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Magnetic geophysical mapping of prehistoric iron production sites in central Norway

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Abstract

The slag pit furnace of the Trøndelag tradition for iron production is a very specific cultural-historical tradition in central Norway in the Early Iron Age, but few of these iron production sites have been excavated in their entirety and there is therefore a lack of information about their size, spatial layout and organisation in the landscape. The aim of this paper is therefore to investigate how magnetic geophysical methods can be used as a way of locating, delimiting and characterising activity zones and specific archaeological features associated with this tradition of iron production. The NTNU University Museum in Trondheim performed geophysical surveys of four different iron production sites, combining topsoil volume magnetic susceptibility measurements and detailed fluxgate gradiometer surveys. Analysing and comparing the survey results with sketches and topographic survey results, as well as comparable geophysical survey data from iron production sites elsewhere in Norway, made it possible to gain new and valuable cultural-historical and methodological knowledge. The topsoil volume susceptibility measurements revealed a strong contrast between the main production areas and the natural background measurement values, often in the range of 7–27 times the median background values. The absolute highest measured values were usually in the area closest to the furnaces, and within the slag mounds. Satellites of high readings could be interpreted as roasting sites for iron ore, and even areas with known building remains related to the iron production sites had readings stronger than the median. The fluxgate gradiometer data helped to characterise individual features further, with strong geophysical contrast between features within the iron production sites and the areas surrounding them. Also, by analysing their physical placement, geophysical characteristics such as contrast, magnetic remanence and size, it was possible to gain further insight into the spatial organisation by indicating the potential location of furnaces, the spread of slag and the handling of iron ore. The latter involved both where the roasted iron ore was stored and where it was roasted. The geophysical characteristics of the furnaces were less uniform than situations reported elsewhere in Norway, which can be explained by the reuse of furnaces and slag pits. The spread of highly remanent material in and around the furnaces and elsewhere within the limits of the iron production sites also created a disturbed magnetic picture rendering it difficult to provide an unambiguous archaeological interpretation of all the geophysical anomalies identified. In conclusion, these results showed that the geophysical methods applied made it possible to indicate the physical size, layout and internal spatial organisation of iron production sites of the Trøndelag slag pit furnace tradition.

Introduction

In upland areas near Trondheimsfjord in central Norway, there was a very specific tradition for iron production in the Early Iron Age, with large slag tips, several slag pit furnaces, an organisation of pits in a rosette-shape around the furnaces, and a work practice that involved the reuse of furnaces (Stenvik, 1997; 2003). This is a tradition which is mainly known from central Norway, although a couple of excavations in Agder in southern Norway have revealed slag pit furnaces that resemble the ones known from Trøndelag, but without the characteristic rosette cluster of pits surrounding them (Kallhovd & Larsen, 2006; Martinsen & Stene, 2017). The excavations performed in central Norway have largely been small ones focusing on parts of the sites, such as the furnaces, pits surrounding the furnaces or remnants of buildings. This has led to a situation where only one known site has been excavated with a wide focus on a larger area around the central furnaces themselves (Stenvik, 1996).

The actual size of the activity area related to the iron production sites of the *Trøndelag slag pit furnace tradition* remains largely unknown. There is also a lack of knowledge of the location of other activities assumed to be present close to the iron production sites, such as roasting places for iron ore, storage of firewood, clay and roasted ore, as well as building remains and traces of food preparation, processing of raw iron or smithing.

In the last decade, we have seen an increase in the application of geophysical methods in Norwegian archaeology (Stamnes & Gustavsen, 2014), with several surveys being performed on iron production sites in southern and eastern Norway giving very interesting and positive results (Larsen, 2009, pp. 221–223; Rundberget, 2007). Several publications from Great Britain involve the geophysical investigations and analysis of the geophysical response of pyrotechnical industries and iron smelting sites, involving detailed magnetic modelling simulations, gradiometer measurements of a model shaft furnace under controlled conditions, and gradiometer surveys of a furnace on a test site (Vernon, 2004), as well as magnetic susceptibility and fluxgate gradiometer surveys of iron production sites (Crew, 1990; Crew & Crew, 1995; Powell et al., 2002). Investigations from Denmark also provide comparable information of the geophysical response of Early Iron Age furnaces and slag pits (Abrahamsen et al., 2003; Smekalova & Voss, 2002).

These investigations provide background knowledge on the typical response of various archaeological features that are expected to be present at iron production sites of the Trøndelag slag pit furnace tradition. The Department of Cultural History and Archaeology at the Norwegian University of Science and Technology (NTNU) University Museum has surveyed several iron production sites around Trondheimsfjord using magnetic geophysical methods to provide geophysical data that can be analysed to increase our cultural-historical understanding and knowledge of these sites. The geophysical results from three of these sites have never before been presented, and a thorough presentation of each of these sites is therefore vital.

The aims of this paper are threefold: 1) To investigate how the results from magnetic geophysical survey methods combining topsoil magnetic susceptibility and fluxgate gradiometer mapping can be used to locate and delineate iron production sites. This will be done by presenting an overview of known magnetic geophysical mapping of iron production sites in Norway and in particular new and in-depth analysis of recent surveys performed by the NTNU University Museum. 2) To investigate how the geophysical methods applied can be used as a way of locating, delimiting and characterising activity zones and specific archaeological features associated with the Trøndelag slag pit furnace tradition of iron production. 3) To investigate if and how magnetic geophysical survey methods can be an asset for the heritage management of outfield iron production sites.

Methods

This section explains the geophysical principles of the magnetic survey methods applied, i.e. magnetic susceptibility sampling and fluxgate gradiometer surveying, as well as outlining the survey strategies and field procedures utilised as part of the investigations presented. This section also contains detailed background knowledge of the geophysical characterisation of iron production sites in Europe, geophysical mapping of iron production sites in Norway and the *status quo* of research on iron production sites of the *Trøndelag slag pit furnace tradition*.

Geophysical methods – principles and survey strategies

Magnetic Susceptibility (MS) is a measure of how magnetised a sample can get when exposed to a magnetic field. An alternating magnetic field is created in a coil, and the change and its effect on the sample are measured. MS investigations are therefore considered an active method. Investigations can be conducted in several ways, either by sampling a volume of an exposed surface with a probe which provides bulk measurements of volume susceptibility (usually denoted as κ or 10^{-5} SI), or by measuring the magnetic susceptibility of a rock or soil sample, called mass specific susceptibility (usually denoted as X or m^3kg^{-1}). By drying, sieving and weighing soil samples, any effects of varying bulk size, inclusions, water content, density, etc. are removed. If the k value is divided by the bulk density of the sample (mass divided by volume), a more accurate measurement of the susceptibility of the material can be estimated. Different soils and parent materials have varying contents of magnetic minerals, iron oxides (FeOx) being among the most magnetic minerals. The MS values of a soil can be enhanced in several ways, including burning, industrial activity, bacterial activity, reducing and oxidising processes, deposition of magnetic anthropogenic material, and decomposition and fermentation (Batt et al., 1995; Dalan, 2008; Dearing, 1999; Fassbinder & Stanjek, 1993). As several of these activities are often associated with human occupation, systematic measurements can be a way of locating and delimiting anthropogenic activity and further help to distinguish and characterise archaeological features and stratigraphy. In many instances, ploughing and bioturbation would help to bring material with enhanced magnetic susceptibility from the subsurface closer to the upper stratum, where an enhancement can be measured (Aspinall et al., 2009; Batt et al., 1995; Clark, 1996; Corney et al., 1994; Dalan, 2008; David et al., 2008; Fassbinder & Stanjek, 1993; Gaffney & Gater, 2003; Linderholm, 2007; Stamnes, 2011). In archaeology, the volume susceptibility is usually measured on the exposed ground surface, and this can be referred to as topsoil magnetic susceptibility mapping.

Figure 1. Measuring magnetic susceptibility with the Bartington MS2 Magnetic susceptibility meter

In the examples provided in this article, all sampling was conducted in a semi-systematic manner using a Bartington MS2 with the D-field loop (Fig. 1). Each geographical position and reading from the MS2 sensor was logged with a CPOS-corrected GPS system, ensuring an accuracy of ±2 cm in plan. Good area coverage was ensured by walking with approximately equal spacing between each sample. Each measurement represents the value at that specific location, so a complete raster map is created of the topsoil MS values as coverage maps by interpolating the values between each sample point. It is possible to inspect the quality of the interpolation, as the interpolation software will provide a map of the calculated prediction standard error of the interpolation, which is an indication of the quality of the interpolations performed. This map can be used to inspect the coverage and indicate areas where additional samples might be needed (Isaaks & Srivastava, 1989). The necessary sampling density depends upon the expected size of the target (Schmidt & Marshall, 1997). When the average distance between each GPS recorded reading is sufficiently low to positively identify the magnetic features you are expecting, and the sampling is performed with the purpose of locating and delimiting archaeological sites, then a grid-based strategy is considered unnecessary due to the qualities of ordinary kriging as an interpolation method. Methodological issues related to sampling density when surveying iron production sites will be discussed below.

Fluxgate Gradiometer surveying (FG) is a passive method. FG works by systematically mapping and measuring variation in the Earth's magnetic field created by anomalies in the ground. As everything is exposed to this magnetic field at all times due to the constant presence of the Earth's magnetic field, any feature in the ground filled with a material with a higher or lower magnetic susceptibility than its immediate surroundings will be magnetically induced and act as a contrasting local magnetic field, which can be detected. It is, therefore, the susceptibility contrast between the feature and the surrounding subsoil that governs whether or not this feature can be detected in this way. Burning, settlement refuse and similar actions enhance the MS values of soil and will increase the chances of archaeological features being detected as anomalies, since dug archaeological features such as pits and ditches might have been backfilled with more magnetic susceptible material. In addition to induced magnetisation, some materials may have an inherent magnetism that remains present even when the induced magnetising field is removed. This is called remanent magnetisation. Several pathways can cause remanent magnetisation, but in archaeology, the thermoremanent magnetisation can be considered the most relevant pathway to magnetisation. This is the heating of materials above the Curie temperature for that specific material, usually between 550 and 770 °C for iron minerals (Powell et al., 2002, p. 660), which will cause the more or less random magnetic domains within the material to realign themselves towards the present-day magnetic north when the material cools below the Curie temperature. Other pathways to remanent magnetisation can be chemical, isothermal or viscous. Different geological conditions might mask this effect if the background variations of rocks and magnetic

Figure 2: The dual sensor Bartington Grad 601 gradiometer used in the surveys presented in this article

inclusions are higher than the magnetic contrast of archaeological features. Typically, an induced magnetic feature will have a negative part towards the magnetic north, while a remanent magnetised feature can have the negative part of the signal pointing in any direction, and sometimes also cancelling out the negative part of the signal created by other magnetised features in the vicinity (Aspinall et al., 2009; Clark, 1996; Evans & Heller, 2003; Gaffney & Gater, 2003; Vernon, 2004).

All FG data presented here were gathered with a Bartington Grad 601 fluxgate gradiometer (Fig. 2). On one site, Tromsdalen in Verdal municipality, data were only collected with a dual configuration, i.e. with two separate sensors fixed one metre apart. Generally, the sensor(s) were fixed on a carrying frame approximately 15–20 cm above the ground. The height was increased to about 25–30 cm above the ground for the Tromsdalen survey due to tree stumps and other obstacles in the survey area, which gave an increased risk of damaging the sensors if they had been positioned lower. The survey direction of each site was planned to improve speed and practical easiness of data capture and it was therefore decided to angle each traverse so that the surveyor walked straight down the sloping ground, instead of having to tackle the topography diagonally or perpendicularly. Therefore, none of the surveys was angled directly north–south, which is usually considered the best survey direction as a north-south traverse gives the best characteristic of changes in the magnetic field gradient of the anomalies you wish to study in detail. Grids were staked out using tape markers and the Pythagoras theorem, and prepared ropes with markers for every metre along the ground surface were positioned along each traverse. As the instrument gives a signal for every metre, it was possible to walk each traverse at the same speed, and therefore same resolution, by making sure to match each audio signal with the markers on the ropes. Grid corners were surveyed using a high-quality GPS with CPOS correction signal, ensuring a positioning quality of ±2 cm in ideal conditions. Although sloping ground might lead to grids not being exactly 20x20 m, the georeferencing of the final result into a map with the GPS surveyed grid corners will correct for this.

Table 1. Overview of survey parameters and areas surveyed

Site and Municipality	FG traverse interval	FG sampling interval	FG Area	MS	MS Samples	MS Area	MS sampling density
Mokk, Steinkjer	0.5 m	0.125 m	575 m²	No	-	-	-
Storbekken 1, Midtre Gauldal	0.5 m	0.125 m	1221 m²	Yes	640	7570 m²	3.44 m
Tromsdalen, Verdal	0.5 m	0.125 m	1477 m²	Yes	431	3865 m²	2.99 m
Roknesvollen, Levanger	-	-	-	Yes	441	8336 m²	4.35 m

Geophysical characterisation of iron production sites with magnetic methods – understanding the geophysical response

Research conducted on prehistoric iron production sites in Europe has led to better insight into the magnetic response of typical archaeological features related to the iron production, such as furnaces, slag tips, tapping channels, roasting and storing iron ore, charcoal storage, traces of settlement or similar activities. Special attention will be given here to iron production utilising shaft furnaces, which is the general technology on which the *Trøndelag slag pit furnace* technology is based. This knowledge is most beneficial for analysing, interpreting and understanding data plots from case studies presented later in this article.

In southwestern Jutland in Denmark, over 80 sites with slag pit furnaces have been located. Some sites have numerous slag pits, for instance, Krarup (1000 pits), Yderik (1300 pits), Gødsvang (>1300) and Snorup (>4000). Each shaft furnace and slag pit was the result of a single smelt made in ovens with clay shafts above ground and pits below (Abrahamsen et al., 2003; Smekalova & Voss, 2002). The average weight of a slag block is calculated to almost 200 kg. Some pits have been found where they were dug, with a magnetic signature that is quite uniform as a magnetic dipole with the negative towards the north and the maximum within quite a wide range, often between 20 and 2000 nT (Smekalova & Voss, 2002). The absolute negative value is usually about 1/6 of the value of the maximum, and the negative part of the anomaly is situated north of the positive one with the minimum point situated about 0.5–1 m north of the maximum (in the latitude of Jutland, this is approximately 56°09' N). How transferable these observations are depends on the differences in the directions and position of the magnetic north pole when the cultural-historical material that is studied was deposited. Moreover, the location of the Trøndelag area at 63°24' to 64° N influences the geophysical characteristic of an anomaly. The magnetic anomaly over a slag pit is seen to become wider and the maximum value measured decreases rapidly as the height difference between the sensor and the archaeological target is increased. Also, clusters of slag pits situated close to each other can make it difficult to distinguish one from the other, and it was only possible to distinguish two neighbouring objects magnetically if the separation between them was more than 1.5 times their depth. In this Danish example, there had to be more than 0.75 m between the slag pits to be able to distinguish them from each other, if they were buried 0.5 m below the sensor (Abrahamsen et al., 2003; Smekalova & Voss, 2002).

In Britain, Vernon (2004) conducted magnetic modelling simulations, gradiometer measurements of a model shaft furnace under controlled conditions, and gradiometer surveys of a furnace on a test site to understand better the effects of the induced and remanent magnetic responses on gradiometer survey data. When the remanent magnetic north of a target was co-aligned with the true magnetic north, the result was a reinforcement of the magnetic signal, with a strong negative response on the north side of the feature. When the remanent magnetic north of the target was pointing towards the true magnetic south, the remanent magnetic part of the signal would be in opposition, and at least partly weaken the measured negative response. Vernon's tests showed that the magnetic anomaly of a furnace was mainly due to remanent magnetism, and to a lesser degree induced magnetisation. The modelling and simulations showed that the magnetic response of a fired clay furnace would give a distinct positive co-aligned between remanent and magnetic north, and with its maximum south of the centre of the source of the anomaly (Vernon, 2004). In the Trondheimsfjord area at 63°24' to 64° N, this would equate with the maximum being close to 0.20 m south of the source of the anomaly, and the lowest minimum part of the signal being about 1.25 m north of the source. The measured response would have a negative halo, with the minimum response towards the north. When the distance to the target increased, i.e. the target was buried deeper in the ground, the measured positive response would be wider, and the negative halo would diminish or have lower positive values. The maximum of the measured signal would still be at the same approximate distance from the target. Other important observations were that the randomised magnetic orientations of the dumped slag could cancel each other out, leaving the overall remanent magnetic signal of slags smaller than the signal produced by a furnace. Also, a slight 'bulge' on the circumference of the positive data may correspond to the lip of a tapping channel. The lessons learned from the modelling and test surveys were used to better interpret data from several investigations of archaeological sites with shaft furnaces and activity associated with iron smelting. Typically, most furnaces generated values over 300 nT, but the surveyed furnaces were often no more than 30 cm below the surface. Measurements over pockets of roasted iron ore also gave very strong magnetic responses, with readings as high as 200–1000 nT (Vernon, 2004, ch. 4 & 7). Powell (2008) combined the results at several sites that Vernon (2004) investigated with volume magnetic susceptibility sampling and subsequent excavations, identifying both areas of iron ore roasting and furnaces.

It has also been suggested that there is a link between high magnetometer readings and the thickness of the slag deposits. Farbregd (1977) illustrates a good correlation between measurements with a proton magnetometer and the thickness of a slag heap at Hoseth in Norway, and the same tendency has been reported at a Roman iron production facility in Hüttenberg (Walach et al., 2011), where a mixture of thermoremanent material partially cancelling out both the induced magnetic properties and pieces of remanent magnetic material randomly oriented would theoretically create a very mixed and random signal overall. The results from Hoseth could indicate that increased thickness might add to the strength of the overall measured strength of the magnetic field over slag tips.

Magnetic susceptibility mapping of the topsoil has proved to be an ideal way of delimiting activity areas on iron production sites in England and is considered to be a good way to complement gradiometer surveys (Powell et al., 2002; Powell, 2008, pp. 79–80). In most instances, slags and areas of iron working should produce high magnetic susceptibility readings, even though the contact between the slag and the soil is compromised. As long as the contrast between the slag and the background geology is sufficient, this should produce good results (Vernon, 2004, p. 20). Crew (1990) observed a close correlation between the measured magnetic susceptibility and the volume of slag. Small heaps of slag can sometimes have a geophysical response as strong as larger heaps, suggesting that this was rather linked to the proportion of the magnetic smithing slags deposited (Crew & Crew, 1995). Powell et al. (2002) combined magnetometry and magnetic susceptibility survey data and showed how the size and shape of the anomalies are dependent on several parameters, such as furnace operation and the amount of heat-affected material remaining in the archaeological record. By combining the survey results with laboratory magnetic susceptibility investigations and microscopic analysis, they also show variability in the mineralogy and morphology in the slags, which they use to understand better the operation of an iron production site.

In addition to the various geophysical responses of features related to iron production, it is important to take into account that various other effects, such as heat affecting the surrounding ground, the state of preservation, relining of furnaces and reusable slag pits would complicate the geophysical signature. Also, the physical dimensions of any buried feature would change the geophysical signature.

A short history of geophysical mapping of iron production in Norwegian archaeology

It is assumed that geophysical mapping of iron production sites could help to delineate activity areas and contribute to characterise specific activity and archaeological features within the sites. Although there is a lack of detailed geophysical analysis, and comparison and analysis of the relationship between the geophysical data and archaeological ground observations in Norway, some geophysical mapping of iron production has taken place.

The history of mapping iron production sites in Norway using geophysical methods started with a survey in 1973 when the Geological Survey of Norway (NGU) did a proton magnetometer survey of an Iron Age production site at Hoset in Stjørdal, Nord-Trøndelag. The general outcome was very positive as the resulting measurements delineated a slag heap of about 45 m^2. The strength of the magnetic signal was also compared with a section of the slag heap, and this elegantly showed a correlation between the magnetic total field strength and the thickness of the slag heap, which was 0.9 m thick at the most (Farbregd, 1977, pp. 124–125). Although the results from Hoset were very useful, it took 15 years before the next geophysical mapping of an iron production site in Norway. This was at Dokkfløyvatn in Oppland, where, due to a restricted budget, the survey was commissioned to help prioritise which area they should increase their efforts in. The work included both ground penetrating radar and proton magnetometer surveys, and it was especially the magnetometer results which were considered encouraging and indicated the presence and location of furnaces, slag mounds and layers of iron ore (Larsen, 1991). Both the Hoset and Dokkfløyvatn surveys were conducted in non-cultivated and forested land. The next survey with the aim of localising an iron production site was on cultivated land, at Hemmestad in Troms in the north of Norway. Iron production sites are scarce in this part of the country, and the farmer had found a pit with slag 50 years earlier while clearing a field. A gradiometer survey was conducted in 1999 and expanded in 2002, and it revealed several anomalies that were considered interesting. Two of these were Iron Age furnaces, two cooking pits and a fifth an anthropogenic pit, and the survey was considered a success as it would otherwise have been very difficult to locate these archaeological features in a large field without the geophysical data (Jørgensen, 2010). See also Jørgensen (this volume).

Between 2000 and 2002, 18 sites in southeastern Norway were investigated by Tatiana Smekalova, a geophysicist from Saint Petersburg State University in Russia, on behalf of the Norwegian Institute for Cultural Heritage Research (NIKU) and related to the Gråfjell survey project in the county of Hedmark in southeastern Norway. In 2004 and

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[1] Tatiana Smekalova and Sergei Smekalov

2005, the Smekalova team[1] returned to Gråfjell on behalf of the Cultural Historical Museum in Oslo, which was in charge of the Gråfjell excavation project. Thus, the use of magnetometers, was included in the Gråfjell fieldwork for several years. The surveys were a combination of scanning (also called "free search") and detailed mapping, and were performed in combination with traditional field survey methods. Areas suspected of containing roasting sites were subjected to magnetometer scanning, or detailed magnetometer surveying was conducted to help delineate sites. Interesting anomalies were not located at all the sites investigated, and this suggested an absence of high-temperature, metal-related activity. Not all investigations were subjected to excavation, but the ones that were showed a good correlation between anomalies interpreted as roasting sites, slag heaps and furnaces, and archaeological ground observations. One survey also positively identified a medieval smithy, a rare observation in these forested areas (Risbøl & Smekalova, 2001; Risbøl et al., 2001; Risbøl et al., 2002a; Risbøl et al., 2002b). In 2005, the Smekalova team also surveyed at Tyin in Oppland , performing a detailed investigation of five iron production sites and some scanning (Smekalova & Smekalov, 2005). In 2006, they also surveyed at Hovden (Smekalova, 2006) in Aust-Agder and Haglebu in Buskerud (Grøtberg & Tveiten, 2015). At Hovden, they did a detailed investigation of two iron production sites and also performed scanning. The work resulted in delimiting the sites and locating several roasting sites for iron ore. At Haglebu, they did a detailed survey of three iron production sites. In most surveys, the location of the furnaces usually gave the strongest magnetic response, with a contrast of some 800–1500 nT, but sometimes the slag heaps produced just as high a response. Charcoal storage areas were generally elusive in the magnetic data. The roasting sites at Gråfjell often produced a geophysical contrast in the range of 180–300 nT but sometimes as high as 650–710 nT (Rundberget, 2007). High responses within the slag heaps might be explained as the result of large slag blocks with high iron content having been tossed into the slag heaps. Larsen (2009) summarises the experience the Cultural Historical Museum in Oslo had using non-intrusive magnetic methods to locate and investigate iron production sites and places for roasting iron ore. Scanning with magnetometers undoubtedly gave the best results as regards locating roasting sites (Larsen, 2009, pp. 206, 221–223; Rundberget, 2007, pp. 279–308; Smekalova & Voss, 2002; Smekalova et al., 2008). In southeastern Norway, there is often a close relation between the charcoal production pits and iron production nearby. Larsen (2009, p. 206), therefore, concluded that the use of metal detectors and/or magnetometers should be mandatory when doing fieldwork aimed at locating slag pits or slag tips, especially when pits from charcoal production were found, but traces of iron production were not seen nearby.

In central Norway, no geophysical surveys were performed on Iron Age iron production sites since the 1973 study (Farbregd, 1977) before Nord-Trøndelag County Council commissioned a survey at an iron production site at Mokk in Ogndalen in Nord-Trøndelag in 2010 (Stamnes, 2010). This initial work was followed up by three more surveys of similar sites linked with the Trøndelag slag pit furnace tradition. Before considering the results, a short review of the research on the Iron Age iron production in this part of Norway will be presented.

Iron Age iron production in central Norway

A research programme in the early 1980s, focused upon dating iron production sites in central Norway, identified trends and variation in the production of iron in Trøndelag over a period of almost 2000 years (Stenvik, 1991). Iron production in the region started around 400–300 BC, in the Pre-Roman Iron Age, using a very specific production technology for this region – usually called Trøndelag slag pit furnaces. This form of production lasted until the Migration period, during which it disappeared completely. Typically, several shaft furnaces were located beside each other and operated contemporaneously, with output reaching as much as 100 tons of iron at one site. These furnaces were also much larger than those observed later. Typically, each shaft furnace consisted of a horseshoe-shaped, stone-lined slag pit dug into the subsurface, with an opening in the bottom of the pit that made it possible to tap the product during the production process. This opening extended the lifetime of the production site. The pit was usually 0.7–0.9 m in diameter and 0.7–1 m deep. When slag remains have been found *in situ*, there has been between 20 and 160 kg, but usually just under 150 kg (Espelund, 1999; Nordlie, 2009; Prestvold, 1999). The shaft would probably have been funnel-shaped, and fired with wood, not charcoal. Usually, each site consisted of four furnaces, but sites with as many as eight are known. The associated slag dumps are relatively large and might contain from tens of tons to as much as 100 tons of slag per iron production site. Usually, the furnaces were placed on or close to the edge of a terrace, with the slag dumps down the slope of the terrace, creating a fan-shaped slag tip below each furnace. In addition to slag, the tips contain fragments of burnt clay from the furnace shafts, earth and stone. A furnace is often surrounded by a number of pits whose purpose is not known. These pits often encircle the furnaces in a rosette pattern – a trait that is unique to the Trøndelag slag pit furnace tradition (see Figs. 3 and 13). They never cut into each other, and are considered to be of some importance for the work carried out in relation to the iron production. Each arrangement of furnace and pits forms an entity without disturbing the other groups of features at the same site. The pits are circular or oval in plan, 1-2.4 m in diameter, 0.1-1 m deep and 0.6-0.8 m from the furnace (Espelund, 1999; Farbregd et al., 1985; Nordlie, 2009; Prestvold, 1999). Excavations have shown that they may contain roasted iron ore, burnt clay and burnt stone and flagstones similar to those lining the floor of the furnaces (Farbregd et al., 1985). They have been interpreted as either a container for roasted iron ore, storage for clay and firewood, or places where the extracted iron was post-processed before transportation (Espelund & Stenvik, 1993; Rundberget, 2010; Stenvik, 1991; 2003; Wintervoll, 2010). Building remains are known on some of the sites. These buildings may have been used both as lodging for the workers and to ensure dry storage of fuel and/or iron ore. Lack of archaeological objects and features reveal little of how these buildings were used, but remnants of roasted iron ore and a hearth have been found in some of them (Espelund & Stenvik, 1993; Farbregd et al., 1985; Nordlie, 2009; Prestvold, 1999; Wintervoll, 2010). In addition to these archaeological features, it is not unusual to find other pits a little further back from the edge of the terrace. Their purpose is not known. They may, for instance, be cooking or charcoal-production pits (Farbregd et al., 1985). Concentrations of roasted iron ore have been found at some sites, such as Storbekken 1 at Tovmoen in Budalen, Sør-Trøndelag and Myggvollen near Meråker in Nord-Trøndelag (Espelund & Stenvik, 1993; Stenvik, 1996; 1997). Similar furnaces to these Trøndelag slag pit furnaces are found at iron production sites in Agder in southern Norway, but they lack the associated pits and postholes, and are smaller in overall size than the sites in central Norway (Kallhovd & Larsen, 2006; Martinsen & Stene, 2017; Rundberget, 2010).

Much of the research focus on the iron production sites in central Norway has centred around socio-economic perspectives (Stenvik, 1997) and metallurgical processes (Espelund, 1999). These sites are often located in upland areas, and far from areas under pressure from modern development. Therefore, few sites have been excavated. The excavations performed have mainly concerned small research projects focusing on parts of the sites, such as detailed excavations of the furnaces, the rosette pits or building remnants. This has led to a situation where only one known site has been documented extensively, with major focus on the terrace and the spatial arrangement of activity away from the central furnace area itself. This is the site at Myggvollen on Fjergen, a lake near Meråker. At this site, activity related with the storage of iron ore and burnt materials was discovered in pits between two ovens, and a concentration of roasted iron ore was also found. Further back on the terrace, a 12x4–5 m large layer was found. It was comprised of fire-cracked rocks, charcoal and soot, and the bottom part consisted of small iron fragments. A pit filled with fire-cracked rocks, and pits with a diameter of 1.6 m and a depth of 0.35 m were found nearby. The first pit could be interpreted as a cooking pit used in the preparation of food for the workers. Twelve to fifteen similar pits were found at Heglesvollen in Levanger (Stenvik, 1996). The observations at Myggvollen indicate that there are remnants of activity near the furnaces, but there is still uncertainty concerning the location of activity such as food preparation, the extraction and roasting of iron ore, settlements and transportation routes related to these iron production sites. In addition to this, the iron was perhaps processed by hammering or similar treatment before transportation, but this remains largely unknown for the sites in Trøndelag. The actual size of the activity areas related to the iron production sites of the Trøndelag slag pit furnace tradition remains largely unknown.

Results

This section presents the survey results from four iron production sites. Both a fluxgate gradiometer survey and a topsoil volume susceptibility survey were undertaken at Storbekken 1 and Tromsdalen. A topsoil volume susceptibility survey was undertaken at Roknesvollen, and a fluxgate gradiometer survey at Mokk (Table 1). Apart from those obtained from Mokk, none of these results has previously been presented and they will, therefore, be thoroughly described here. In 2018, the two counties, Sør- and Nord-Trøndelag, were merged, and called Trøndelag, but the old names are kept in this article.

Storbekken 1 at Tovmoen, Midtre Gauldal, Sør-Trøndelag

A sketch of the site based on visual ground inspections and the use of a small soil auger indicates a site containing five furnaces with the well-known pattern of pits around the ovens (Fig. 3). Letters A–F on the figure give the positions of test pits dug into the slag tip. This investigation indicates the presence of an area with a concentration of roasted iron ore, as well as house foundations, but no recognisable features further in from the terrace edge. This edge is indicated by a line just below test pit A. Storbekken 1 has been the subject of limited research excavations focusing on two of the visible furnaces and a

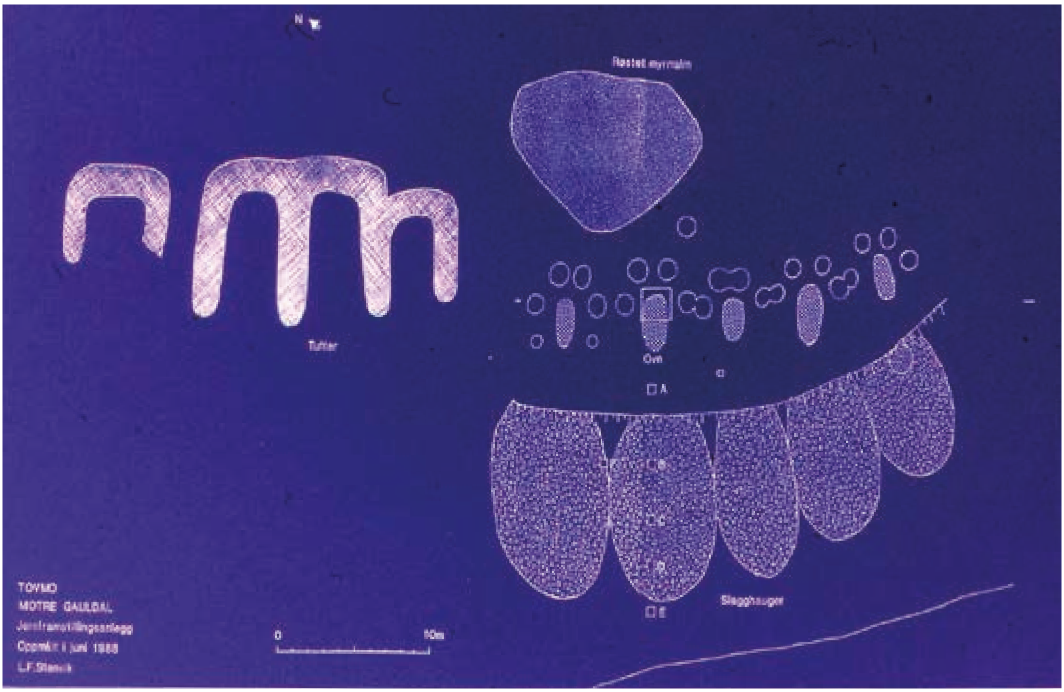

Figure 3. Sketch of the iron production site called Storbekken 1 at Tovmoen in Budalen, made by Stenvik in 1988. The top of the sketch is approximately northeast.

6x7 m excavation of expected building foundations – building number 2 from the right on figure 3. The excavations revealed two stone-lined slag pits from shaft furnaces, with an opening towards the terrace edge in the southwest, as well as a hearth within one of the buildings. 71 kg of *in situ* slag were found in the bottom of the stone-lined furnace and slag pit indicated as "oven" on figure 3, and charcoal from the bottom of this pit gave a ^{14}C date of 2050–85 BP – calibrated to BC 180–AD 25 (Espelund & Stenvik, 1993).

The site was investigated with magnetic geophysical methods in autumn 2014 to obtain topsoil volume magnetic susceptibility and fluxgate gradiometer data. Some of the pits and furnaces were visible as depressions and were mapped using a centimetre-accurate GPS system. This indicates that the distance between each furnace is relatively uniform – about 5–5.5 m.

The sample values give the following statistical distribution:

Table 2. Descriptive statistics for the geophysical survey data collected at Storbekken 1

	Topsoil Volume MS*	**Fluxgate Gradiometer (nT)**
Min.	-2	-1000
Max.	3226	803
Mean	185.41	-1.33
Median	10.5	-2.6
St. Dev.	420.88	79.1
Skewness	3.49	0,.5
Kurtosis	17.43	29,.9
1st quartile	2	-29.3
3rd quartile	110,.5	6.2
IQR	108.5	35.5

*measurements in 10^{-5} SI

Topsoil Volume Magnetic Susceptibility

The sampled area and sample values are presented in Table 1 and Table 2.

This was the only site where it was possible to identify visually and digitally survey associated archaeological features on the ground surface. It is, therefore, possible to report some general observations on the topsoil volume MS readings intersecting the archaeological features:

Apart from the excavated Evenstad furnace, it is the embankment, marked in green, which has very high MS readings – higher average reading than the exposed and excavated furnaces. The unexcavated furnaces also had higher readings than the pits and the slag tip, all of which had readings well above the median value reported in Table 2. It

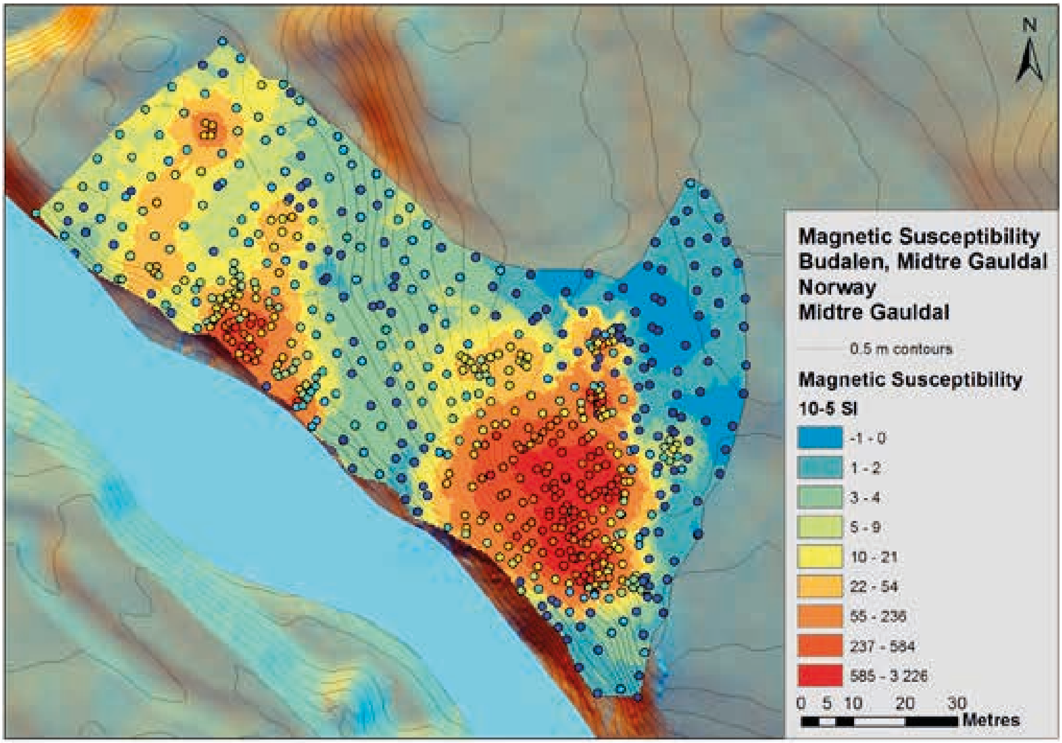

Figure 4. Topsoil volume MS measurements from Storbekken. The Early Iron Age iron production site is in the centre of the image (Storbekken 1). The next area with high readings towards the northwest, close to the stream, is a smaller Viking age iron production site, and far to the northwest is a modern summer dairy farm.

Table 3. Topsoil volume MS measurement values over known archaeology at Storbekken 1			
Topsoil volume MS measurements over known archaeology*			
	Min.	**Max.**	**Mean**
Excavated furnaces	1184	1833	1508.5
Unexcavated furnaces	339	1560	929.3
”Evenstad” furnace	1180	2093	1636.5
Pits	418	901	593.5
Embankment	824	2587	1618
Slag tip	12	3226	452.8
Area with reported building remains	8	131	35.3
Charcoal kiln	8	31	15
Anomalous area A1	28	2014	803.2
Anomalous area A2	13	453	150.7

*measurements in 10^{-5} SI

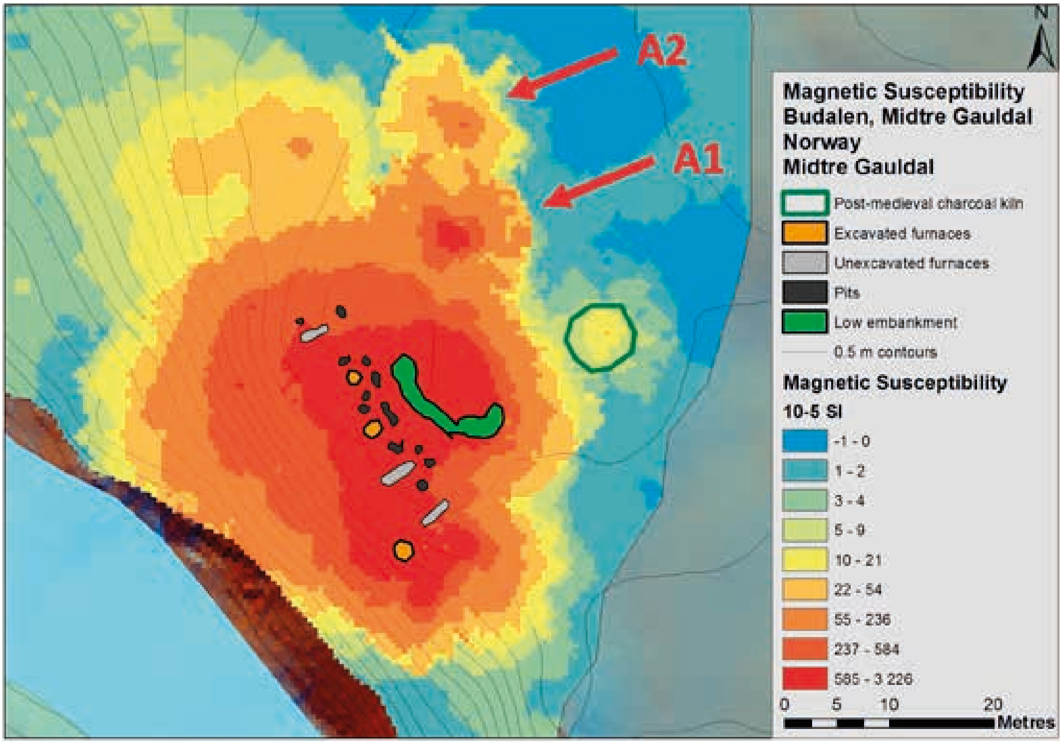

Figure 5. Detail of the topsoil volume MS map. The iron production complex of Storbekken 1 with known archaeology. The slag tips are southwest of the furnaces, down the slope towards the river. Note the hotspots north of the furnace area, and the area of above median readings north-northwest of the northernmost furnace. The southernmost furnace is an "Evenstad furnace", dating to the 18th or early 19th century.

was possible to distinguish two small areas north of the main area; A2 is furthest north and A1 is just north of the embankment. These were previously unknown and had no surface manifestation. An area extending north from where the building remains are reported also had readings well above the median value, but far lower than within the main area of activity. Note also the high readings southeast of the southernmost known furnace, indicating that anthropogenic activity extended this way.

Fluxgate Gradiometer Survey

The comparison with the known archaeological remains indicates that what is denoted as an embankment, visible as a small ridge on the surface, is a symmetrical oval feature measuring 12x7.5 m and oriented northwest-southeast. Inside this anomaly, there are several smaller anomalies with strong readings. On figure 3, this was interpreted as an area of roasted iron ore. There are high readings with their maximum just south of the unexcavated furnaces, and strong readings related to the slag tips which give a fan-shaped pattern outside and downslope from each furnace. The excavated anomalies still reveal a magnetic response, but much smaller than the unexcavated furnaces. There are also anomalies within the two small areas with high susceptibility readings north of the main area. Some general observations on the strength of the magnetic response are summarised in Table 4.

Table 4. Observed strength of the magnetic response over known archaeological features at Storbekken 1. Values are in nT.

	MIN. NEGATIVE	MAX. POSITIVE	SHAPE	POSITION OF NEGATIVE	DISTANCE TO CENTRE OF FEATURE	CORRE-LATION
UNEXCAVATED FURNACE 1	-139	277	Oval	NNW	0.45 m	Very good
UNEXCAVATED FURNACE 2	-128	318	Amor-phous	W, WSW, N and NE	0.7 m	Good
UNEXCAVATED FURNACE 3	-103	260	Circular	NNW	0.7 m	Very good
PITS	-77	238	Semi-oval	NW	0.7–1.1 m	Poor
EMBANKMENT	-277	555	Oval	Mainly N	0.75–1.1 m	Very good
SLAG PITS	-210	300	Fan-shaped	Various	Difficult to assess	Good
ANOMALOUS AREA A1	-87	363	Semi-oval	N, NW	Unknown	Very good
ANOMALOUS AREA A2	-62	320	Amor-phous	Various	Unknown	Good

Unexcavated furnaces are numbered from northwest to southeast; the one farthest northwest has the lowest number.

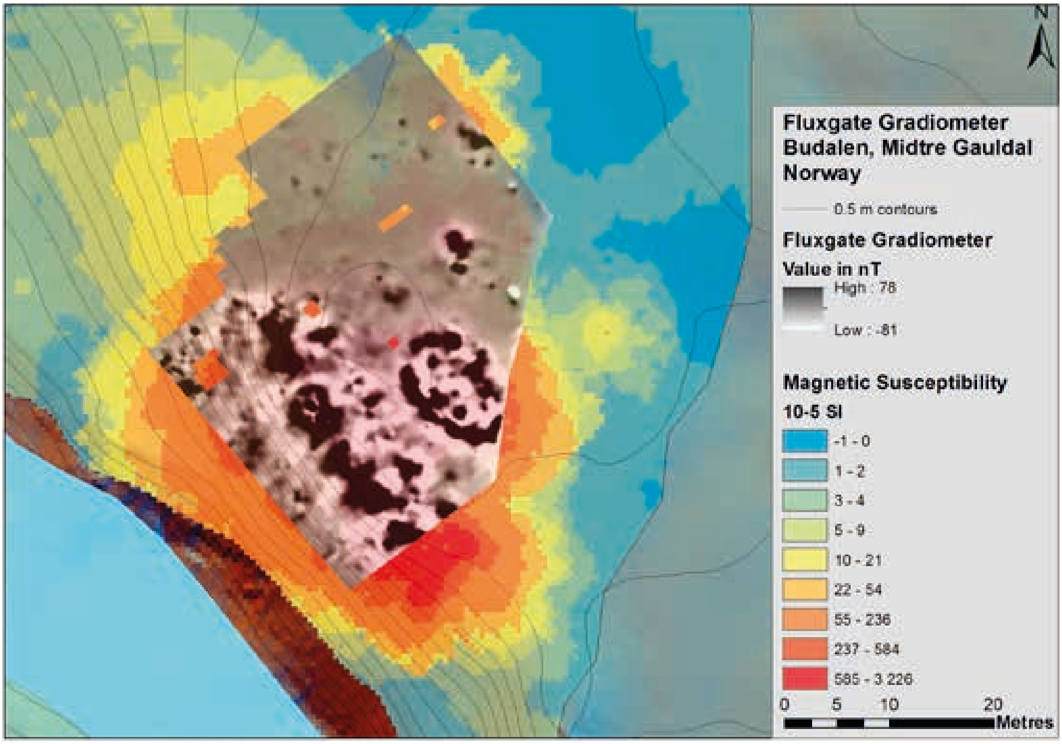

Figure 6. Fluxgate gradiometer survey results from Storbekken 1 overlaid on the topsoil volume MS map. The gradiometer data are presented at ±1 standard deviation around the mean.

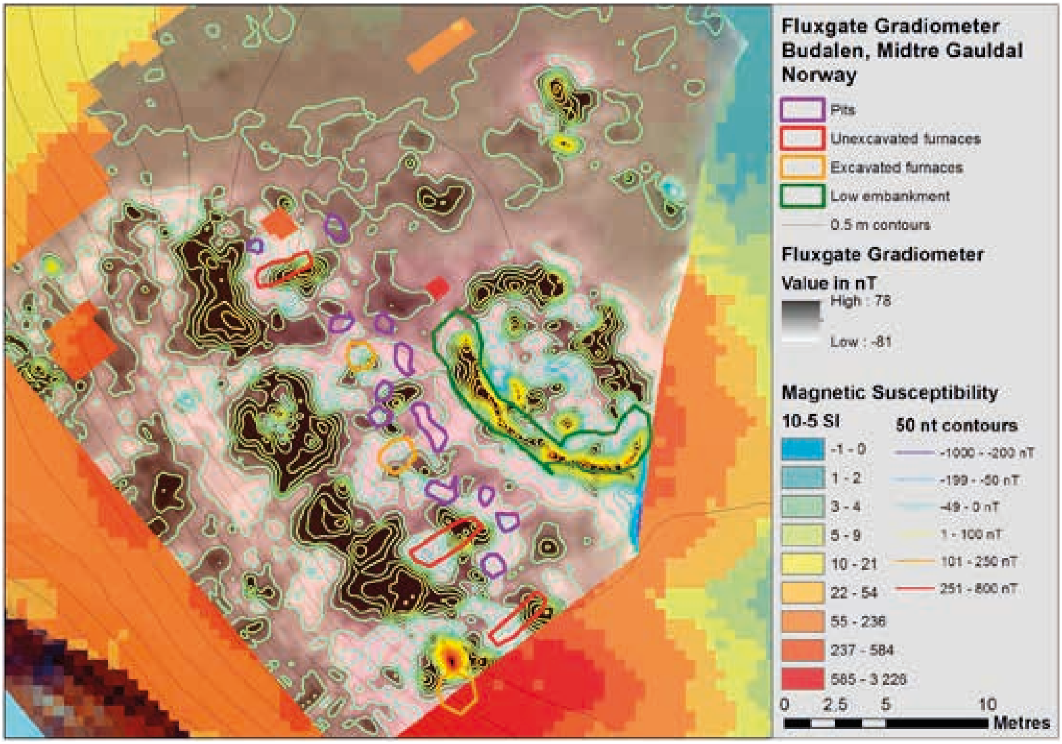

Figure 7. Detailed data plot from Storbekken 1 compared with known archaeological remains. Contour lines every 50 nT, with red lines for positive values and blue lines for negative values.

Tromsdalen in Verdal, Nord-Trøndelag

The site at Tromsdalen was discovered by the landowner in the 1970s when a road was constructed through the area; pieces of slag were noted after bulldozing a path for the road. No sketch of the site exists, but figure 8 shows how it looked in 2014. The site was first made

Figure 8. Overview of the Tromsdalen site. The slag mounds are between the large tree just right of the centre of the image and the fence to the left.

known to archaeologists during an archaeological assessment survey in 2011 and 2012. The site was then interpreted as consisting of one slag mound and probably up to four associated ovens (Arnkværn, 2013). A budget and a project plan for excavating the Tromsdalen site were drawn up before the geophysical survey, and were based only on the visual observations and test pits (NTNU University Museum, 2013). Based on the geophysical results, it is possible to use the survey and interpretation results and assess the accuracy and assumptions made in the project plan and associated budget. Since this site has still not been excavated as of 2019, it can be used as a helpful contribution to the discussion of whether and how magnetic geophysical survey methods can be an asset for heritage management.

The sample values give the following statistical distribution:

Table 5. Descriptive statistics for the geophysical survey data collected at Tromsdalen

	Topsoil Volume MS*	Fluxgate Gradiometer (nT)
Min.	0	-124.8
Max.	1673	446.7
Mean	86.37	-1.13
Median	19	-0.1
St. Dev.	192.15	-26.8
Skewness	3.97	2.02
Kurtosis	22.634	28.11
1st quartile	10	-3.55
3rd quartile	41.75	2.2
IQR	31.75	5.75

*measurements in 10-5 SI

Topsoil Volume Magnetic Susceptibility

The sampled area and sample values are presented in Table 1 and Table 5.

The main area of maximum values coincided well with the boundary of the site as entered in the national monument registry, and delineated by test pits (Arnkværn, 2013). The topsoil volume MS readings indicate that the spread of slag is larger than the registered site borders and that the site extends to the eastern side of the road. There are also relatively high readings northwest of the main area, indicating potential activity associated with the iron production in this direction.

Fluxgate Gradiometer

A visual inspection of the data showed very large minimum values along the road caused by a metal fence. It was therefore decided to remove all values below −125 nT before calculating the descriptive statistics, as all these values were concentrated along this fence and clearly influenced the measurements. The sensor height was increased

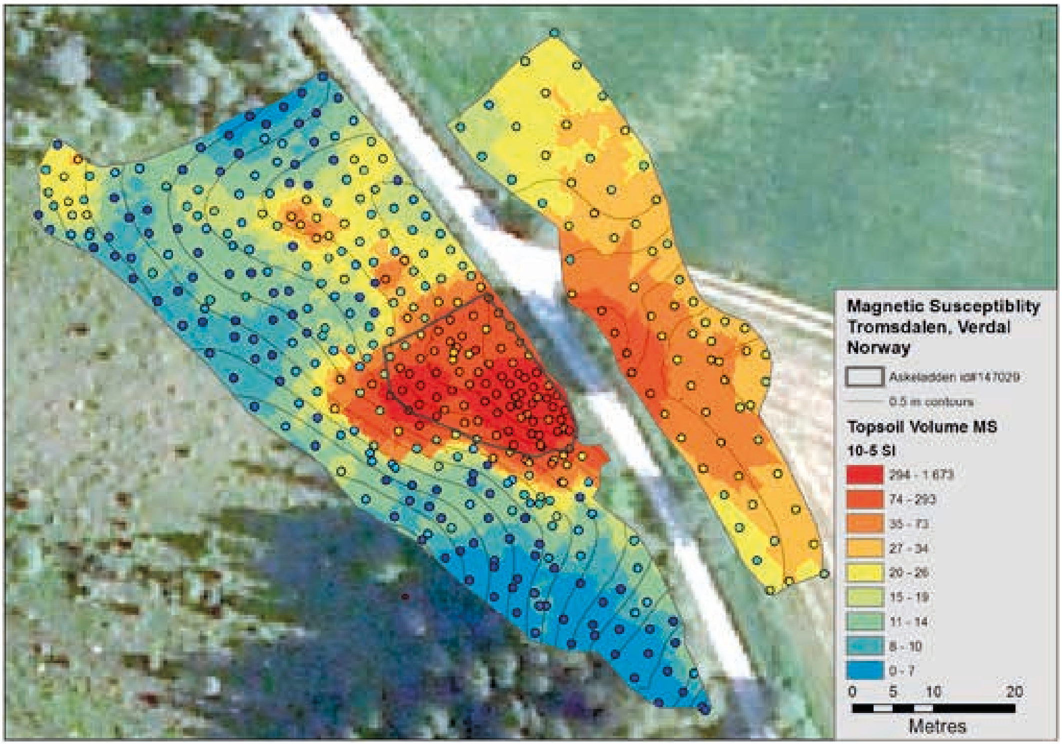

Figure 9. Topsoil volume magnetic susceptibility survey results from Tromsdalen, Verdal in Nord-Trøndelag

due to the risk of damaging the instrument on tree stumps or similar obstructions, and this increase would decrease the measured geophysical contrast of any magnetic anomaly in the ground and widen the geophysical signature (Vernon, 2004).

The fluxgate gradiometer data show large positive anomalies with a negative halo in areas of high magnetic susceptibility readings. The location of these large anomalies coincides well with the spread of slag, as indicated by test pits in 2011 and 2012 (Figs. 8 and 9). High positive and negative readings and several hotspots occur within these large areas of positive anomalies. A couple of more distinct, strong anomalies occur northwest of the main area. No linear anomalies are visible in the data.

Roknesvollen, Levanger, Nord-Trøndelag

Roknesvollen is a summer dairy farm located approximately 400 m above sea level. The iron production site was discovered by Bjarne Berre in the 1980s, and according to the national monument registry (askeladden id. # 103631) it is south of a stream and east of the farm, approximately 15–20 m from the stream. He also noticed roasted iron ore downstream from the furnaces, and also a bit closer to the stream, but the records do not say how far. A pollen analysis of a peat core taken approximately 200 m east of the

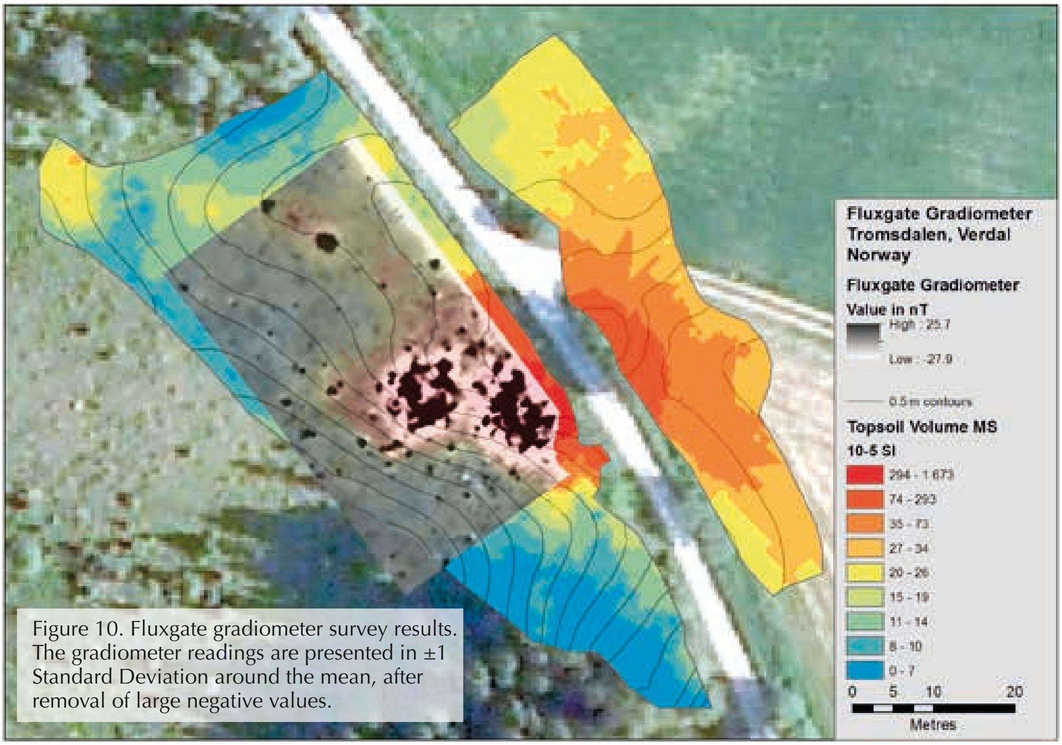

Figure 10. Fluxgate gradiometer survey results. The gradiometer readings are presented in ±1 Standard Deviation around the mean, after removal of large negative values.

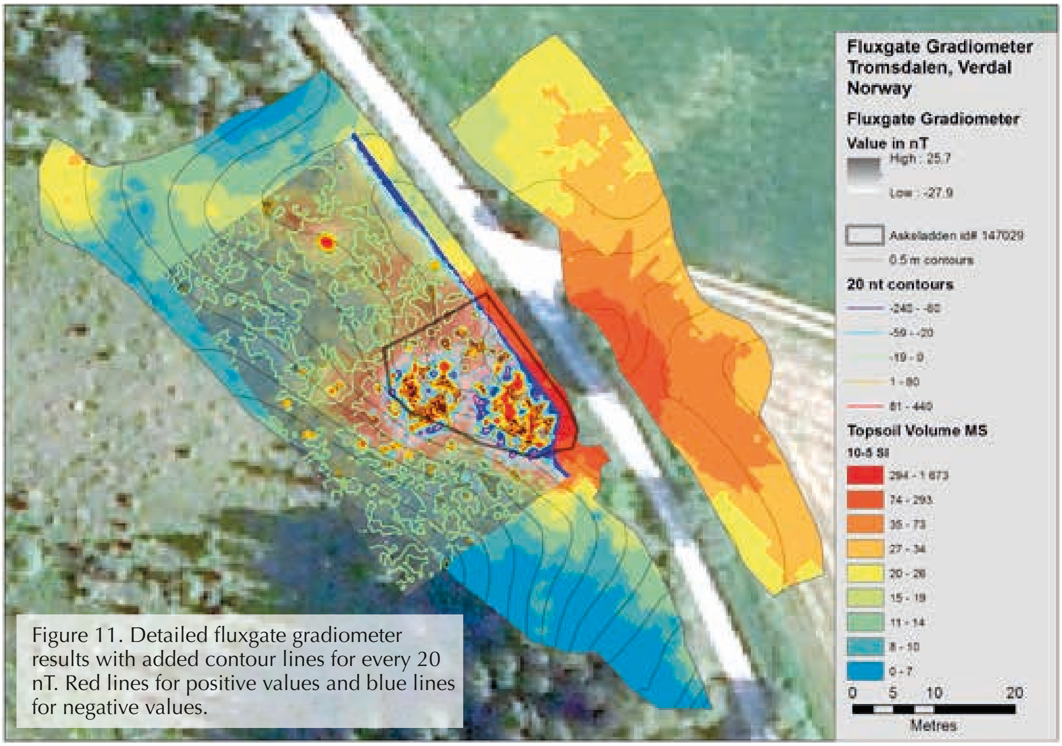

Figure 11. Detailed fluxgate gradiometer results with added contour lines for every 20 nT. Red lines for positive values and blue lines for negative values.

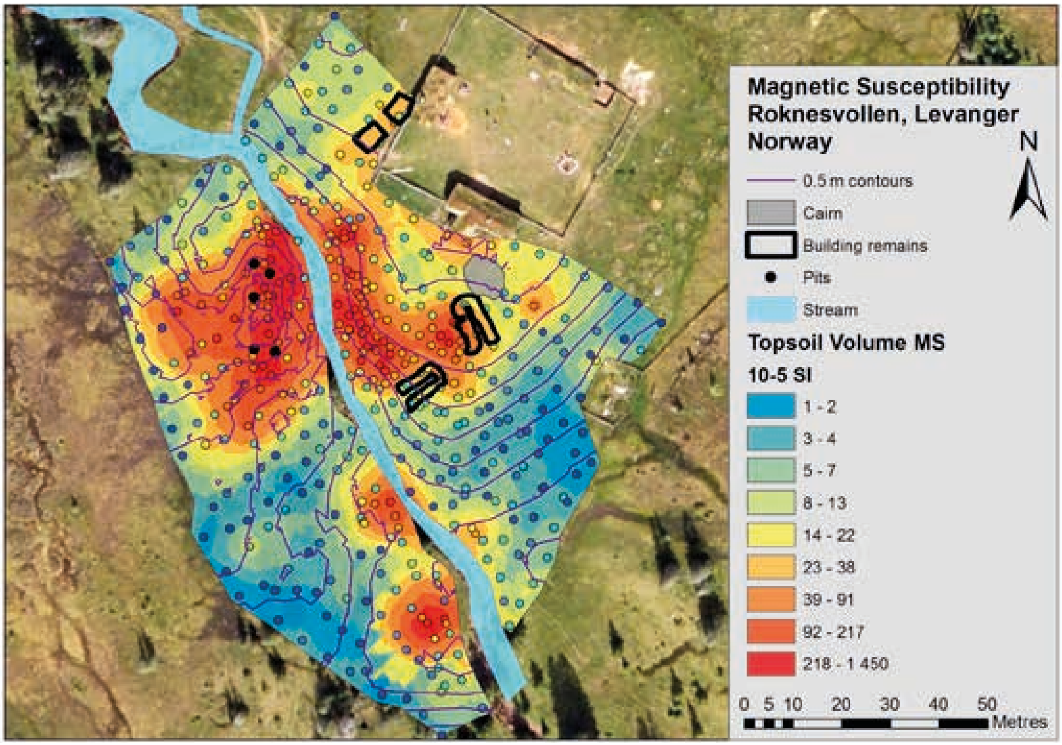

Figure 12. Topsoil volume magnetic susceptibility survey results from Roknesvollen, Levanger, Nord-Trøndelag.

farm indicated temporary human presence in the area from 1775–1590 BC, at the 60 cm level of the core sample. Iron ore particles are continuously present above a depth of 10–40 cm, and the 40 cm level coincides with the onset of a decrease in the pine pollen curve and an increase in the charcoal curve. The 40 cm level was not dated, but the observations are assumed to indicate the onset of the iron production at Roknesvollen. The summer dairy farming seems to have started around the 25 cm level, but is also not dated (Solem, 1991). This may indicate that the iron production and the summer dairy farming co-existed for a period. Two house foundations and a cairn (Fig. 12) were observed during the topsoil volume MS survey in September 2014; the cairn may be a clearance cairn or a prehistoric grave monument.

Topsoil Volume Magnetic Susceptibility

The sampled area and sample values are presented in Table 1 and Table 6.

The sample values give the following statistical distribution:

Table 6. Descriptive statistics for the geophysical survey data collected at Roknesvollen

	Topsoil Volume MS*		Topsoil Volume MS*
Min.	2	Skewness	4.74
Max.	1450	Kurtosis	33.11
Mean	65.38	1st quartile	3
Median	10	3rd quartile	53.25
St. Dev.	148.84	IQR	50.25

*measurements in 10-5 SI

The most prominent observation at Roknesvollen is the high readings on both sides of the stream (Fig. 12). There are some outlying high readings on the western side of the stream, south of the main area of high readings, and these may represent the roasted iron ore deposit mentioned by Bjarne Berre. High values occur just beyond the western wall of the building remains immediately south of the cairn, but relatively low readings within both this building and the one just to the southwest, nearer the stream.

Mokk, Steinkjer, Nord-Trøndelag

The site was visited by Lars Stenvik in 1989, and he made a sketch of the iron production site (Fig. 13) and took a charcoal sample from one of the slag pits. This sample was ^{14}C dated to BP 1875 ± 90, giving a calibrated age of AD 25–235. The site was surveyed on behalf of Nord-Trøndelag County Council in October 2010, and is located 285–295 m above mean sea level.

Fluxgate gradiometer scanning and area survey

This is the only site where magnetometer scanning with mapping and recording high values was tested (Fig. 14). Although an area survey clearly is the preferred strategy, the vegetation cover and time constraints did not permit this.

The sampled area and sample values are presented in Table 1 and Table 7.

The sample values give the following statistical distribution:

Table 7. Descriptive statistics for the geophysical survey data collected at Mokk

	Fluxgate Gradiometer (nT)		Fluxgate Gradiometer (nT)
Min.	-290	Skewness	2.50
Max.	1000	Kurtosis	25.32
Mean	10.59	1st quartile	-17.5
Median	-0.3	3rd quartile	21.55
St. Dev.	76.66	IQR	39.05

*measurements in 10-5 SI

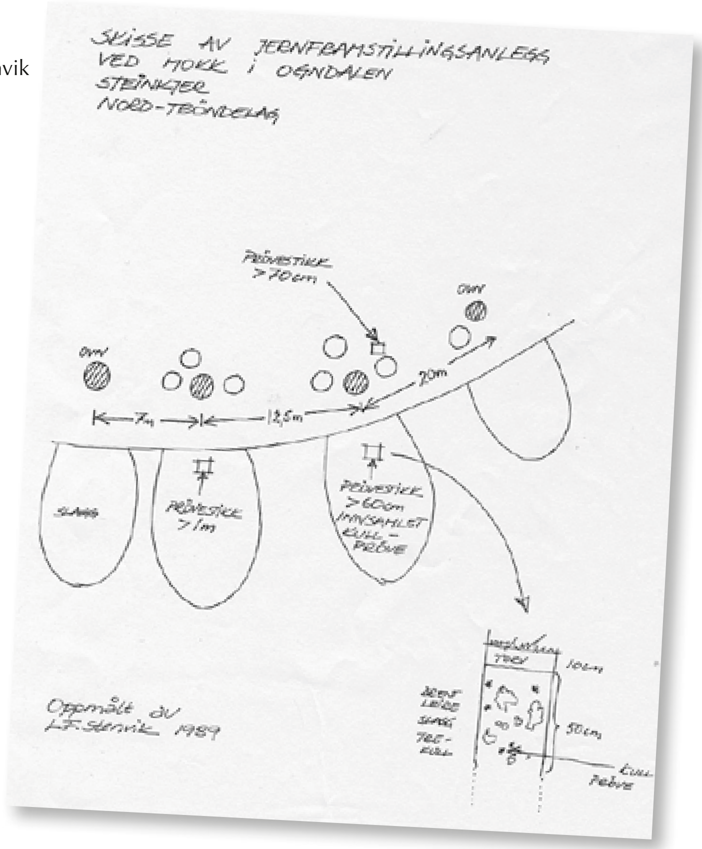

Figure 13. Sketch of the iron production site made by Lars F. Stenvik in 1989.

It is assumed that the area covered by the fluxgate survey includes the furnace to the far left on figure 13, and probably the next furnace to the right as well as the associated slag dumps downslope towards the southwest. The scanning revealed a hotspot east of the main survey area, as well as several moderately high readings north of the main survey area. The western part of the area survey gave relatively low readings, but very high readings were acquired approximately 40–70 m further east. Several slag blocks were observed in this area, indicating the presence of another iron production site.

Discussion

The general impression is that topsoil volume magnetic susceptibility measurements with the Bartington MS2 with a D-loop are very applicable for locating, delineating and partly characterising activity at and relating to the iron production sites. On the basis of the median value for each site, which is regarded as a good indication of the natural background value there, it is possible to estimate the approximate area of the site, including the Late Iron Age iron production site at Storbekken in Budalen. In addition, it is possible to extract some additional descriptive statistics from the interpolated raster data sets:

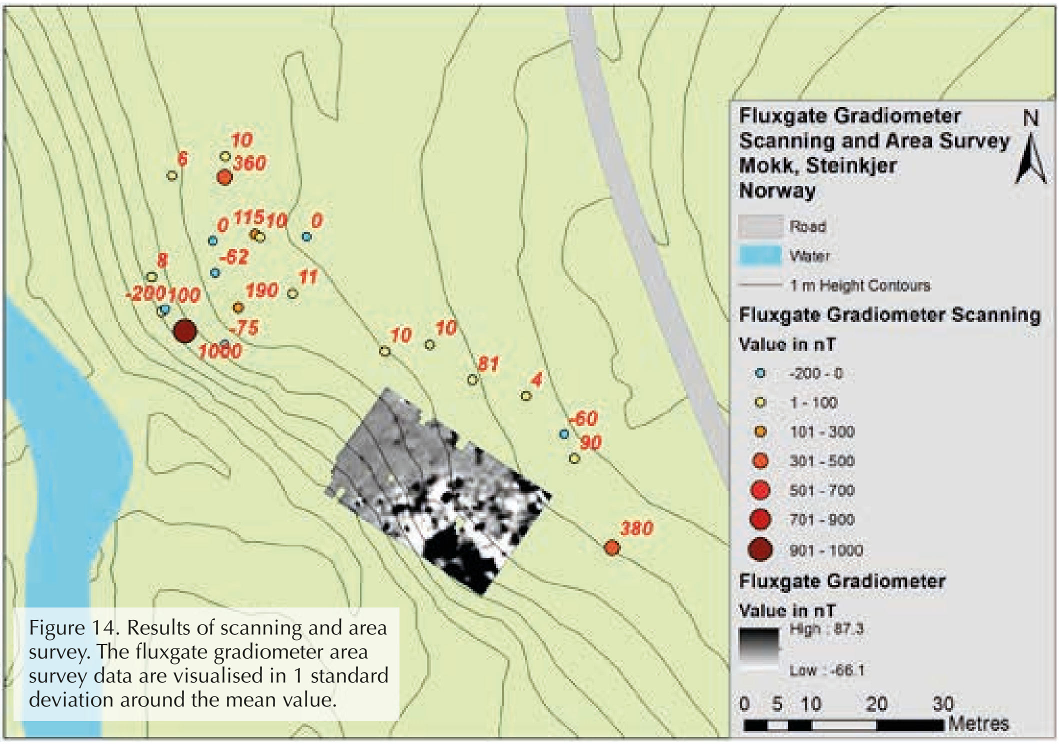

Figure 14. Results of scanning and area survey. The fluxgate gradiometer area survey data are visualised in 1 standard deviation around the mean value.

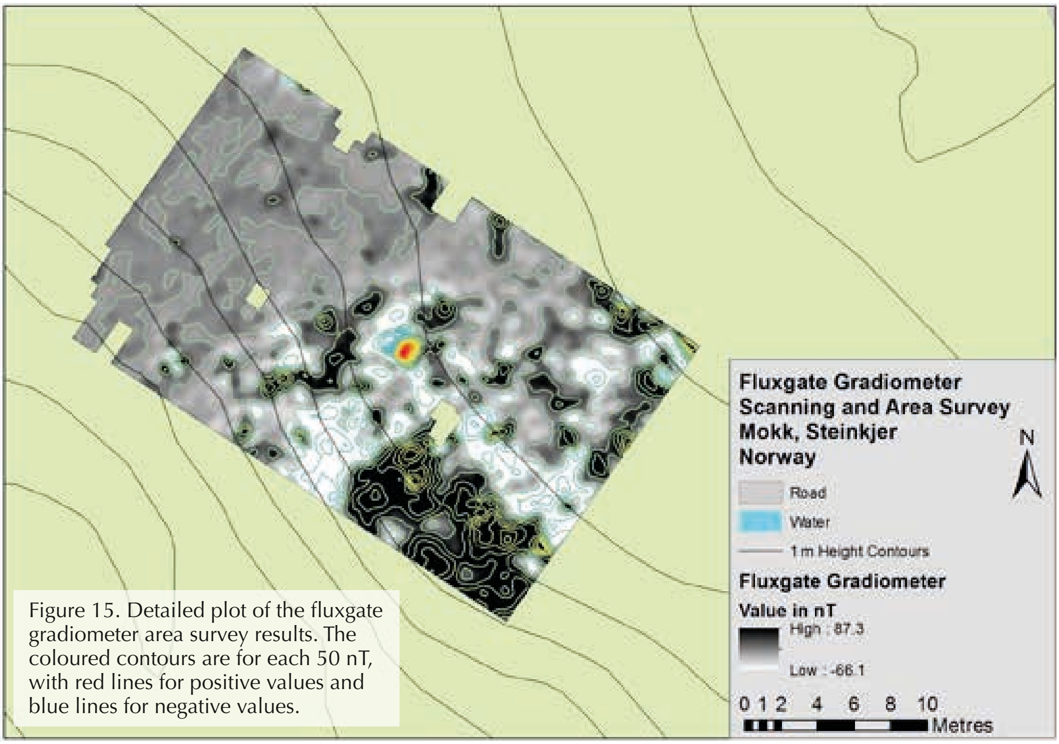

Figure 15. Detailed plot of the fluxgate gradiometer area survey results. The coloured contours are for each 50 nT, with red lines for positive values and blue lines for negative values.

Table 8. Descriptive statistics for the delimited iron production sites						
	M²	MEAN	RANGE	MIN. *	MAX.	STD
STORBEKKEN LATE IRON AGE	531.5	118.0	1413.0	10.5	1416.0	157.7
STORBEKKEN 1 EARLY IRON AGE	1940	287.5	2391.0	10.5	2392.0	348.4
TROMSDALEN	1152	144.9	1537.8	19.0	1551.9	175.5
ROKNESVOLLEN	3020	94.5	680.3	10.0	686.4	88.2

*Equals the median value for the test area. At Tromsdalen, the median value was different on the cultivated surface east of the road, so an interpreted eastern edge was used to estimate the size of the area.

Being able to indicate the approximate size of the iron production areas is of considerable scientific value as only one of the Trøndelag slag pit furnace sites has been fully excavated and the size and activity zones relating to the iron production have remained largely unknown. The ability of magnetic susceptibility to delineate iron production areas coincides well with the experience reported by Powell et al. (2002) and Powell (2008). Such information can, therefore, be taken into account when new sites are to be investigated in the future, to ensure proper delineation when recording the sites in the national monument registry or budgeting for excavations. Although this statement is not considered to be valid for all archaeological features, our results show a clear correlation between the areas of iron production sites surveyed and the MS readings at these sites.

At Storbekken 1, enhanced values were observed as far as 30 m onto the flat terrace behind the furnaces (Figs. 4 and 5). The highest readings were near the furnaces and in the immediate area towards the east. At Tromsdalen, the same was noticed some 15 m northeast, on the opposite side of the road, and about 30 m northwest on the flatter part of the terrain extending in that direction (Fig. 9). At Roknesvollen, high values were observed about 20–30 m westwards, away from the brink above the stream, and this also divided the site in two (Fig. 12). The division is based on the susceptibility measurements alone and it is difficult to assess whether the activity on either side of the stream co-existed, or was separated by time and function. Interesting observations here are the lower values within the house foundations and the increased values just west of the building oriented NNW-SSE. These observations can be interpreted as the result of potential smithing or pre-processing of the raw iron produced on the site. Generally, there are low readings within the southernmost building, which is surrounded by relatively high values. The buildings may have been kept intentionally free of any susceptibility-enhancing material, magnetically susceptible deposits may have been removed when building them, or perhaps magnetically-enhanced material remains stratigraphically below the construction and was not reached by the sensors when the fieldwork took place. The origin of the enhanced values outside the building and the reason for lower values within the buildings have not been investigated by conventional archaeological investigations. Higher values were recorded at Storbekken 1 compared to the median value of the measurements in the area with possible house foundations (Figs. 3 and 6), indicating that the activity in the houses at least to some degree led to magnetic enhancement of the subsoil. At Storbekken, an additional strong susceptibility contrast appeared to mark a low embankment, but in combination with the fluxgate gradiometer results, it proved to be an oval feature measuring 12x7.5 m. This is interpreted as a man-made feature. It had some of the strongest magnetic susceptibility readings, even stronger than those at the exposed excavated furnaces and within the unexcavated furnaces. Roasting iron ore is a necessary step when producing iron and is a process that increases the magnetic susceptibility of the iron ore. Thus, it is possible that this feature is a storage area for roasted iron ore. The fact that the contrast measured within the building area was far lower can be used as an argument against these buildings being stores for roasted iron ore, but rather were used for residential purposes and/or to store unroasted iron ore, firewood or clay used to construct the furnaces. At Storbekken 1, the mean value within the slag tip area was 452.8 10^{-5} SI, which is approximately 43 times the median background value – i.e. a very strong contrast is expected on slag tips or heaps. Some very high readings within the slag tips can be explained as due to measuring more or less directly on a very susceptible piece of slag such as a larger piece of a slag block with a high iron content. At Tromsdalen, the furnaces should be expected to be located high in the landscape, with the slag heaps or tips downslope from the furnaces. If this assumption is correct, the highest maximum readings at Tromsdalen were within the slag tip as well. Figure 16 illustrates data along a 22 m long line from the excavated furnace in figure 3, across the five test pits and continuing 5 m further downslope. There is a clear correlation between the depth of the slag tip and the topsoil volume MS readings, which are highest at the furnace on the edge of the terrace, with a tendency for increasingly lower MS values and decreasing thickness down the slope. The amount of slag found in these test pits does not indicate the same trend. A possible explanation is that the heavier and/or larger pieces more easily fall further down the slope, which might explain the large amount of slag found in test pit D.

Although there are some variations in the average range, maximum measured value and standard deviation when all the measurements within the estimated site area are considered, the mean measured values within the sites are 7–27 times the median value. This indicates that the main areas of the iron production sites have a very strong contrast with respect to the natural background, suggesting that topsoil volume susceptibility sampling is a very useful method to apply if the intention is to locate and delimit additional iron production sites in the future. The resolution applied, i.e. a sample between 2.99 m and 4.35 m between each measurement, proved detailed enough to identify additional activity areas – for instance, the areas denoted as A1 and A2 at Storbekken 1 (Fig. 5), areas to the south on the eastern side of the stream

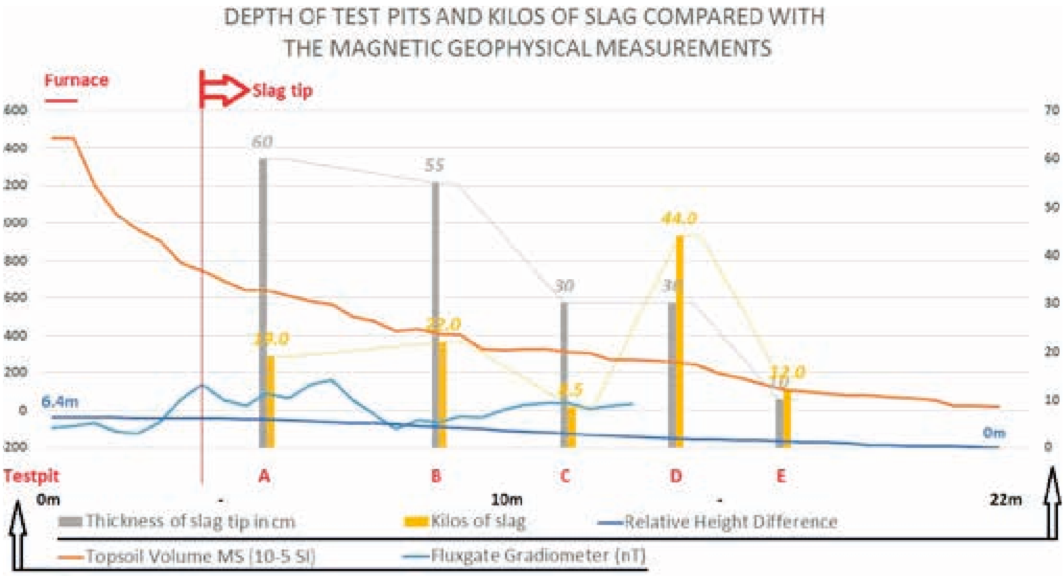

Figure 16. The relationship between the depths of the slag tips and the amount of slag found in test pits, compared with the magnetic geophysical measurements at Storbekken 1. The median MS value was 10.5 10^{-5} SI.

at Roknesvollen (Fig. 12) and northwest of the main area at Tromsdalen (Fig. 9). The smallest of these areas was approximately 5x6 m, equal to 30 m^2. This means that to obtain measurements within this area, a sample density of maximum 3.87 m between each measurement should be regarded as a minimum requirement. These areas are interpreted as potential roasting sites for iron ore, an interpretation strengthened by the fluxgate gradiometer response within these areas of increased magnetic susceptibility response. This will be discussed below. Also, by indicating the approximate size of the iron production areas, this information can be used to calculate the approximate survey resolution needed to identify similar sites in the future. As it is assumed that readings from an iron production site will be, on average, between 7 and 27 times the median value, with extreme values sometimes over 200 times the median (Table 8), relatively few measurements are necessary to ensure that some fall within the target area. As soon as points with extreme measurements are located, the average sample distance around this anomalous point can be reduced and the sample resolution increased. A good rule of thumb is that the sample resolution should not exceed the size or depth of the expected feature (Schmidt & Marshall, 1997), but more sample points within the feature may be necessary to properly characterise the geophysical properties of the feature you want to investigate. With an intended sample density of 3–5 points within the iron production site, this would give a maximum sample distance shown in Table 9.

Table 9. Maximum sample distance required for a minimum sample resolution of three and five samples within the main area of iron production.

		MAX. SAMPLE DISTANCE		MAX. SAMPLE DISTANCE	
SITE	**m²**	**3 samples within the main area**	**Sample coverage in m²**	**5 samples within the main area**	**Sample coverage in m²**
Storbekken late iron age	531.5	13.3	177.2	10.3	106.3
Storbekken early iron age	1940	25.4	646.7	19.7	388
Tromsdalen	1152	19.6	384.0	15,2	230.4
Roknesvollen	3020	31.7	1006.7	24.6	604

This means that to positively identify the smaller Late Iron Age site at Storbekken, which is 531.5 m², a sample density of at least 10–13 m between each sample should be used. A sample density of 15–20 m between each sample would have been necessary to locate Tromsdalen, the smallest of the surveyed Trøndelag slag pit furnace sites, which is approximately 1152 m². This resolution estimate is only valid for indicating the site, and not to reveal the internal organisation of activity zones within the site. Nine hectares could be surveyed in one day if 400 sample points with a 15 m sample interval were measured. This does not take into account any additional detailed investigation of areas close to the hotspots themselves. A sequential approach is, of course, possible by going back later and resurveying areas with hotspots using an increased resolution.

The fluxgate gradiometer data from the surveyed sites gave additional information about the structural layout and activity within the sites. Also, the very strong magnetic response of the measurements could in itself be indicative of the main areas of iron production related activities in the landscape. While gradiometer surveys gave more detailed information about the activity on these sites, the data also have a more complex geophysical signature making them inherently more complicated to interpret than the MS data.

When encountering satellites of high magnetic susceptibility measurements, such as the A1 and A2 area at Storbekken 1 or within the area extending northwest of the main area at Tromsdalen, the fluxgate gradiometer measurements confirmed the presence of strong magnetic anomalies and helped delineate and characterise these. At Storbekken, anomaly A1 had a maximum of 363 nT, and anomaly A2 had a maximum of 320 nT (Figs. 6 and 7). The anomaly at Tromsdalen had a maximum of 198 nT (Fig. 17); it is semi-oval in shape and covers approximately 2.7x2.2 m, being longest in the SE-NW direction. This anomaly had a distinct negative with a minimum value of -16.4 nT due north – suggesting that it is mainly caused by induced magnetism. It can be

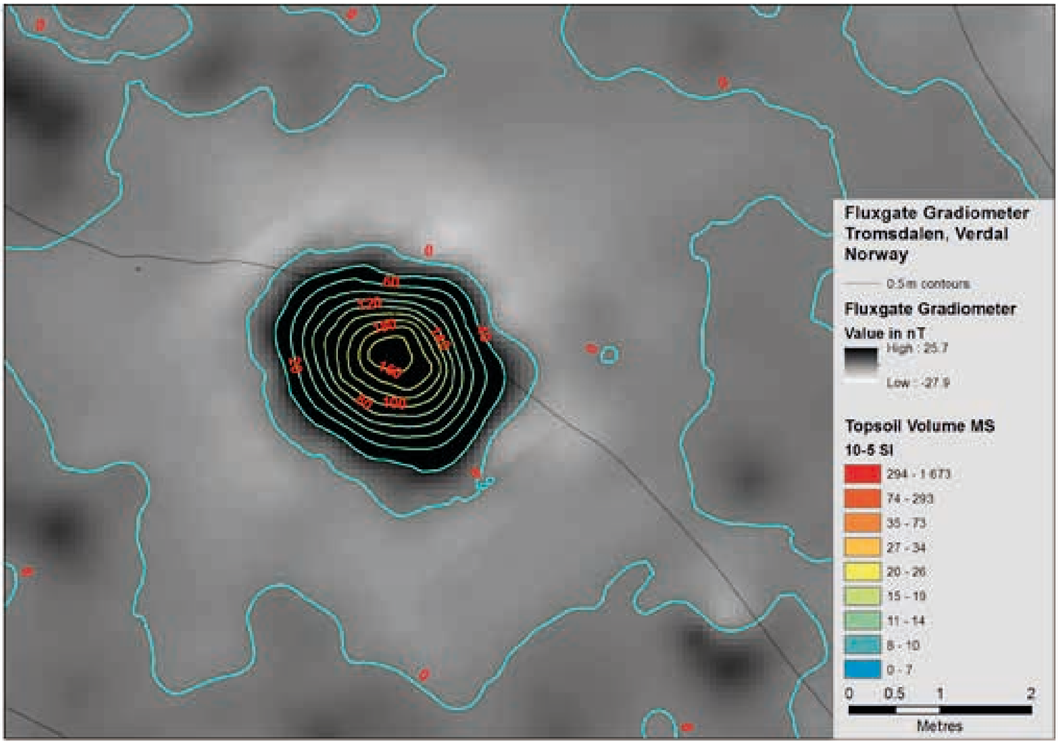

Figure 17. The possible roasting site for iron ore at Tromsdalen. Contours are for every 20 nT, with red lines for positive values and blue lines for negative values.

interpreted as traces of burning and to have been largely undisturbed *in situ* since its initial firing. Anomaly A1, the southernmost of the two areas at Storbekken 1, has a similar shape and dimensions – semi-oval and covering 3.2x2.0 m, roughly aligned SSE-NNW. This anomaly has its strongest negative due north, but it has a negative halo surrounding it. The minimum measured value was -86.5 nT. Anomaly A2 has a more amorphous shape and covers at least 4.2x1.8 m. It also has a negative halo, and it has some strong negative hotspots to the south and north, indicating that it is composed of both induced and remanent magnetism. This might be interpreted as a more disturbed context than A1 and the anomaly at Tromsdalen. Since all these three anomalies occur a short distance from the main area and from the terrace edges, but still have a strong magnetic signature within the areas with MS readings above the median, they may be the result of similar activity. Their size and their geophysical signature indicate that these anomalies might mark sites for roasting iron ore, and their geophysical contrast is comparable with observations at Gråfjell, where such anomalies often had a geophysical contrast in the range of 180–300 nT (Rundberget, 2007). They could mark stores of roasted iron ore, but the presence of the semi-oval patch with extremely high MS readings mentioned earlier, which was interpreted as just such a store, indicates that the expected gradiometer readings for a store of roasted iron ore could be even higher than the values observed at hotspots A1 and A2, as well as the one at Tromsdalen. The maximum nT reading of the larger oval patch at Storbekken 1 was 555 nT, with the strongest negatives mainly towards the north, but with a more mixed signal of positives and negatives within and also surrounding the anomaly. There is a clear correlation between the visible embankment and the geophysical anomaly, but the gradiometer results also show the remaining layout of the feature forming a complete semi-oval.

The slag mounds at Tromsdalen are very clearly seen in the fluxgate gradiometer data from the site (Figs. 10 and 11). The maximum responses of topsoil volume MS coincide with the strong readings from the slag mounds identified at the site. The strong positive gradiometer results are surrounded by a halo of negative readings. Within and around the main areas of high gradiometer readings are some relatively random hotspots which could derive from larger slag blocks removed from the furnaces and thrown into the slag mounds. The response from the Storbekken 1 site is different, with fan-shaped, strongly positive readings oriented around the perceived opening of the known furnaces and about 2–8 m away from the known locations of the furnaces. Visual surveys of the site, Stenvik's sketch and the topsoil volume MS results suggest that the slag heaps extend further downslope towards the east. Further away from these fan-shaped, strongly positive anomalies is a combination of strongly negative and positive readings with a clear contrast to the natural background but without a clear shape or pattern. When the response is plotted in nT along a line where the depth of the slag heap and a quantification of the amount of slag are known, the varied response across the slag heap is also seen (Fig. 14). This is a somewhat different response than Farbregd (1977) and Walach et al. (2011) reported from other slag tips, and also differs from that observed at Tromsdalen. Within these fan-shaped slag heaps are random strong hotspots, like those interpreted as relating to large pieces of slag blocks observed in the slag mounds at Tromsdalen. At Mokk, the large positive signal down the slope to the south has a maximum reading of 313 nT and is interpreted as recording a slag mound. A band of higher magnetic material further west and the areas of magnetic response clearly delineate the limits of the iron production towards the west and northwest. The slag heaps extend further south and east than the area covered by this survey (Fig. 15).

The results reported by Vernon (2004), Abrahamsen et al. (2003), and Smekalova and Voss (2002) indicate relatively easily identifiable shaft furnaces when the slag blocks remain *in situ*. The geophysical signatures, when measured with a magnetometer, are often strong circular positives, with the negative part of the signal mainly to the northern side and potentially with a negative halo. When the furnace is further away from the sensor, i.e. it is buried at some depth, the negative halo around the central part of the signal diminishes. At Storbekken 1, the location of the furnaces was already known, and the unexcavated furnaces have maximum values between 260 and 318 nT (Table 4 and Fig. 18).

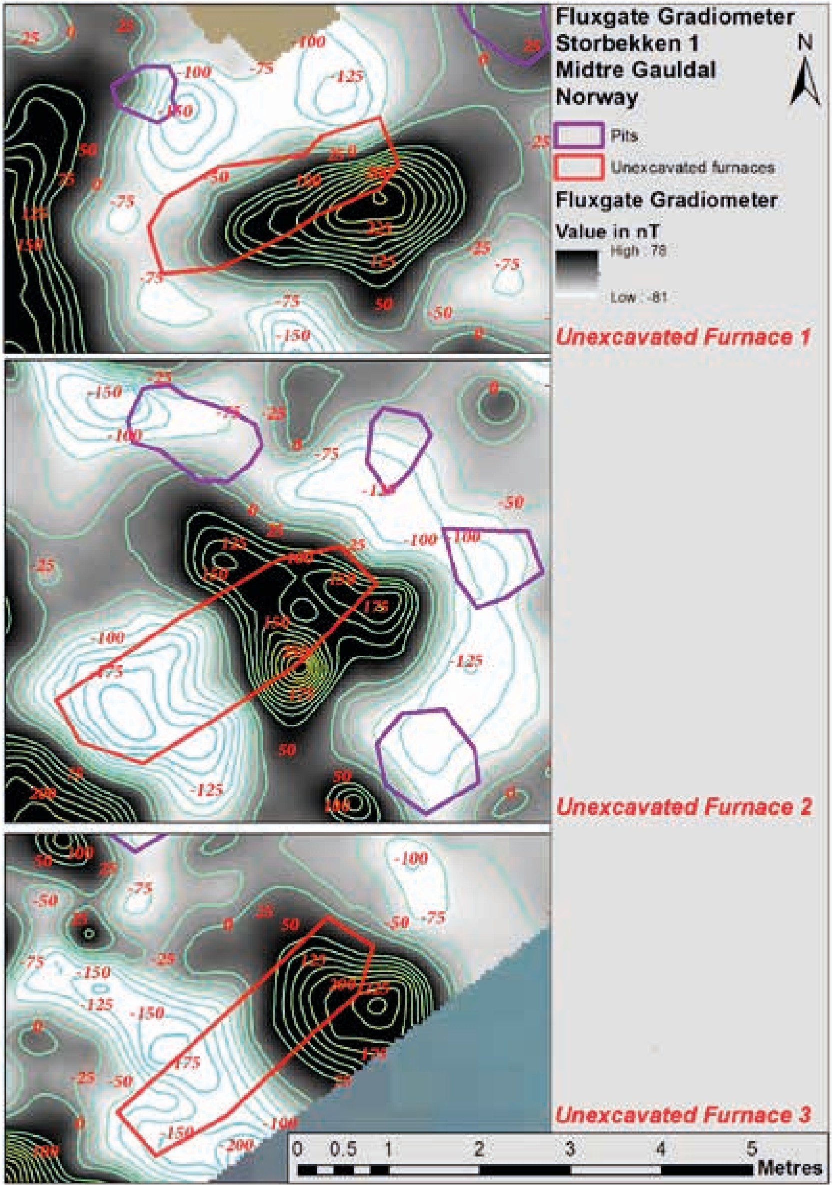

Figure 18. Detailed illustration of the fluxgate gradiometer response of the unexcavated furnaces at Storbekken 1.

The maximum response is relatively high (between 260 and 318 nT), but not as high as readings reported from the Gråfjell project and at Haglebu, where readings with a maximum of 800–1500+ nT were reported (Rundberget, 2007). This could be due to the depth of the Trøndelag slag pit furnaces, which is known to be up to 0.7–1 m (Espelund, 1999; Nordlie, 2009; Prestvold, 1999); an increased depth decreases the geophysical contrast of the feature. The unexcavated furnace 1 has an elongated ENE-WSW response, with the maximum of 277 nT just south of the elongated ditch, indicating that the most magnetic response within the feature is on the eastern end of the visible ditch (Fig. 18). The negative part of the signal is strongest due north, but surrounds the anomaly. The other unexcavated furnaces have the same tendency when it comes to the location of the most magnetic response, but they lack the elongated shape. The unexcavated furnace 2 has several hotspots of approximately 150, 175 and 318 nT, and an elongated or round to oval shape of the positive part of the signal is lacking; moreover, the hotspots are surrounded by strong negative responses, indicating a more disturbed context. The positive part of the signal marking the unexcavated furnace 3 has a more rounded and symmetrical geophysical response, and its maximum reading of 260 nT is just south of the eastern edge of the ditch that is visible on the surface. The negative values are strong due north and to the east, indicating a mixture of remanent material. The geophysical response at Storbekken 1 is not uniform, but the physical placement just in from the terrace edge, the strong geophysical response and the size of the anomaly enable this anomaly to be distinguished from the anomalies marking the slag tips at this site.

At Tromsdalen, there is a strong positive and relatively circular anomaly at the northwestern edge of the slag mound, on the higher, flatter area (Fig. 19). The furnaces

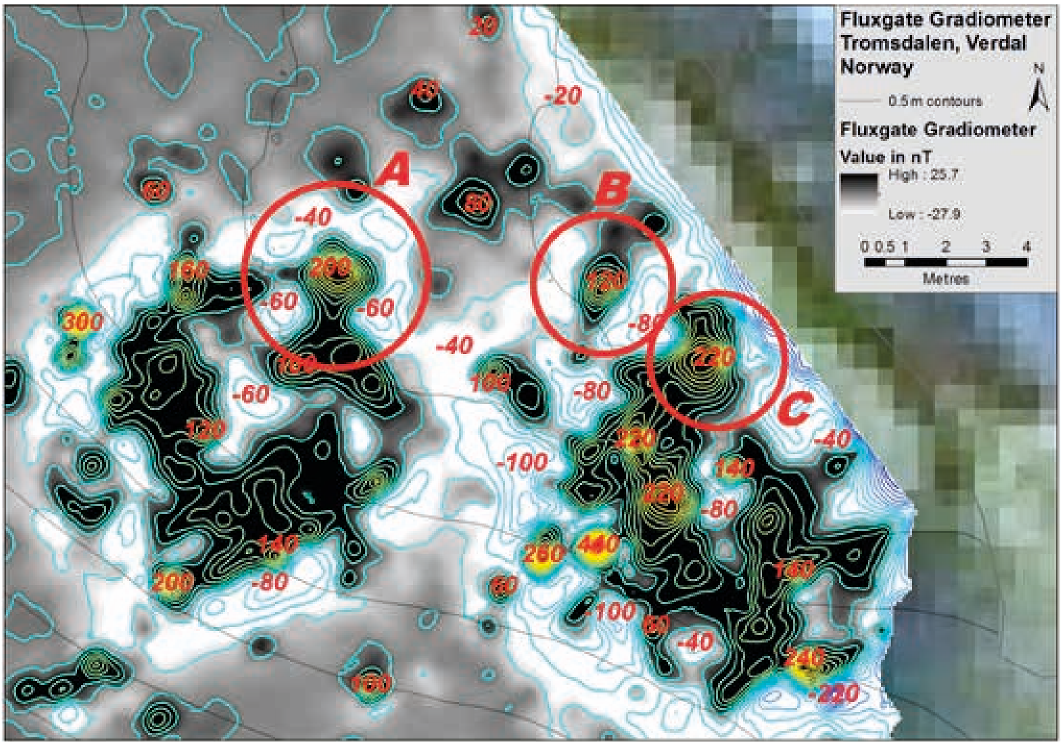

Figure 19. Possible furnaces at Tromsdalen. Fluxgate gradiometer data. The contours are 20 nT apart, with red lines for positive values and blue lines for negative values

could be expected to be located on this part of the terrace edge, although the terrace edge is less pronounced at this site than at Storbekken 1. This anomaly has a maximum of 204 nT with a small outlier protruding towards the south (anomaly A in Fig. 19), surrounded by a negative halo with the strongest minimum values in several directions. If this anomaly is the furnace, the outlier bulging out towards the south may indicate its opening. Anomaly B is elongated and semi-oval, oriented roughly perpendicular to the slope, with a maximum of 148 nT surrounded by negative values to the northwest and southeast. Anomaly C has a higher maximum with strong negative readings due east indicating strong remanent magnetism, with a maximum reading of 226 nT. Compared with the results from Storbekken 1, there does not seem to be a clear separation in space between the maximum values interpreted as potential ovens in figure 19, and the slag tips or heaps downslope. It is, however, possible to regard anomaly B as a similar feature to the unexcavated furnace 1 at Storbekken 1, with anomaly C being the result of a large slag block within the slag heap. The distance between anomalies A and B would then be similar to the distances between the furnaces at Storbekken 1. If anomaly B represents a furnace, there is a reasonable chance for another furnace further east that either falls just outside the investigated area or was destroyed by the construction of the road in the 1970s.

At Mokk, three anomalies can be interpreted as potential furnaces (Fig. 20); all are close to the flatter part of the terrace. Anomaly A is a very strong positive with a maximum of 1061 nT and a minimum of -358 nT towards the northeast. The strength of the positive is above the range of the instrument, which is ±1000 nT for Bartington gradiometers in full-scale setting, indicating that the actual maximum reading in nT at this feature can potentially be even higher. There is another strong positive due north. The shape is semi-oval. Anomaly B has a maximum of 248 nT, and the slag mound encircles it 2-3 m downslope from the anomaly, in a similar way to the Storbekken 1 observations. The distance of approximately 6.5 m between anomalies A and B is also similar to that shown between the westernmost furnaces in Stenvik's sketch (Fig. 11). Anomaly C is strong with a maximum of 314 nT, but is further in from the edge and was not surveyed in its entirety due to dense vegetation at the time of the survey.

Our results indicate a more complicated geophysical response than was reported by Vernon (2004), Abrahamsen et al. (2003), and Smekalova and Voss (2002). Although strong anomalies are reported in every case, there are variations in their shape and geophysical contrasts in relation to both the strength and the position of the negative values associated with the strong positives. This might be explained by the Trøndelag slag pit furnace iron production being based on the *reuse* of the slag pits, instead of the furnaces and slag pits below them being the result of a single event. Also, the construction of a stone-lined, horseshoe-shaped back wall under the furnace, can contribute to a more complicated magnetic geophysical response. In addition, post-depositional processes

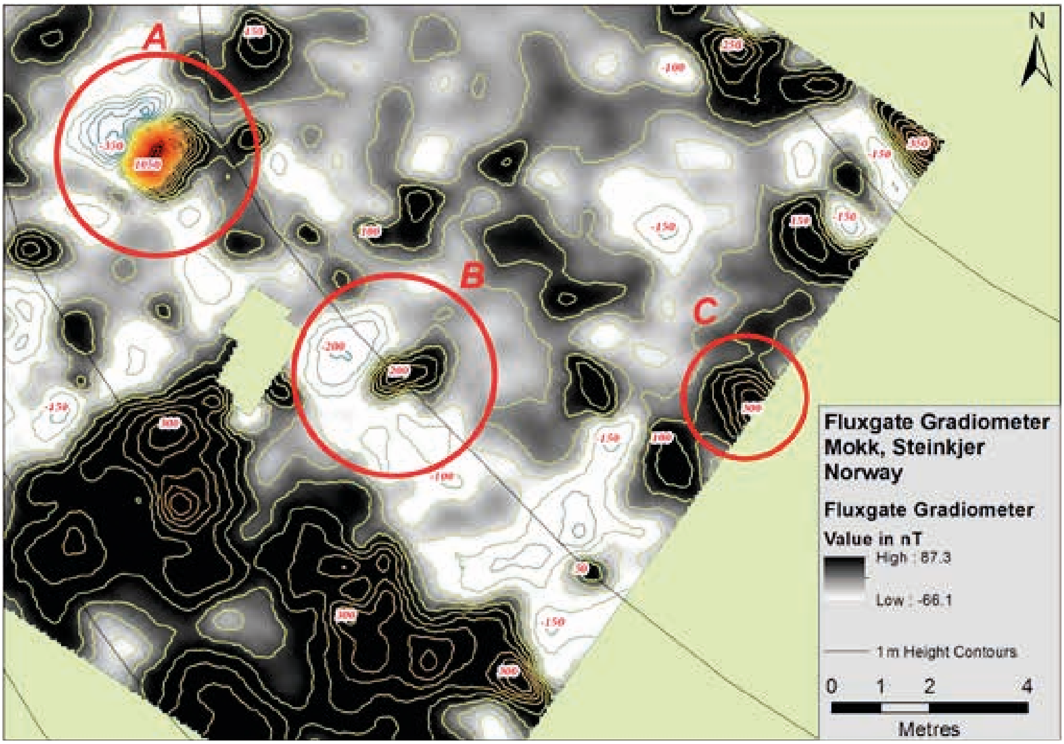

Figure 20. Possible furnaces at Mokk. Fluxgate gradiometer data. The contours are y 50 nT apart, with red lines for positive values and blue lines for negative values

such as ploughing, modern disturbance or other human activities from the time of the construction and use of the site until today could alter the geophysical responses at these sites. In fact, there is evidence of burnt shaft material having been intentionally placed in the slag pit (Berre, 1999) and the slag pit being covered with a large slab of flagstone, perhaps to hide the knowledge associated with the iron production (Rundberget, 2002).

A characteristic of the Trøndelag slag pit furnace tradition is that pits encircle the furnaces. They have been shown to contain roasted iron ore, burnt clay and burnt stone and flagstones, and have been interpreted as possible containers for roasted iron ore, stores for clay and firewood, or places for post-processing the extracted iron (Espelund & Stenvik, 1993; Farbregd et al., 1985; Rundberget, 2010; Stenvik, 2003; Wintervoll, 2010). When the pits surrounding the unexcavated furnace 2 in figure 18 are studied, a lack of correlation between the gradiometer results and the location of these pits can be observed. The susceptibility values are high for the pits (Table 3), and can be explained as marking the most intensive part of the iron production activity area, where there is a large quantity of burnt remains from the furnaces, slag and burnt furnace clay. Although some hotspots with high readings are roughly co-located with the known location of the pits at Storbekken 1, this appears more coincidental than deliberate. The fact that they are located so close to the actual furnace, often not more than 0.7–1.5 m, might result in a situation where the gradiometer readings could be cancelled out by strong remanent effects from the furnace and any other highly remanent or otherwise magnetic material around the furnace.

The general spread of magnetic material such as slag, iron ore and burnt clay is expected to create a generally magnetically disturbed situation, which explains the overall high values around and within the main activity areas of the iron production sites. There might also be a situation where the latest stage in the iron production transects earlier activity, as known at the Heglesvollen site, where one of the rosette pits cuts into an older furnace (Farbregd et al., 1985). This further complicates the geophysical response. A possible example of this from Storbekken 1 is seen in figure 21. Although the anomaly may well be the result of activity related to the general work at the site, or food preparation, it is difficult to provide a coherent interpretation of it.

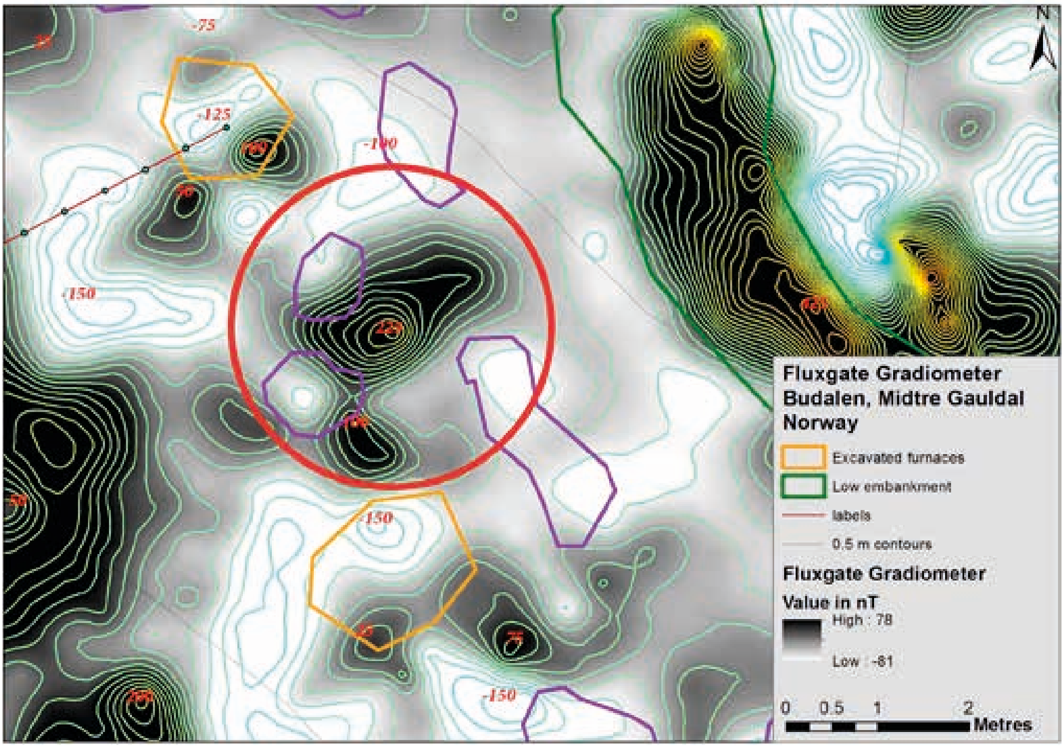

Figure 21. A semi-oval anomaly perpendicular to the edge of the terrace, with a strong maximum reading of 237 nT. This anomaly is situated between the two excavated furnaces. Can this mark a furnace from an earlier phase of activity?

The role of magnetic geophysical methods in outfield heritage management of iron production sites

The case studies presented in this article have demonstrated how magnetic geophysical mapping can be an aid to locating, delimiting and characterising prehistoric iron production sites. Topsoil magnetic susceptibility mapping has proved effective in outfield conditions and is an easy and time-efficient way of achieving these goals. New impressions of the size and intensity of activity were obtained at all the sites investigated, and the analysis of the sites gave new cultural-historical knowledge that had previously been unattainable since only one of all the known Trøndelag slag pit furnace sites had been delineated and the typical total size, organisation and layout of the activity areas were largely unknown. This has implications that are relevant for cultural heritage management as well, as the results presented in this article can serve as reference material and advice for how large an area around the iron production sites should be protected in the national monument registry. This, in turn, can have implications for project descriptions and budgeting in the event of future excavations. At Tromsdalen, for instance, a total of 75 working hours for the geophysical survey helped characterise the site and its constituent archaeological features of slag mounds, activity area and possible slag pit furnaces. The initial budget was drawn up with the intention of excavating four furnaces and slag pits, but the geophysical surveys revealed that there are more likely to be three furnaces and two slag pits, which could reduce the budget by as many as 525 working hours (Stamnes, 2016, pp. 142–144). This can be used as an argument for including magnetic geophysical mapping when planning field surveys where iron production sites are expected to be present. Methodological advice on survey resolution is presented in Table 9, and this may have relevance for other types of iron production sites in Norway and elsewhere.

The information and data plots produced by gradiometer surveys gave new insights into geophysical contrast and response patterns of typical archaeological features at such archaeological sites. At the same time, the plots attainable can be quite confusing, with scattered and diverse responses that might not always be easy to interpret.

In the scientific evaluation programme for iron production sites, Larsen (2009, p. 206) recommended that the use of metal detectors and/or magnetometers should be mandatory when doing fieldwork to locate slag pits or slag tips. While metal detectors were not part of this particular study, personal experience has shown that such instrumentation can be a relatively low-tech and versatile solution as it is fairly easy to indicate strong responses from metals and slag with such apparatus. Systematic mapping and recording the positions of responses might be helpful in locating and delineating such sites, but magnetic susceptibility and gradiometer mapping will yield more qualitative and quantitative information, and paired with precise positioning information be more beneficial for such investigations.

Conclusions

The aim of this paper was to investigate how the results of magnetic geophysical methods, combining topsoil magnetic susceptibility and fluxgate gradiometer mapping, could be used to locate and delineate iron production sites and be used as a way of characterising activity zones and specific archaeological features associated with the Trøndelag slag pit furnace tradition of iron production. In addition, this study discusses whether and how magnetic geophysical survey methods can be an asset for the heritage management of outfield iron production sites.

Topsoil volume susceptibility mapping proved to be a good way of delineating the main activity areas at such sites. The areas with the highest mean values were the main areas of production closest to the furnaces and the activity in their immediate surroundings, as well as within the slag tips. All sites had traces of magnetic enhancement extending back several tens of metres onto the flatter terraces behind the furnaces, which are usually found a few metres from the edge of the terrace, with the slag tips downslope from the terrace. There was also a close relationship between the measured susceptibility values and the thickness of the slag tip, and an area with known building remains at Storbekken 1 also showed enhanced values – higher than the median but not as high as the main activity area. Satellites of heightened values were measured, and were connected to but placed a little away from the main areas. These areas were interpreted as possible sites for roasting iron ore. The median value for the whole area surveyed is considered indicative of the natural background values. The average susceptibility values within the iron production site were between 7 and 27 times the background median values, indicating that these types of sites yield a very strong magnetic susceptibility contrast. This information made it possible to indicate the approximate size of the iron production sites and derive an estimate of the necessary sample resolution for locating such sites with topsoil volume magnetic susceptibility when performing a rapid assessment of a survey area. There was a variation in the descriptive statistics between the sites.

The fluxgate gradiometer results led to several interesting observations, which helped characterise the iron production sites even further. Although a more detailed picture emerges, the data sets resulting from these surveys also had a more complicated response. The site at Storbekken 1 indicated several interesting observations:

- Strong magnetic response from the unexcavated furnaces, with maximum values between 260 and 318 nT
- The shape of the anomalies from the furnaces varied - an elongated oval perpendicular to the terrace edge, an amorphous shape with several higher remanent peaks, and a roughly circular form. They were all in the eastern part of the elongated depression visible on the surface, furthest away from the terrace edge.

- Strong magnetic response from the upper parts of the slag mound, where the slag tip is thickest, with maximum values up to 286 nT, and generally a higher response closer to the furnaces
- Varied response with strong positive and negative values from the slag tips, with increasing variation further downslope and away from the furnaces
- Very distinct and strong remanent magnetic signal shaped as an oval, just behind the furnaces. Possible storage area for roasted iron ore.
- The possible site for roasting iron ore further back onto the terrace coinciding with areas of increased magnetic susceptibility

Many of the same observations were made at Tromsdalen, such as the presence of a strong anomaly with induced magnetic geophysical properties a short distance from the slag tips, which was interpreted as a roasting site for iron ore. An additional observation was the potential location of three possible furnaces with strong remanent magnetic contrasts and giving maximum readings of 148–226 nT. The sensor at this survey was about 10 cm further from the ground than at Storbekken 1, which would decrease the maximum values. The response from these possible furnaces was therefore comparable to the unexcavated furnaces at Storbekken 1. The response from the slag tips was more uniform than at Storbekken 1, where the spatial distribution in the strong geophysical anomalies in the fluxgate gradiometer data was comparable with high readings in the topsoil volume magnetic susceptibility. At Mokk, the potential location of three possible furnaces was highlighted, where the fluxgate gradiometer data helped indicate the limits of the iron production site towards the northwest. It was clear that this survey did not cover the entire site, and several strong magnetic anomalies indicate further activity on the terrace behind the slag tip and furnaces. The typical response from the furnaces was different from observations reported by Vernon (2004), Abrahamsen et al. (2003) and Smekalova and Voss (2002). There is a variation in the shape and geophysical contrast of the furnaces in relation to the strength and the position of the negative values associated with the strong positives, and this created a less uniform geophysical response from the furnaces than previously reported. The magnetic geophysical mapping of the iron production sites presented here made it possible to assess the physical size of the iron production sites of the Trøndelag slag pit furnace tradition, which has not been achieved before. Also, it was possible to prove additional activity relating to the iron production at these sites as far back as 30 m from the furnaces – an observation that should be taken into account when investigating new sites in the future. The geophysical observations presented and discussed in this article can function as important reference material for future geophysical mapping of iron production sites in Scandinavia, both in relation to the quantification and identification of various associated archaeological features in the geophysical data, but also from a methodological point of view. As regards the latter, statistics presented on the typical geophysical response of various features known from iron production sites demonstrate the value of performing such field surveys, as well as studies of the survey resolution required to locate iron production sites of particular sizes and character as important methodological contributions.

The combination of topsoil volume magnetic susceptibility measurements and fluxgate gradiometer surveys provided the possibility of locating, delineating and characterising the main activity areas as well as additional activity in the vicinity of the iron production sites. While topsoil MS was well suited for outlining the activity zones, fluxgate gradiometer data provided valuable additional detail, both geophysical and spatial, and helped provide new and valuable cultural-historical knowledge of these sites, including details of their size, spatial layout and extent as well as methodological experience concerning spatial resolution and sampling strategies. This, in turn, demonstrates how magnetic geophysical mapping can be an asset for heritage management when faced with the challenge of locating, delineating and characterising iron production sites in outfield conditions.

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