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IRON AGE SLAGS AT SNORUP (DENMARK): MAGNETIC PROSPECTING, MODELLING, RECONSTRUCTION AND DATING

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Abstract: A description of the archaeological reconstruction of iron production (100 to 700 AD) based upon bog-iron ore and charcoal in Denmark during the Iron Age is given, the total number of furnaces being of the order of 100,000. Examples of magnetic prospection for slags in general and in more detail, including simple interactive interpretation by inclined magnetic dipoles (spheres) are illustrated. Finally the mean magnetic remanent direction determined by a paleomagnetic study of oriented cores from three slag pits, as well as by magnetic inversion of the surface magnetic field from the same slag pits, is used to obtain a magnetic dating of the slag pits by comparison with the geomagnetic secular variation, suggesting that the mean age of the slag pits is between the 2nd and 5th centuries AD.

Key words: Iron Age, Denmark, iron production, slags, magnetic prospecting, magnetic modelling, magnetic secular variation, magnetic dating, archaeomagnetism.

Introduction

Denmark is rather poor in natural resources such as black coal and iron-ores for modern industrial production, but bog-iron ore occurs widely just below the soil as thin, compact layers typically 0.1 to 1 m thick. Mostly during the Holocene the bog-iron ore has been segregated by geochemical redox processes in the circulating groundwater, and occurs especially in the sandy plains in Jutland west of the limit of the last glaciation (Christensen 1966). Bog-iron ore has been exported to some extent (about 1 mill. tons ore in the period 1951–1960; Christensen 1966), but today bog-iron ore is not smelted in Denmark.

However, local production of metallic iron has earlier occured in Denmark, mainly between about the 2nd century BC and 1300 AD (Voss 1993a,b). The production was quite intense in some periods (Nielsen 1924; Mortensen 1940), being based upon the locally occurring bog-iron ore and locally produced charcoal. Especially in SW Jutland more than 50 locations with slag-pit furnaces have now been localized, and the total number of furnaces is estimated to be around 100,000. With a production of some 40–50 kg of metallic iron from each pit, the estimated total production of metallic iron amounts to some 4–5000 tons, mostly from prehistoric time (Voss 1993a).

The kilns were usually destroyed immediately or shortly after the production, but the vestiges of the iron production are still often well preserved as slag pits. Pits, which have not been disturbed or broken up by the farmers during ploughing, are situated just below the soil, the slag pit surface being typically some 0.4–0.5 meter below the present-day soil surface. The weight of the undisturbed slag pits are typically 200±100 kg, and as the slags are strongly magnetic due to the high content of iron-oxides (which were not successfully reduced to metallic iron), it is an easy target to locate by means of a detailed magnetic survey.

Magnetic surveying, a standard geophysical tool in geological mapping and prospection (Sharma 1974), has been used in archaeology since about 1960 (e.g. Aitken 1961; Linington 1964). In Denmark it has been in use since 1964 for mapping of iron-age slag pits, medieval brick-kilns and other old constructions (Abrahamsen 1965, 1982; Abrahamsen & Breiner 1993; Smekalova et al. 1993a,b, 1996; Bevan & Smekalova 1996; Koppelt et al. 1996; Moller et al. 1996; Abrahamsen et al. 1997).

The purpose of the present communication is to describe some detailed magnetic surveys for iron-age slag pits in the Snorup area in Jutland, to present a simple magnetic modelling tool, to date the slag pits magnetically, and to compare the magnetic findings with the facts as interpreted by means of archaeological excavations.

Iron production at Snorup: reconstruction and smelting technique

The distribution of shaft furnaces known in Europe from the Iron Age is illustrated in Fig. 1.

Snorup is one of these iron-producing areas, situated in Denmark in SW Jutland (Fig. 2), comprising 23 or more smelting sites with remains of slag-pit furnaces dating from the period 100–700 AD (Voss 1993b). The amount of iron produced in prehistoric time may rank this area among the more important prehistoric iron production areas in Europe.

Excavations over the years in SW Jutland, and most recently especially in the Snorup area (Fig. 3), have revealed

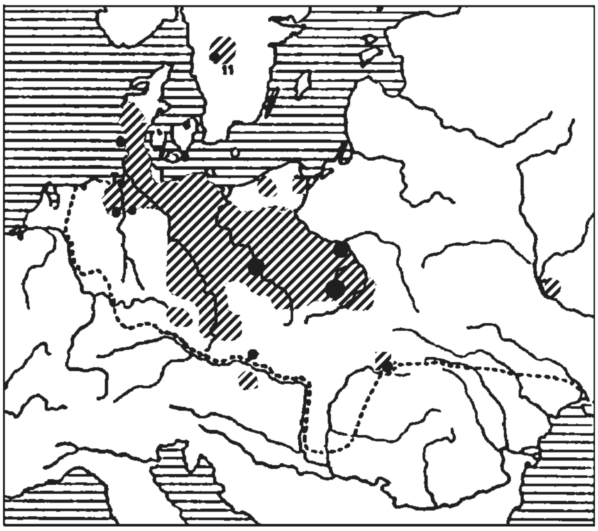

Fig. 1. Areas of Iron Age shaft furnaces known in Europe (redrawn from Smekalova et al. 1993a).

Fig. 3. Local map of Snorup with magnetically explored areas (modified from Voss 1993b). Field E11 is specifically shown.

Fig. 2. Index map of Denmark with slag-pit areas indicated by dots. The biggest dot indicate the Snorup area in the SW of the Jutland penninsula (from Smekalova et al. 1993a).

details of the original construction of furnaces, as well as of the smelting process itself.

The iron production process reconstructed is demonstrated in details in Fig. 4 (color photos of various details may be found in Voss 1993b). Full scale experiments with a reconstruction of this type of furnace have been promising and have contributed to the credibility of the reconstruction. The slag production process by means of bog-iron ore and charcoal are as follows (Fig. 4). A: The hole for the slag-pit is first dug and stuffed with straw, preventing the charcoal and ore in the 1.2 m high kiln from falling down. Fresh air is supplied via small holes at the base. The glowing charcoal develops CO-gasses, which reduce the iron-oxides to spongy metallic iron, filling holes in the slag. B: When the iron-sponge sinks down to the zone with a temperature of 1200–1300 °C just above the air-holes, the slag smelts completely and runs down, being stopped at first by the straw. C: Some times later the weight of the accumulating liquid slag compresses the straw, and runs down in the hole, solidifying immediately to a thin plate. D: Now the kiln has been heated so much, that the liquid slag produced sequentially does not crystallize in the upper part of the kiln in contrast to the metallic iron, which (having a higher smelting temperature) is typically caught at the sides just under the air-holes. In the reconstruction experiment (Voss 1993b), continuous heating for 48 hours, during which sequentially shifting layers of charcoal and bog-iron ore (280 kg of each) were added into the kiln, ca. 60 kg of metallic spongy iron-luppe was produced.

In Poland and the Ukraine so called “organized” smelting sites including between 8 and 230 slag-pits are found. Because of their uniformity it is assumed that these sites were result of short-term efforts, for instance lasting just a few months in the autumn. The 23 clusters in Snorup containing between 28 and 171 slag-pits must also be a result of such short-term productions. Variation in the number of slag-pits in each smelting site in those areas therefore is likely to be dependent on the amount of charcoal available at or near the site.

Furnaces of this type were only used once; when no more charcoal could be produced within a reasonable distance, the iron-smelting was moved to another site, selected for its proximity to iron ore and charcoal. The charcoal was probably produced in an oak coppice which could be harvested only once every 20 years. This “coppicing” technique is actually a way of producing charcoal, which was described much later by Duhamel du Monceay (1761) in his book “Art du Charbonnier” (the art of making charcoal). Because of the 20-year cycle of the coppice, smelters were forced to continuously move their craft to another site where the forest was matured for charcoal production.

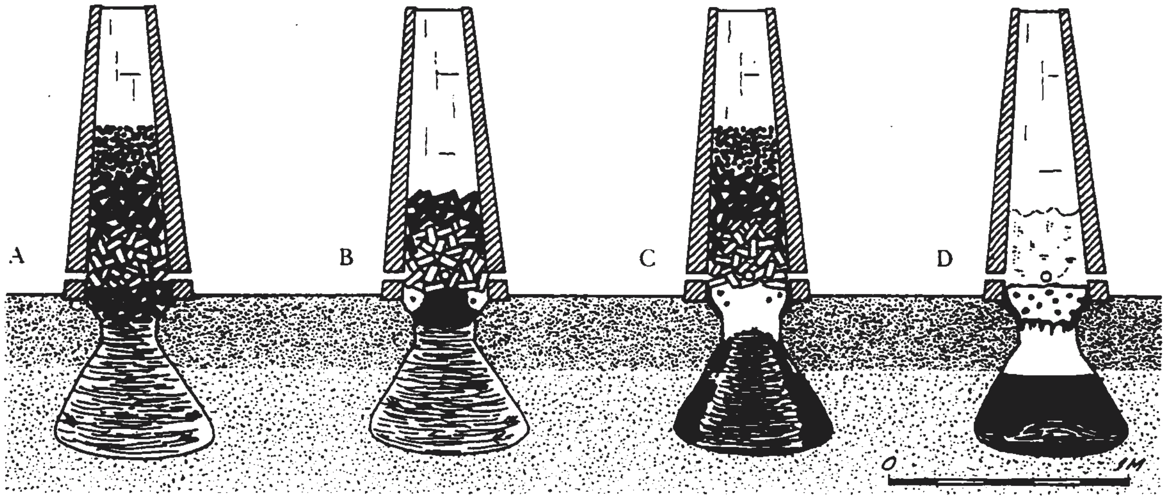

Fig. 4. Reconstruction of slag production from bog-iron ore and charcoal at Snorup. A: The slag-pit is first dug and stuffed with straw, preventing the charcoal and ore in the 1.2 m high kiln from falling down. Fresh air is supplied via the holes at the base. The glowing charcoal develops CO-gas, which reduces the iron-oxides to the metallic spongy iron, filling holes in the slag. B: When the iron-sponge sinks down to the zone with a temperature of 1200–1300 °C just above the air-holes, the slag smelts completely and runs down, being stopped at first by the straw. C: After some time the weight of the accumulating liquid slag compresses the straw and runs down in the hole, solidifying immediately to a thin plate. D: Now the kiln has been heated so much, that the liquid slag produced afterwards does not crystallize in the upper part of the kiln in contrast to the metallic iron, which (having a somewhat higher smelting temperature) is typically caught at the sides just under the air-holes. Continuing the heating for 48 hours, adding sequentially shifting layers of charcoal and bog-iron ore (280 kg of each) in the kiln, produced ca. 60 kg of metallic spongy iron-luppe in this experiment (from Voss 1993b).

In Denmark the origin of coppicing is ancient. It dates back to the Mesolithic period, in which willow and hazel trees were coppiced to provide material for fishing traps and weirs. This method produces long, straight and slender rods which are also very useful as roof-rafters. Literary sources from the 18th to the 20th century give very variable information about the charcoal capacity of oak-coppices, ranging from 5 to 20 tons per hectare. These differences arise partly from the varying quality of the land and partly from the different uses of this kind of forest. Coppices can be used for grazing around the year, since in wintertime the cattle can eat the buds and also the fine twigs.

The mean weight of the well-preserved slag-blocks is 200 kg. According to an analysis of slag and iron ore from the same slag pit, the theoretical output has been determined as 60 kg of sponge iron, which could result in 40 kg of smithing iron. An iron deposit of 20 kg has been found within the Snorup area. It consisted of approximately 100 axe-shaped bars with an average weight of 130 grams, another 100 smaller bars of the same type, weighing 30 to 40 grams, and 6 pieces of iron with a total weight of 3.7 kg. This deposit has not yet been dated.

Air photos have revealed settlements of Iron Age character within the iron smelting area of Snorup, as well as in the area of Tirslund about 1 km further south. None of these settlements have been fully excavated yet. The Snorup smelting area is certainly not unique in Jutland. At the present more than 60 locations with slag-pit furnaces are known there. It is believed that there must have been 50 or more smelting areas in Jutland like that in Snorup; this means that there may have been a total of some 100,000 furnaces in Jutland, with a production of 4–5000 tons of iron. Such a production may place the area at the same level as the major Polish centers known from Kielce and Warsaw, which include slag-kilns from the same period.

Magnetic prospecting for slag pits

Because of the surface position, the high magnetic susceptibility, and the strong remanent magnetization of the slags (as compared to the magnetically fairly neutral surrounding sediments), a local magnetic survey is a very effective way of finding the exact locations, the areal extent and even the numbers of the still remaining slag pits. In the Danish localities the slag pits are typically buried at depths of 40–50 cm, i.e. at ploughing depths, just below the soil.

In Fig. 5 the total field magnetic anomaly of one of the slag areas at Snorup, which has been magnetically surveyed, is shown (a part of Field A in Fig. 3). Individual slag pits show up as circular anomalies of typically between 200 and 500 nT. When the slag pits are separated by more than ca. one slag dimension from each other, the number of individual slag pits may easily be counted just from the number of almost circular magnetic anomalies. Elongated and more irregular shaped anomalies indicate slag pit rows or clusters. Especially within the clusters the number of individual slag pits are more difficult to evaluate. The measurements were made by a proton magnetometer along north-south profiles in a 1×1 m^2 grid, the equidistance of the anomaly curves shown being 50 nT. The magnetic daily variation was monitored by repeated measurements at a local base station.

Following a more general survey of another Field E (c.f. Fig. 3), a detailed gradient magnetic survey in the subfield E11 showed a linear row of magnetic anomalies (measured in a dense grid of 0.25×0.25 m^2). The configuration of the

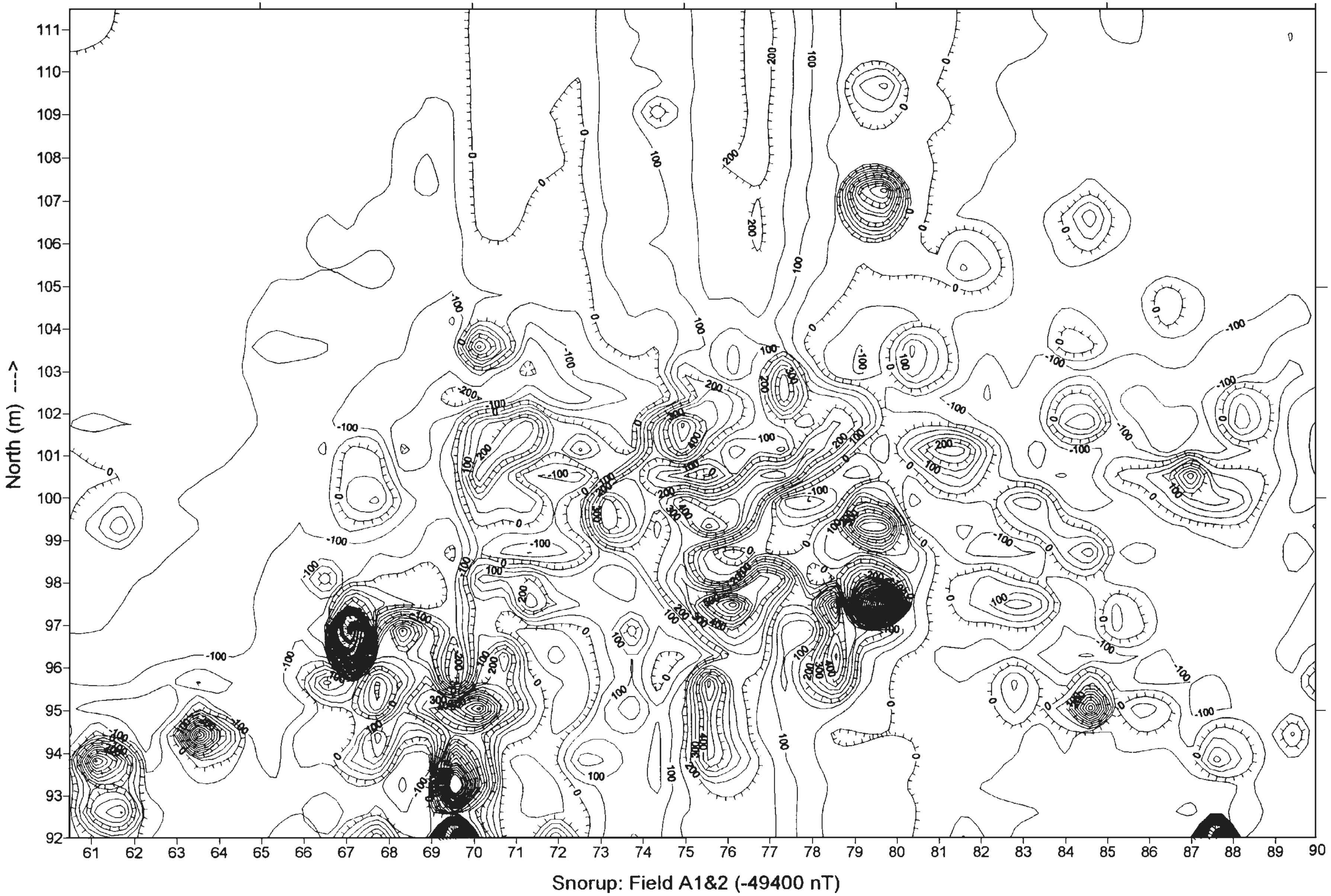

Fig. 5. Total field magnetic anomaly of one of the slag areas at Snorup investigated in detail (part of Field A, Fig. 3). Individual slags show up as circular anomalies of typically between 200 and 500 nT. Elongated and more irregular shaped anomalies indicate slag rows or clusters. (Proton magnetometer, aequidistance 50 nT, 1×1 m^2 grid).

gradient magnetometer, as used in this survey, is sketched in Fig. 6, and the vertical gradient map is shown in Fig. 7. The magnetic map revealed a string of positive anomalies in the range of 10–170 nT/m.

As an initial interpretation, prior to detailed archaeological excavation, the magnetic anomalies were grouped into three categories: 1) solid slag pits, 2) disturbed or partly incomplete slag pits, and 3) slag fragments (Fig. 7). After this, the anomalies were interpreted by means of a number of simple inclined dipoles (or magnetic spheres), resulting in an indication of 10 solid slag pits, 4 disturbed/incomplete slag pits, and one major fragment.

After the excavation the weights of the 14 slag pits found in Field E11 were determined by weighting. In this case a fairly linear relationship between slag weight and magnetic anomaly of the bottom sensor was found (Fig. 8). The (relative) magnetic anomaly thus may be used as a first indicator of the (relative) slag weight, and hence also of the volume of the slag, the mean density being rather constant. Detailed information from the excavations (Table 1) also showed, that the initial magnetic interpretation (by sorting the slags in solid and disturbed slag pits) was only partially correct. Thus, the weight of the remaining slag appears to be the most important parameter for the size of the anomaly amplitude, whereas it is less simple from the anomaly amplitude to estimate whether a slag has being slightly disturbed (whether just after the iron production, or much later in recent time); if, however, it has been strongly disturbed, randomly orientated by fracturing and/or partially removed by the recent farming, it will show up as a smaller anomaly or as a dipole with an unusual dipole direction.

Magnetic properties of slags

Magnetic susceptibility was measured *in situ* with a hand-held Czech kappametre, the susceptibility values being around 17 ± 6×10^{-3} SI. Standard AF (alternating field) demagnetization experiments of two non-oriented slag specimens from Field E11 are shown in Fig. 9, the intensity of

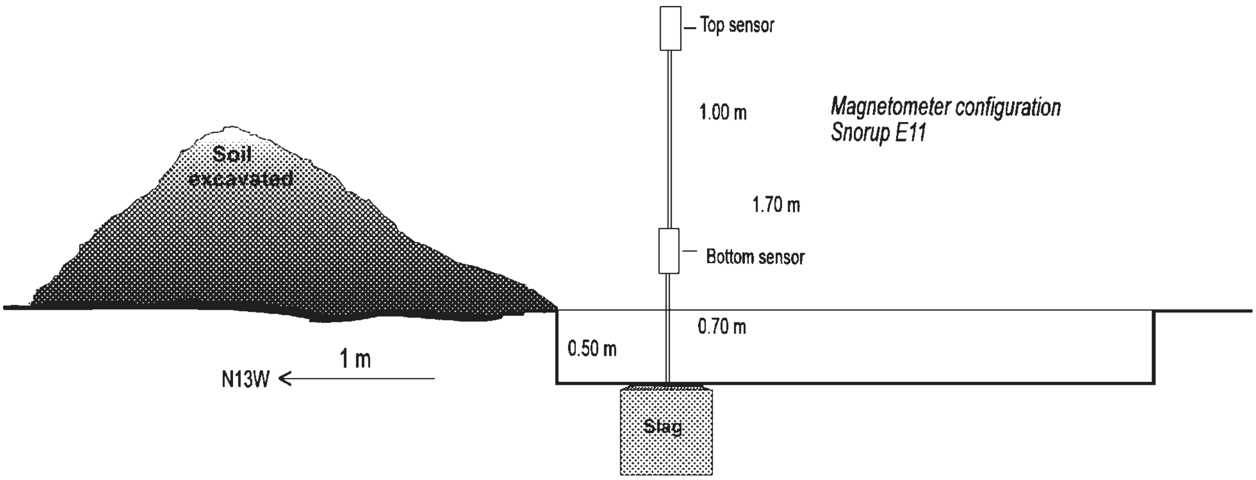

Fig. 6. Sketch of proton magnetometer gradient configuration, as used in the detailed survey of Field E11 (c.f. Figs. 3 and 7).

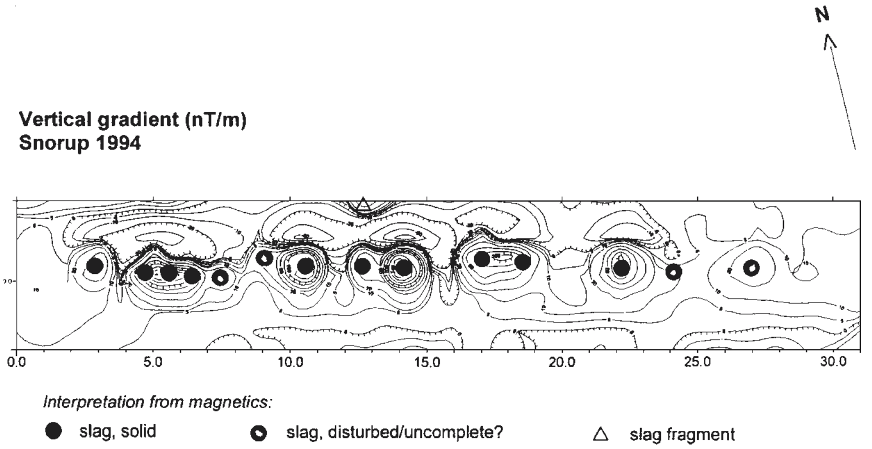

Fig. 7. Following a more general survey of Field E, a detailed magnetic survey revealed a row of slags in Field E11. The vertical total field magnetic gradient showed a string of positive anomalies in the range of 10–170 nT/m. Before the excavation the magnetic anomalies were initially grouped in three categories as 1) solid slags, 2) disturbed or partly incomplete slags, or 3) slag fragments. The anomalies were interpreted as simple inclined dipoles (or magnetic spheres), indicating 10 solid slags, 4 disturbed/incomplete slags, and one major fragment. (Proton magnetometer, aequidistance 5 nT, 0.25×0.25 m^2 grid).

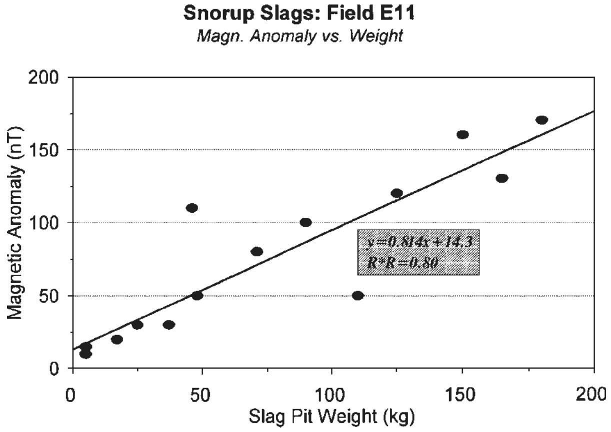

Fig. 8. After being excavated the weights of the 14 slags found in Field E11 were determined by weighting. A fairly linear relationship between slag weight and magnetic anomaly of the bottom sensor was found in this case. The (relative) magnetic anomaly thus may be used as a first indication of the (relative) weight, and hence the volume, of the slag. Detailed information by the excavation later (Table 1) showed that the initial magnetic interpretation (sorting the slags in solid and disturbed slags) was only partially correct, the weight of the remaining slag apparently being the most important parameter for the amplitude of the magnetic anomaly.

the NRM (natural remanent magnetization) being 28 and 19 A/m, respectively. The stereograms as well as the orthogonal plots (solid/open signature indicate horizontal/vertical projection, respectively) show, that the remanent magnetization of the slags is a directionally stable primary TRM with median destructive fields around 25 mT (250 Oe). Thermomagnetic experiments (Lewandowski, pers. com.) showed unblocking temperatures between 460 and 580 °C, suggesting the dominant magnetic carrier to be titanomagnetite. Chemical analysis (Grundvig, pers. com.) indicate the dominant presence of Fayalite, with some Wustite and small amounts of metallic iron.

Magnetic modelling

A simple magnetic modelling (Jacobson & Abrahamsen 1997) by adjusting inclined dipoles programmed for MATLAB (as applied in Fig. 7) is illustrated in more detail for each of the two magnetic sensors in Fig. 10a–b. For each of the sensors the *top figure* shows the measured total magnetic anomaly, the *middle figure* shows the magnetic response from a number of simple dipoles (spheres), each dipole being individually and interactively adjusted in coordinates (X, Y, depth), declination, inclination, and dipole moment (propor-

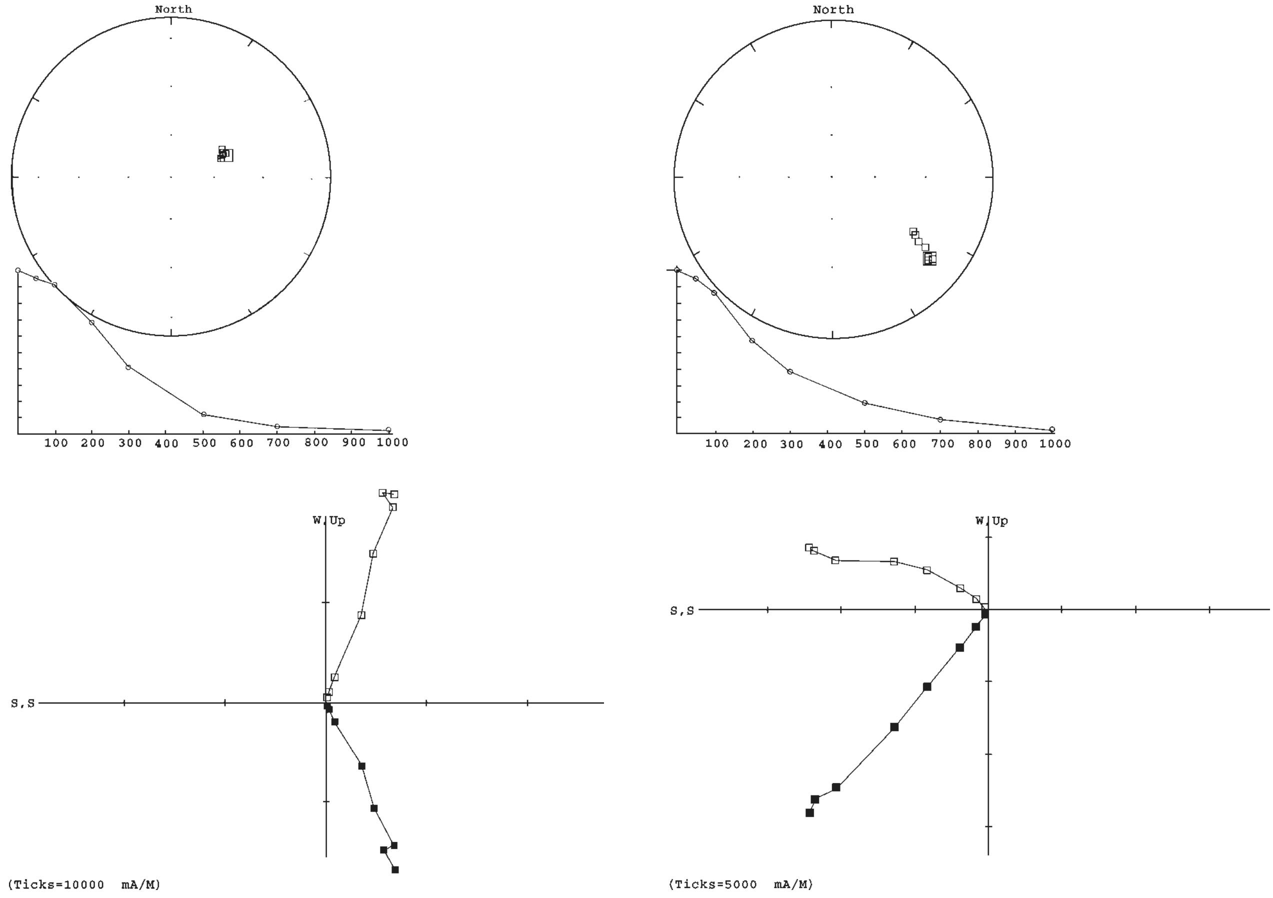

Fig. 9. Standard AF (alternating field) demagnetization experiments of two not-oriented slag specimens from Field E11. The stereograms as well as the orthogonal plots (solid/open signature indicate horizontal/vertical projection, respectively) show, that the remanent magnetization of the slags is a directionally stable primary TRM with median destructive fields around 25 mT (250 Oe).

tional to the area of the spheres shown), and the *bottom figure* show the residual field. (The maximum number of spheres to be handled was set at 10 in this case for practical reasons).

For the top sensor (a) the contour interval shown is 2 nT, the magnetic anomalies being fairly smooth, and the dipole approximation appears to be a fair assumption at this distance between slag and sensor (ca. 2.0 ± 0.3 m). For the bottom sensor (b) the contour interval is 10 nT, the magnetic anomalies being stronger and more irregular, because the slag pits are rather close to the bottom sensor (ca. 1.0 ± 0.3 m), the slag shape and magnetic inhomogenity thus reducing the validity of a simple dipole assumption.

For the 10 dipoles modelled, the residual anomalies (measured field - model response) are between 10 and 30 nT, corresponding to 5-15 % of the measured anomaly (the two small anomalies in the right part of the field were not modelled).

Paleomagnetic results

Archaeologically the slag pits are difficult to date in detail, the wood and straw usually being totally burned, and tools very rarely being found closely associated with the slags. To investigate in more details the remanent magnetization properties, as a possible tool for magnetic dating of the slags by the geomagnetic secular variation, three well preserved and undisturbed slag pits (E16, E24 and E25) from Field E therefore were detailed paleomagnetically sampled *in situ*, using a portable, water-cooled drill. Although the slag is often brittle and full of minor cracks, a number of 7-8 individually oriented cores from each slag were obtained. These cores were later cut into one-inch

Table 1: List of 14 slag pits excavated in Snorup, Field E11. The slag weight, diameter and peak magnetic anomaly is indicated.

Slag	Slag pit No.	Weight kg	Diameter cm	Anomaly nT	Comment
1	1531	48	65	50	Incomplete. Quarter of slag 38 kg still in situ
2	1532	150	62	160	Complete block
3	1533	125		120	Complete, with roasted ore and straw
4	1534	25	70	30	Incomplete, with red-burned clay, TL-dating
5	1535	37	70	30	Incomplete, TL-dating
6	1536	165	70	130	Complete; imprints of straw
7	1537	110		50	Destroyed in recent time; imprints of straw
8	1538	180	65	170	Complete; imprints of straw
9	1539	71	65	80	Incomplete; imprints of straw
10	1540	46		110	Destroyed in recent time; bottom and w. side in situ
11	1541	90	75	100	Complete, but fragmented; bottom slag up to 5 cm thick
12	1542	5	65	10	Incomplete, destr. in recent time; only 13 cm of bottom plate left
13	1543	5	65	15	Incomplete, removed in recent time; only 8 cm of b. was left
14	1544	17	75	20	Incomplete, removed in recent time; 10 cm of pit was left

Of the 14 slag pits, 5 contained a complete block. Average weight of 5 slag blocks: 142 kg. From 2 slag pits the slag had been removed immediately after the smelt. 7 were destroyed by recent farming.

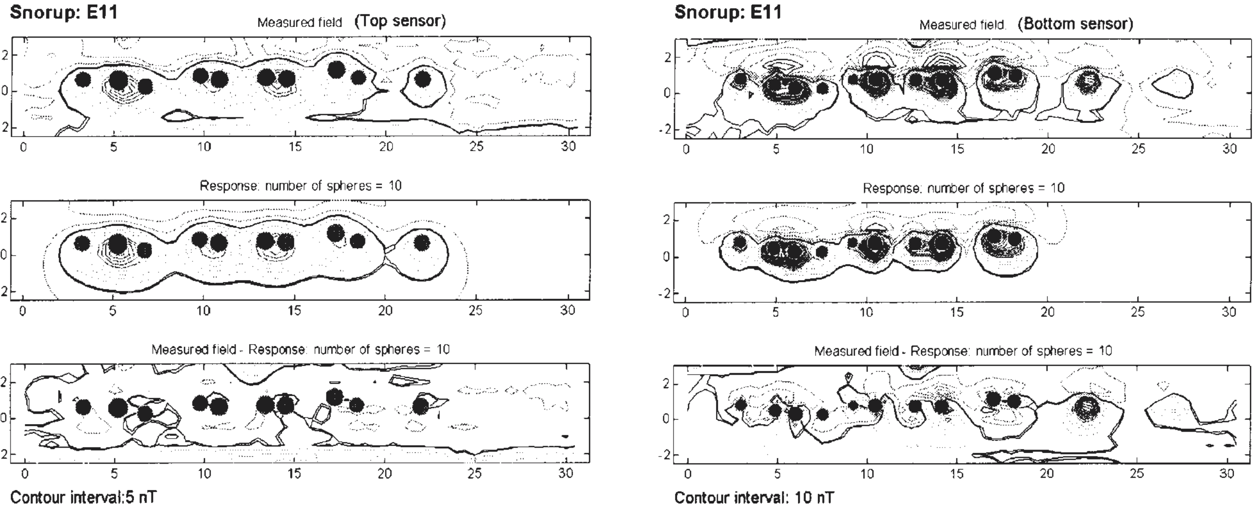

Fig. 10. Simple magnetic modelling by adjusting inclined dipoles using MatlabŇ (as applied in Fig. 7) is illustrated in more detail for each of the two magnetic sensors. For each sensor, the *top figure* shows the measured total magnetic anomaly, the *middle figure* shows the magnetic response from a number of simple dipoles (spheres), each dipole being interactively adjusted individually (Jacobsen & Abrahamsen 1997) in coordinates (X, Y, depth), declination, inclination, and dipole moment (proportional to the area of the spheres shown), and the *bottom figure* show the residual field. (The maximum number of spheres to be handled were set to 10 in this case for practical reasons). a—Top sensor: The contour interval is 2 nT, the magnetic anomalies being fairly smooth. b—Bottom sensor: The contour interval is 10 nT, the magnetic anomalies being more irregular than for the top sensor. For the 10 dipoles modelled, the residual anomalies are between 10 and 30 nT, corresponding to 10 ± 5 % of the measured anomaly.

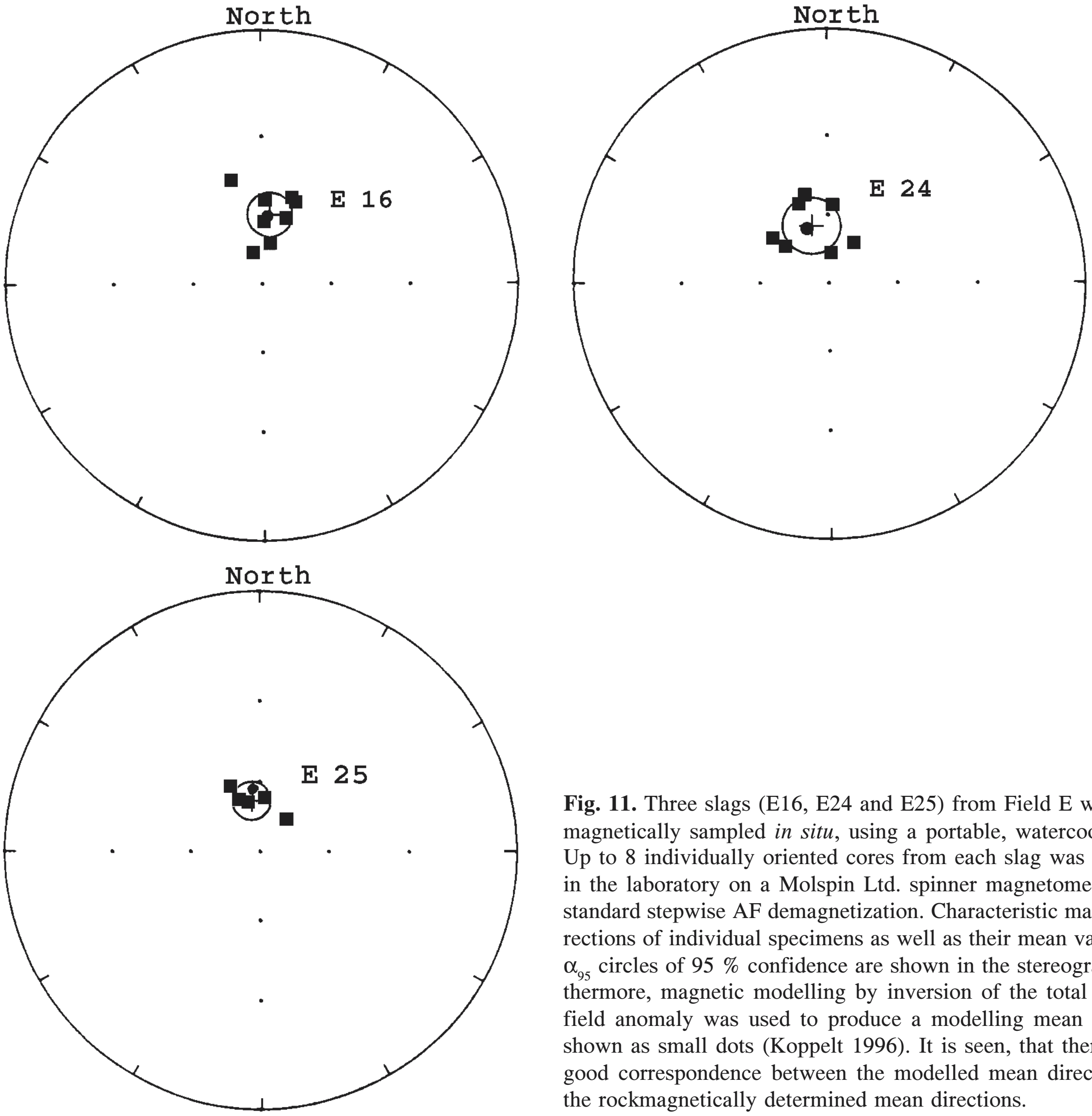

Fig. 11. Three slags (E16, E24 and E25) from Field E was paleomagnetically sampled *in situ*, using a portable, watercooled drill. Up to 8 individually oriented cores from each slag was measured in the laboratory on a Molspin Ltd. spinner magnetometer, using standard stepwise AF demagnetization. Characteristic magnetic directions of individual specimens as well as their mean values with α_{95} circles of 95 % confidence are shown in the stereograms. Furthermore, magnetic modelling by inversion of the total magnetic field anomaly was used to produce a modelling mean direction, shown as small dots (Koppelt 1996). It is seen, that there is very good correspondence between the modelled mean directions and the rockmagnetically determined mean directions.

standard specimens and measured in the laboratory on a Molspin Ltd. spinner magnetometer, using standard stepwise AF demagnetization (c.f. Fig. 9). Characteristic magnetic directions of individual specimens as well as their mean values with α_{95} circles of 95% confidence are shown in the stereograms (Fig. 11).

Furthermore, after a detailed magnetic survey over each of the three slag pits, magnetic modelling by inversion of the total magnetic field anomaly was used to produce a modelling mean direction, the result of which is shown as a small dot in each stereogram (Koppelt 1996). It is seen, that there is very good correspondence between the modelled mean directions and the paleomagnetically determined mean directions for each slag. Numerical details are given in Table 2.

Table 2: Cleaned stable remanent mean directions with spherical Fisher statistics on oriented cores from the three slags E16, E24 and E25 investigated paleomagnetically, as well as the mean directions determined from inversion of the magnetic surface anomaly.

Slag	Reg. no	Dec	Inc	N	k	α_{95}
Paleomagnetic results:						
E16	4034	6.3	59.6	8	36.3	9.3
E24	4033	343.9	63.8	7	26.0	12.1
E25	4032	350.4	67.7	6	68.7	8.1
mean		354.3	64.0	3	148.7	7.0
Magnetic inversion results:						
	4034	359.0	62.1			
	4033	341.8	64.5			
	4032	352.4	62.3			
mean		351.3	63.1	3	386.9	4.3
mean of all:		352.8	63.6	6	260.4	3.8

Magnetic dating

The directional mean results for the three slag pits E16, E24 and E25 (Table 2), as obtained by the remanent magnetization of oriented cores and by inversion, are shown in Fig. 12, plotted onto the magnetic secular variation curve for Denmark for the period 0 to 2000 AD. The curve is based upon the British archaeomagnetic mastercurve (Clark et al.

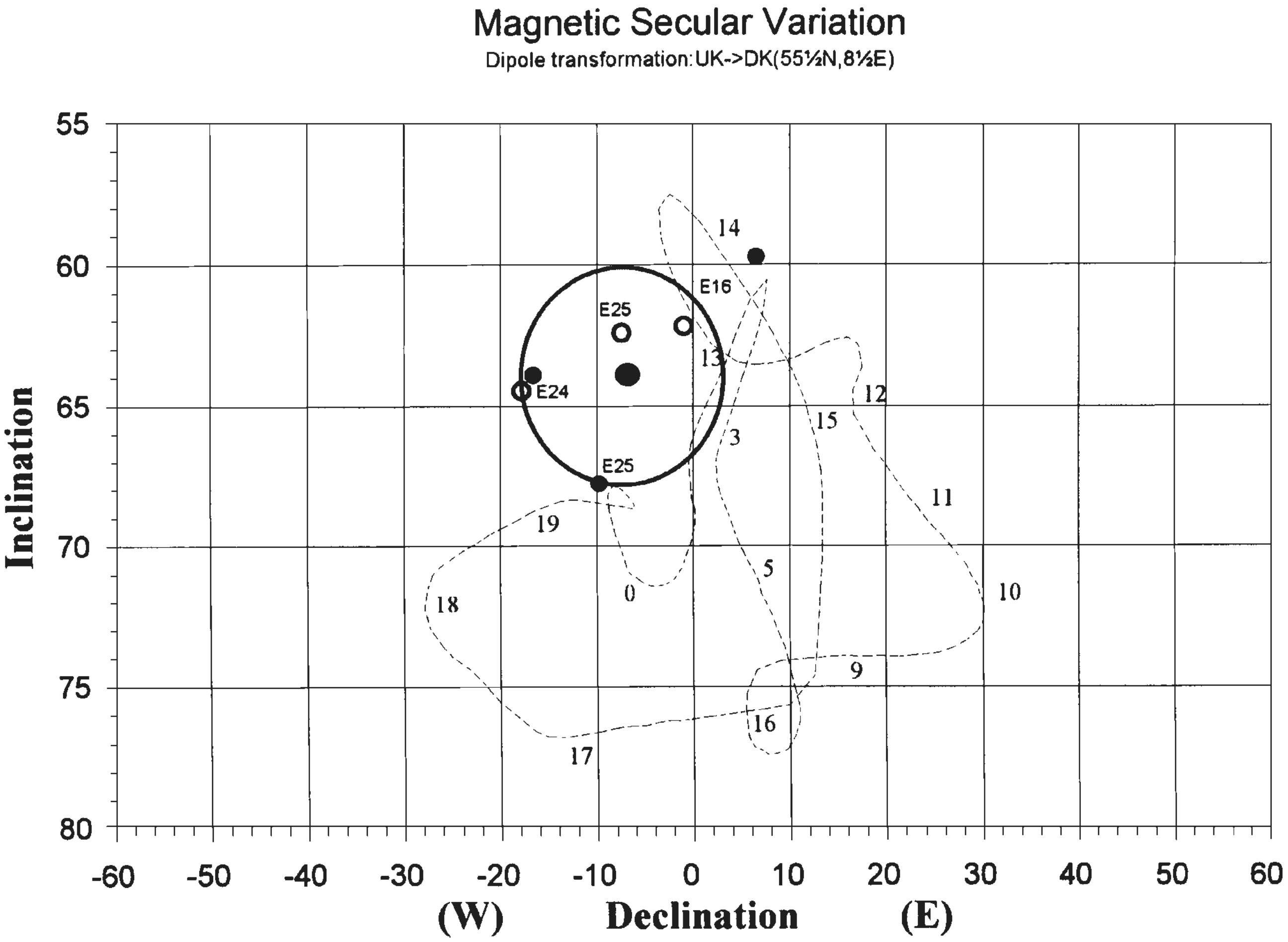

Fig. 12. Preliminary magnetic secular variation curve for Denmark for the period 0 to 2000 AD, based upon a central dipole transformation of the British mastercurve from UK to Denmark (Abrahamsen 1996). Small numbers indicate century AD. The directional results for the slag pits E16, E24 and E25 obtained by magnetic cleaning of oriented cores (small solid dots) and by inversion (open dots) are also shown. Solid dot with corresponding 95% significance circle indicate the overall mean direction.

1988), recalculated from Meriden in UK to Snorup in Denmark by a central dipole transformation (Abrahamsen 1996), a distance of 800 km. The α_{95}-circle shown is the 95% significance circle of the combined mean direction. It appears, that the paleomagnetically determined directions are rather scattered (solid dots), and a dating based upon these alone is not well constrained (α_{95}= 7°), the direction suggesting a paleomagnetic age of before the 6th Century AD.

The inverted mean directions are less scattered (open dots) and the trend is in general agreement with the paleomagnetic mean directions (and well within the individual α_{95}-circles of the latter ones). Although scattered, the two magnetic techniques thus appear to agree with each other, thus supporting each other quite well.

The grand mean of all 6 mean directions gives a value of (D, I) = (352.8°, 63.6°), α_{95}= 3.76°, k = 260. Considering the uncertainties of the magnetic master-curve, which may well be at least ±2° in inclination and ±5° in declination, the magnetic mean direction suggests a mean age of the three slag pits in Field E between the 1st and 5th Century AD. Whether the scatter (or systematic trend from E24 via E25 to E16) in the magnetic mean directions is due to a real trend in the age of the three slag pits, or it is due to scatter in the magnetic data, is not known.

Conclusions

Our experience from the joint archaeological and geophysical investigations performed in the Snorup and nearby areas over the last few years has confirmed, that the Snorup area was an important iron production area in prehistoric time. Magnetic surveying, in a "free search mode", in a systematic mapping, and in a very detailed mapping sense, has given valuable insight into the extent and amount of the old slag pits still present and often well preserved below the soil. Magnetic modelling has been useful to estimate the extent, amount and number of slag pits present, and the magnetic inversion and paleomagnetic methods may be useful for dating the slag pits when these are undisturbed and geometrically "well behaved".

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