Eisen **56,** 252-263.

Gilles, J.W. 1958: Versuchsschmelze in einem vorgeschichtlichen Rennofen. Stahl und Eisen **78,** 1690-1695.

Gillespie, R., Gowlett, J.A., Hall, E.T., and Hedges, R.E.M. 1984: Radiocarbon measurements by accelerator mass spectroscopy. Archeometry **26**, No. 1: 15-20.

Glob, P.V. (ed.) 1980: Danefæ. Nationalmuseet, København. 200 pp.

Grabe, Alf 1920: Iron and Steel in Sweden. Jernkontoret. AB Svenska Teknologföreningens Förlag. Stockholm. 183 pp.

Graham, A.L., Bevan, A.W.R. & Hutchison,R. 1985: Catalogue of Meteorites. 4th Edition.. British Museum (Natural History), London. 460 pp.

Graham, Frank 1979: The Roman wall. Comprehensive history and guide. Newcastle upon Tyne. 287 pp.

Grandin, Lena 2000: Spadformade ämnesjärn från Torsåker, Gästrikland. Geoarkeologiskt Laboratorium, Riksantikvarieämbetet, Uppsala. Report 16-2000. 9 pp.

Grandin, Lena & Hjärthner-Holdar, Eva 2003: Early iron production in the Red Earth area, South Central Sweden, p. 33-36 in Nørbach, L.C. (ed.) Prehistoric and Medieval direct iron smelting in Scandinavia and Europe. Acta Jutlandica **76**, No. 2. Aarhus University Press.

Grandin, Lena & Hjärthner-Holdar, Eva 2001: Bronsålderns järnproducenter. Research Report R 0011. Riksantikvarieämbetet. UVGAL. Uppsala.

Gregersen, Johan 1933: Sønderjysk Maanedskrift **9**: 161-180.

Grieg, Sigurd 1943: Hugg- og stötvåben fra Middelalderen, p. 90-133 i Bengt Thordeman (ed.) Vaaben. Nordisk Kultur XII B.

Grundtvig, N.F.S. 1820: Bjowulfs Drape. Et gothisk Heltedigt. København. 325 pp.

Guzman, Fernando Vazquez 1983: Depositos minerales de Espana. Instituto Geologico y Minero de Espana. Madrid.

Haarder, Andreas 1975: Beowulf. The appeal of a poem. Akademisk Forlag. København. 341 pp.

Hadfield, Robert A. 1925: Metallurgy and its influence on modern processes. Chapman & Hall. London. 387 pp.

Hagberg, Ulf Erik 1988: The bronze shields from Fröslunda, near Lake Vänern, West Sweden. Acta Archaeologica Lundensia, Series in 8°. No. 16: 119-126.

Hagberg, Ulf Erik 1996: Fröslundasköldarna, in Mellan bronssköld och JAS-plan-glimtar av Lidköpings-bygdens historia. Lidköping.

Hagberg, Ulf Erik & Jacobzon, L. 1986: Bronssöldarna från Fröslunda. Västergötlands Fornminnes- förenings Tidskrift, p. 137-146.

Haglund, Kerstin 1978: Rod-shaped and scythe-shaped currency bars. Exvavations at Helgö V: 1: 38-45. Lund.

Haglund, Kerstin 1979: Järn och slagg, in Kalmar Stads Historia I. Kalmar.

Haldane, Warner 1970: A study of the chemical composition of Pre Roman ironwork from Somerset. Bulletin of the Historical Metallurgy Group **4,** No. 2: 53-66.

Halkon, Peter 1995: Fieldwork on early ironworking sites in east Yorkshire, p. 17-20 in Crew, P. & Crew, S. (eds.) Iron for Archaeologists. Plas Tan y Bwlch, Snowdonia National Park.

Hallinder, Pär 1978: Currency bars of Mästermyr type. Excavations at Helgö. **V**: 1: 45-58.

Hallinder, Pär, Flyge, Hanne & Randrup, Jørn 1986: The iron slag from Helgö. Excavations at Helgö. **X**: 131-151.

Hallinder, Pär & Haglund, Kerstin 1978: Iron currency bars in Sweden. Excavations at Helgö **V**: 1:30-37.

Haneman, H. 1930: Untersuchung eines eisernen Spitzbarrens aus der vorrömischer Zeit. Praehistorische Zeitschrift **21**: 271-274.

Hansen, Henrik Jarl 1991: Dankirke. Jernalderboplads og rigdomscenter. Kuml 1988-89: 201-247.

Hansen, Henrik Jarl 1991: Dankirke. En myte i dansk arkæologi, p. 15-23 in Jysk Arkæologisk Selskabs Skrifter **XXVII**. Århus.

Hansen, Torben Egebjerg 1986: Lønhøjvej, Tarm by. Arkæologiske Udgravninger i Danmark 1985, p. 123.

Hansen, Torben Egebjerg 1991: Dejbjergs døde. Skalk No. 3, 4-9.

Hansen, Ulla Lund 2003: 150 years of weapon-offerings finds. Research and interpretation, p. 84-89 in Jørgensen, Lars et al (eds.) The spoils of victory. Catalogue. The National Museum, Copenhagen. 452 pp.

Hansson, Pär 1985: Finnbäcken och Smedsgården. Årbok för Örebro Läns Hembygdsförbund **39**: 59-66.

Hansson, Pär 1989: Samhälle och järn i Sverige under järnåldern och äldre medeltiden. Exemplet Närke, Aun **13**, Uppsala, 174 pp.

Hansson, Torsten & Modin, Sten 1973: A metallographic examination of some iron findings with high nickel and cobalt content. Antikvariskt Arkiv **50**: 5-23.

Hatt, Gudmund 1936: Nye iagttagelser vedrørende oldtidens jernudvinding i Jylland. Aarbøger for Nordisk Oldkyndighed og Historie, 19-45. København.

Hatto, A.T. 1970: The Nibelungenlied. A new translation. Penguin Books. 404 pp.

Hauge, T. Dannevig 1946: Blesterbruk och myrjern. Universitets Oldsaksamlings Skrifter. Vol. **3,** 221 pp. Oslo.

Hauptmann, Andreas 1985: 5000 Jahre Kupfer in Oman. Der Anschnitt, Beiheft 4. 137 pp.

Hauptmann, A., Begemann, F., Heitkemper, E., Pernicka, E. & Schmitt-Strecker, S. 1992: Early copper produced at Feinan. Archeomaterials **6,** No. 1: 1-33.

Heaney, Seamus 1999: Beowulf. Faber & Faber. London. 106 pp.

Hedeager, Lotte 1993: Førromersk og ældre romersk jernalder, p. 172-176 in Hvass, S. & Storgaard, B. Da klinger i muld. Aarhus Universitetsforlag. 312 pp.

Hedges, R. E. M. & Salter, C. J. 1979: Source determination of iron currency bars through analysis of the slag inclusions. Archaeometry **21,** 161-175.

Henger, G. W. 1970: The metallography and chemical analysis of iron-base samples dating from antiquity to modern times. Bulletin of the Historical Metallurgy Group **4**, No. 2: 45-52.

Henriksen, Mogens Bo., Jacobsen, Jørgen A. & Lorentzen, Asger H. 1997: Fynske jernalderbopladser, Vends, Skovby, Skam og Lunde herreder. Skrifter fra Odense Bys Museer. Vol **1**, 1. Odense. 284 pp.

Hingley, R. 1990: Iron age 'Currency bars', the archaeological and social context. Archaeological Journal **147,** 91-117.

Hjärthner-Holdar, Eva 1993: Järnmetallurgins introduktion i Sverige. Aun **16,** 206 pp. Uppsala.

Hjärthner, Eva, Krestin, Peter, Larsson, Lena & Lindahl, Anders 1997: Iron production and smithing on the Närke plain during 2500 years. Report nr. 9728. Geoarcheological Laboratory UV GAL, Uppsala.

Hofrén, M 1927: Velands Hög och smedmästaren från Brunneskärret. Fornvännen, p. 127-129.

Holmqvist, Wilhelm (ed.) 1961-1970: Excavations at Helgö. **1,** 1961. 241 pp. +77 pl. **2,** 1964. 290 pp. + 79 pl. **3,** 1970. 235 pp. + 49 pl.

Holmqvist, Wilhelm 1963: Helgö, vårt äldsta järnhandelscentrum. Jernkontorets Annaler, **147,** 905-911.

Holmqvist, Wilhelm 1972: Rapport från Helgö. 20 års arkeologiska undersökningar. Jernkontorets Annaler, **157,** 139-146.

Holtedahl, Olaf (ed) 1960: Geology of Norway. Norges Geologiske Undersøgelse Nr. **208**, 540 pp.

Hvass, Lone 2001: Oldtiden i Danmark. Jernalderen. Sesam.

Hvass, Steen 1975: Das eisenzeitliche Dorf bei Hodde, Westjütland. Acta Archaeologica **46,** 142-158.

Hvass, Steen 1977: Udgravningerne i Vorbasse. Fra Ribe Amt **20,** 345-385.

Hvass, Steen 1980: Vorbasse. The Viking Age Settlement at Vorbasse, Central Jutland. Acta Archaeologica **50,** 137-172.

Hvass, Steen & Storgaard, Birger 1993: Da klinger i muld – 25 års arkæologi i Danmark. Aarhus Universitetsforlag. 312 pp.

Hyenstrand, Åke 1979: Iron and iron economy in Sweden, p. 134-156 in Clarke, H. (ed.) Iron and Man in Prehistoric Sweden. Jernkontoret, Stockholm, 180 pp.

Høst-Madsen, Lene & Buchwald, V.F. 1999: The characterization and provenancing of ore, slag and iron from the iron age settlement at Snorup. Journal of Historical Metallurgy Society **38, No.** 2: 57-67.

Ige, Akin & Rehren, Thilo 2003: Black sand and iron stone. Iron smelting in Modakeke, Ife, south Western Nigeria. iams **23,** 15-20.

Ilkjær, Jørgen 1990: Illerup Ådal. Die Lanzen und Speere. Textband 404 pp. Tafelband 245 pp. Jysk Arkæologisk Selskabs Skrifter, Band **25**.

Ilkjær, Jørgen 2000: Illerup Ådal, et arkæologisk tryllespejl. Moesgård Museum, Aarhus Universitet. 151 pp.

Ilkjær, Jørgen 2003: Danish war booty sacrifices, p. 44-65 in Jørgensen, L. et al (eds.) The spoils of victory. Catalogue. National Museum, Copenhagen. 452 pp.

Ilkjær, J., Jouttijärvi, A. & Andersen, J. 1994: Proveniensbestemmelse af jern fra Illerup Ådal, et pilot-projekt. Højbjerg, Jysk Arkæologisk Selskab.

Jacobsen, Jørgen A. 1979: Bruneborg, en tidlig førromersk boplads med jernudvinding, p. 4-14 in Thrane, H. (ed.) Fra jernalder til middelalder. Skrifter fra Historisk Institut, Odense Universitet, **27**, Odense.

Jacobsen, Jørgen A. 1994: Bruneborg. Da jernet kom til Danmark. p. 54-55 in Milner, Per & Olsen, Olaf (eds.) 5000 år under motorvejen. Vejdirektoratet og Rigsantikvarens Arkæologiske Sekretariat. København. 84 pp.

Jacoby, Gerhard 1974: Werkzeug und Gerät aus dem Oppidum von Manching. Wiesbaden 1974.

Jankowska, N. B. 1969: The economy of the Assyrian empire, in Diakonoff, I. M. (ed.) Ancient Mesopotania. Moscow, p. 253 f.

Jankuhn, Herbert 1976: Haithabu. Ein Handelsplatz der Wikingerzeit. 6. Auflage. Wachholtz Verlag, Neumünster. 311 pp.

Jensen, Jørgen 1997: Fra bronze- til jernalder. En kronologisk undersøgelse. Nordiske Fortidsminder, Serie B, **15,** 423 pp. København.

Jensen, Jørgen 2002: Danmarks Oldtid. **2**, Bronzealder 2000-500 f.Kr. Gyldendal. 612 pp.

Jensen, Jørgen 2003: Danmarks Oldtid. **3**, Ældre jernalder 500 f.Kr. 400 e.Kr. Gyldendal. 685 pp.

Jensen, Stig 1980: Fredbjergfundet. En bronzebeslået pragtvogn på en vesthimmerlandsk jernalderboplads. Kuml, p. 169-216.

Jensen, Stig 1991 a: Dankirke-Ribe, p. 73-87, in Fra Stamme til Stat, Jysk Arkæologisk Selskabs Skrifter **22**, No. 2. Aarhus.

Jensen, Stig 1991 b: Ribes Vikinger. Den Antikvariske Samling. Ribe. 72 pp.

Jensen, Stig 1993: Bydannelser (Ribe), p. 202-205, in

Hvass, S. & Storgård, B. (eds.) Da klinger i muld, 25 års arkæologi i Danmark. Aarhus Universitetsforlag.

Jensen, Xenia Pauli 2003: The Vimose find, p. 224-238, in Jørgensen, L.et al. (eds.) The spoils of Victory. Catalogue. The National Museum, Copenhagen.

Jockenhövel, Albrecht 1980: Die Rasiermesser in Westeuropa. Prähistorische Broncefunde Abt.VIII, **3**. München. 238 pp + 103 pl.

Johanssen, Otto 1953: Geschichte des Eisens. Verlag Stahleisen, Düsseldorf. 621 pp.

Jovanovic, Borislav 1980: The origins of copper mining in Europe. Scientific American, May, p. 114-120.

Jöns, H. 1992: Der Vergangenheit auf der Spur. Wachholtz Verlag, Neumünster.

Jørgensen, Anne Nørgård 1999: Waffen und Gräber. Typologische und chronologische Studien zu skandinavischen Waffengräbern, 520/530 bis 900 n. Chr. Nordiske Fortidsminder, Serie B, **17**. Kopenhagen.

Jørgensen, Erik & Petersen, Peter Vang 2003: Nydam Mosenye fund og iatttagelser, p. 258-284 in Jørgensen, L. et al. (eds.) The spoils of Victory. Catalogue. The National Museum, Copenhagen.

Jørgensen, Mogens Schou 1987: Metaldetektorer, p. 400 in Hertz, J. et al. (eds.) Danmarks længste udgravning. Rigsantikvarens Arkæologiske Sekretariat. København. 516 pp.

Jørgensen, Mogens Schou & Møller, Jens Tyge 1999: Ravning Enge i vikingetid og middelalder. Vejle Amts Årbog, Kolding, p. 67-82.

Karlsson, Catarina 2001: Möre, järnet och människan, p. 345-366 in Magnusson, G. (ed.) Möre, historien om ett Småland. Kalmar Läns Museum. 672 pp.

Kaul, Flemming 1988: Da våbnene tav. Hjortspringfundet og dets baggrund. Nationalmuseet, København. 96 pp.

Kaul, Flemming 2003: Hjortspringfundet. Det ældste af de store nordiske krigsbytteofre. p. 212-223 in Jørgensen, L. et al (ed.) The spoils of Victory. Exhibition catalogue, National Museum, København. 451 pp.

Kempinski, A. & Kosak, S. 1977: Hittite metal inventories. Tel Aviv. **4**, 87 f.

Key, Mac 1982: Myten om Ubsola. Skövde. 168 pp.

Kirknæs, Jesper 1981: Jernsmeden. Sådan arbejder warongosmedene i Tanzania. Skarv's Etnografiske Serie. 49 pp.

Kivikoski, Ella 1964: Finlands förhistoria. Almqvist & Wiksell. Stockholm. 318 pp.

Kjær, Hans 1901: To nye mosefund fra jernalderen. Aarbøger for Nordisk Oldkyndighed og Historie. ap. 26-54.

Klaeber, Fr. 1950: Beowulf and The fight at Finnsburg. 3rd edition. Heath and Company. Lexington. Massachusetts. 471 pp.

Kleemann, Otto 1961: Stand der archäologischen Forschung über die eisernen Doppelpyramiden. Archiv für das Eisenhüttenwesen **32**, 581-585.

Kohler, Christoph & Naso, Alessandro 1991: Appunti sulla funzione di alari e spiedi nelle societa arcaiche dell'Italia centro-meridionale, in Herring, E. et al (eds.) The archeology of Power. Fourth Conference of Italian Archaeology. University of London. 1990.

Köster, Werner 1931: Über die Ausscheidungshärtung der Eisen-Phosphor Legierungen. Archiv für das Eisenhüttenwesen **4,** 609-11.

Kuziminych, S.V. 1983: Metallurgia Volgo-Kamija v rannen zjelezenom veke. Medi i Bronza. Moskva.

Künzl, Ernst 1993: Die Alamannen Beute aus dem Rhein bei Neupotz. Römisch- Germanischen Zentralmuseum. Mainz. Vol. **1-4**.

Lamm, Kristina & Lundström, Agneta (eds.) 1978: Excavations at Helgö **V**, 1. Workshop. Part II. Kungl. Vitterhets Historie och Antikvitets Akademien. Stockholm. 150 pp.

Lang, Janet 1984: The technology of Celtic iron swords. p. 61-72 in B. G. Scott & H. Cleere: The crafts of the blacksmith, 180 pp.

Langebek, Jacob 1758: Anledning til en historie om de norske bergverkers oprindelse og fremvext. Videnskabernes Selskabs Skrifter **7**, 235-526.

Larsen, Jan Henning 1991: Jernvinna ved Dokkfløyvatn. Varia 23, Universitetets Oldsakssamling. Oslo.

Larsen, Jan Henning 1992: Iron production at Dokkfløy in Oppland, Norway. p. 69-78 in Espelund, A. (ed.) Bloomery Ironmaking during 2000 years, vol. **2**. Trondheim.

Larsson, Lars & Hårdh, Birgitta 1998: Uppåkra, fokus för ett nytt projekt. Lunds Universitets Historiska Museum. Lund.

Larsson, Lars-Olof 1993: Det fantastiske Huseby. En rundvandring i tid og rum. Domän Arrende AB/Huseby Bruk. Växjö. 65 pp.

Larsson, Lars-Olof & Rubensson, Leif 2000: Smålands Järnhantering under 1000 år. **II**, Jernkontorets Berghistoriska Skriftserie Nr. 35, 334 pp.

Leoni, M. & Panseri, C. 1961: La technologia del ferro presso gli Etruschi. Studi Etruschi **29**, 235-43.

Levi, Hilde & Tauber, Henrik 1976: 25 år med C-14 datering. Naturens Verden **60**, 409-424.

Levinsen, Karin 1984 a: Jernets introduktion i Danmark. Kuml 1982-83 p. 153-168.

Levinsen, Karin 1984 b: En ældre romertids smedegrav fra Tolstrup ved Års. Hikuin **10**, 199-206.

Libby, W. F. 1954: Radiocarbon dating. Endeavour, p. 5-16.

Liestøl, Aslak 1951: Blodrefill og mål. Viking **15**, 71-98. Oslo.

Lindroth, Sten 1955: Gruvbrytning och kopparhantering vid Stora Kopparberget intill 1800-talets början. Vol. I-II. Uppsala.

Lindskog, P., Tengzelius, J. & Kvist, S.Å. 1977: Phosphorus as an alloying element in ferrous P/M. Plenum Press, New York. pp. 97-128.

Linné, Carl von 1734: Linnés Dalaresa. Iter Dalekarlicum. Udgivet af Svenska Linnésälskapet och Nordiska Museet. Med udförlig kommentar. Ed. A.H. Uggla. Stockholm 1953, 432 pp.

Linné, Carl von 1749: Skånska Resa. Reprinted 1975. Wahlström & Widstrand, Stockholm. 562 pp.

Livadefs, C. J. 1956: The structural iron of the Parthenon. Journal of the Iron and Steel Institute, January, 49-66.

Liversage, D. & Liversage, M. 1989: A method for the study of the composition of early copper and bronze artifacts. Helinium **29**, 42-76.

Ljung, Jan-Åke 1990: Valbo i Gästrikland, järnframställning med lång tradition. Jernkontorets Bergshistoriska Utskott H **46**, 35-46. Stockholm.

Longauerova, M, Longauer, S. & Makarius, P. 1999: Metallography of ancient bronze swords, p. 77-95 in Archaeometallrgy in ancient Europe, Mihok, L. & Mirossayova (eds). Kosice. Hutnicka Fakulta T.U.

Lorange, Anders Lund 1889: Den yngre jernalders sværd. Udgivet posthumt af C. Delgobe. Bergen.

Lorenzen, J. 1882: Kemisk undersøgelse af det metalliske jern fra Grønland. Meddelelser om Grønland **4**, København.

Luckenbill, D.D. 1926-27: Ancient records of Assyria and Babylonia. Chicago.

Lund, Carsten & Ørsnes, Mogens 1982: Metaldetektorenfund og fortidsminder. Fredningsstyrelsen og Nationalmuseet. 24 pp.

Lyngström, Henriette 1993: Ketting – en vikingetidsgravplads med ryttergrave. Aarbøger for Nordisk Oldtidskundskab og Historie, p. 143-179.

Lyngstrøm, Henriette 2002: Myremalmens mestre. Ved jernalderbondens ovn og esse. Forsøg med Fortiden **8**, 1-66. Historisk-Arkæologisk Forsøgscenter, Lejre.

Lysdahl, Per, Lundbæk, M., Gottlieb, B., Sørensen, J.N. & Aaby, B. 1990: Lurparret fra Ulvkær i Vendsyssel. Kuml, p. 7-43.

Löthman, Lars 1993: Talrika stenåldersboplatser, järnframställningsplatser och gruvor i Västmanlands Läns norra delen. Arkeologi i Sverige. **2**, 255-269.

Macmullen, Ramsay 1960: Inscriptions on armor and the supply of arms in the Roman Empire. American Journal of Archaeology **64**, 23-40.

Madsen, Claus & Thrane, Henrik 1985: Skibsjubileum (The Ladby Ship). Skalk No. 1: 3-7. Højbjerg.

Madsen, Helge Brinch 2004: Smithing debris. Ribe Excavations 1970-76, Volume 5, 187-222. Jutland Archaeological Society Publications No.46. Moesgård.

Madsen, Orla 1992: Midtjysk magt (om Hedegård, Ejstrup sogn). Skalk No. 2: 3-8. Højberg.

Madsen, Orla 1999: Hedegaard – a rich village and cemetery complex of the early Iron age on the Skjern River. Journal of Danish Archaeology 1996-97 **13**, 57-93.

Magnus, Olaus 1555: Historia om de nordiska folken. 1-4. Rome. Translated and reprinted by Gidlunds Förlag. Stockholm.

Magnusson, Gert 1985: Lapphyttan. An example of medieval iron production. Jernkontorets Forskning, Heft 34, Stockholm, p. 21-60.

Magnusson, Gert 1986: Lågteknisk järnhantering i Jämtlands län. Jernkontorets Bergshistoriska Skriftserie No. **22**, 437 pp. Stockholm.

Magnusson, Gert 1994: Järnet i Hälsingland. Bebyggelseshistorisk Tidskrift, **27**. Stockholm.

Magnusson, Gert 1997: Bergsmän, arbetare, bönder, gruvor, hyttor och oxar. Dædalus, Tekniska Museets Årsbok, p. 31-50.

Magnusson, Gert & Rubensson, Leif 2001: Järnhanteringens etablering i Sverige. p. 331-344 in Magnusson, Gert (ed.) Möre, historien om ett Småland. Kalmar Läns Museum. Kalmar. 672 pp.

Magnusson, Gert & Millberg, Per-Olof 1982: Lågteknisk järnframställning i Skaraborgs Län. Västergötlands Fornminnesförenings Tidskrift. 1981-82.

Magnusson, Nils H. 1953: Malmgeologi. Jernkontoret. Stockholm. 439 pp.

Mangin, Michel 1989: La production du fer en France avant le haut fourneau, p. 239-252 in Pleiner, R. (ed.) Archaeometallurgy of iron. International Symposium in Liblice 1987. Prague. 495 pp. 34 pl.

Mangin, M., Keesmann, I., Birke, W., & Ploquin, A. 1992: Mines et Métallurgie chez les Eduéens, Annales littéraires de l'Université de Besancon 456, Paris, 364 pp.

Manning, W.H. 1976: Blacksmithing. p. 143-153 in Strong, Donald & Brown, David (eds.) Roman crafts. London. 256 pp.

Manning, W.H. & Hurrell, M.M. 1976: Catalogue of Romano-British Ironwork in the Museum of Antiquities. The University of Newcastle upon Tyne. 61 pp.

Markvad, Jørgen 2004: Danske Konger – før Gorm den Gamle – Yduns Æbler, 8751 Gedved. 142 pp.

Marseen, Oscar 1992: Lindholm Høje. With summary in English. Aalborg Historiske Museum. 5th edition. 23 pp.

Martens, Irmelin 1968: Jernvinna i Norge. Teknisk Ukeblad **115**, No. 17: 368-376.

Martens, Irmelin 1972: Mösstrond i Telemark. En jernproducerende fjellbygd för svartedauen. Viking, 83-114. Oslo.

Martens, Irmelin 1979: Blåsterjern og fellujern. Noen synspunkter på en lite påaktet funngruppe. Universitetets Oldsaksamling 150 år. Jubileumsårbok 1979, p. 190-197. Oslo.

Martens, Irmelin 1981: Noen synspunkter på produksjon og distribution av jern i Norge i yngre jernalder. Universitetets Oldsaksamling Årbok 1980/81, p. 97-102. Oslo.

Martens, I. & Rosenqvist, A. M. 1988: Jernvinna på Mösstrond i Telemark. Universitetets Oldsaksamling. 189 pp.

Martin, Th. & Ruffat, H. 1998: Un dépôt de lingots de fer du début de la Tène III à Montans (Tarn), p. 110-115 in Feugère, M. & Serneels, V. (eds.) : Monographies Instrumentum Vol. 4.

Matteoli, L. & Storti, C. 1982: Metallographic research on four pure copper flat axes and one related metallic block from an Eneolithic Italian cave. Historical Metallurgy **16**, 65-69.

Matthiesen, Henning 2003: The preservation of the past for the future, p. 356-363 in Jørgensen, L. et al. (eds). The spoils of victory. Catalogue. National Museum. Copenhagen. 452 pp.

Maxwell-Hyslop, R. 1974: Assyrian sources of iron. Iraq **36**, 36-139 f.

McCartney, A.P. 1991: Canadian arctic trade metal. MASCA Research Paper in Science and Archaeology **8**, part 2.

Mc Cartney, A. P. & Mack, D.J. 1973: Iron utilization by Thule eskimos of Central Canada. American Antiquity **38**, 328-338.

Meinander, C.F. 1985: Akozino, Achmolyvo och Mälaryxorna. Finskt Museum. Helsingfors.

Mejdahl, Jørgen 2004: Sagnet om Nibelungerne. Gyldendal. København. 158 pp.

Merkel, J. & Barret, K. 2000: " The adventitious production of iron in the smelting of copper" revisited. Metallographic evidence against a tempting model. Journal of Historical Metallurgy **34**, part 2, 59-66.

Merwe, Nikolaas J. van der 1980: The advent of iron in Africa, p. 463-506 in Wertime, T. A. & Muhly, J. D. (eds.) The coming of the age of iron. Yale University Press, 555 pp.

Michaelsen, K. K. & Thomsen, P. O. 1991: Broholmskatten. Historien om et Guldfund, p. 8-23 in Årbog For Svendborg & Omegns Museum.

Michaelsen, K. K., Thomsen, P. O. & Sørensen, P. Ø. 1993: Fynsk guldalder (Gudme). Skalk No. 6, 1-12.

Mikkelsen, Peter Hambro 2003: Slag – with an impression of agricultural plants. p. 43-48 in Nørbach, L.C. (ed.) the Sandbjerg Conference, Acta Jutlandica **76: 2,** Aarhus University Press.

Minto, Antonio 1943: Populonia. Instituto di Studi Etruschi. Firenze. 359 pp.

Minto, Antonio 1954: L'antica industria mineraria in Etruria e il porto di Populonia. Studi Etruschi **23**, 293-319.

Modin, Sten 1960: Mikrostruktur hos glödskal på järn och stål. Jernkontorets Annaler **144**, 799-833.

Modin, Sten & Thålin, Lena 1969: Förhistoriskt spjutsmide i metallografisk belysning. Jernkontorets Annaler **153**, 231-239. Stockholm.

Money, J.H. & Cleere, H.F. 1974: Iron age and Romano-British iron-working site in Minepit Wood, Rotherfield, Sussex. Historical Metallurgy **8**, 1-16.

Montelius, Oscar 1917: Minnen från vår fortid. I. Stenåldern och bronsåldern. Faksimiltryk, PM- Bokförlag, Gamleby. 2002, 100 + 63 pp.

Montelius, Oscar 1921: Hur länge har järnet tjänat oss? p. 1-5 in Ambrosiani et al. (eds.), En bergsbok tillägnad Carl Sahlin. Stockholm. 289 pp.

Moorey, P. R. S. 1985: Materials and manufacture in ancient Mesopotamia. BAR International Series **237**, 302 pp.

Moosleitner, Fritz & Moesta, Hasso 1988: Vier Spangenbarrendepots aus Obereching, Land Salzburg. Germania **66**, 29-67.

Mortensen, Rasmus 1920: Jydsk Jærn. Nogle smeltepladser. Vejle Amts Aarbøger.

Mortensen, Rasmus 1939: Jysk jærn. Jyske Samlinger, 5. række, 4. bind, 91-213.

Müller, Sophus 1897: Vor Oldtid. Danmarks forhistoriske arkæologi. København. 711 pp.

Müller, Sophus 1933: Jernalderens kunst i Danmark. Førromersk og romersk tid. København. 133 pp.

Müller- Wille, M. 1980: Ein Barrenhort aus Haithabu. Offa **37**, 129-145. Neumünster.

Müller-Wille, Michael 1981: Der Schmied im Spiegel archäologischer Quellen. Abh. Akad. Wiss. Göttingen, p. 216-259. Phil. Hist. Klasse, III Folge, No. 122.

Müller-Wille, M. 1983: Der Schmied im Spiegel archäologischer Quellen zur Aussage von Schmiedegräbern der Wikingerzeit. Abh. Akad. Wiss. Göttingen, Phil. Hist. Klasse III Folge, No. 123. Göttingen.

Myrdal, Janken 1982: Jordbruksredskap av järn före år 1000. Fornvännen **77**, 81-104.

Nakkerud, T. B. & Schaller, Eva 1979: Slaggroper på Eg ved Kristiansand, Vest- Agder. Varia **4**, Arkeologisk Museum i Stavanger.

Narmo, Lars Erik 1996: Jernvinna i Valdres og Gausdal, et fragment av Middelalderens økonomi. Varia **38**, 239 pp. Universitetets Oldsaksamling. Oslo.

Narmo, L E. 1997: Jernvinne, smie og kullproduksjon i Österdalen. Arkeologiske undersökelser på Rödsmoen i Åmot 1994-1996. Varia **43**. Universitetets Oldsaksamling. Oslo.

Naumann, E. 1922: Södra och mellersta Sveriges sjö- och myremalmer. Sveriges Geologiska Undersökning. Serie C 297. 193 pp.

Naumann, Friedrich Karl 1971: Metallkundliche Untersuchungen an drei wikingerzeitlichen Zieheisen aus Haithabu. Berichte über die Ausgrabungen in Haithabu **5**, 84-99.

Neumann, Bernhard 1927: Römischer Damaststahl. Archiv für das Eisenhüttenweswn. **1**, 241-244.

Neumann, Bernhard 1954: Die ältesten Verfahren der Erzeugung technischen Eisens. Freiberger Forschungshefte, Kultur und Technik D6. Berlin. 107 pp.

Nie, Matthijs van 1995: Three iron production areas in the Netherlands, in The Importance of Ironmaking, Magnusson, G. (ed.), p. 100-106. Jernkontorets Berghistoriska Utskott H 58. Stockholm.

Nie, Matthijs van 1997: Germanic iron provision in the second half of the third century AD. In Early Iron Production, Nørbach, L. C. (ed.) Technical Report No. 3, p. 115-122. Historical- Archaeological Experimental Centre. Lejre.

Nielsen, Karen Høilund & Petersen, Peter Vang 1993: Detektorfund, p. 223-227 in Hvass, S & Storgård, B. (eds.) Da klinger i muld ... Aarhus Universitetsforlag. 312 pp.

Nielsen, Niels 1924: Studier over jærnproduktionen i Jylland. 189 pp. Disputats. Københavns Universitet.

Nielsen, Niels 1926: Jærnudvindingen på Island i fordums tider. Aarbøger for Nordisk Oldkyndighed og Historie, p. 129-174.

Nihlén, John 1932: Studier rörande äldre svensk järntillverkning med särskild hensyn till Småland. Jernkontorets Bergshistoriske Skriftserie Nr. 2. Stockholm. 211 pp.

Nihlén, John 1939: Äldre järntillverkning i Sydsverige. Jernkontorets Bergshistoriska Skriftserie, No. 9, 139 pp. Stockholm.

Nikander, Gabriel 1928: Myr- och sjömalmsmältning i äldre tid. p. 53-85 in Historisk Tidskrift för Finland.

Nikulka, Frank 2003: The development of iron production in northwestern Germany, p. 63-66 in Nørbach, L.C. (ed.) Technical Report No. 3, Historical-Archeological Experimental Centre, Lejre.

Nilsen, Odd 1993: Fra myrmalm til kismalm i Budalen. Geonytt No. 3, 3. Oslo. Norsk Geologisk Forening.

Nordenskiöld, A.E. 1871: Redogörelse för en ekspedition til Grønland i 1870. Öfversikt Vetenskaps Akademiens Förhandlingar **27**, 973-1082.

Nygård-Nilssen, Arne 1944: Norsk jernskulptur. Oslo, Vol. 1-2.

Noe-Nygaard, Arne 1962: Geologi – Processer og materialer. Gyldendal. 3. udgave. 422 pp.

Nordman, Ann-Marie 1994: Dubbelugnar i Axamo, Småland, p. 69-77 in Jernkontorets Bergshistoriska Utskott H 55. Stockholm.

Näsman, Ulf 1991: Mammen 1871, p. 217-260 in Iversen, Mette (ed.) Mammen. Jysk Arkæologisk Selskabs Skrifter **28**, 1-343.

Nørbach, Lars Christian (ed.) 1997: Early iron production. Archaeology, technology and experiment. Technical Report No. 3, Historical- Archeological Experimental Centre. Lejre. 142 pp.

Nørbach, L. C. 1998: Ironworking in Denmark from the late Bronze age to the Early Roman Iron Age. Acta Archaelogica **69**.

Nørbach, L. C. 2003: A short history of Danish iron research, p. 67-70 in Nørbach, L. C. (ed.) Iron Smelting. Acta Jutlandica **76**, 2. Humanities Series 75. Aarhus University press. 335 pp.

Nørgaard, F., Roesdahl, E. & Skovmand, R. (eds.) 1986: Aggersborg gennem 1000 år. Herning.

Nørlund, Poul 1948: Trelleborg. Nordiske Fortidsminder. Bind IV, 1. København. 296 pp.

Oddy, W. A. & Swaddling, Judith 1985: Illustrations of metalworking furnaces on Greek vases, p. 43-57 in P.T. Craddock & M. J. Hughes (eds.) Furnaces and smelting Technology in Antiquity. Brit. Mus. Occ. Paper No. 48. London.

Oldeberg. Andreas 1966: Metalteknik under Vikingetid och Medeltid. Stockholm. 296 pp.

Oldeberg, Andreas 1974: Die ältere Metallzeit in Schweden. Vol. 1-2. Kung. Vitterhets Historie och Antikvitets Akademien. Stockholm.

Olsen, Olaf 1975 a: Viking fortresses in Denmark, p. 90-110 in Bruce-Mitford, R. (ed.). Recent Archeological Excavations in Europe. London.

Olsen, Olaf 1975 b: Nogle tanker i anledning af Ribes uventet høje alder. Fra Ribe Amt. **19**, 225-258.

Olsen, Olaf & Crumlin- Pedersen, Ole 1969: Fem vikingeskibe fra Roskilde Fjord. Vikingeskibshallen i Roskilde. 136 pp.

Olsen, Olaf, Jørgensen, Axel & Lavesen, Holger (eds.) 1987: Danmarks længste udgravning. Rigsantikvarens Arkæologiske Sekretariat. 516 pp.

Ortiz, Mark A. Hunt 1988: Consideraciones sobre la metalurgia del cobre y del hierro en epoca romana en la provincia de Huelva. Habis **19**, 601-611.

Pare, C. F. E. 1992: Wagons and wagongraves of the early iron age in Central Europe. Oxford University Committee for Archaelogy. Monograph No. **35**. 382 pp. + 136 pl.

Parker, A. J. 1992: Ancient shipwrecks of the Mediterranean and the Roman provinces. BAR S-580, Oxford. 547 p. + plates.

Parker, G. 1982: Metallurgical notes on three Bronze age implements found in the West of England. Historical Metallurgy **16**, 46-49.

Peary, Robert E. 1898: Northward over the Great Ice. Vol. 1-2. Methuen, London.

Percy, John 1864: Metallurgy. Iron. Steel. London. Faksimile Reprint. De Archæologisch Pers Nederland 1984. Part I-III.

Petersen, Henry 1888: Vognfundene i Dejbjerg Præstegårdsmose ved Ringkøbing 1881 og 1883. København.

Petersen, Jan 1918: Jernbarrer. Oldtiden **7**: 171-186. Kristiania.

Petersen, Jan 1923: Jernbarrer. Oldtiden **10**: 71-77. Oslo.

Petersen, Jan 1951: Vikingetidens redskaper. Skrifter utgitt av Det Norske Videnskaps-Akademi i Oslo. II. Historisk-Filosofisk Klasse. 2. bind. 536 pp.

Philip's Atlas of the Celts. 2001. University College, Dublin. Clint Twist. Octopus Publishing Group.

Photos, E., Koukouli-Chrysanthaki, H. & Gialoglou, G. 1984: Iron metallurgy in Eastern Macedonia, A preliminary report. p. 113-120. In Scott & Cleere (eds.) The crafts of the blacksmith.

Piaskowski, Jerzy 1983: Metallographische Untersuchungen zur Eisen- und Stahltechnologie in Haithabu. Berichte über die Ausgrabungen in Haithabu, **18**: 45-62. Neumünster.

Place, Victor 1867: Niniveh et l'Assyrie. Paris.

Pleiner, Radomir 1962: Staré evropské kovárstvi. Praha. Summary in German: Alteuropäisches Schmiedehandwerk, 252-293. 66 pl, 49 figures.

Pleiner, Radomir 1979: The technology of three Assyrian artifacts from Khorsabad. Journal of the Near Eastern Studies, Chicago **38** No. 2, 83-91.

Pleiner, Radomir 1980: Early iron metallurgy in Europe. p. 375-415 in Wertime, T.A. & Muhly, J.D. The coming of the age of iron. Yale University Press.

Pleiner, Radomir 1984: Examination of some early La Téne period knives from Bohemia, p. 73-82, in B.G. Scott & H. Cleere (eds.) The Crafts of the blacksmith.

Pleiner, Radomir 1993: The Celtic sword. Clarendon Press, Oxford. 196 pp. 36 plates.

Pleiner, Radomir 2000: Iron in archeology. The European bloomery smelters. Archeologicky Ustav AVCR. Praha. 400 pp.

Pleiner, R. & Bjorkman, J.K. 1974: The Assyrian iron age. Proceedings of the American Philosophical Society **118** (4), 283-313.

Plutarch's Lives. II Themistocles and Camillus. The Loeb Classical Library. Harvard University Press. (1914), 1968.

Possnert, Göran & Wetterholm, Allen 1995: Radiocarbon dating of iron, p. 135-139 in The Importance of Ironmaking. Jernkontorets Bergshistoriska Utskott H 62. Stockholm.

Pringle, Heather 1997: New respect for metal's role in ancient Arctic cultures. Science **277**, 766.

Purhonen, Paula 1982: Ylivieska Kettukallion harkkolöytö. Studia Minora. Helsingin Yliopiston Arkeologian Laitos. Moniste no. 29.

Rambaud, Michel 1974: C. Julius Caesar. Bellum Gallicum, Liber Quintus. Edition, introduction et commentaire. Paris. Presses Universitaires de France.

Ramdohr, P. & Strunz, H. 1967: Klockmanns Lehrbuch der Mineralogie. Ferdinand Enke, Stuttgart.

Ramskou, Thorkild 1976: Lindholm Høje. Gravpladsen. Nordiske Fortidsminder. Bind 2, 199 pp.

Ramskou, Thorkild 1981: Lindholm Høje. A Danish Viking period field. Tools and Tillage **4**, 2.

Randsborg, Klavs 1980: Kobberalder. Skalk no. 5, 9-11.

Randsborg, K. 1995: Hjortspring. Warfare and sacrifice in early Europe. Aarhus University Press. Aarhus. 251 pp.

Ranløv, A. & Henriksen, E.K. 1941: Jern og stål. København 1941. Vol. 1, 564 pp. Vol. 2, 536 pp.

Rasmussen, B. 1995: Brokær. Ein Reichtumszentrum der römischen Kaiserzeit in Südwestjütland. Acta Archeologica **66**, 39-109.

Rasmussen, Kaare Lund 1992: Neutronaktiveringsanalyse af 4 skibsnagler. Nationalmuseets Naturvidenskabelige Undersøgelser. Rapport No. 7. København.

Rasmussen, Kaare Lund 1994: Kulstof-14 datering. Datering af arkæologiske fund. København. 63 pp.

Rasmussen, K.L., Rahbek, U. & Voss, O. 1998: Radiocarbon dating of the iron production in slag-pit furnaces in Jutland. Journal of Danish Archeology.

Resi, H.G. 1995: The Norwegian iron bar deposits. Varia **30**, 131-146. Universitetets Oldsaksamling. Oslo.

Richardson, M.T. 1978: Practical blacksmithing. Four volumes in one, originally published in 1889. Weathervane Books. New York. 1066 pp.

Rieck, Flemming 2003: The ships from Nydam Bog, 296-309 in Jørgensen, L. et al (eds.). The spoils of victory. Catalogue. National Museum, Copenhagen. 452 pp.

Rieck, Flemming 2004: The anchor from Sct.Nicolaigade in Ribe. Ribe Excavations 1970-76, Volume 5, 173-182. Jutland Archaeological Society Publications, No.46, Moesgård.

Riederer, Josef 1987: Archäologie und Chemie, Einblicke in die Vergangenheit. Rathgen-Forschungslabor. Berlin. 276 pp.

Riis, R.G. 1961-62: Hama. Fouilles et Recherches. Copenhague.

Rijk, Patrice de 1997: Slag-pit furnaces between the rivers Elbe and Weser. Early Ironworking in Europe. Abstracts Plas Tan y Bwlch. 43 pp.

Rinman, Swen 1782: Försök till Järnets Historia. 1-2. Stockholm. 1084 pp.

Risbøl, Ole & Smekalova, Tatyana 2001: Archaeological survey and non-visible monuments. Nicolay, arkeologisk tidsskrift, Oslo. No. 85, p. 32-45.

Robins, Frederick W. 1953: The smith. The traditions and lore of an ancient craft. Rider and Company. London. 160 pp.

Robinson, H. Russell & Embleton, Ronald 1985: The Armour of the Roman Legions. Frank Graham, Newcastle upon Tyne. 39 pp.

Roesdahl, Else 1976: Otte vikingetidsgrave i Sdr. Onsild. Aarbøger for Nordisk Oldkyndighed og Historie. 1978, 22-51.

Roesdahl, Else 1981: Aggersborg in the Viking Age, 107-122 in Bekker-Nielsen, H. et al. (eds.) Proceedings of the Eigth Viking Congress, Århus 1977. Odense University Press.

Rollins, John G. 1981: Needlemaking. Shire Publications Ltd. 32 pp.

Rosenberg, G.A. 1917: Antiquités en fer et en bronze. København.

Rosenberg, G.A. 1937: Hjortspringfundet. Nordiske Fortidsminder 3, 1-111.

Rosenqvist, Anna M. 1968: Sverd med klinger ornert med figurer i kopperlegeringer fra eldre jernalder. Universitetets Oldsaksamling. Årbok 1967-68, p. 143-200. Oslo.

Rosenqvist, Anna M. 1979: Undersøkelse av sammensetning og struktur av nagler og spiker fra båtgraver fra Vikingetida i Sør-Norge. Universitetets Oldsaksamling 150 år, 181-189. Oslo.

Ross, John 1819: A voyage of discovery, made under the orders of the Admiralty, in his Majesty's ships Isabella and Alexander ... Longman et al. London. Second edition in two volumes.

Rostoker, William & Bronson, Bennett 1990: Pre-Industrial Iron, its Technology and Ethnology. Archeomaterials, Monograph No. 1. Philadelphia. 232 pp.

Rothenberg, Beno & Palomero, Felix G. 1986: The Rio Tinto enigma – no more. Institute for Archaeo-Metallurgical Studies, Newsletter No. 8, 3-5.

Rothenberg, Beno & Tylecote, R.F. 1991: A unique Assyrian iron smithy in the Northern Negev, Israel. Institute for Archaeo-Metallurgical Studies, No. 17, 11-14.

Rychner, V. 1984: La matière première des bronziers lacustres. Archaeologie Suisse. **7**, 73-78.

Rygh, O. 1885: Norske oldsager. Kristiania.

Rädeker, Wilhelm & Naumann, F.K. 1961: Untersuchung vor- oder frühgeschichtlicher Spitzbarren. Archiv für das Eisenhüttenwesen. **32**, 587-595.

Rønne, Preben 1988: Spiralens gåde. Skalk No. 6, 9-12.

Salin, Édouard 1957: La civilisation mérovingienne. III, Les techniques. Paris. 307 pp. 21 pl. 103 figures.

Salter, Chris & Ehrenreich, Robert 1984: Iron Age metallurgy in central southern Britain. In Cunliffe, B.W. & Miles, D. (eds.) Aspects of the Iron Age in central southern Britain, 146-161. Oxford University Comitte for Archaeology, Monograph No. 2.

Sandwall, Ann (ed.) 1980: Vendeltid. Statens Historiska Museum. Stockholm. 368 pp.

Santi, Luisa 1969: Il mondo degli Etruschi. Biblioteca di Storia Patria. Roma. 377 pp.

Savory, H.N. 1980: Guide catalogue to the Bronze age collection. National Museum of Wales. Cardiff.

Saxo 1907: Saxo Grammaticus. Danmarks Krønike. Translated by F. Winkel Horn, in 15 books. Copenhagen. 1907. 427 + 309 pp.

Schmid, W. 1932: Norisches Eisen. Beiträge zur Geschichte des österreichischen Eisenhüttenwesens. Abt.1, Heft 2, 167-211. Wien.

Schmidt, Peter R. 1995: Culture and technology of African iron production. University Press of Florida.

Schmirler, Otto 1981: Werk und Werkzeug des Kunstschmieds. Verlag Ernst Wasmuth, Tübingen. 128 pp.

Schubert, H.R. 1957: History of the British iron and steel industry, c.450 B.C. to A.D. 1775. London.

Schürmann, Eberhard 1959: Untersuchungen an Nydam-Schwertern. Archiv für das Eisenhüttenwesen **30**, 121-126.

Schürmann, Eberhard & Schroer, Hermann 1959: Härte und Glühversuche an dem Klingenbruchstuck eines Nydam-Schwertes. Archiv für das Eisenhüttenwesen **30**, 127-130.

Schulz, Eeva-Liisa 1986: Ein Eisenverhüttungsplatz aus der älteren Eisenzeit in Kajaani. Suomen Muinaismuistoyhdistys. Iskos 6, 169-173.

Scott, David A. 1991: Metallography and microstructure of ancient and historic metals. The J. Paul Getty Museum, Los Angeles. 155 pp.

Sehested, N.F.B. 1878: Fortidsminder og oldsager fra egnen om Broholm. København. 317 pp. 46 pl.

Sehested, N.F.B. 1884: Archæologiske undersøgelser 1878-1881. København. 180 pp. 36 pl.

Serneels, V. 1993: Archéométrie des scories de fer. Cahiers d'Archéologie Romande **61**, 240 pp Lausanne.

Serneels, V. & Maulvilly, M. 2001: The early la Tène metallurgical workshop at Sévaz, Switzerland. Acta Metallurgica Slovakia **7**, Special Issue, p. 268-277.

Serning, Inga 1960: Övre Norrlands järnålder. Publications of the Umeå Research Library, No. 4. Umeå. 289 pp.

Serning, Inga 1966: Dalarnas järnålder. Stockholm. 256 pp. 113 pl.

Serning, Inga 1973: Förhistorisk järnhantering i Dalarna. Jernkontorets Forskning, Serie H 9, 139 pp. Grängesberg.

Serning, Inga 1979: Prehistoric iron production, p. 50-98 in Clarke, Helen (ed.) Iron and man in prehistoric Sweden. Jernkontoret. Stockholm. 180 pp.

Serning, Inga 1984: Tidigt järn i Mellansverige. Gotländskt Arkiv. **56**, Visby.

Sherby, Oleg D. & Wadsworth, Jeffrey 1985: Damascus steels. Scientific American 252, 94-99.

Smekalova, Tatjyana & Voss, Olfert 2001: Magnetisk kortlægning af arkæologiske anlæg i Danmark 1992-2000. Nationalmuseets Arbejdsmark, p. 148-161.

Smekalova, Tatjyana & Voss, Olfert 2003: Field procedures for magnetic investigations of iron-smelting sites with slag pits, p. 223-226 in Nørbach, L.C. (ed.) Iron Smelting. Aarhus University Press. Acta Jutlandica **76**, 2. 335 pp.

Smith, Cyril Stanley 1960: A history of metallography. University of Chicago Press. 293 pp.

Sönnecken, Manfred 1994: Grabungsberichte zur Rennfeuerverhüttung. 391-405 in Knau, H.L. & Potyka, Reiner (eds.) Kierspe. Wirtschaft, Kultur, Geschichte. Sparkasse Kierspe – Meinerzhagen. Stuttgart. 537 pp.

Solberg, Bergljot 2000: Jernalderen i Norge. Cappelen. Akademisk Forlag. Oslo. 371 pp.

Solem, Thyra 1991: Effects of early iron production on vegetation, p. 50-70 in Espelund, A. (ed.) Bloomery Ironmaking during 2000 years. Trondheim.

Sperl, Gerhard 1977: Technologische Beziehungen zwischen der frühgeschichtlichen Kupfer- und Eisenmetallurgie, p. 181-83 in Wissenschaftliche Arbeiten aus den Burgenland Heft 59. Eisenstadt 1977.

Sperl, Gerhard 1980: Über die Typologie urzeitlicher, frühgeschichtlicher und mittelalterlicher Eisenhüttenschlacken. Österreichische Akademie der Wissenschaften. Wien. 68 pp. + 61 figures.

Sperl, Gerhard 1982: Norisches Eisen. Versuche zur Herkunftsdefinition. Berg- und Hüttenmännische Monatshefte **127**, 263-265.

Sperl, Gerhard 1992: Das Beil von Hauslabjoch. 454-461 in Der Mann im Eis. Frank Höpfel et al (ed.) Band 1. Universität Innsbruck.

Sperl, Gerhard 1993: Wege des Eisens. Die Europäische Eisenstrasse. Österreichischer Kalender für Berg, Hütte, Energie. p. 28-68.

Starley, David 1994: The assessment of slag and other metalworking debris from Ariconium. Ancient Monuments Laboratory. Reports Series. English Heritage. London. 11 pp.

Starley, David 1995: The analytical examination of metalworking debris from the 1989-90 Ribchester graveyard excavations, Lancashire. Ancient Monuments Laboratory. Report 23/95. English Heritage, London. 49 pp.

Steenstrup, K.J.V. 1882: Om forekomsten af nikkeljern med Widmanstättenske figurer i basalten i Nord-Grønland. Meddelelser om Grønland **4** (3), 114-132. København.

Stenberger, Mårten 1966: Eketorps Borg, a fortified village on Öland, Sweden. Acta Archeologica **37**, 203-221. Copenhagen.

Stene, Kathrine (ed.) 2004: Gråfjellprojektet. Årsrapport 2003. Universitetets Kulturhistoriske Museer, Oslo. 106 pp.

Stenvik, Lars 1991: Iron production and economic "booms" during 2000 years, p. 100-115 in Espelund, A. (ed.) Bloomery ironmaking during 2000 years. Trondheim. 142 pp.

Stenvik, Lars 2003: Recent results from investigations of iron production in Northern Europe. p. 77-82 in Nørbach, L.(ed.) Iron smelting. Sandbjerg Conf. Sept.1999. Acta Jutlandica **76**, 2. Aarhus. 335 pp.

Stjernquist, Bertha 1951: Vä under järnåldern. Gleerups Förlag, Lund. 176 pp.

Stjernquist, Bertha 1970: Einige Gesichtspunkte zu vorgeschichtlichen Eisenverarbeitung. Meddelanden från Lunds Universitets Historiska Museum 1969-1970, p. 150-191.

Stodte, Hermann 1956: Nibelungenlied. Kohlhammer Stuttgart. 308 pp.

Straube, Harald 1996: Ferrum Noricum und die Stadt auf dem Magdalensberg. Springer. Wien, New York. 187 pp.

Strömberg, Bo 1995: Spor av järnhantering i Halland från äldre järnålder till sen medeltid, 36-51 in Olsson, S.O. (ed.) Medeltida danskt järn. Högskolan i Halmstad.

Svane, Hege 1991: Rhombic iron axes and axiform currency bars from Norway. Materialy Archeologiczne **26**, 31-32.

Swedenborg, Emanuel 1734: De Ferro; Om Järnet. Translated from Latin to Swedish, by Arrhenius, S., Carlheim-Gyllersköld,V. & Sjögren, H. Stockholm 1923, 470 pp.

Sølver, Carl V. 1946: The Ladby ship anchor. Acta Archaeologica **17**, 117-126.

Sørensen, Anne C. 2001: Ladby. A danish ship-grave from the Viking Age. The Viking Ship Museum. Roskilde. 292 pp.

Sørensen, Søren A. 2000: Hørup, en sjællandsk værkstedsplads fra romersk jernalder. Museet Færgegården. Jægerspris. 104 pp.

Sørensen, Søren A. & Ulriksen, Jens 1995: Selsø – Vestby. Vikingernes anløbsplads ved Selsø. Museet Færgegården. Jægerspris. 40 pp.

Taavitsainen, J-P. 1990: Ancient hillforts of Finland. Helsinki. 294 pp.

Tanelli, Giuseppe 1983: Mineralizzazioni metallifere e minerogenesi della Toscana. Memorie Soc. Geol. Ital. **25**, 91-109.

Termansen, Peter Bang 1960: Filehugger Niels Knudsen i Herslev. 46-54. Købstadmuseet, Den Gamle By, Aarhus.

Theophilus. The various arts. De diversis artibus. Translated from the Latin with introduction and notes by C.R. Dodwel. Thomas Nelson and Sons Ltd. London 1961. 76+2x176 pp.

Tholander, E. 1982: How ancient technology could influence the properties of artefacts of iron and steel. PACT no. 7, 477-486.

Thomsen, Per O. 1989: Lundeborg. p. 8-35 in Årbog for Svendborg & Omegns Museum.

Thomsen, Per O. 1997: Jernbarrrer fra Lundeborg – indikationer på germansk handel med jernbarrer. p. 8-18 in Årbog for Svendborg & Omegns Museum.

Thomsen, Per O., Blæsild, B., Hardt, N. & Michaelsen, K.K. 1993: Lundeborg, en handelsplads fra jernalderen. Svendborg & Omegns Museum. Bind 32, 117 pp.

Thomsen, Robert 1963: Forsøg på rekonstruktion af en fortidig jernudvindingsproces. Kuml, 60-74.

Thomsen, Robert 1964: Forsøg på rekonstruktion af fortidige smedeprocesser. Kuml, 62-85.

Thomsen, Robert 1966: Metallographic studies of an axe from the Migration age. Journal of the Iron and Steel Institute, **204**, 905-909.

Thomsen, Robert 1971a: Untersuchung von Eisengegenständen aus der Vikingerzeit. Radex- Rundschau, Heft 3, 479-486.

Thomsen, Robert 1971b: Metallographischen Untersuchungen an wikingezeitlichen Eisenbarren aus Haithabu. Berichte über die Ausgrabungen in Haithabu, **5**, 9-29. Neumünster.

Thomsen, Robert 1971c: Essestein und Ausheizschlacken aus Haithabu. Berichte über die Ausgrabungen in Haithabu **5**, 100-109. Neumünster.

Thomsen, Robert 1971 d: Metallographische Untersuchung einer wikingerzeitlichen Lanzenspitze aus Haithabu. Berichte über die Ausgrabungen in Haithabu **5**, 58-83.

Thomsen, Robert 1975: Et meget mærkeligt metal. Varde Staalværk A/S. 102 pp.

Thomsen, Robert 1992: Metallografiske undersøgelser af sværd og spydspidser fra mosefundene i Illerup og Nydam. Aarbøger for Nordisk Oldkyndighed og Historie, p. 281-310.

Thorsen, K.Å. 1971: Mikrohårdhedsmåling, p. 241-257 in Metallurgens Værktøj, V.F.Buchwald (ed.) Dansk Metallurgisk Selskab. Vintermøde.

Thorvildsen, Knud 1951: Et tylvt økser fra Vikingetiden. Aarbøger for nordisk Oldkyndighed og Historie. 1950, 352-357.

Thorvildsen, Knud 1957: Ladbyskibet. Nordiske Fortidsminder IV, 1. København. 121 pp.

Thrane, Henrik 1993: Guld, guder og godtfolk. Gudme, Fyn. Nationalmuseet, København. 64 pp.

Thun, Egon 1967: Medieval Tommarp. Archaeological excavations 1959-1960. Gleerup Förlag. Lund. 91 pp.

Thålin, Lena 1967 a: Metallografisk undersökning av ett vendeltida praktsvärd. Fornvännen, 225-235.

Thålin, Lena 1967 b: Svenskt förhistoriskt järn, ett forskningsprojekt. Jernkontorets Annaler, **151**, 305-324.

Thålin, Lena 1969: Järnet på Helgö. Helgö, den gåtfulla ön.

Thålin, Lena 1973: Notes on the ancient iron currency bars of Northern Sweden and the nickel alloys of some archaeological objects. Antikvariskt Arkiv **50**, 24-41.

Thålin-Bergman, Lena 1981: Der wikingerzeitliche Werkzeugkasten vom Mästermyr auf Gotland. Abh.Akad.-Wiss. Göttingen. Phil.Hist.Klasse III Folge No. 122, 193-215.

Tobiassen, Anna Helene 1981: Smeden i eldre tid. Universitetsforlaget. Oslo. 126 pp.

Tomtlund, Jan-Erik 1973: Metallographic investigation of 13 knives from Helgö. Antikvariskt Arkiv **50**, 42-63.

Trotzig, Gustaf 1984: Gefässe aus Kupfer und seinen Legierungen, p. 219-230, in Birka II, 1, (ed. Arwidsson, G.), Stockholm.

Trotzig, Gustaf 1991: Craftsmanship and Function. Monograph No. 1. Statens Historiska Museum. Stockholm. 278 pp.

Tylecote, R.F. 1962: Metallurgy in Archaeology.

Tylecote, R.F. 1975: Iron working at Meroe, Sudan, p. 157-171 in Wissenschaftliche Arbeiten aus dem Burgenland. (eds. A. Ohrenberger & K. Kaus). Eisenstadt 1977.

Tylecote, R.F. 1976: A history of metallurgy. The Metals Society. London. 182 pp.

Tylecote, R.F. 1979: The effect of soil conditions on the long-term corrosion of buried tin-bronzes and copper. Journal of Archaeological Science **6**, 345-368.

Tylecote, R.F. 1987: The early history of metallurgy in Europe. Longman Archeology Series. London. 391 pp.

Tylecote, R.F., Austin, J.N. & Wraith, A.E. 1971: The mechanism of the bloomery process in shaft furnaces. Journal of the Iron and Steel Institute. Vol. 209, 342-63.

Tylecote, R.F., Balmuth, M.S. & Massoli-Novelli, R. 1983: Copper and bronze metallurgy in Sardinia. Historical Metallurgy **17**, 63-78.

Tylecote, R.F. & Thomsen, Robert 1973: The segregation and surface-enrichment of arsenic and phosphorus in early iron artefacts. Archaeometry **15**, 193-198.

Ucelli, Guido 1950: Le navi di Nemi. Roma. 474 pp.

Ussing, N.V. 1913: Danmarks Geologi. Danmarks Geologiske Undersøgelse. III. Række Nr. 2. Kjøbenhavn. 372 pp.

Vadstrup, Søren 1993: I vikingernes kølvand. Vikingeskibshallen i Roskilde. 188 pp.

Vaiman, A.A. 1982: Eisen in Sumer. Archiv für Orientforschung, Beiheft. Graz **19**, 33.

Vandkilde, Helle 1989: Det ældste metalmiljø i Danmark. Jysk Arkæologisk Selskabs Skrifter **24**, 29-45.

Vandkilde, Helle 1996: From stone to bronze. Jysk Arkæologisk Selskabs Skrifter **22**, 492 pp.

Vellev, Jens 1978: Rungende malm. Skalk No. 3: 18-26.

Vellev, Jens 1988: Et middelalderligt bronzestøberi i Odense. Forlaget Hikuin, Moesgård, Aarhus. 56 pp.

Vellev, Jens 1991: Bjerringhøjundersøgelsen 1868, p. 11-25 in Iversen, Mette (ed.) Mammen. Jysk Arkæologisk Selskabs Skrifter **28**, 1-343.

Verhoeven, J.D. & Pendray 1992: Experiments to reproduce the pattern of Damascus steel blades. Materials Characterization **29**, 195-212.

Vigfusson, Sigurd 1882: Rannsokn i Bredafjardölum og i Thorsnesthingi og um hina nyrdri strönd 1881. p. 100 in Arbok hins Islenzka Fornleifafelags. Reykjavik.

Vogel, Conrad, Juhl, Celia, & Maahn, Ernst 1998: Metallurgi for ingeniører. 8.udgave. Akademisk Forlag, København. 734 pp.

Voss, Olfert 1962: Jernudvinding i Danmark i forhistorisk tid. Kuml, p. 7-32.

Voss, Olfert 1976: Drengsted, et bopladsområde fra 5. århundrede e.Kr. ved Sønderjyllands vestkyst. Iskos, Helsinki **1**, 68-71.

Voss, Olfert 1986: Jernudvindingsanlæg i Danmark fra forhistorisk og historisk tid. Arkæologiske Udgravninger i Danmark 1985. Det Arkæologiske Nævn. København.

Voss, Olfert 1988: Hedegård, et sjældent jernudvindingsanlæg fra ældre romersk jernalder, p. 19-24 in Horsens Museums Årsskrift 1987-88.

Voss, Olfert 1991: Jernproduktionen i Danmark i perioden 0-550 e.Kr. p. 171-186 in Fabech, C. & Ringtved, J. (eds.) Symposium April 1989, Sandbjerg Slot. Jysk Arkæologisk Selskabs Skrifter, Aarhus **27**, 352 pp.

Voss, Olfert 1993: Snorup. Et jernudvindingsområde i Sydvestjylland. p. 97-111 in Nationalmuseets Arbejdsmark, København.

Voss, Olfert 1995: Snorup, an iron producing settlement in west Jutland, 1st-7th century A.D. p. 132-139 in Magnusson, G. (ed.) Jernkontorets Bergshistoriske Utskott, H 58, Stockholm. 428 pp.

Voss, Olfert 2003: The archeology of iron smelting in Denmark, p. 497-505 in Archaeometallurgy in Europe: Conference September 2003, Milano, Italy, Preprint.

Wainwright, G.A. 1936: The coming of iron. Antiquity **10**, 5-24.

Waldbaum, Jane C. 1978: From bronze to iron. Studies in Mediterranean Archeology **54**, 1-106.

Waldbaum, Jane C. 1980: The first archeological appearance of iron and the transition to the iron age, p. 69-98 in Wertime, T.A. & Muhly, J.D. (eds.) The coming of the age of iron. Yale University Press, 555 pp.

Warden, P.G. 1984: The Colline Metallifere, p. 349-364 in Hackens, T et al. (eds.) Crossroads of the Mediterranean, Brown University, Providence, Rhode Island.

Wasson, J.T. 1974: Meteorites. Springer Verlag. Berlin, New York. 316 pp.

Watt, Margrethe 1979: Depotfund fra Tingsted, Vestermarie. p. 28-32 in Nyt fra Bornholms Museum 1978-79.

Wayman, M.L. 1989: All that glisters. Readings from Metallurgical History. Canadian Institute of Mining and Metallurgy, Montreal.

Wayman, M.L., King, J.C.H. & Craddock, P.T. 1992: Aspects of early North American metallurgy. British Museum Occasional Paper **79**, 1-144.

Wedberg, Viking 1984: Här gjordes äldsta järnet. Populär Arkeologi **1**, 10-13.

Weeks, M.E. 1968: Discovery of the elements. 7th edition. Journal of Chemical Education. Easton, Pennsylvania. 896 pp.

Wegewitz, Willi 1957: Ein Rennfeuerofen aus einer Siedlung der älteren Römerzeit in Scharmbeck (Kreis Harburg). Nachrichten aus Niedersachsens Urgeschichte, Hildesheim **26**, 1-25

Wertime, T.A. 1973: Science **182**, 885.

Westphalen, Petra 1989: Die Eisenschlacken von Haithabu. Berichte über die Ausgrabungen in Haithabu **26**, 1-111.

White, J.S., Henderson, E.P. & Mason, Brian 1967: Secondary minerals produced by weathering of the Wolf Creek meteorite. American Mineralogist **52**, 1190-1197.

Wilsdorf, Helmut 1954: Historische und archäologische Quellen zur Geschichte des Eisens. Freiberger Forschungshefte, Kultur und Technik **D 6**, 67-89.

Wranglén, Gösta 1970: Den "rostfria" järnpelaren i Delhi. Jernkontorets Annaler **154**, 35-43.

Wranning, Per 1995: En förromersk järnframställningsplats vid Genevads ån. Arkeologiske Rapporter från Hallands Länsmuseer, Halmstad **1**, 1-29.

Wranning, Per 1997: Leregård, förromerska boplatslämningar med spår av järnhantering. Arkeologiska Rapporter från Hallands Länsmuseer, Halmstad **5**, 1-22.

Yadin, Yigael 1963: The art of warfare in biblical lands. Weidenfeld & Nicholson, London. 484 pp.

Zecchini, Michelangelo 1983: Archaelogia e storia antica dell' isola d'Elba. Con guida al museo archeologico di Marciana. Comune di Marciana. 119 pp.

Zwicker, Ulrich 1980: Investigation on the extractive metallurgy of Cu-Sb-As-ores, in Oddy, W.A. (ed.) Aspects of early metallurgy. British Museum Occasional Paper **17**, 13-26.

Ödman, Anders 1992: Iron and castles in Scania, p. 45-53 in Espelund A, (ed.) Bloomery ironmaking during 2000 years. Vol. 2, Trondheim.

Ödman, Anders 2001: Vittsjö. En socken i dansk järnbruksbygd. University of Lund. Institute of Archeology, Report Series **76,** 1-178.

Ørsnes, Mogens 1968: Der Moorfund von Ejsbøl bei Hadersleben. Abhandlungen der Akademie der Wissenschaften, Göttingen, 172-187.

Ørsnes, Mogens 1984: Sejrens pris. Våbenofre i Ejsbøl Mose ved Haderslev. Haderslev Museum, 57 pp.

Østensen, Per Øyvind 1999: Smeltehytter for kopper i Midt-Norge. Norsk Bergverksmuseum, Kongsberg No. 16, 98 pp.

Index

Pages in *Italics* refer to an illustration

General guidelines

The Academy invites original papers that contribute significantly to research carried on in Denmark. Foreign contributions are accepted from temporary residents in Denmark, participants in a joint project involving Danish researchers, or those in discussion with Danish contributors.

Instructions to authors

Manuscripts from contributors who are not members of the Academy will be refereed by two members of the Academy. Authors of papers accepted for publication will receive galley proofs and page proofs; these should be returned promptly to the editor. Corrections other than of printer's errors will be charged to the author(s) insofar as the costs exceed 15% of the cost of typesetting.

Authors receive a total of 50 free copies. An order form, quoting a special price for additional copies, will accompany the page proofs. Authors are invited to provide addresses of up to 20 journals to which review copies could profitably be sent.

Manuscripts can be returned, but only upon request made before publication of the paper. Original photos and artwork are returned upon request.

Manuscript

General. – Manuscripts and illustrations must comply with the details given below. The original manuscript and illustrations plus one clear copy of both should be sent to the editor of the series. Manuscripts on digital media are accepted; contact the editor in advance, giving technical specifications.

A manuscript should contain no less than 48 printed pages. This also applies to the Mat.fys.Medd. where contributions to the history of science are welcome.

Language. – Manuscripts in Danish, English, German and French are accepted; in special cases other languages too. Linguistic revision may be made a condition of final acceptance.

Title. – Titles should be kept as short as possible, preferring words useful for indexing and information retrieval.

Abstract, Summary. – An abstract in English is required. It should be of 10-15 lines, outline main features, stress novel information and conclusions, and end with the author's name, title, and institutional and/or private postal address. – Papers in Danish must be provided with a summary in another language as agreed between author and editor.

Manuscript. – Page 1 should contain title, author's name and the name of the Academy. Page 2: Abstract, author's name and address. Page 3: Table of contents if necessary. Consult a *recent* issue of the series for general layout. Indicate the position of illustrations and tables. A printout must accompany manuscripts submitted electronically.

Figures. – All illustrations submitted must be marked with the author's name. It is important that the illustrations are of the highest possible quality. Foldout figures and tables should be avoided.

References. – In general, the editor expects all references to be formally consistent and in accordance with accepted practice within the particular field of research. Bibliographical references should be given in a way that avoids ambiguity.

Det Kongelige Danske Videnskabernes Selskab

The Royal Danish Academy of Sciences and Letters

Priser ekskl. moms/Prices excl. VAT

Historisk-filosofiske Skrifter, HfS
Hist. Filos. Skr. Dan. Vid. Selsk.

Vol.

17 P.J.RIIS, JØRGEN JENSEN, MARIE-LOUISE BUHL & BENEDIKT OTZEN: *Sūkās X. The Bronze and Early Iron Age Remains at the Southern Harbour.* (Publications of the Carlsberg Expedition to Phoenicia 12). 1996. 65 pp .... 130 DKK

18 KNUD SØRENSEN: *A Dictionary of Anglicisms in Danish.* 1997. 405 pp. .... 600 DKK

19 P.J.RIIS: *Vulcientia vetustiora. A Study of Archaic Vulcian Bronzes.* 1998. 137 pp. 123 fig .... 360 DKK

20 SØREN EGEROD: *Atayal-English Dictionary,* edited by Jens Østergaard Petersen. 1999. 358 pp. .... 480 DKK

21 *A Comparative Study of Thirty City-State Cultures,* edited by *Mogens Herman Hansen.* 2000. 636 pp. .... 600 DKK

22 *War as a Cultural and Social Force.* Edited by *Tønnes Becker-Nielsen* and *Lise Hannestad.* 2001. 288 pp. ..... 300 DKK

23 JESPER EIDEM OG JØRGEN LÆSSØE: *The Shemshara Archives 1. The Letters.* 2001. 272 pp. .... 400 DKK

24: FRITZ SAABY PEDERSEN:
1-4 *The Toledan Tables,* vol.1. 2002. 323 pp. .... 400 DKK
The Toledan Tables, vol.2. 2002. 413 pp. .... 400 DKK
The Toledan Tables, vol.3. 2002. 501 pp. .... 400 DKK
The Toledan Tables, vol.4. 2002. 425 pp. .... 400 DKK
The Toledan Tables, vol.1-4. 2002. 1.662 pp. ....1.200 DKK

25 *Videnskab og Værdier. Den humanistiske udfordring.* Beretning fra symposiet: 31.3.-2.4.2000. Edited by *Kirsten Hastrup.* 2002. 288 pp. Fig. .... 200 DKK

26 *The Nag Hammadi Texts in the History of Religion.* Proceedings of the International Conference at The Royal Danish Academy of Sciences and Letters in Copenhagen, September 19-24, 1995. Edited by *Søren Giversen, Tage Petersen* and *Jørgen Podemann Sørensen.* 2002. 228 pp. .... 200 DKK

27 *A comparative Study of Six City-State Cultures,* edited by *Mogens Herman Hansen.* 2002. 144 pp. .... 200 DKK

28 P.J. RIIS, INGOLF THUESEN, JOHN LUND & THOMAS RIIS: *Topographical Studies in the Ǧabla Plain.* (Publications of the Carlsberg Expedition to Phoenicia 13). 2004. 192 pp. 145 fig. .... 260 DKK

29 VAGN FABRITIUS BUCHWALD: *Iron and Steel in Ancient Times.* 2005. 372 pp. Ill. .... 360 DKK

Historisk-filosofiske Meddelelser, HfM
Hist. Fil. Medd. Dan. Vid. Selsk.

Vol.

79 SUNE DALGÅRD: *Poul Laxmands Sag. Et dyk i dansk historie omkring år 1500.* 2000. 233 pp. .... 248 DKK

80 JØRGEN MEJER: *Die Vermittlung der Philosophie im Altertum.* 2000. 240 pp. .... 180 DKK

81 ERLING LADEWIG PETERSEN: *Magtstat og Godsdrift.* 349 pp. .... 336 DKK

82 *Denmark and Scotland: The cultural and environmental resources of small countries,* edited by *Gillian Fellows-Jensen.* 2001. 304 pp. Fig. .... 200 DKK

83 DANIEL TUHANUKU: *Na tau'a Mungiki* (Raids on Bellona Island). Edited by *Rolf Kuschel & 'Angikinui F.T. Takiika.* 2002. 209 pp. .... 140 DKK

84 ELI FISCHER-JØRGENSEN: *Tryk i ældre dansk. Sammensætninger og afledninger.* 2001. 516 pp. .... 375 DKK

85 FEREYDUN VAHMAN & GARNIK ASATRIAN: *Notes on the Language and Ethnography of the Zoroastrians of Yazd.* 2002. 115 pp. .... 120 DKK

86 *H.C.Ørsted's Theory of Force.* An unpublished textbook in dynamical chemistry. Edited and translated by *Anja Skaar Jacobsen, Andrew D. Jackson, Karen Jelved and Helge Kragh.* 2003. 320 pp. Fig. .... 200 DKK

87 HERMAN KØLLN: *Westkirchliches in altkirchenslavischer Literatur aus Grossmähren und Böhmen.* 2003. 96 pp. .... 100 DKK

88 HELGE KRAGH: *Phosphors and Phosphorus in Early Danish Natural Philosophy.* 2003. 75 pp. Fig. .... 80 DKK

89 *John Buridan and Beyond.* Topics in the language sciences, 1300-1700. Acts of Symposium. Edited by *Russell L. Friedman and Sten Ebbesen.* 2004. 275 pp. .... 200 DKK

90 SUNE DALGÅRD: *Kanslere og Kancellier – især »tyske« – i Danmark og Holsten hen imod Enevælden.* 2005. 238 pp. Ill. .... 240 DKK

91 *The Imaginary Polis.* Acts of the Copenhagen Polis Centre 7. Symposium, January 7-10, 2004. Edited by Mogens Herman Hansen. 2005. .... in preparation

92 C. BARKER JØRGENSEN: *Daniel Frederik Eschricht (1798-1863) Peter Wilhelm Lund (1801-1880): Danish pioneers in experimental physiology. Historians, philosophers and practitioners on Claude Bernard's* Introduction à l'étude de la médecine expérimentale. 2005. 44 pp. .... 48 DKK

Printed in Denmark by Special-Trykkeriet Viborg a-s. ISSN 0023-3307. ISBN 87-7304-308-7