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Investigating early iron production by modern remote sensing technologies

Arne A. Stamnes, Ole Risbøl & Lars F. Stenvik (Eds.)

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The use of lidar and geophysical methods for locating and investigating prehistoric iron production sites in Scandinavia

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NTNU University Museum

The workshop

This publication presents advances in the archaeological surveying of iron production sites using geophysical methods and lidar ("light detection and ranging"). The papers published here were given at a workshop arranged by the NTNU University Museum in Trondheim on 12–13 March 2015. The workshop was supported by grants from Norges forskningsråd (Norwegian Research Council) and was part of the research project "Utmark" ("Outfield") that was carried out jointly by the Norwegian university museums. At this workshop, researchers, heritage officials and scholars from Norway, Sweden and Denmark presented their work on ways of locating and investigating prehistoric iron production sites in Scandinavia using lidar or geophysical methods.

The following were invited from Norway: Bernt Rundberget[1] and Jan Henning Larsen from the Cultural Historical Museum in Oslo, Kjetil Loftgarden from the

[1] Now at the NTNU University Museum

University of Bergen, Roger Jørgensen from the University of Tromsø, Ole Risbøl[1] and Lars Gustavsen from the Norwegian Institute for Cultural Heritage Research (NIKU), Christer Tonning from Vestfold County Council and Lars Pilø[2] from Oppland County Council. Participants from Sweden were: Eva Hjärthner Holdar[3] from the National Historical Museums and their geoarchaeological laboratory and Anders Biwall[4], also from the National Historical Museums. Denmark was represented by Martin Winther Olesen and Constanze Rassmann[2] from Museum Midtjylland.

Lars F. Stenvik and Arne Anderson Stamnes represented the Department of Archaeology and Cultural History in Trondheim, Norway, NTNU University Museum, and were the local organisers of the workshop.

The following presentations were given at the workshop:

Bernt Rundberget (Cultural Historical Museum, University of Oslo):
Magnetometerkartlegging av jernvinneanlegg på Østlandet (The mapping of iron production sites by magnetometers in southeast Norway)

Roger Jørgensen (Tromsø Museum, University of Tromsø):
Som nåla i høystakken. Søk etter jernvinne i innmark (A needle in a haystack – an infield survey for iron production sites)

Eva Hjärthner-Holdar (Geoarchaeological Laboratory, National Historical Museums, Uppsala) and Anders Biwall (National Historical Museums – Editing and Technology, Uppsala):
Järnproduktionen i Torsåker – en presentation av resultat från den arkeologiska prospekteringen och undersökningen (Iron production in Torsåker, Gätrikland, central Sweden – a presentation of the results of archaeological prospection and excavation)

Lars Pilø (Oppland County Council):
Lidar in action: Fra identifikasjon av de enkelte JKS-anlegg til stor-skala kartlegging (Lidar in action: From identifying single JKS sites to large-scale mapping)

Arne Anderson Stamnes (NTNU University Museum, Trondheim):
Geofysisk kartlegging av jernvinnelokaliteter i Midt-Norge ved hjelp av magnetiske metoder (Magnetic geophysical mapping of prehistoric iron production sites in central Norway)

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[2] Gave notice of absence
[3] Now retired
[4] Now Uppsala University

Ole Risbøl and Lars Gustavsen (Norwegian Institute for Cultural Heritage Research NIKU, Oslo):
Kartlegging av jernvinnerelatert virksomhet i Østerdalen – hva har teknologiske nyvinninger bidratt med? (Mapping early iron production features in woodland using remote sensing techniques)

Constanze Rassmann and Martin Winther Olesen (Museum Midtjylland, Herning):
Jernudvinding på Fjeldet – midt i Jylland. Nye perspektiver for opfattelsen af jernalderens arealorganisering (Iron smelting during the Late Iron Age in central Jutland. New information from two recently discovered settlements with traces of iron production from both infield and outfield)

After the workshop, the attendees were invited by the organising committee to publish their presentations as articles in the DKNVS (Royal Norwegian Society of Sciences and Letters) *Transactions*. After the workshop was held, some of the presentations have been published elsewhere, and for various reasons, some attendees were unable to submit their papers. Ultimately, four papers from the workshop constitute this publication, written by Jørgensen, Olesen, Risbøl and Gustavsen, and Stamnes, Stenvik and Gaffney. As the deadline for submitting manuscripts was late 2015, the articles generally do not include research on the respective topics published after 2015.

We would like to thank all the presenters, authors and attendees for their interest in this topic, and the generous sharing of their knowledge and competence, as well as their participation and contributions to the discussions during the workshop.

Remote sensing and its use on iron production sites

The use of various remote sensing techniques such as lidar and geophysical survey methods might be perceived as something rather new in archaeology, but that is not the case since such techniques have been used sporadically for decades when it comes to geophysics and a couple of decades as regards lidar. In later years, there has been a large change in the accessibility and availability of remote sensing techniques that can be drawn into projects one might be engaged in. The background for arranging the workshop was a wish to gather researchers and colleagues involved in cultural heritage management, in particular those with experience in working with iron production sites, in order to share knowledge and experience in the use of remote sensing techniques as a way to locate, delineate, map and characterise such sites.

Traditional ways of locating iron production sites

The earliest Norwegian records of iron production sites were mere verbal and without any plans, sketches or drawings. Such early written records go back to the late 18th century and mention traces of iron production by observation of slag, but without describing furnaces or other elements (Schøning, 1778). Between the two World Wars, there was increasing interest for archaeological research on iron production sites and for conducting excavations which had particular focus on the furnaces. Early excavations and registration schemes revealed patterns of characteristic features, and archaeologists and local laymen started to develop competence in recognising, locating and describing iron production sites and their individual features, mainly dependent on their visual properties usually combined with test pits. Typically, the documentation was made with the help of tape measures and a local coordinate system or by making sketches by pacing the distance between identified elements. Such approaches depend completely on visual identification. In many cases, sketches made this way contain valuable information on the number of furnaces, pits, slag heaps and their preservation conditions, as well as the location of buildings, roads and streams in the vicinity. The reliability of such registrations is often low, as registrations based solely on visual observations would only record some traces of a complex activity. They are also greatly dependent on the skills and experience of those doing the work. Dwellings, houses or tents might have been light constructions that are difficult to identify above ground. Also, roasting sites and places for storing iron ore might not leave any traces that are visible on the ground surface.

Lidar and mapping of iron production

The introduction of lidar in archaeology some two decades ago offered a new possibility for surveying cultural features, like traces of iron production, using remote sensing. Lidar is a remote sensing technology that measures the distance to the ground from an aeroplane or a helicopter by using laser light. The travel speed of the laser light from the airborne vehicle to the ground, where it is reflected and sent back to the aeroplane or helicopter, is used to calculate the unevenness of the ground surface. This unevenness is depicted with high resolution and accuracy by generating digital 3D models. Such models are well suited for identifying cultural features on the ground. It is a prerequisite that these are visible as elevations that can be measured. Filtering algorithms make it possible to produce models with or without vegetation. Vegetation often obstructs visual access to the ground and archaeologists using lidar-generated models usually prefer bare ground models devoid of vegetation.

Lidar has been successfully employed in archaeology with particularly good results in outfield archaeology where all sorts of cultural features have been identified and mapped in forested or mountainous environments across the world (e.g. Chase et al., 2014; Crutchley, 2009; Doneus & Briese, 2011; Evans, 2016; Georges-Leroy, 2011; Risbøl et al., 2006). The underlying reasoning behind employing lidar and other remote sensing techniques and methods is the lack of sufficient overview of cultural features in the landscape. This is particularly poor when it comes to outfield areas, only a small proportion of which is surveyed and mapped. In Norway, the most common features mapped with lidar are charcoal pits and kilns, pitfalls, slag heaps, hollow-roads, etc. (Risbøl & Gustavsen, 2016).

Two of the papers given at the workshop leading to the publication of this volume were about lidar and its contribution to studies of early iron production. That is to say, the potential of lidar for identifying, mapping and describing iron production sites. The paper "Mapping early iron production features in woodland using remote sensing techniques" presented by Ole Risbøl and Lars Gustavsen (see this volume) addressed two objectives. The first and primary one was to study and discuss to what extent conventional interpretation of lidar-generated digital terrain models can benefit from the application of available supplementary visualisation methods like Local Relief Model, Sky View Factor, etc. The second part of the presentation was to put forth some ideas of applying an airborne magnetometer as a potential and additional approach to identify slag heaps from the air. This included the presentation of the initial phase of an actual test using magnetometer devices from the air. This test has not been accomplished and what was emphasised in the presentation was a discussion about the potential for using this as an approach, together with a short description of the data collection carried out in the study area near Elverum, southeast Norway.

The study concerning the additional value of adopting a set of visualisation methods was set up to detect how successful two test persons were when assigned the task of interpreting lidar-generated models using various visualisation methods. The task focused on pre-industrial iron production and was restricted to identifying as many slag heaps and charcoal pits as possible. The data collected were used in plain statistical analysis showing unequal effects on slag heaps and charcoal pits, respectively.

Even though lidar is an unsurpassed method when it comes to surveying large outfield areas, it still has some well-known limitations. One of these is the difficulty in distinguishing man-made cultural features from natural features. Many slag heaps belong to this category, despite their large volume. This led to considerations about applying other remote sensing methods to outfield archaeology, for instance airborne magnetometry. Risbøl and Gustavsen discuss this potential and refer to a few tests. They also initiated data collection from a plane equipped with airborne magnetometer instrumentation - a test that has not been completed. Thus, this part of their paper is meant to present some ideas about a potential, innovative approach to add another tool to the archaeologist's remote sensing toolbox.

Lars Pilø, who was supposed to give the other paper on lidar at the workshop, was unable to attend and reported his absence in advance. His paper was given by Arne Stamnes instead, using a power-point presentation Pilø had prepared. Oppland County Council has for some years put priority on large-scale lidar scanning of extensive areas in the county as a basis for mapping cultural features. To improve the interpretation of lidar-generated digital terrain models, a WMS service has been developed in cooperation with COWI that enables the seamless use of four visualisation techniques in addition to ordinary hillshaded models. These are Local Relief Model, Sky-View Factor, Slope and MDOW Hillshade. In terms of mapping features from pre-industrial iron production, Pilø pointed out the difficulty of identifying small charcoal pits and pits covered with logging waste or disguised by vegetation. In addition, slag heaps and foundation walls from buildings are seldom visible in Oppland. On the other hand, many iron production sites in the region have a layout where charcoal pits are situated at the actual production site, thus permitting the more visible charcoal pits to be used as indicators when looking for sites where iron has been produced.

To improve the efficiency of detecting cultural features with lidar-generated data, semi-automated approaches have been developed and tested by the Norwegian Computing Centre in close cooperation with Oppland County Council (Trier & Pilø, 2012). Areas have been studied using semi-automatic, computer-based detection and the results followed up by ground truthing with good results (Trier & Pilø, 2015).

Geophysical methods for locating, delineating and characterising iron production sites

Iron production sites are characterised by traces left from various stages of the production, from handling of iron ore and charcoal, to the smelting process leaving large amounts of waste products, such as slag. Roasted iron ore and slag are highly magnetic due to their content of highly magnetic iron ore in some stage or another. These make such features or areas of activity relatively easy to map by magnetic geophysical methods. In addition, the storage of charcoal and firewood, as well as the presence of various forms of dwellings such as houses or tents, are known from iron production sites. The latter might not have the same magnetic traces associated with them.

In Sweden, the magnetic properties of the ore were recognised early. In 1668, it was reported that a prospector used a declination compass (later developed into a mining compass) to locate new iron ore deposits. An early version of a magnetometer, known as the Thalén-Tiberg magnetometer, was developed as early as 1874 and was widely used (Viberg et al., 2011). In Norway, the earliest known archaeological use of a magnetometer system on an iron production site is from Hoset in Stjørdal, Trøndelag, where a total field magnetometer system was used in 1973 to delineate a slag mound, and where the intensity of the total field reading corresponded well to the thickness of the slag mound (Farbregd, 1973; 1977). In southwestern Denmark, the work of geophysicist Tatiana Smekalova and archaeologist Olfert Voss has proved how large systems of slag pit furnaces in ploughed fields can be located by systematic magnetometer surveys. They located over 80 sites, some of them with over 1000 pits (Smekalova & Voss, 2001; 2002). This work serves as important comparable material for the geophysical characterisation and interpretation of such data sets.

Some of the presentations at the workshop can be seen as a continuation of these works, and demonstrate the usefulness of magnetometers in both infield and outfield conditions. A total of five papers presented at the workshop focused on the use of geophysical methods on iron production sites, and three of these case studies are included in this book.

The first is Roger Jørgensen's paper "A needle in a haystack – an infield survey for iron production sites", which presents the results of a relatively early survey undertaken in collaboration with a geologist, Richard Binns, in 1999 and 2002 at Hemmestad in Troms in northern Norway. This particular survey is an interesting case study of an early use of this methodology, and although the resolution and software processing options utilised were not as advanced as todays', the results were still good. Two iron age furnaces, two cooking pits and other anthropogenic activity were located, and the surveys were considered a success as it would otherwise have been very difficult to locate these features without the geophysical data.

The second paper is by Arne Anderson Stamnes, Lars F. Stenvik and Chris Gaffney, named "Magnetic geophysical mapping of prehistoric iron production sites in central Norway", which combines the use of topsoil magnetic susceptibility mapping and gradiometer surveys to study the particular slag pit furnace of the Trøndelag tradition. This tradition is very specific to the Trøndelag region in central Norway and dates back to the Early Iron Age. As very few of these sites have been excavated in their entirety, presenting and analysing the results from four different sites demonstrated how the use of these two geophysical methods helped to successfully delimit such sites and for the first time give a good indication of their size and extent. By using these two methods, interesting patterns of anomalies and zones of activity could be mapped and interpreted in the collected data, which most probably related to roasting sites for iron ore and the location of iron ore deposits, demonstrating the presence of activity related to iron production up to 30 m from the slag mounds indicating the actual production site. The authors demonstrate typical anomaly characteristics for furnaces, slag mounds, roasting sites for iron ore and their deposits, and give additional advice on survey strategies (e.g. sampling density and anomaly characterisation) for using these geophysical methods in archaeological registration schemes when faced with the challenge of locating and delineating iron production sites of various sizes.

The third paper presented in this volume is by Martin Winther Olesen and Constanze Rassmann entitled "Iron smelting during the Late Iron Age in central Jutland. New information from two recently discovered settlements with traces of iron production from both infields and outfields". The article presents the results from a series of large-scale magnetometer surveys conducted by the Midtjylland Museum, and shows how they can be used within a broader context and contribute better understanding of both the in-site organisation of iron production within Iron Age settlements, and the size, complexity and role of iron production for the wider Iron Age society.

Bernt Rundberget presented a paper entitled "Magnetometerkartlegging av jernvinner på Østlandet" (The mapping of iron production sites by magnetometers in southeast Norway). This work has been published elsewhere (Rundberget, 2017). In the presentation, he gave a short historic overview of the use of magnetometers on iron production sites in southeast Norway, where the earliest survey was performed as part of the Dokka project as early as 1988 (ref: Larsen, 1991). Later, Tatiana Smekalova and Sergej Smekalov were engaged to perform a series of surveys as part of a major development project at Gråfjell in connection with the establishment of a military training and firing range in Østerdalen, southeast Norway. Several roasting places were detected using magnetometers, and these were otherwise quite elusive and a challenge to identify. In addition, the Smekalovs identified and mapped several bloomery sites (Risbøl & Smekalova, 2001; Smekalova & Smekalov, 2006). These results gave new information on aspects of location of the bloomery sites, the internal layout of sites and associated activity such as the roasting sites. These results were used by Rundberget to discuss questions such as exploitation of iron and organisation of iron production, thus moving the emphasis from observed anomalies in the geophysical data to using this knowledge for more overall cultural-historical results (Rundberget, 2017).

The last talk was by Anders Biwall and Eva Hjärthner-Holdar entitled "Järnproduktionen i Torsåker – en presentation av resultat från den arkeologiska prospekteringen och undersökningen" (Iron production in Torsåker, Gätrikland, Central Sweden – a presentation of the results of archaeological prospection and excavation). Unfortunately, due to various circumstances, this talk is not included as an article in this publication. The authors presented the results of a magnetometer survey undertaken in a remote, forested area near Torsåker in Gätrikland, where they wanted to test how a magnetometer system could be used to locate and identify iron production sites and their related activity zones. The survey was successful because they managed to identify the spatial extent of the magnetised deposits related to the iron production activity and particularly individual anomalies. These very useful results later formed the basis for an excavation plan. During this excavation, they uncovered a slag pit, six furnaces, a charcoal pit and roasting sites for iron ore. The roasting sites were impossible to delimit in the magnetometer data because they were situated within a larger response of ferromagnetic magnetised objects. In this case, the charcoal pit also showed a distinct anomaly, and the furnaces were easy to interpret as such due to the presence of high magnetism.

Remote sensing and advances in its use for studying iron production sites

The lesson to be learnt from this workshop is that the advances presented in these case studies constitute an important contribution to knowledge about iron production and are interesting for a larger audience. The shared experience related to improvements with impact on fieldwork (survey and excavation), as well as increased understanding of the layout of iron production sites, lays the groundwork for better understanding and management of these important heritage sites. While the accessibility of lidar data improves our possibilities to identify iron production sites in large-scale surveys at an early stage of land-use development projects, it is also important to know what can be located, how the data can be optimised for the specific aims and objectives investigated, and the limitations of the method. The same applies to the use of magnetic geophysical methods. The combination of lidar and geophysics for better mapping of these features in outfield conditions has great potential. This is especially the case in areas where it is difficult to identify slag heaps, but where detectable charcoal pits can serve as indicators of iron production in the vicinity. Also, the successful indication of ore roasting sites adds another level to an improved understanding of the organisation of the iron blooming process. The results from Midtjylland and northern Norway, despite large differences in size and complexity, demonstrate the usability of magnetic geophysical mapping in infield conditions. These results add to the conclusions of the earlier work of Tatiana Smekalova and her colleagues (Smekalova & Voss, 2001; 2002; Smekalova et al., 2008), and expand the knowledge available on the role of iron production as seen from a cultural-historical perspective – showing how it is possible to move the use of remote sensing techniques beyond mere prospection and location of features.

Acknowledgements

We would like to thank all who contributed to a successful workshop and those who were able to submit their manuscripts that made this publication possible. We are also grateful to the Norwegian Research Council for helping to fund the "Utmark" research project that constituted the initial background for the workshop. The Royal Norwegian Society of Sciences and Letters and the Department of Archaeology and Cultural History at the NTNU University Museum have provided financial support to realise this publication, and Tina Skjærvik Thomsen at the Royal Norwegian Society of Sciences and Letters has made a great practical contribution to ensure the publication of these articles.

References

Chase, A. F., Chase, D. Z., Awe, J. J., Weishampel, J. F., Iannone, G., Moyes, H., Yaeger, J., Brown, M. K., Shrestha, R. L., Carter, W. E., Fernandez Diaz, J. C. (2014). Ancient Maya regional settlement and inter-site analysis: The 2013 West-Central Belize lidar survey. *Remote Sensing*, (6), 8671–8695.

Crutchley, S. (2009). Using lidar in archaeological contexts: The English heritage experience and lessons learned. In G. L. Heritage & A. R. G. Large (Eds.), *Laser scanning for the environmental sciences* (pp. 180–200). Hoboken, NJ: Wiley-Blackwell.

Doneus, M. & Briese, C. (2011). Airborne laser scanning in forested areas – potential and limitations of an archaeological prospection technique. In D. C. Cowley (Ed.), *Remote sensing for archaeological heritage management* (EAC Occasional Paper No. 5, pp. 59–76). Brussel: Europae Archaeologia Consilium (EAC).

Evans, D. (2016). Airborne laser scanning as a method for exploring long-term socio-ecological dynamics in Cambodia. *Journal of Archaeological Science*, 74, 164–175.

Farbregd, O. (1973). *Hosetprosjektet 1973. Arkeologisk utgravning.* (Report in the digital topographical archive, doc. number 7350). Trondheim: NTNU University Museum, Norwegian University of Science and Technology (NTNU).

Farbregd, O. (1977). Archaeological field work and evidence. *Norwegian Archaeological Review, 10*(1-2), 119–126.

Georges-Leroy, M. (2011). Airborne laser scanning for the management of archaeological sites in Lorraine (France). In D. C. Cowley (Ed.), *Remote sensing for archaeological heritage management* (EAC Occasional Paper No. 5, pp. 229–234). Brussel: Europae Archaeologia Consilium (EAC).

Larsen, J. H. (1991). *Jernvinna ved Dokkfløyvatn. De arkeologiske undersøkelsene 1986–1989. Varia* (vol. 23). Oslo: Museum of Cultural History, University of Oslo.

Risbøl, O. & Smekalova, T. (2001). Archaeological survey and non-visible monuments. The use of magnetic prospecting in outfield archaeology. *Nicolay. Arkeologisk Tidsskrift, 85*(3), 32–45.

Risbøl, O., Gjertsen, A. K. & Skare, K. (2006). Airborne laser scanning of cultural remains in forests: Some preliminary results from a Norwegian project. In S. Campana & M. Forte (Eds.), *From space to place: 2nd international conference on remote sensing in archaeology*. (British Archaeological Reports, International Series, 1568, pp. 107–112). Oxford: Archaeopress.

Risbøl, O. & Gustavsen, L. (2016). *Håndbok. Bruk av luftbåren laserskanning (lidar) i arkeologien*. Oslo: Riksantikvaren.

Rundberget, B. (2017). *Tales of the iron bloomery. Ironmaking in South-eastern Norway – foundation of statehood c. AD 700–1300. The Northern world* (vol. 76). Leiden & Boston: Brill.

Schøning, G. (1778). *Reise som giennem en deel af Norge i de aar 1773, 1774 1775 paa Hans Majestet Kongens bekostning er giort og beskreven af Gerhard Schøning. Første Bind [1979]*. Tapir: Copenhagen.

Smekalova, T. & O. Voss (2001). Magnetisk kortlægning af arkæologiske anlæg i Danmark 1992-2000. In J. Nordqvist & B. Gammeltoft (Eds.), *Nationalmuseets arbejdsmark* (pp. 148–161). Copenhagen: The National Museum.

Smekalova, T. & Voss, O. (2002). Field procedures for magnetic investigations of iron-smelting sites with slag pits. In L. Nørbach (Ed.), *Prehistoric and medieval direct iron smelting in Scandinavia. Aspects of technology and science* (pp. 223–226). Aarhus: Aarhus University Press.

Smekalova, T. & Smekalov, S. (2006). *Magnetic survey in Gråfjell, Regionfelt Østlandet, Åmot kommune, Hedmark, South-eastern Norway in 2000, 2001, 2002, 2004 and 2005. Final report*. St. Petersburg: St. Petersburg State University.

Smekalova, T., Voss, O. & Smekalov, S. L. (2008). *Magnetic surveying in archaeology. More than 10 years using the Overhauser GSM-19 gradiometer*. Aarhus: Wormanium.

Trier, Ø. D. & Pilø, L. H. (2012). Automatic detection of pit structures in airborne laser scanning data. *Archaeological Prospection, 19*(2), 103–121.

Trier, Ø. D. & Pilø, L. H. (2015). Archaeological mapping of large forested areas, using semi-automatic detection and visual interpretation of high-resolution lidar data. In *CAA2014. 21st century archaeology. Concepts, methods and tools. Proceedings of the 42nd annual conference on computer applications and quantitative methods in archaeology, Paris, France, 22–25 April 2014* (pp. 81–86). Oxford: Archaeopress.

Viberg, A., Trinks, I. & Lidén, K. (2011). A review of the use of geophysical archaeological prospection in Sweden. *Archaeological Prospection, 18*(1), 43–56.

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Iron smelting during the Late Iron Age in central Jutland.

New information from two recently discovered settlements with traces of iron production from both infield and outfield

Martin Winther Olesen
Museum Midtjylland, Herning

Abstract

An overview of known traces of iron smelting from the Late Iron Age (AD 150–600) in central Jutland shows how the iron smelting generally is found within the farm and village area. The scale of the production seems limited and the general interpretation is that the production perhaps can satisfy the need for iron in the local area itself. However, recent geophysical surveys combined with excavations in more marginal areas have shown traces of quite intensive iron smelting in, for instance, heaths, meadows and grazing land. The article gives a status of the research in central Jutland and presents an example of the traditional organisation of the iron smelting, and the results of the geophysical surveys and archaeological excavations in these more remote areas. The article suggests that geophysical surveys of outfield areas are necessary if one wants to estimate the scale and the aim of iron production in a certain area.

Introduction

Beginning in the early 1990s, Museum Midtjylland has conducted a series of comprehensive excavations that have given us good insight into the location and organisation of settlements during the early and late periods of the Iron Age. Traces of iron smelting in clear connection with farms is one of the most noteworthy elements observed during the excavations, and iron smelting appears to have been an integral part of the area's economic strategy.

At first, it was the iron production from the earliest part of the Iron Age that attracted the museum's research interest. Among other things, the finds included the oldest dated iron smelting features (ca 600–400 BC) from the North European lowlands (Olesen, 2012a, p. 115). However, soon attention became focused on a locality from the 1st century AD that had a row of iron smelting huts that were associated with a contemporary settlement and a nearby locality that had a major farmstead and a cemetery with extraordinarily rich, princely graves (Jensen, 2006, p. 67; Olesen, 2010, p. 17).

The results from Museum Midtjylland have since been greatly supplemented by finds from the area west of Silkeborg, strengthening the hypothesis that the central Jutland area was a significant player in iron production in the time around the beginning of the 1st century AD (Olesen, Hansen, Christensen & Hansen, in press). The essence of these investigations is that central Jutland suddenly plays a pivotal role in the *introduction* of iron smelting to Denmark and probably a major role as such in Danish iron production in the 1st century AD. This is prior to the apparently relatively comprehensive concentration of iron production in southwest Jutland that occurred throughout the later part of the Iron Age. This concentration is well documented through both excavations and geophysical prospection. During this period, the slag-pit furnace was introduced, and it became the completely dominant type in the whole period from ca. AD 150–600 (e.g. Mikkelsen & Nørbach, 2003; Smekalova et al., 1996; Voss, 1993; 1995). Seen from this perspective, the production in central Jutland has to some extent been neglected in overviews of the topic and it was first in 2012 that a systematic review of finds from recent excavations led to a greater appreciation of the importance of iron smelting in the period AD 150–600 (Olesen, 2012b, pp. 119ff). The most important points of this overview will be summarised below. But the main point, that the production in central Jutland hardly reached a level that would satisfy more than the needs of the village, remains valid.

So far, any cultural historical analyses have solely been drawn from the results of excavations. However, since 2012 two new sites (HEM 2642 Neder Julianehede and HEM 5227 Mosebo) have been investigated with a combination of excavations and geophysical prospection, which is a different approach. The geophysical prospections covered large areas near the settlements, as well as surveys of areas not directly connected to arable land. These two sites will be described in more detail later in this article, and serve as case studies for the aim of this article, which is therefore to investigate how the use of magnetic geophysical prospection combined with excavations can lead to new and important cultural historical insights on similar sites. This article will also investigate how this approach can quantify both our estimation of the scale and our understanding of the spatial organisation of the iron smelting. This will in turn provide more substantial material as a basis for discussing the importance of iron smelting in areas such as central Jutland, and how both the arable landscape and the more marginal parts of the landscape have been utilised.

A general picture of iron smelting in central Jutland

The research area that was part of the overview is seen in figure 1. The landscape in this area of Jutland consists of a series of relatively well-defined, isolated moraines, typically with subsoil consisting of sand mixed with clay. The agricultural potential of the land

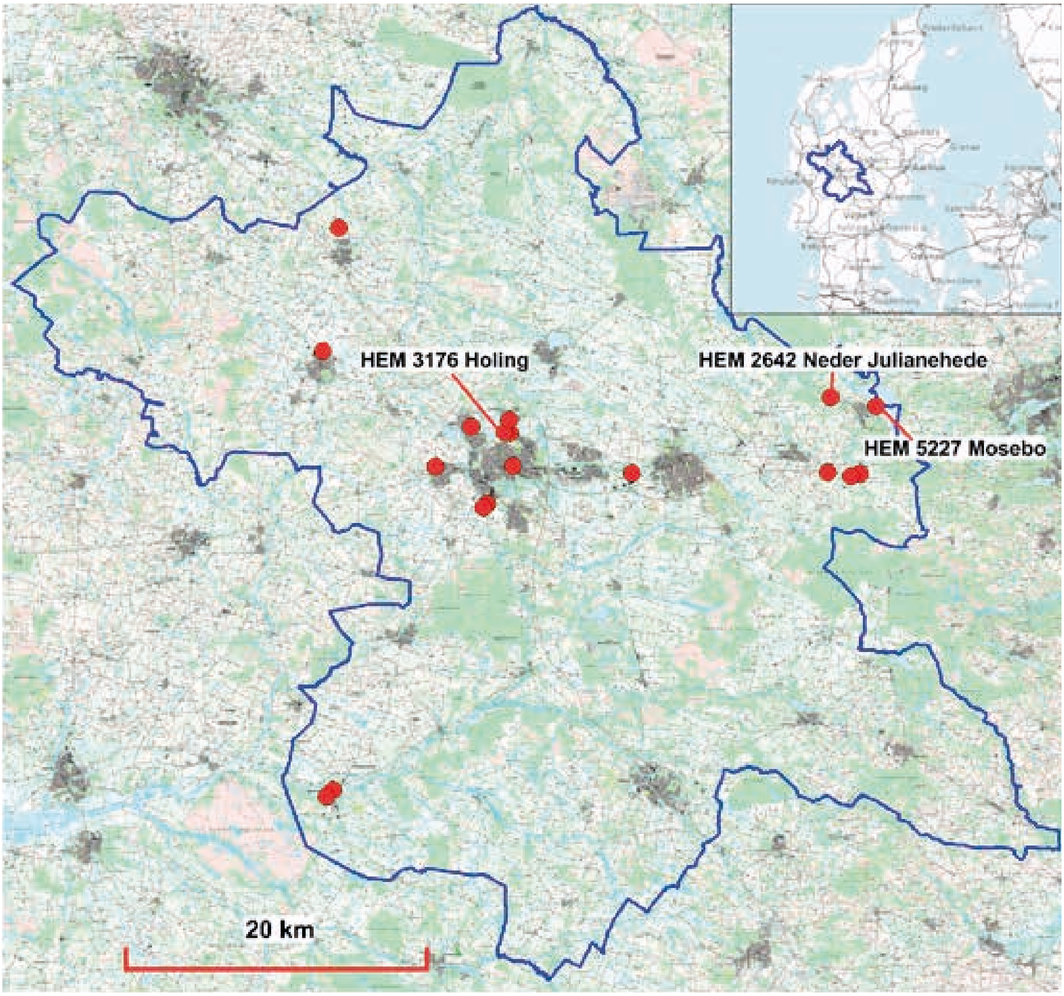

Figure 1. Sites in central Jutland where iron smelting furnaces from AD 250–600 have been excavated (red dots). Locations that are specifically discussed in the text are marked.

is fine, but by no means the best in Denmark. It is on these moraines that one finds the settlements from the Late Iron Age up through the Middle Ages. The "moraine islands" are delimited by quite extensive meadows and spacious heathlands. These areas were seldom directly used for settlements during the Late Iron Age and were, until now, only regarded as hay meadows, grazing land, woods, or simply "outfield".

The general picture of the distribution of iron smelting is that we find traces of iron smelting at practically every Iron Age village, but relatively few furnaces are preserved, and they tend to be concentrated at certain farmsteads. In general, the iron smelting is located within the settlements, and is therefore a common feature in the economy; however, the scale of the production seems to be limited. Most likely one was just aiming for production of iron to supply the needs of the village itself. An example of this organisation pattern will be outlined below (HEM 3176 Holing). Another common feature is found in the operation of the furnaces in central Jutland. They were all broken up after smelting. That is to say, they were demolished immediately after smelting, also under the plough zone today. This practice is also known from southwest Jutland sites, but it was not as consistently done as in central Jutland, and in southwest Jutland there are many examples where the slag was left *in situ* as large blocks. It is possible to imagine various explanations for the difference in operational practice. It has been suggested that the broken-up furnaces are failures showing that the bloom flowed down into the slag in the pit, but this would hardly have been done so consistently (Helt, 2015, p. 36). It can more likely be explained by some nuance of construction or operation, or as suggested in the 2012 article, it might be connected with the physical placement of the furnaces. If they lie in close association with the farmstead's outer fence, they also lie in the primary agricultural zone – therefore in areas that were actively part of the individual farm's crop rotation system and large lumps of slag were obviously in the way of later ploughing. Thus, it was quite reasonable to remove them after smelting (Olesen, 2012b, p. 131). These patterns seemed to be general to all the sites in the research area (Olesen, 2012b, p. 119).

There were still a few elements, however, where it was possible to detect a difference between the sites in the eastern and western parts of the investigated area. In general, the easternmost sites are not as well preserved as the westernmost and it is harder to identify fences and, hence, more difficult to identify the individual farmsteads. Furthermore, whereas the furnaces in the westernmost parts of central Jutland are organised in strings parallel to the fences, they tend to be organised in rounded clusters on the easternmost sites.

A general feature in the slag-pit furnaces is that they contain a carbonised straw plug in the bottom of the slag pit – prior to the iron smelt the pit was filled with fresh straw to prevent the charcoal and bog ore from filling the pit. The straw would carbonise during the smelting process and leave the necessary space to drain the smelting slag. When the straw plugs that were preserved in a carbonised form in the bottoms of the furnaces were analysed it became clear that in general the furnaces in the western part of the research area contained plugs made from primarily barley, thereby strengthening the connection between the iron smelting, the infields and the farmsteads in this area. On the other hand, in the furnaces found on the sites in the eastern part of the research area, the plug was predominantly made of heather, which is a plant with clear connections to the outfield. The increased frequency of pasture plants coincides with the fact that iron production in this area apparently was more peripherally placed in relation to the settlements and spatially organised in rounded clusters, and not in relation to any visible linear fence boundaries, but apparently still in close connection to the village. This was interpreted as a difference in the organisation of the village and the agricultural strategy in west and east, rather than a difference in the organisation or the scale of iron production (Olesen, 2012b, p. 127). When compared to the material from southwest Jutland, the most important point is that the organisation, location, technology and operation of iron production are quite similar in southwest and central Jutland, but the scale and intensity of iron smelting on sites like Snorup and Drengsted are much higher. In these cases, the production clearly exceeds the immediate needs of the local villages.

HEM 3176 Holing

A typical example of the scope and organisation of iron smelting in the Late Iron Age settlements in central Jutland is found in Holing, near Herning. With a few exceptions, the general picture from this site applies to all of the settlements in the analysis (Fig. 1) apart from Neder Julianehede and Mosebo.

During the 1990s, Museum Midtjylland excavated around 250 000 m^2 of a settlement area that includes farmsteads from the period AD 200 to the Late Viking Age. The village is on the southern edge of a "peninsula" of good agricultural land surrounded by meadowland with the potential for haymaking and grazing (Fig. 2). There is so far no evidence of iron smelting in these areas, but it is important to note that no geophysical surveys have yet been carried out near the excavated area.

During the period AD 300–600, the settlement consisted of 10 to 12 farmsteads, and a total of 88 furnaces were found (Fig. 3). They were all slag-pit furnaces with an average diameter of approximately 75 cm and a preserved depth between 4 and 60 cm. The furnaces only contained small lumps of slag and they had all been demolished after smelting. Some of the furnaces contained a thin layer of carbonised plug. It was charred straw, and where it could be identified it predominantly originated from barley and rye.

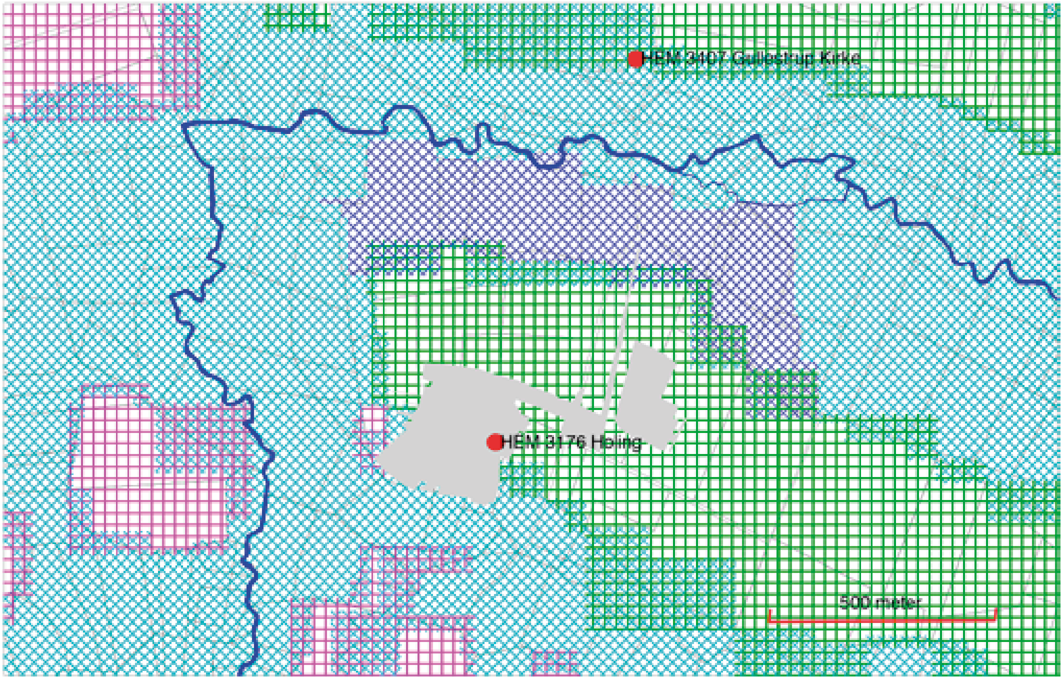

Figure 2. Land use around Holing based on the 1844 cadastral map. Green is arable land, red is heath/heather, light blue is dry meadow and dark blue is wet meadow. The excavated area is marked grey.

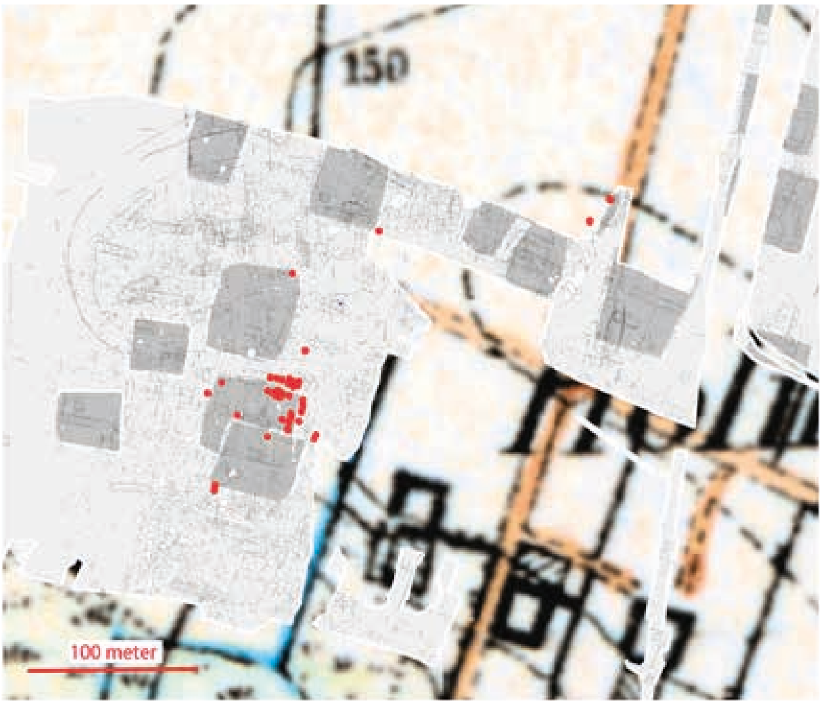

Figure 3. Section of the settlement HEM 3176 Holing. The farmsteads are coloured grey and the iron furnaces are red. The material was reviewed and revised in 2015 by Jonas Helt.

The clear majority of the furnaces were situated near one of the farm's outer fences. This farm had a very long duration of use (ca. AD 300–600) and multiple phases of rebuilding. However, divided over the expected lifetime of the farm, there are very few smelting episodes per generation (around 15 – or just one every second year).

The dominant status of this one farm is evident when it comes to iron production, but it is not in any other respect different from the other farms at the site. Similar patterns were found in southwest Jutland, for example in Snorup, where one farm dominates the iron production (Mikkelsen & Nørbach, 2003, p. 23). However, the explanation is not clear. One could argue that iron smelting, for instance, could be a handicraft that was restricted to certain families and farms. The excavation zone is limited to the village area, which means that more marginal areas are not seen here. Obviously, the farmsteads had, for instance, pastures near the farms and, as we will see below, iron smelting could also take place in more remote areas.

Neder Julianehede and Mosebo

In 2013, a new and very significant locality was added to the material (HEM 5227 Mosebo IV). It was intensively reviewed in 2015 in connection with a BA project (Helt, 2015). At the same time, another new, small excavation took place at a nearby site (HEM 2642 Neder Julianehede). This was an already known iron smelting location that was not included in the primary review of the material because there was inadequate information about the find. In addition to the excavation of these two sites, we had the opportunity to conduct geophysical surveys over a large, contiguous area surrounding the two sites. The two localities of interest are briefly described in the following.

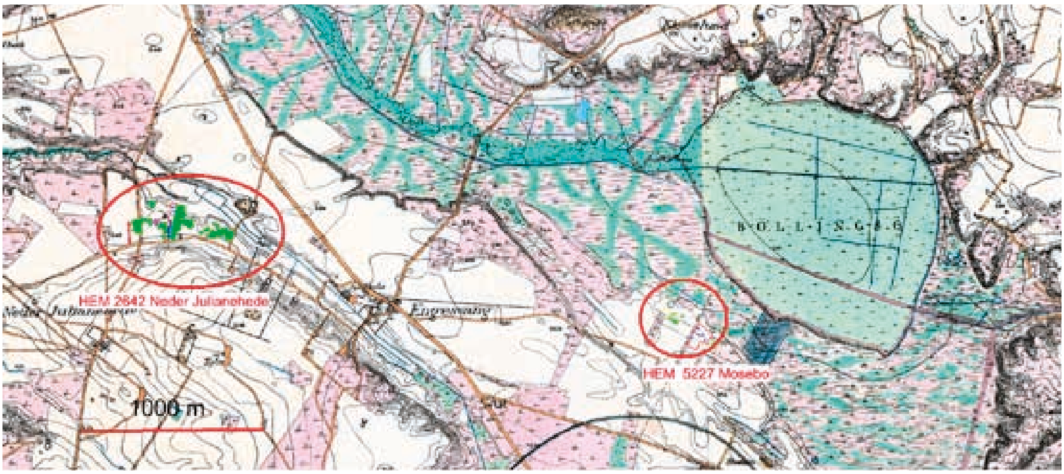

Figure 4. The two locations shown on a topographical map from 1874.

Figure 5. Niels Nielsen's photo from 1924 of the very obvious slag heaps that had accumulated near HEM 2642 Neder Julianehede.

Both sites are in the parish of Engesvang, one east and the other west of the village of Engesvang (Fig. 4). The nearby Lake Bølling is a notable feature of the landscape that, already in the Iron Age, was partially overgrown into raised bog. The unique feature of Lake Bølling is that it lies right on the watershed of Jutland and therefore drains to the west through the Karup river system while to the east it drains into the River Funder and thereafter into the Gudenå system. Furthermore, in the vicinity of the two sites there are many references to iron production in the form of place names (e.g. Klode Mølle ("Klode" means 'ingot')), and in historical sources dealing with iron production. In written sources, this area is mentioned as the last place in Denmark where taxes were paid in iron (Buchwald, 1991, p. 270). In 1924, Niels Nielsen, one of the great pioneers in the investigation of Danish iron smelting, also specifically mentions the area in his review of the material from Jutland where he mentions that "several slag heaps are known west of Ingelsvang (Engesvang) Church" and, moreover, describes them as being of quite considerable size (Nielsen, 1924, p. 77), (see also Fig. 5). All traces of the sites, however, disappeared during agricultural development in the 1950s and -60s.

HEM 2643 Neder Julianehede

One of the places where these slag heaps were supposed to be located partially reappeared in 1984 about 1000 m west of Engesvang Church, on an even, slightly north-facing slope near a small stream. Traces of a settlement with intensive iron smelting appeared in connection with deep ploughing in preparation for planting trees. All the material had been ploughed up, and the site was therefore very difficult to interpret. It was estimated that there were 215 furnaces in an area of ca. 30x100 m. Because of ploughed up potsherds, there is little doubt that the settlement dated to the Late Iron Age – probably AD 400–500 (this part is marked in blue in figure 6).

Apart from a field walking survey and some metal detector searches in the 1990s, not much more happened before December 2014 when the owner contacted the museum

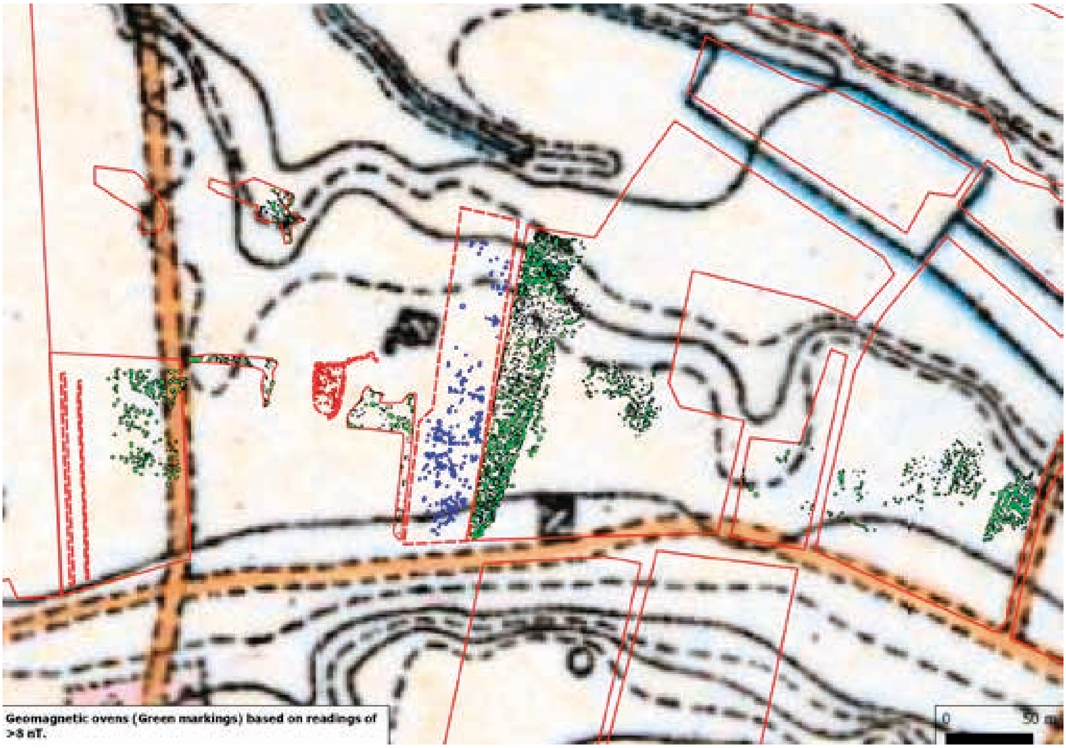

Figure 6. Overview plan of the finds at HEM 2642 Neder Julianehede. The furnaces marked in blue were deep ploughed. The violet ones were found during the excavation in 2014 and the green ones were registered by geomagnetic surveys in 2015. The red squares are the geomagnetically surveyed fields. Two empty test trenches dug in 2015 can be seen on the far left.

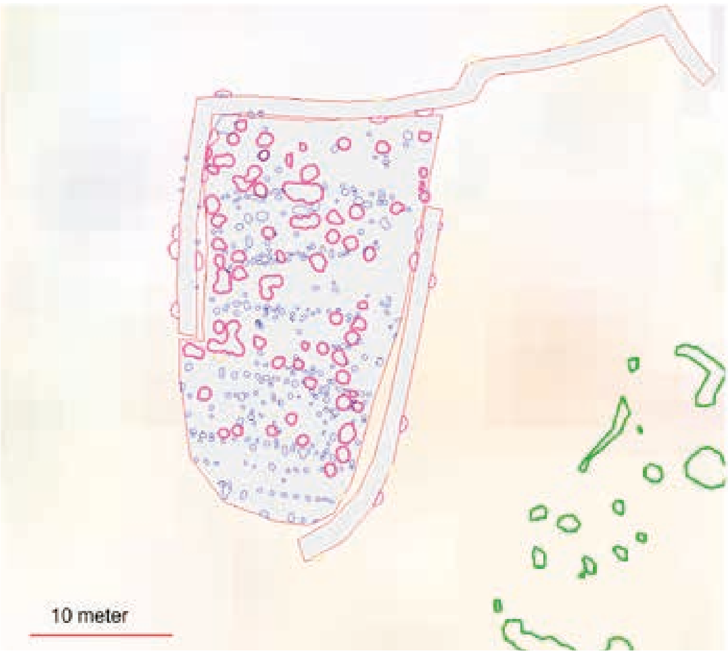

Figure 7. The excavated area at HEM 2642 Neder Julianehede. Postholes and similar features from houses are marked in blue while the furnaces are marked in violet.

because he had started to lay pipes for a heat pump system and came upon quite a few furnaces. The museum conducted a very limited rescue excavation of the area and completed an overall documentation of the site (the part marked in violet in figure 6), although some parts were lost during the pipe laying. Figure 7 shows what remained. Settlement traces in the form of 3 or 4 houses that are very typical for the Late Iron Age could be documented and also a large number of smelting features, at least 80, could be added to an unknown number that were destroyed by the trenches for the heat pump. Everything was located in an area of just 18x35 m. In all, the quantity and density of furnaces are much higher than anything we knew previously from central Jutland.

Another very important observation from the excavation was that the stratigraphy showed that the furnaces were both stratigraphically older and younger than the houses. In other words, we must expect that it is a quite long-lived settlement with more phases and rebuilding, and that smelting took place during several phases. Many samples for radiocarbon dating were taken, but the results are not available yet. Concurrently with the excavation, available sets of historical photographs and aerial photographs were reviewed. The iron production could not clearly be seen in this material, but cropmarks about 200 m to the south revealed several houses. These are probably not contemporary, but date to around the beginning of the 1st century AD.

Geophysical prospection

Since the spring of 2014, Museum Midtjylland has had the possibility to conduct geophysical surveys as an integrated part of its projects. The museum invested in a geomagnetic pushcart sensor system (Sensys MXPDA) with five sensors. One of the major ideas behind this investment was to be able to quantify the extent and content of our Iron Age sites at a relatively low cost, and with a non-destructive approach. Because of the nature of Neder Julianehede, it was obvious that surveys around the excavation area would be interesting. Figure 6 shows the areas in the immediate vicinity of the locality that have been surveyed to date. Anomalies interpreted as furnaces are marked in green in the figure. A huge number of furnaces seem to be present, but it is of course a problem that we presumably are dealing with broken-up furnaces. Thus, the identified slag is not a single, buried lump, but bits widely scattered in the plough zone due to cultivation. In other words, the geophysical prospecting does not show the number of furnaces, but it clearly shows the activity areas. Figure 8 shows some of the geomagnetic measurements, but in this case interpolated. The picture seen in figure 8 harmonises well with the archaeological observations. The form and organisation greatly resemble what we saw in the excavated area, and an example will be discussed a little later. Figure 12 indicates that the picture is substantially correct and most likely reflects preserved iron smelting furnaces.

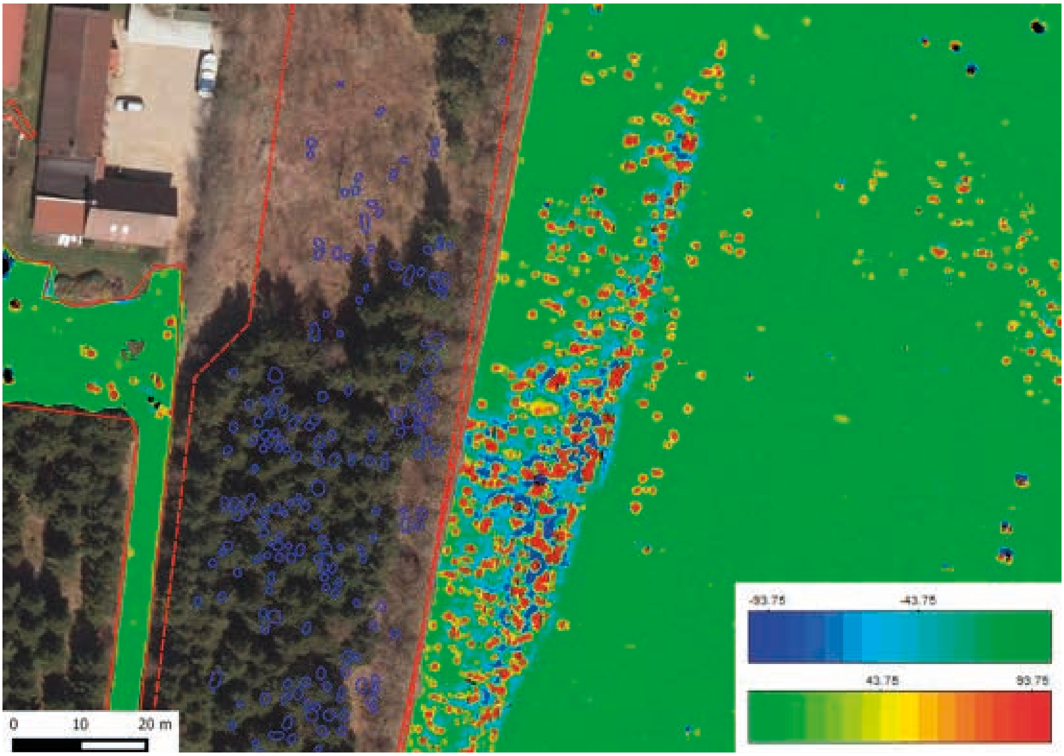

Figure 8. Interpolated section of the geomagnetic survey at HEM 2642 Neder Julianehede. Mikkel Fuglsang, who also created the plan views, conducted the geophysical surveying.

The most distinctive result is the strictly linear demarcation of the furnaces to the east. This can most likely be explained as the result of organising the furnaces along a linear fence. We see a rural settlement where smelting took place on a massive scale within, and in this instance, also outside the fence. But they are very sharply delineated within a "restricted area".

Combining the geophysical surveys and the results of the excavation, it seems that the settlement area covers an area of ca. 250x180. The settlement zone includes quite intensive iron smelting within the farmsteads and the whole settlement seems to be surrounded by a zone with many iron smelting furnaces. The settlement and smelting areas are placed at the edge of a contiguous area with tillable fields. That is, a picture that is congruent with the general image of a fairly tightly organised settlement from the Late Iron Age, but now somewhat further away from the "handicraft" iron production that was the general picture in central Jutland. Again, the nearest parallel would be locations like Snorup and Drengsted in southwestern Jutland (Mikkelsen & Nørbach, 2003, pp. 22ff).

However, a significant group of furnaces immediately east of the "village" is separate from the larger concentration. The furnaces are clustered and distinct, but without clear linear boundaries. It could very well have been a field or a pasture that was used for the purpose, which would explain why the smelting was so concentrated. Farthest to the east in figure 6 we see one or two similar concentrations, but fewer immediately west of these, but apparently linearly limited areas with furnaces. A possible interpretation is that these furnaces lie along a fence belonging to another farmstead. Perhaps the same picture as we see in the example from Holing. Apparently, the pattern repeats itself with iron production along the fence lines and on delimited fields/pastures closely connected to a central farm.

There have so far been no excavations outside the settlement zone. The interpretations are only based on the results of the geophysical survey. At this point, it is not possible to determine whether we see a chronological sequence reflected in this pattern. Another explanation could be that the iron smelting was of such high intensity that nearby fields were incorporated into the production.

HEM 5227 Mosebo

About 2.5 km east of Engesvang Church (also on a north-facing, flat surface, but in this instance above Lake Bølling), 64 iron furnaces were uncovered within a relatively limited excavation area (Fig. 9). Six C-14 dates suggest that the iron smelting took place in the

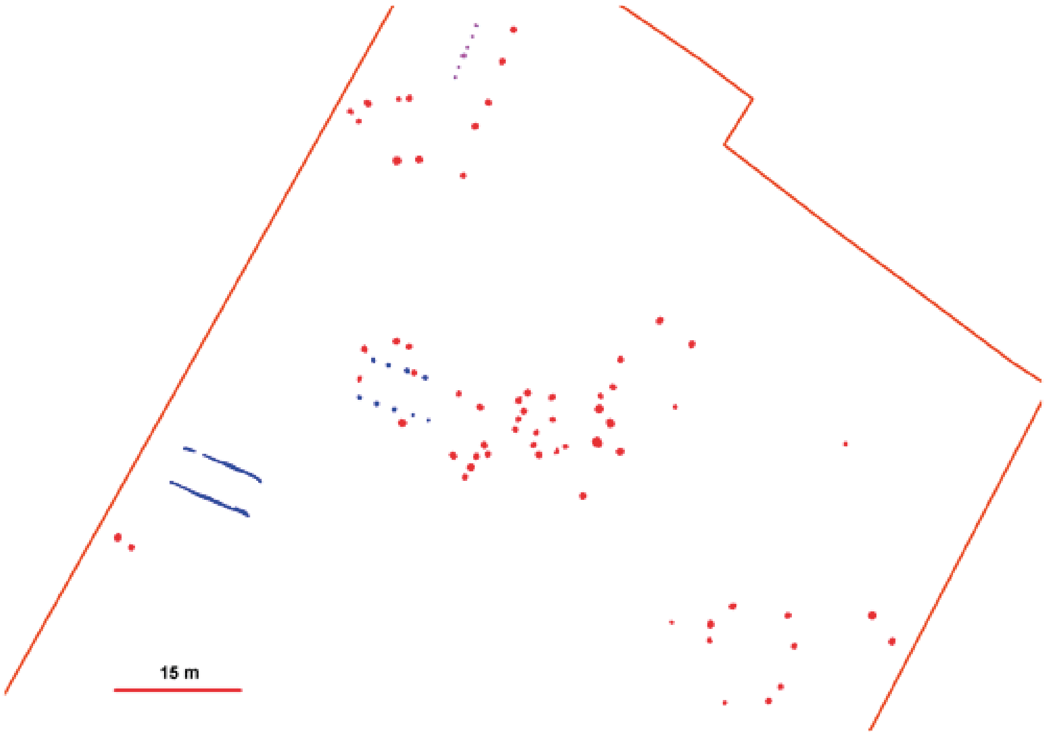

Figure 9. Overview plan of the excavation at HEM 5227 Mosebo. The iron furnaces are marked in red. House remains from the Late Viking Age and the Middle Ages are marked in blue.

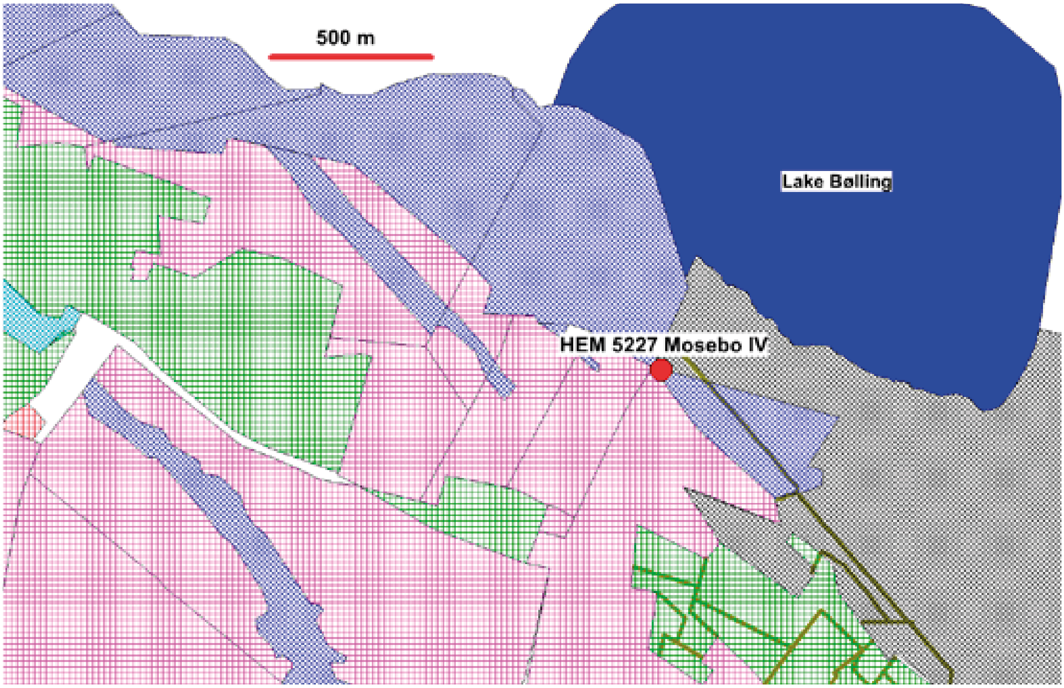

Figure 10. Land use around HEM 5227 Mosebo in 1844, digitalised from cadastral maps. Green is arable land, red is heath/heather, blue is swampy meadow and black is marsh.

3rd century AD. The furnaces are of the same type and dimensions seen at the other sites. The slag pits are 50–100 cm in diameter and 11–50 cm deep. Slag had also been dug up here, and relatively few and sporadic pieces of slag were preserved in the furnaces and on the site overall, taking into account the large number of furnaces. The bottom layers of the furnaces were generally well preserved and there were extraordinarily good conditions for examining them. New results are expected when the material is fully analysed, but we already know that the carbonised plant remains consisted of both straw and heather, but with a clear dominance of heather. Heather was used exclusively in 54 of the ovens, while only 6 contained both heather and straw. There was only a single example where only straw was used. The composition of this material therefore highlights a very clear connection to the outfield.

The location of the smelting is also markedly different from the other known places, as can be seen in figure 10. Here, the smelting locality is not at the edge of, or on, cultivated fields, but about 500 m north of the nearest "usable" arable land and on the boundary between a heath and areas of meadow and marsh. Furthermore, the site is on the bank of Lake Bølling. Very intensive pollen analyses were carried out in the area and it is apparent that, during the Iron Age, the lake had more or less the extent shown on the map, but to the west it is "dammed" by a raised bog. The dominance of heather in the furnaces suggests that the iron production apparently did not interfere with agriculture. It is noteworthy that, in contrast to all of the other sites, there is no other contemporaneous settlement activity in the immediate vicinity.

The results were supplemented by geomagnetic mapping in the area. The survey was carried out after the excavation. Figure 11 shows the excavation area and the area mapped with geophysics. Additional furnaces are certainly seen in the immediate vicinity of the excavation, but only a few and spread towards the east. However, there is a lucky example of a furnace that was documented during the excavation, but half of it remained in the wall of the trench. The remaining half was captured in the geophysical plan view. This furnace provides an excellent interpretive key for the geomagnetic mapping in the rest of the area, and thus great certainty that we are really seeing iron smelting furnaces in the remaining parts of the geophysical survey (Fig. 12).

A somewhat denser concentration can be seen to the west, where two quite distinct groups of furnaces occur in relatively well-defined clusters (Fig. 13). In other words, there are three such clusters with an estimated total of 160 furnaces. Apart from HEM 2642 Neder Julianhede, this is by far the largest number of furnaces on any of the investigated central Jutland sites.

Figure 11. Aerial photograph showing the excavation (red) and the geomagnetically surveyed fields in the vicinity. The black rectangles show the two sections reproduced below.

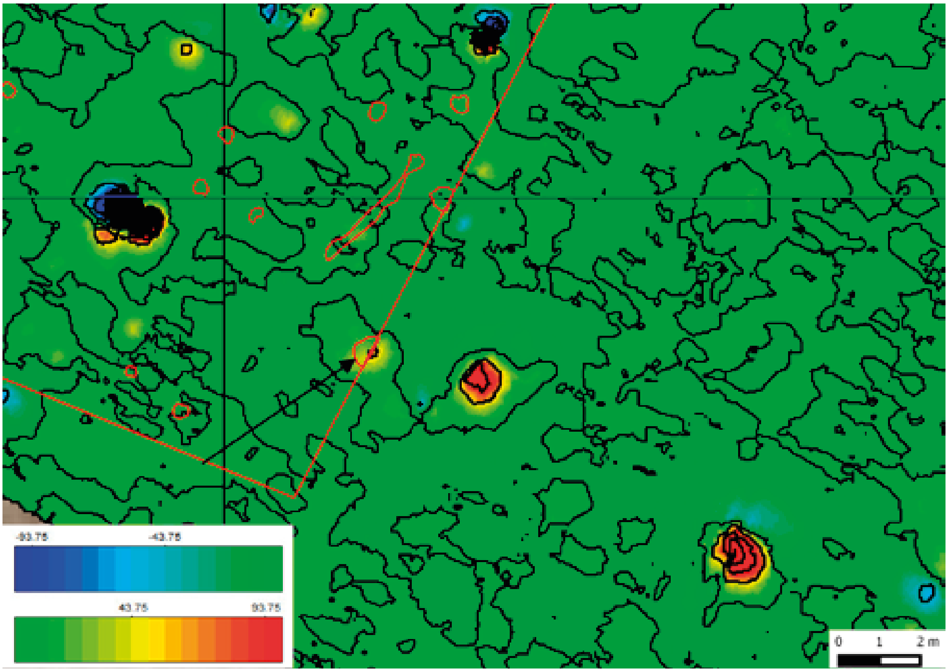

Figure 12. Section of the easternmost geophysical plan. The arrow shows the iron furnace that was half dug during the excavation and the signature it gave during the geophysical mapping. As such, it is a good key for interpreting the rest of the anomalies.

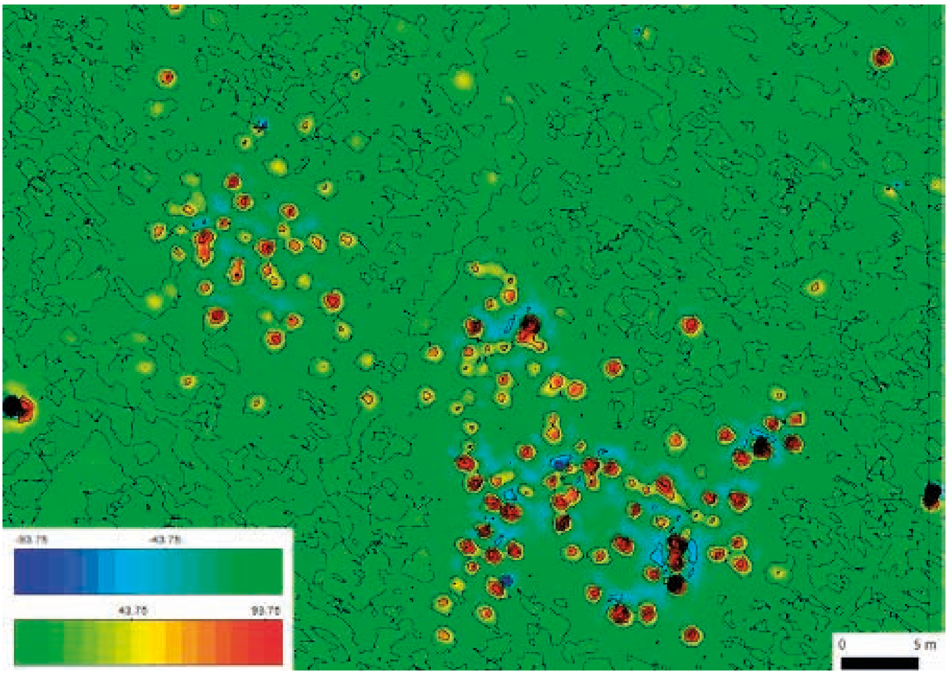

Figure 13. Section of the two clusters of furnaces west of the excavation. The westernmost one may contain about 70 furnaces with relatively high values while the easternmost has about 20–25 furnaces, but with much lower values that might be attributed to slightly worse preservation or a higher degree of demolition.

Conclusions

The combination of geophysical surveys of lager areas and excavations on these two sites has given us a quite detailed picture of the activity at a relatively low cost. The method has revealed more important points that have changed our understanding of both the scale and the organisation of iron production and the utilisation of the landscape.

At Neder Julianehede, iron production was apparently quite intensive within the farmsteads in the excavated area. The excavation has confirmed that the settlement is indeed from the Late Iron Age. However, the geophysical surveys show that iron production on the infields was greatly supplemented by many furnaces just outside the village. These furnaces are found in a string that is interpreted to be shaped by the village demarcation, but we also find them in more isolated, rounded clusters. These clusters might be interpreted as reflecting a field system in the vicinity of the settlement area.

Mosebo, on the other hand, represents quite intensive iron production in what would seem to be an agriculturally marginal area. The excavation supports this assumption, showing a clear dominance of heather in the furnaces. The excavation also provided a dating of the activity which indicates that the smelting area had no traces of contemporary farmsteads. If the settlement behind this production was located on arable land, as seems to have been the general situation, it must have been quite distant from the smelting site. The supplementary geophysical surveys give a clear picture of very intensive iron smelting activity in the area in general.

Even though the area seems agriculturally marginal, the furnaces are organised in similarly distinct, rounded clusters as seen at Neder Julianehede. If this is not just pure coincidence, the explanation could be that even these marginal areas were controlled and regulated in a well-marked field system.

Celtic field systems are well known in Jutland in general and are also widely found in what are nowadays agriculturally marginal areas, for instance in heaths. The Celtic fields are generally older and they are seldom preserved in areas with a high level of modern agricultural activity. But their presence more than indicates that well-marked field systems were a common feature prior to the Late Iron Age in Denmark and one must expect that marking of land ownership survived, perhaps in an altered form.

If the rounded clusters of furnaces reflect field systems, this is a new, indirect way of identifying land ownership and landscape utilisation in areas where iron production is integrated in the economy.

Both Neder Julianehede and Mosebo are in the eastern part of the research area, and the surveys and excavations have shown them to be sites that indeed produced more iron than was needed locally. The general picture of iron smelting in the western part of the research area, where we see iron smelting as an integrated part of the farmstead's production, but hardly on a scale that would supply more than the farm or the village itself, still stands. This could easily lead to a thesis that we actually see a specialisation of iron smelting in the area around Lake Bølling and in the eastern part of central Jutland in general. This might indeed be the case. However, it should be emphasised that there have been no large-scale geophysical surveys of areas surrounding the villages in the western part and if we suddenly identify similar concentrations of furnaces in this area, it would rapidly change this picture.

References

Buchwald, V. F. (1991). Jernfremstilling i Danmark i Middelalderen – lidt om bondeoven og kloder. In Det kongelige Nordiske Oldskriftsselskab (Ed.), *Aarbøger for Nordisk Oldkyndighed og Historie 1991* (pp. 265–286). København: Det kongelige Nordiske Oldskriftsselskab.

Helt, J. (2015). *Jernudvinding i Midtjylland 1–650 e.Kr. Rumlig organisation og landskabsmæssig placering af lokaliteter med slaggegrubeovne*. (Bachelor project). Aarhus University, Aarhus.

Jensen, E.-M. (2006). Den romerske villa og fyrsten fra Tjørring. Økonomiske, sociale og politiske forhold i ældre jernalder ved Herning. In Museum Midtjylland (Ed.), *Midtjyske fortællinger 2006* (pp. 67–106). Herning: Museum Midtjylland.

Mikkelsen, P. H. & Nørbach, L. C. (2003). *Drengsted. Bebyggelse, jernproduktion og agerbrug i yngre romersk og ældre germansk jernalder. Jysk Arkæologisk Selskabs skrifter, 43*. Højbjerg: Jutland Archeological Society.

Nielsen, N. (1924). *Studier over Jærnproduktionen i Jylland – Med nogle Bemærkninger om Jærnudvindingens Udviklingsgang*. Copenhagen: Arnold Busck.

Olesen, M. W. (2010). Stenbjerg smedjerne. Åbne eller lukkede værksteder – en diskussion af emnet lukkede eller åbne værkstedsrum med udgangspunkt af de nyeste overfladeanalyser. In H. Lyngstrøm, M. W. Olesen & L. G. Thomsen (Eds.), *Smedens rum 1. Værkstedet. Arbejdsrapport fra det første seminar i netværket Smedens Rum 14. oktober 2010 på Københavns Universitet. Arkæologiske Skrifter* (vol. 9, pp. 17–45). Copenhagen: SAXO-Institute, University of Copenhagen.

Olesen, M. W. (2012a). Kulstof-14 dateringer af midtjyske jerudvindingsovne fra ældre jernalder. In H. Lyngstrø & M. Ravn (Eds.), *Smedens rum 4. Produktionen. Arbejdsrapport fra det fjerde seminar i netværket Smedens Rum 14. oktober 2012 på Københavns Universitet. Arkæologiske Skrifter* (vol. 11, pp. 115–132). Copenhagen: SAXO-Institute, University of Copenhagen.

Olesen, M. W. (2012b). Midtjysk jernudvinding i yngre jernalder. In Museum Midtjylland (Ed.), *Midtjyske fortællinger 2012* (pp. 119–134). Herning: Museum Midtjylland.

Olesen, M. W., Hansen, A. S., Christensen, P. M. & Hansen, T. E. (In press). *Iron smelting in central and western Jutland in the Early Iron Age, 500 BC to AD 200*.

Smekalova, T., Abrahamsen, N. & Voss, O. (1996). Magnetic investigation of a Roman/Early Germanic Iron Age iron-smelting centre at Snorup, Denmark. In V. Mejdahl & P. Siemen (Eds.), *Proceedings from the 6th Nordic Conference on the Application of Scientific Methods in Archaeology* (Arkæologiske Rapporter, 1/1996, pp. 227–245). Esbjerg: Esbjerg Museum.

Voss, O. (1993). Snorup. Et jernudvindingsområde i Sydvestjylland. In Nationalmuseet (Ed.), *Nationalmuseets arbejdsmark 1993* (pp. 97–111). Copenhagen: National Museum of Denmark.

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Mapping early iron production features in woodland using remote sensing techniques

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Abstract

Traces of early iron production are commonly recorded when outfield areas are searched for archaeology. A relatively new technique like lidar has made it possible to identify iron production sites from aloft, including charcoal pits associated with pre-industrial production of iron. This paper is about remote sensing, primarily lidar, and how this can be employed in woodland environments to identify and map early iron production. Previous studies with a similar purpose are elaborated on in this study. This is done by applying a series of visualisation techniques developed for archaeological use over the last decade and quantifying the effects of employing such techniques. The study is based on the involvement of two independent archaeologists with lidar experience who interpreted a range of different models. Their effort produced figures used for statistical calculations indicating the added value of adopting various visualisation techniques. The last part of the paper reviews another remote sensing technique, airborne magnetometry, and its potential for identifying slag heaps and similar highly magnetic features present in the landscape. This includes a short description of the initial steps in a test which has not been completed yet.

Introduction

Knowledge of archaeological monuments, sites, remains and items is a vital precondition for working in archaeology, whether you are involved in research or cultural heritage management. Archaeological knowledge is a wide concept, embracing information about culture, environment, function, dating, chronology and location, and it also involves expertise in surveying, excavation, analysis and interpretation. In this article, the focus will be on archaeological field survey and especially the location of archaeological monuments, features and sites. To find and map archaeology is an important part of the archaeological process and often serves as the initial step in a project. Surveying and mapping are meant to encapsulate information about what is present in a certain area – large or small – as the basis for investigation through landscape studies, excavations, or as means of safeguarding cultural heritage. Surveying and mapping are first and foremost connected with the field of archaeological method, and customarily comprise the use of a wide range of techniques. There is a longstanding tradition within archaeology for rapidly adopting advanced technologies (often developed for other purposes initially) and employing these as means for attaining better results and/or increasing the efficiency of different aspects of the archaeological procedures. This applies not least to the art of surveying and mapping, which has a long tradition of employing advanced on-ground remote sensing technologies such as geophysics (magnetic surveys, ground penetrating radar, etc.) and off-ground remote sensing techniques and methods such as aerial photography, satellite and lidar ("light detection and ranging").

This paper will concentrate on the use of remote sensing, primarily lidar, in woodland environments. When lidar emerged as a new method in archaeology around the turn of the millennium, it soon garnered the interest of the archaeological community and especially those archaeologists engaged in woodland archaeology. In Norway, we carried out the first archaeological lidar project as a test in Elverum in 2005 (Risbøl et al., 2006a). The driving force behind this project was a general interest in developing and implementing survey and mapping methods to improve the poor inventories concerning archaeology in outfield areas. The exploitation of a large range of outfield resources in the past is today present as numerous traces of human impact in forest and outfield areas. These traces, however, are seldom mapped. In particular, the remnants of prehistoric and medieval iron-production are extensive in large parts of the Norwegian woodland (Larsen 2009). The large scale of this production is of utmost importance for understanding the development of Late Iron Age society in general culture historical terms, but it also sheds light on aspects related to state formation in Norway (Larsen, 2009, pp. 191-194; Rundberget, 2012, pp. 323–327). Improving our knowledge of the extent of iron production and thereby creating a basis for more detailed studies of all facets of pre-industrial iron production, is therefore essential.

To improve our knowledge of archaeology in woodlands, lidar with its particular properties emerged just over a decade ago as an unrivalled possibility. The most significant characteristic of lidar compared to other remote sensing techniques is that it uses laser pulses to collect data. It is an active method which collects high-resolution data from the ground surface, making it possible to generate digital terrain models (DTMs) of the Earth's surface with a considerable level of detail. Its ability to penetrate vegetation indisputably makes it a favourable method for identifying archaeological monuments and features in woodland. This is evidenced by many projects carried out in woodlands and forests worldwide since the dawn of lidar in archaeology (see, for instance, Bofinger & Hesse, 2011; Chase et al., 2014; Doneus & Briese, 2011; Evans, 2016; Johnson & Ouime, 2014).

Although the implementation of lidar in archaeology has been successful, the application of the method has its limitations. One such limitation – which will be addressed in this article – is the challenges in interpreting DTMs and successfully identifying as large a variety of cultural features as possible. Studies have shown the effects on detection success in relation to data resolution and smoothing (Bollandsås et al., 2012) and the morphology of archaeological features (Risbøl et al., 2013), respectively. Concerning the morphology of features, it was concluded that, largely speaking, size matters, i.e. that it is – perhaps not unexpectedly – easier to identify large features than small ones. Yet, this is not definitive since some archaeological features, even though they are large, may still be difficult to distinguish from natural features. This is the case with slag heaps which, although of considerable size but lacking a clearly defined morphology, may easily be mistaken for natural features. This was one significant conclusion of our first test using lidar in a woodland environment in Elverum in 2005 (Risbøl et al., 2006b, p. 112). Considering new visualisation techniques recently developed specifically for archaeological lidar interpretation, such as Local Relief Model (Hesse, 2010), Sky-View Factor (Kokalj et al., 2011), Slope Contrast Mapping (McCoy et al., 2011) and Openness (Doneus 2013), this conclusion must be re-examined. Another issue we will address regards the fact that slag heaps are highly magnetic – a property that makes them stand out from the surrounding natural environment, creating certain possibilities in terms of detection by other remote sensing techniques such as those developed with the purpose of mapping geology. Thus, the objective for this paper is twofold:

i) To what extent can recently developed visualisation techniques improve the identification of indistinct archaeological features?
ii) Can airborne remote sensing techniques developed for measuring the strength of magnetism of the Earth's surface supplement lidar in identifying archaeology?

Methods

To address the first objective, we revisited the Elverum project a decade after it was concluded. Results from the lidar interpretations made at the time constituted the basis for the new interpretations and comprised some of the newly developed visualisation techniques. The original interpretations were carried out using Quick Terrain Modeler[1]

(QTM), a modelling software developed to facilitate real-time manipulation of large amounts of 3D data. QTM allows for the interactive manipulation of data, such as surfing through the data sets, altering the light angles both in the vertical and the horizontal, as well as exaggerating the elevation. It is also possible to generate digital profiles through the data sets, greatly aiding the interpretation of observed anomalies.

The archaeology in the Elverum study area is dominated by iron production related features which can be dated to the Late Iron Age and the Early Middle Ages (approx. 950–1300 AD). Broadly speaking, the features consist of 1) charcoal pits (Fig. 1), 2) sites where bog ore was roasted, and 3) the actual iron production sites (Fig. 2), which are usually visible due to the presence of slag heaps – occasionally alongside charcoal and iron ore depots (Table 1).

Figure 1. Example of a charcoal pit. Note the substantial enclosing bank. Photo: Arve Kjærsheim, RA/NIKU

The roasting sites are, in all material aspects, invisible above ground. They are therefore not detectable by lidar and seldom found by ordinary field walking. When found, it is either by the digging of

Figure 2. Example of an iron production site with two slag heaps. Photo: NIKU

Table 1. Some characteristics representative for features related to iron production in the Elverum region. The figures are from the nearby Gråfjell area where a large archaeological project was carried out from 1999 – 2007 (Risbøl 2005; Rundberget 2007).
The features surveyed and excavated as part of the Gråfjell project are similar to the ones found in the Elverum study area. The distance between the two areas is approximately 10 kilometres.

	Roasting sites	Charcoal pits	Iron production sites
Visible above ground	No	Yes	Yes
Magnetic property	Yes	No[2]	Yes
Average extent (m^2)	5.5[3]	44[4]	756[5]
Variance (m^2)	0.96 – 15.54[3]	1.53 – 152.62[6]	214 – 1776[5]

trial pits or trial trenches, the use of magnetometer or through accidental exposure by, for instance, forestry activities. This is not the case with charcoal pits and most of these were identified in the 4 points per square metre lidar data sets in the previous Elverum study, and the detection rate was proven to be at least 74%, with 83% as the best result (Risbøl, 2009, p. 216). The same study, however, showed that the detection rate for iron production sites (indicated by slag heaps) was much lower. Of 17 anomalies interpreted to be iron production sites, only five (29%) turned out to be correct interpretations when investigated in the field (Risbøl et al., 2006a; 2006b). In another case, none of the six iron production sites were found in the lidar-generated DTM, and in a third case only one of two sites was identified (Risbøl, 2010). These results clearly showed that the use of lidar is particularly suited for detecting charcoal pits in this case. However, it also identified the need for improving the method as well as the development of new remote-sensing based solutions, especially with reference to identifying iron production sites.

Supplementary visualisation techniques

One approach to an improvement was to test if the use of various visualisation techniques developed to enhance lidar-generated models could be beneficial. The most common visualisation of lidar data sets is undoubtedly the simple shaded relief model, also known as hillshading. This visualisation technique is relatively easy to generate, analyse and interpret. Since the introduction of lidar for archaeological purposes, however, several shortcomings in using the hillshade model have been identified (Hesse, 2010, p. 68). Hillshade models are generated using a single imagined light source from a fixed position in relation to the data set. Linear features lying parallel to this light, subtle features or features in highly illuminated or shaded areas might become indistinct and thus difficult to identify (Challis et al., 2011). This is generally not a problem when using software solutions where the light angle can be altered interactively, but this requires the interpreter to focus on separate small areas before moving on to the next. By creating several individual hillshade models with differing light settings, attempts have been made to counter this effect, but this approach has been found to be inconvenient when analysing large data sets, or data sets featuring archaeological structures with varying morphology (Zakšek et al., 2011, p. 400).

Since the abovementioned studies of the Elverum data in 2005 and 2006, a series of supplementary visualisation techniques have been developed to circumvent these issues, and to improve the identification and interpretation possibilities when manually searching lidar data sets for cultural monuments and remains. In the present study, we created a series of models using these visualisation techniques to examine whether they could improve the identification of slag heaps and charcoal pits in lidar-generated DTMs (Fig. 3). The models were created using the Relief Visualisation Toolbox 1.1 (RVT)[7], a standalone software solution developed by the Institute of Anthropological and Spatial

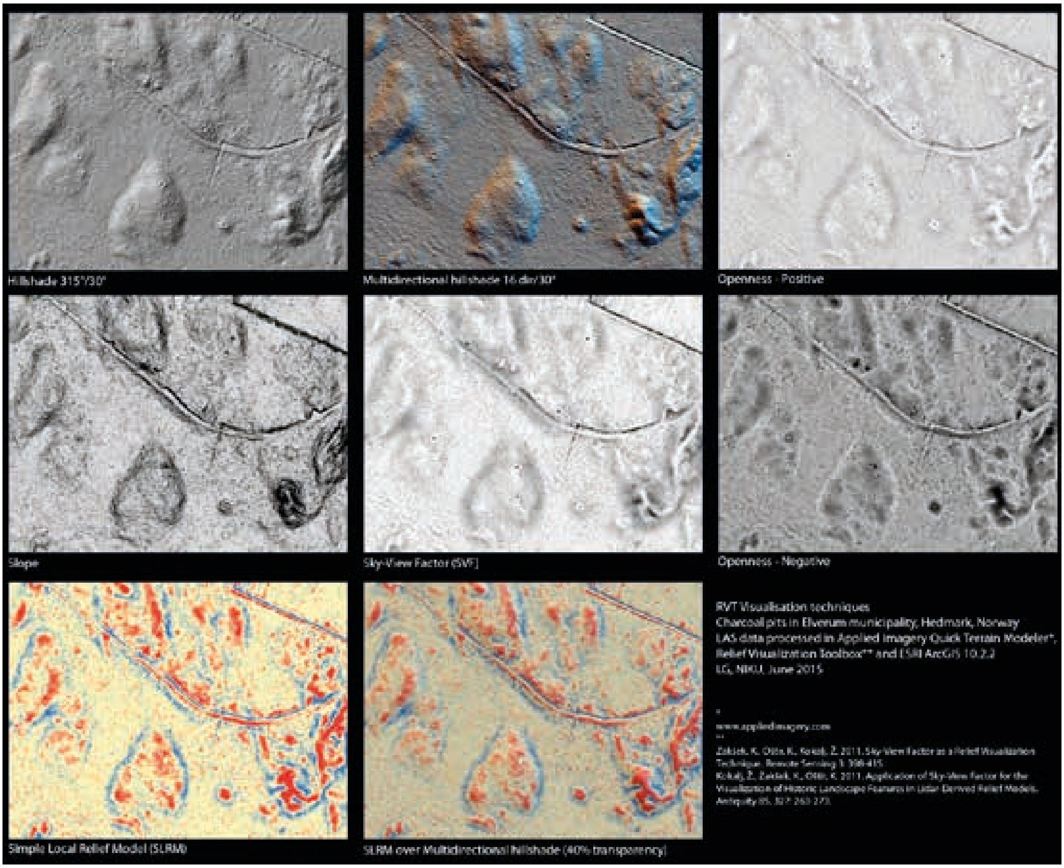

Figure 3. A section of the Elverum study area with examples of common visualisation techniques used for the interpretation of lidar data sets where iron production sites are present. The models were created using a combination of Quick Terrain Modeler, Relief Visualisation Toolbox and ArcGIS 10.2.2.

Studies at the Research Centre of the Slovenian Academy of Sciences and Arts (ZRC-SAZU). This software has been developed to aid scientists in the visualisation of raster-based elevation models, and more particularly to help identify small-scale features in the data sets. In addition to the hillshade models, RVT can generate hillshading from multiple directions, PCA (principal component analysis) of hillshading, slope gradient models, simple local relief models (SLRM), as well as various forms of sky-view factor (SVF) and openness.

For the purpose of our test, elevation models generated from the last pulses (the ground points) of the entire lidar data set were imported to RVT in the form of georeferenced .tif files and from this, the following visualisation models were generated:

Visualisation model	Settings
Hillshade (HS)	Sun azimuth 315°, elevation 30°
Hillshading with multiple directions (MHS)	16 directions, elevation 30°
Slope gradient model	Inverted
Simple Local Relief Model (SLRM)[8]	Search radius 20 px (10 m)
Sky-View Factor (SVF)	16 directions, search radius 20 px (10 m)
Openness – Positive	16 directions, search radius 20 px (10 m)
Openness – Negative	16 directions, search radius 20 px (10 m)
Combination of SLRM and SVF	40% transparency

All models were generated using a vertical exaggeration of factor 2 in order to enhance the visualisations.

The next step was to study the effects of using these new visualisation techniques. This was done by interpreting the newly generated models and comparing the results with a) previous fieldwork results and b) the results of the previous study of detection success conducted in 2005 and 2006. For that purpose, a section of the original Elverum project area was chosen as the study area. The study area has an extent of slightly more than 3.5 km^2 and has been surveyed archaeologically on previous occasions by systematic field walking, by which 14 iron production sites and 149 charcoal pits were found and mapped (Fig. 4).

To carry out the interpretations, we decided to involve two interpreters who were assigned the task of finding as many iron production sites and charcoal pits as possible in the hillshade model using QTM as well as in the newly generated models of the

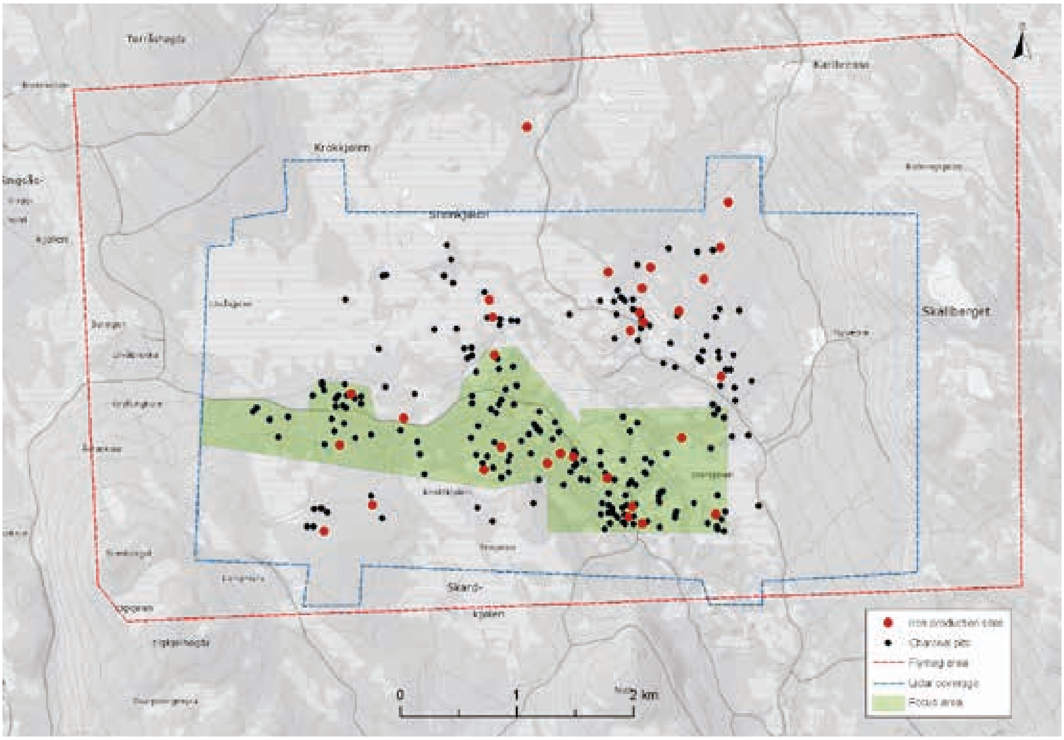

Figure 4. The Elverum case study area showing the distribution of known iron production sites and charcoal pits. The area surveyed using lidar in 2005 is outlined in blue and the area covered by airborne magnetometry is outlined in red. The focus area for the visual interpretation is shaded in green. Background map: Norwegian Mapping Authority, Geovekst and Municipalities, 2015.

study area. This was done to avoid introducing bias to the interpretations. Alternatively, we could have carried out the interpretations ourselves, but it was felt this would have increased the risk of bringing in bias as a consequence of our own knowledge about the area and the localisation of the archaeological features. Both interpreters were archaeologists with experience (but different experience) in working with lidar data. They were not, however, familiar with the study area, but were shown examples of similar features from other areas in advance. The interpreters were not given any further supervision, and they were not allowed to collaborate during the session. Their use of time was restricted to eight hours.

A hillshade model based on the lidar scanning carried out in 2005 was used as a basis for the interpretations. This scanning provided a model generated with an average of 4 points per square metre[9]. The test persons first identified and interpreted as many anomalies as possible using the hillshade model in QTM. Then the interpretations were supplemented with the identification of anomalies using the abovementioned set of pre-prepared visualisation techniques. This step of the test was carried out using ESRI ArcGIS 10. The results of the interpretations were then entered into a spreadsheet, with the numerical results distributed on the two interpreters and the two categories of cultural remains (Table 2). These figures were then divided into three categories connected with detection success: True positive (TP), False positive/commission error (FP), and False negative/omission (FN). TP are those identifications that were interpreted correctly, FP are those interpreted incorrectly and FN the cultural remains that the interpreters did not find. As a next step, these figures were analysed with regard to their distribution on interpretations done using QTM on the one hand, and the set of supplementary visualisation techniques on the other. The figures were handled as numbers and calculated into percentages.

Traditional vs supplementary visualisation techniques – results

The total number of iron production sites and charcoal pits found within the test area (Fig. 4) is 14 and 149, respectively – a result established by systematic field search. One of the interpreters managed to detect five of the iron production sites, while the other found seven through the digital interpretations. Corresponding figures concerning the 149 charcoal pits are 114 and 116. Regarding false positive detections, the risk of confusing natural features with cultural features is ever present. One of the interpreters wrongly indicated 10 charcoal pits, but no iron production sites, while the other misinterpreted what must be natural features to be iron production sites in nine cases and charcoal pits in 19.

Table 2. The results of the interpretation test. TP = True positive, FP = False positive, FN = False negative, TPR = True positive rate, TPNI = True positive number of interpretations

		Interpreter 1			**Interpreter 2**		
		Markings (N)	TPR (%)	TPNI(%)	Markings (N)	TPR (%)	TPNI (%)
TP	Iron prod. sites	5	36		7	50	
	Charcoal pits	114	77		116	78	
FP	Iron prod. sites	0			9		
	Charcoal pits	10			19		
Sum		**129**		**92**	**151**		**81**
FN	Iron prod. sites	9			7		
	Charcoal pits	35			33		
Sum		**44**			**40**		

On average, the two interpreters managed to detect 43% of the iron production sites and 78% of the charcoal pits. In previous studies where hillshade models from the study area were interpreted solely using the QTM software, 25% of the iron production sites and 77% of the charcoal pits were detected (Risbøl, 2010; Risbøl, et al. 2007). Regarding the total sum, therefore, the results show almost no effect of using additional visualisation techniques when aiming to detect charcoal pits, but a substantial effect concerning the iron production sites, where the detection success increased by 18 percentage points, i.e. from 25% to 43%. Nevertheless, what the figures also show is that the detection rate in this test increased by 20 percentage points for iron production sites and 18 for charcoal pits as an effect of supplementing the QTM interpretations with additional visualisation techniques. This indicates a gain of using supplementary visualisation techniques, but also a poorer result of the QTM-based interpretations in the present test compared to the ones carried out a few years back.

As expected, a clear majority of the identifications were done in QTM (79%), which was used as a first stage approach to the data, while 21% were based on the supplementary enhanced visualisation techniques. A somewhat larger proportion of the charcoal pits were detected in QTM (80%) compared to 70% of the iron production sites. If we compare the two interpreters, a difference between the use of the two alternative interpretation modes appears. The distribution of interpretations based on QTM on the one hand and the supplementary visualisation techniques on the other is 72% versus 28% for one test person and 86% versus 14% for the other.

Concerning the false positive rate, 33% of the wrongly indicated iron production sites and 38% of the charcoal pits are a result of interpretations based on the new visualisation techniques.

Discussion

The aim of the first part of the study was to highlight the effect of using a set of visualisation techniques developed in recent years to improve the analysis and interpretation of lidar-generated DTMs. The result of the present test using a variety of visualisation techniques is measured against initial studies where hillshades were analysed and interpreted using the QTM software. The effect of applying more visualisation techniques was quite substantial concerning the iron production sites where 43% were detected as opposed to 25% originally. In terms of charcoal pits, the increase was only 1 percentage point up, from 77 to 78 percentage points. This difference must be related to the general challenge in detecting slag heaps which are very low and/or have a poorly defined morphology as opposed to charcoal pits. Still, it is worth noticing that the benefits of using a range of visualisation techniques are almost absent regarding the normally morphologically well-defined charcoal pits[10]. This is probably because the omitted charcoal pits are in a state of preservation that makes them unrecognisable or, perhaps more likely, they are covered by dense vegetation that prevents laser pulses reaching the ground. To manipulate or enhance lidar data to improve the interpretation of the bare ground conditions will only have an effect where ground points exist. The relationship between vegetation cover and *identification* of anomalies has been pointed out in previous studies (Corns & Shaw, 2009, p. 75; Crow et al., 2007; Risbøl et al., 2006b, p. 111). The improved effect upon the iron production sites, on the other hand, must be a result of improved possibilities for *interpreting* identified anomalies.

79% of the interpretations were made in QTM – 70% of the iron production sites and 80% of the charcoal pits. That most of the interpretations are based on QTM is probably caused by the sequence of the test where the QTM-based interpretations were carried out first followed by the supplementary visualisation techniques. If we compare the results of the two interpreters, the TP figures concerning charcoal pits were quite similar, with 77% and 78% TPR, respectively. On the other hand, regarding the iron production sites there is a difference between the two interpreters who managed a TPR of 36% and 50%, respectively. The slightly poorer result obtained by one of the interpreters must be seen in light of the fact that this person did not have any FP for iron production sites as opposed to the one with the best TP who, in nine cases, wrongly determined natural features to be iron production sites. The overall true positive number of interpretations (TPNI) performed by the two interpreters was 92% and 81%, respectively. The apparent difference between the two interpreters in terms of the rate of QTM-based versus supplementary visualisation techniques-based interpretations might be explained by different experience in interpreting lidar data sets. This might also explain the abovementioned difference concerning the TPR and TPNI.

The test has indicated a quite substantial improvement of detection success concerning the features most difficult to identify in lidar-generated DTMs, namely iron production sites, more of which are found using additional visualisation techniques. This seems not to be the case concerning the charcoal pits where the gain was marginal. It is also important to stress the fact that improved interpretation conditions also led to an increase in FP as is the case in this study where the figures show a 33% and 38% increase in incorrectly detected iron production sites and charcoal pits, respectively. A similar tendency was proven in a study concerning the effect of increased point density on detection success where higher resolution led to a higher TPR but also a higher number of FPs (Bollandsås et al., 2012).

Other studies carried out support the contention that the use of more than one visual approach to a data set is beneficial as better results will be obtained (Bennett et al., 2012, p. 47; Challis et al., 2011, p. 288; Štular et al., 2012, p. 3359). Bennett et al. (2012, pp. 43-44) report that none of the techniques used in their study managed to identify more than 77% of the cultural features in their study area, but this number increased to 97% when additional visualisation methods were used on the same data set. A general experience gained from these studies is that no single technique will outdo the others, but that the different approaches will have advantages which are related to the character of the landscape studied and the morphological characteristics of the cultural features in it. Landscape varies in terms of topography, vegetation, etc., and cultural features constitute an almost infinite variation regarding their appearance. A previous study has proven the relation between detection success and the physical property of cultural features; mainly their size and shape (Risbøl et al., 2013). Challis et al. (2011, p. 287) and Štular et al. (2012, p. 3357) drew similar conclusions. The present study has also shown that size matters, but only to a certain extent. Even though the slag heaps at the iron production sites are usually of a considerable size, less than 50% were identified in the study area. As mentioned above, this might partly be related to the lack of a clearly defined morphology which makes it difficult to distinguish these man-made features from natural ones. In figure 5, the iron production sites that constitute part of this study have been divided into four different classes in accordance with their size on the one hand and the number of times they were identified on the other. As the figures show, there is no absolute consistency in the connection between size and detection success. Provided conditions are ideal, it is possible to detect cultural features with a very low elevation, down to 5–15 cm as shown by Bennett et al. (2012, p. 44) and 5–20 cm, as shown by Sittler (200, p. 285). However, as mentioned above, other relations such as size (spatial extent) and geometrical shape are also important, in addition to relative elevation. The average height of the slag heaps in the present study is 98 cm and, still, less than 50% were detected.

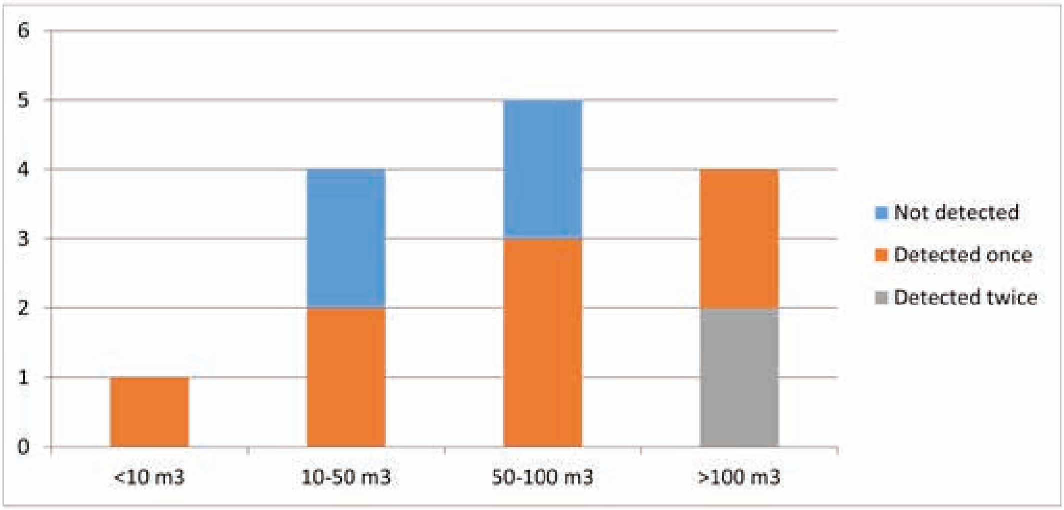

Figure 5. The iron production sites divided into four groups according to their relative size (based on slag volume[11]) and the number of times they were identified by the interpreters.

Thus, the size and visibility of iron production sites are not sufficient circumstances to ensure their identification based on lidar. In other iron producing regions in Norway, the distribution of iron production sites and charcoal pits differs from that in our study area. In the county of Oppland and neighbouring areas, 1–4 charcoal pits are normally situated at the iron production sites adjacent to the slag heaps (Larsen, 2009; Narmo, 2000, pp. 139–140), a situation that makes it possible to use the more readily detectable pits to indirectly identify where the iron production sites are situated (Trier & Pilø, 2015). In some areas, quite well-defined house foundations are also co-localised with the iron production sites – another situation which also makes indirect identification possible.

Still, in order to improve the identification of iron production sites from aloft in large areas, it is of current interest to look to other remote sensing methods as a supplement to lidar. The use of an airborne magnetometer is highly relevant in that respect.

Airborne magnetometer

The use of magnetometers, whether ground based or airborne, adheres to the same general principles. Highly sensitive instruments can detect minute changes in the Earth's magnetic field (Aspinall et al., 2008; Gaffney & Gater 2003, p. 61–72). These changes may or may not be a result of human activity. The successful detection of archaeological features by means of magnetic instruments relies on the relative magnetic properties of the soil compared to the surrounding soil matrix. Generally speaking, soils can reach higher levels of magnetism as a result of direct heating, or by reduction and oxidation. Weakly magnetic iron oxide compounds are ubiquitous in all soils (Birkeland 1999). When soil is heated to temperatures beyond the *Curie point* (c. 600° ± 100°C, varying according to the minerals present in the soil), the iron content is demagnetised and loses its magnetic properties. If the soil is then allowed to cool, it will be re-magnetised, acquiring new magnetic properties according to the Earth's magnetic field at the time. This process is called magnetic thermoremanence and is generally seen as the hallmark of archaeological features involving relatively high temperatures, such as hearths and kilns. Soils can also attain a higher level of magnetisation through reduction and oxidation, although these processes are to a lesser degree understood. What is known is that the weakly magnetised iron oxides in the soil can be altered to more magnetic oxide forms through processes involving reduction. When a soil is heated in the presence of organic matter, oxygen is removed, creating reducing conditions where the soil's haematite is converted to magnetite. This is called the Le Borgne effect and occurs at approx. 200°C. Upon cooling and re-oxidation, some of the magnetite is altered into maghemite, thus increasing the magnetic properties of the soil. Both processes take place in iron processing, creating strong positive magnetic anomalies (Vernon et al., 1999). Iron, cobalt and nickel are elements largely similar to ferromagnetic minerals, which are among the strongest forms of magnetism (Aspinall et al., 2008, p. 13). Iron also has the property to retain its magnetisation when external magnetic fields are absent (Aspinall et al., 2008, p. 16).

Many of the stages involved in early iron production are inextricably linked with the use of heat: charcoal was produced in turf-covered piles, where wood was slowly burnt in order to carbonise. Ore had to be meticulously roasted before being transferred to high-temperature furnaces for further processing.

Bog iron ore is a form of iron oxide-hydroxide carried by water from iron-rich bedrock and, depending on the chemical, physical and biological conditions present, deposited in nearby bogs (Larsen, 2009, pp. 28–30). Prior to reduction in furnaces, the ore had to be extracted from the bogs, dried and then roasted to remove chemically bound water and impurities such as sulphur and phosphate, as well as organic matter (Larsen, 2009, p. 56). The ore was roasted on open log fires, where it was placed on top of the logs in some form of pan. When the fire had burnt out, the ore had been roasted through (Rundberget, 2007, p. 23). In this process, the ore oxidises into ferrimagnetic maghemite, the detection of which has been amply demonstrated in the Gråfjell project, where the remnants of 220 roasting sites were registered by magnetic survey (Rundberget, 2007, p. 279). Further processing took place in furnace shafts made of clay where roasted iron ore and charcoal in layers were burnt to remove the impurities in the iron. In order to separate the slag from the iron, the temperature was raised to c. 1150–1200°C, well above the Curie point, thus demagnetising the clay. After firing, the furnace shafts were broken up and the slag was shovelled out into heaps surrounding the site of the furnace to access the iron. As such, both the (now re-magnetised) burnt clay of the shafts, the soils in the near vicinity of the furnaces as well as the slag, which, because of the imperfect process of removing the impurities, still contains considerable amounts of iron, will generate substantially increased, localised magnetic levels. Although the production of charcoal, an essential ingredient of iron production, also involved burning, little is known about the magnetic characteristics of these production sites. The remains of such sites are visually identified as sub-circular or sub-rectangular pits surrounded by substantial banks, a result of the extraction process where the charcoal was excavated from the site. They are thus easily detectable during visual surveys, and indeed in lidar data, and there has been little incentive for investigating these abundant features using geophysical methods. This could, for instance, be a potential approach to identify charcoal pits that are not visible above ground. As far as we know, no such surveys have so far been carried out. Charcoal, being an organic component, is undetectable by geophysical methods, but because of the temperatures involved in its creation, it is assumed that the surrounding soils must, at least to a certain degree, have been affected by the heat.

Accordingly, many of the archaeological features associated with iron production, such as those found in the Elverum area, should be readily detectable using magnetometers.

That was the reasoning behind the decision to apply handheld magnetometer mapping as part of the Gråfjell project where it soon proved successful (Risbøl & Smekalova, 2001). Within the framework of the Gråfjell project, magnetometers were employed both in searching for potential iron production and roasting sites, and in detailed surveys of individual sites. A handheld magnetometer was used at some sites both in the first stage of the project, when the entire area was surveyed and mapped for archaeology (Risbøl, 2005), and in the subsequent stage of archaeological excavations (Rundberget, 2007). The application of a magnetometer provided the project with detailed maps of the layout of iron production sites consisting of furnaces, slag heaps, depots of roasted ore, depots of charcoal, etc. (Fig. 6). Some of these features were visible above ground, others were hidden below the turf. This information has been important to better understand how iron production was organised whilst improving the planning of the excavations. Nevertheless, the most profitable benefit was probably the detection of a large number of roasting sites located in clusters in areas around the production sites. The use of magnetometers turned out to be a very efficient approach to the mapping of these features, which are usually invisible above ground and thus very difficult to find. This is because they only cover a few square metres and the bulk of the roasted ore was removed from the site and used in the iron production, leaving only a thin layer of discarded roasted ore. The distribution of roasting sites contributed vital information for understanding how extensive iron production was organised socially, politically and economically (Rundberget, 2012). The successful application of magnetometers in research concerning prehistoric iron production has also been proven in other contexts, not only in Norway but also internationally (Abrahamsen et al., 2003; Crew et al., 2003; Larsen, 2009, pp. 221–222; Smekalova, 1993, p. 85).

Aeromagnetic techniques were developed during the Second World War with the aim of detecting submerged submarines. Soon after the war, the methods were developed and implemented for civil purposes, mainly for geological or mineralogical mapping (Reeves 2005). The development and introduction of digital acquisition technology in the early 1970s, and especially the advent of satellite navigation systems some twenty years later, widened the usability of airborne magnetometers and their areas of application. Mapping subsurface geology is still the most important task, although mapping pipelines and detecting unexploded ordnance are now among the areas of utilisation. Aeromagnetic equipment has barely been used for archaeological purposes. In a marine archaeological project carried out in the late 1970s, a magnetometer was used from a helicopter over Matagorda Bay, Texas, in an attempt to find sunken vessels (Barto Arnold III 1998). Parts of the bay were not accessible by boat and as an experiment, a magnetometer was towed on a handheld cable beneath a helicopter. The flight altitude was 120 feet (≈ 37 metres) and the sensor was kept 20 feet (≈ 6 metres) above the water surface. A range of anomalies were identified when the data set was processed and twelve of these were verified underwater by divers, resulting in the finding of five shipwrecks.

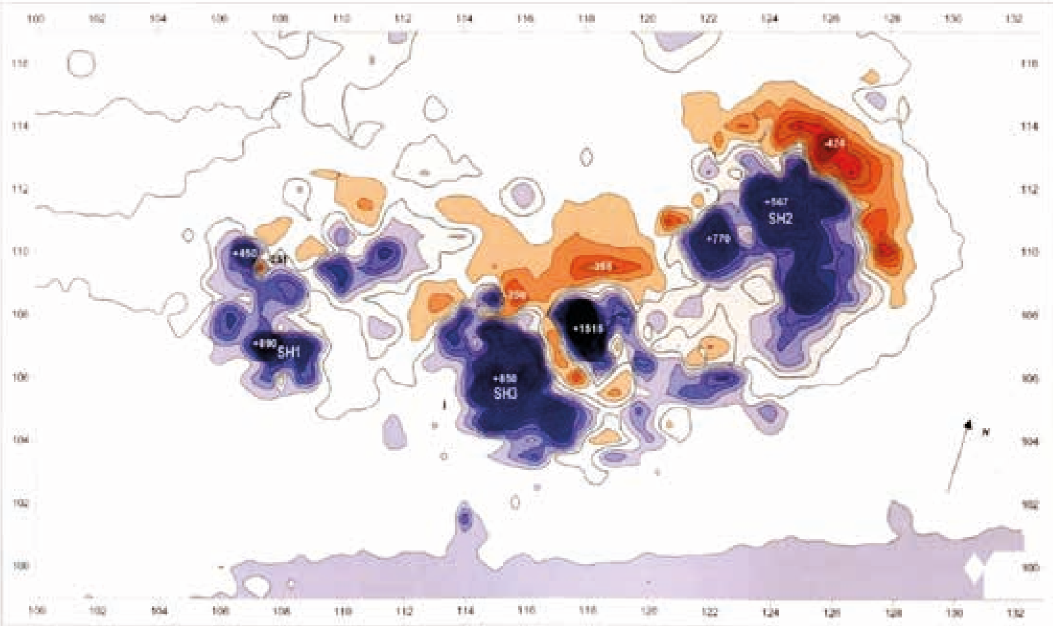

Figure 6. An iron production site similar to the ones in our study area mapped with a handheld magnetometer in 2005 by geophysicist T. Smekalova. SH = slag heap; the dark blue anomalies between slag heaps 2 and 3 are where remnants of the furnaces are situated. After Rundberget (2007, p. 234, Fig. 174).

Another project was carried out in an approximately 500 km^2 large area along the Missouri river in South Dakota and Nebraska in 2001. The main goal was to detect buried or submerged steamboat wrecks (Molyneaux, 2002). The reasoning behind the application of aeromagnetics was to cover this large area in an efficient manner as well as getting around problems with accessibility, as the main part of the area is private property. A fixed-wing aeroplane was used, and data were collected from 80 metres above ground level in flight line traverses which were set 100 metres apart. By considering the size and shape of identified magnetic anomalies, in combination with their position in relation to the river, as well as present and past river channels, 20 anomalies (12 with A priority and eight with B priority) were prioritised for future verification on the ground. Due to a lack of funding, the data collection, processing and interpretation were never followed up by ground testing. Thus, the results of the project still remain unresolved.[12]

In order to test if airborne magnetometry could be a suitable remote sensing method for archaeological purposes, a test project was launched in 2013. The project was led by NIKU and carried out in cooperation with Airborne Technologies/Geoprospectors from Austria, and Hedmark County Council. In November 2013, data were collected from a 36 km^2 large area in Elverum, Hedmark (Fig. 7). This area was chosen because we knew it contained a large number of slag heaps from iron production, i.e. remains

Figure 7. A light aircraft from Airborne Technologies with magnetometer sensors mounted on the wing tips and ready for take-off. Photo: NIKU

potentially detectable by magnetometer due to their magnetic properties. The presence of 26 iron production sites (all with one to four slag heaps) recorded previously proves that the potential for finding more iron production sites in this region is high. Only limited resources were allocated to the processing and interpretation of the data, but the collection of data was followed up by fieldwork, where a few anomalies identified during the preliminary processing were investigated in the field to gain experience about how the data relate to conditions on the ground. During the fieldwork, five more iron production sites were found within the test area. None of these sites were found as a direct result of the preliminary interpretations of the airborne magnetometry data, but they highlight the potential of identifying similar sites in the area.

Airborne magnetometry – preliminary results

The data from the airborne magnetometry survey consist of total magnetic field maps from each of the two sensors.[13] By subtracting one data set from the other, a horizontal gradient map can be generated showing intensity differences observed over horizontal intervals between the two sensors (Fig. 8). This map has been compared visually with available DTMs of the area, maps of the local bedrock and drift geology, and the recorded archaeology of the area. There is little, if any, correlation between the data sets, and the magnetic responses can therefore not be adequately explained at present.

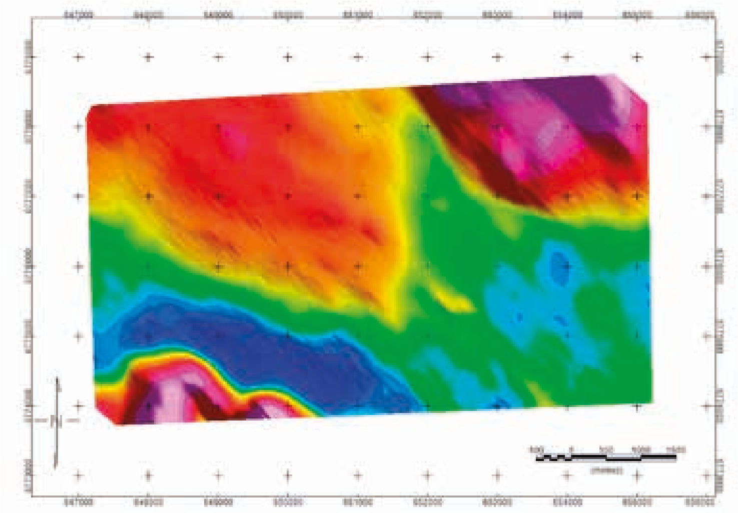

Figure 8: Preliminary map from the airborne magnetometer survey. Red and purple are high relative values, blue is low relative values. There is no scale on the strength of the measurements in this particular example.

The application of airborne magnetometry to identify archaeology offers a potential approach that is interesting to pursue. It is a question of being able to point out highly magnetic features on or near the surface – features of a much smaller scale compared to the geological mapping that airborne magnetometry is usually used for. To be able to isolate highly magnetic, confined areas would be helpful when mapping large areas or whole landscapes for archaeology. This will be an especially efficient approach to combine with other remote sensing techniques, primarily lidar. At present, airborne magnetometry is carried out from fixed-wing aircraft or helicopters. This has obvious limitations in terms of flight altitude, data resolution and cost. The successful employment of autonomous or semi-autonomous drone-based magnetometers might offer a tenable solution and will be an area of research worth pursuing.

If successful, it would be an important step forward in developing the implementation of a still larger set of remote sensing-based tools in archaeology.

Conclusion

Due to its suitability, lidar has become a widely used approach to the mapping of cultural features in large areas. Initial analysis and interpretations of lidar data were solely carried out based on hillshaded models. To obtain better results in terms of identifying as many, and as great a variety of, cultural features as possible, a range of additional visualisation techniques has been developed. As a consequence of some evident limitations of hillshade models, new approaches have been implemented and are now used by an increasing number of archaeologists and other professionals using lidar data in their work. A few studies have demonstrated an improved outcome of employing two or more visualisation techniques, but it is still difficult to detect some categories of cultural features, even though they may be quite large. In this study, only two categories of cultural features are used, iron production sites and charcoal pits, but basically the lidar approach can be usefully employed to identify all kinds of visible manifestations in the landscape that come from human activity. In addition to developing and refining visualisation techniques adapted to analysing lidar data, it is therefore also important to employ additional remote sensing techniques. The challenge of identifying iron production sites and similar features with magnetic properties may perhaps be solved using airborne magnetometry. A test of airborne magnetometry has been initiated in an area which has already been mapped with lidar and studied for a decade. As this test also involves the use of handheld magnetometers, it is in line with a growing trend in archaeology to employ integrated prospection approaches.

Acknowledgements

Thanks to Lars F. Stenvik from the NTNU University Museum in Trondheim for inviting us to the workshop on pre-industrial iron production and encouraging us to publish our work. The two archaeologists and colleagues, Anneli Nesbakken and Monica Kristiansen, who kindly agreed to do the interpretations of the lidar data, deserve special thanks for providing important results used in the present study. We would also like to thank our collaborating partners from the airborne magnetometer test, especially Michael Pregesbauer and his colleagues from Airborne Technologies, Geoprospectors KG and the Ludwig Boltzmann Institute (LBI). We would also like to thank Kjetil Skare from Hedmark County Council for his practical and professional contributions to the project. We also greatly appreciate the financial contributions from the Norwegian Forest and Landscape Institute and Hedmark County Council. Thanks, too, to Brian L. Molyneaux, University of South Dakota, for being so helpful with additional information about the aeromagnetic test conducted in Missouri some years ago.

Notes

[1] See http://www.appliedimagery.com/.
[2] Charcoal is not magnetic, but it is assumed that the heat created when burning wood in a pit will create a magnetisation of the surrounding soil.
[3] Calculated after Rundberget (2007, p. 297, Table 44).
[4] Calculated after Rundberget (2007, p. 248, Table 34).
[5] Calculated after Rundberget (2007, pp. 39–246).
[6] Calculated after Norwegian National Cultural Heritage Database (https://askeladden.ra.no/Askeladden/Pages/LoginPage.aspx?ReturnUrl=%2faskeladden).
[7] See http://iaps.zrc-sazu.si/en/rvt#v.
[8] As the SLRM generated in the RVT software was considered unsuitable for our requirements, a similar model was generated using a GIS extension developed by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology.
[9] For further information about scanning parameters, see Risbøl et al. (2006b, p. 108).
[10] It is expected that this also applies to other pit-shaped features like pitfalls for elk and reindeer; features found in relatively large numbers in outfield areas in several parts of Norway.
[11] The calculated volume must be considered as relative and does not reflect the absolute size of the quantity of slag. The figures are based on measurements of length, width and height carried out when the sites were mapped and documented as part of the fieldwork. As pointed out by Rundberget (2012, p. 240), accurate calculations are only obtainable if the slag is measured and weighed as an element of archaeological excavations.
[12] Supplementary information kindly provided by Dr. Molyneaux in an email dated 21 July 2015.
[13] Project Report, Doc. No.: PM-NIKU-FR, Airborne Technologies, Vienna, 7 April 2014.

References

Abrahamsen, N., Holm Jacobsen, B., Koppelt, U., de Lasson, P., Smekalova, T., Grundvig, S. & Voss, O. (2003). Archaeomagnetic mapping, modelling, analysis and dating of Iron Age slags in Denmark. In L. C. Nørbach (Ed.), *Prehistoric and Medieval direct iron smelting in Scandinavia and Europe. Aspects of technology and society* (pp. 205–208). Aarhus: Aarhus University Press.

Aspinall, A., Gaffney, C. & Schmidt, A. (2008). *Magnetometry for archaeologists*. Lanham, Md. & Plymouth: AltaMira.

Barto Arnold III, J. (1998). An airborne magnetometer survey for shipwrecks and associated underwater test excavations. Maritime archaeology. In L. E. Babits & H. V. Tilburg (Eds.), *Maritime archeology. A reader of substantive and theoretical contributions* (pp. 363–373). New York & London: Plenum Press.

Bennett, R., Welham, K., Hill, R. A. & Ford, A. (2012). A comparison of visualization techniques for models created from airborne laser scanned data. *Archaeological Prospection*, *19*(1), 41–48.

Birkeland, P. W. (1999). *Soils and geomorphology*. New York: Oxford University Press.

Bofinger, J. & Hesse, R. (2011). As far as the laser can reach...Laminar analysis of LiDAR detected structures as a powerful instrument for archaeological heritage management in Baden-Württemberg, Germany. In D. C. Cowley (Ed.), *Remote sensing for archaeological heritage management. EAC Occasional Paper* (no. 5, pp. 161–171). Brussels: Europae Archaeologia Consilium (EAC).

Bollandsås, O. M., Risbøl, O., Ene, L. T., Nesbakken, A., Gobakken, T. & Næsset, E. (2012). Using airborne small-footprint laser scanner data for detection of cultural remains in forests: An experimental study of the effects of pulse density and DTM smoothing. *Journal of Archaeological Science, 39*, 2733–2743.

Challis, K., Forlin, P. & Kincey, M. (2011). A generic toolkit for the visualization of archaeological features on airborne lidar elevation data. *Archaeological Prospection, 18*(4), 279–289.

Chase, A. F., Chase, D. Z., Awe, J. J., Weishampel, J. F., Iannone, G., Moyes, H., Yeager, J., Brown, K., Shresta, R. L., Carter, W. E. & Diaz, J. F. (2014). Ancient Maya regional settlement and inter-site analysis: The 2013 West-Central Belize lidar survey. *Remote Sensing, 6*, 8671–8695.

Corns, A. & Shaw, R. (2009). High resolution 3-dimensional documentation of archaeological monuments & landscapes using airborne lidar. *Journal of Cultural Heritage, 10*(1), e72-e77.

Crew, P., Smekalova, T. & Bevan, B. (2003). High resolution magnetic surveys of prehistoric and medieval iron-smelting furnaces in North-West Wales. In L. C. Nørbach (Ed.), *Prehistoric and Medieval direct iron smelting in Scandinavia and Europe. Aspects of technology and society* (pp. 209–222). Aarhus: Aarhus University Press.

Crow, P., Benham, S., Devereux, B. J. & Amble, G. S. (2007). Woodland vegetation and its implications for archaeological survey using lidar. *Forestry, 80*(3), 241–252.

Doneus, M. (2013). Openness as visualization technique for interpretative mapping of airborne lidar derived digital terrain models. *Remote Sensing, 5*(12), 6427–6442.

Doneus, M. & Briese, C. (2011). Airborne laser scanning in forested areas – potential and limitations of an archaeological prospection technique. In D. C. Cowley (Ed.), *Remote sensing for archaeological heritage management. EAC Occasional Paper* (no. 5, pp. 59-76). Brussels: Europae Archaeologia Consilium (EAC).

Evans, D. (2016). Airborne laser scanning as a method for exploring long-term socio-ecological dynamics in Cambodia. *Journal of Archaeological Science, 74*, 164–175.

Gaffney, C. & Gater, J. (2003). *Revealing the buried past: Geophysics for archaeologists*. Stroud: Tempus.

Hesse, R. (2010). Lidar-derived local relief models. A new tool for archaeological prospection. *Archaeological Prospection, 17*(2), 67–72.

Johnson, K. M. & Ouimet, W. B. (2014). Rediscovering the lost archaeological landscape of southern New England using airborne light detection and ranging (lidar). *Journal of Archaeological Science, 43*, 9–20.

Kokalj, Ž., Zakšek, K. & Oštir, K. (2011). Application of the sky-view factor for the visualization of historic landscape features in lidar derived relief models. *Antiquity, 85*(327), 263–273.

Larsen, J. H. (2009). *Jernvinneundersøkelser. Faglig program, bind 2. Varia* (vol. 78). Oslo: Museum of Cultural History, University of Oslo.

Martens, I. (1979). Øverst i Tellemarken have de i gammel Tid veldet Jern. In *Fortiden i søkelyset. ^{14}C datering gjennom 25 år* (pp. 121–129). Trondheim: Laboratoriet for radiologisk datering.

McCoy, M. D., Asner, G. P. & Graves, M. W. (2011). Airborne lidar survey of irrigated agricultural landscapes: an application of the slope contrast method. *Journal of Archaeological Science, 38*, 2141–2154.

Molyneaux, B. L. (2002). *Report on an aeromagnetic survey of the Missouri National Recreational Rover: Data acquisition, geophysical processing, and base map interpretation* (Cultural Resources Management Series Report no. 200128). Omaha: US Army Corps of Engineers.

Narmo, L. E. (2000). *Oldtid ved Åmøtet. Østerdalens tidlige historie belyst av arkeologiske utgravinger på Rødsoen i Åmot.* Åmot: Åmot historielag.

Reeves, C. (2005). *Aeromagnetic surveys. Principles, practice & interpretation.* Delft.

Risbøl, O. (2005). Registrering av kulturminner i skytefelt – kulturhistoriske resultater. In K. Stene, T. Amundsen, O. Risbøl & K. Skare (Eds.), *"Utmarkens grøde". Mellom registrering og utgravning i Gråfjellområdet, Østerdalen. Varia* (vol. 59, pp. 5–26). Oslo: Museum of Cultural History, University of Oslo.

Risbøl, O. (2009). Fugleperspektiv på kulturminner. Bruk av flybåren laserskanning i arkeologien. In E. H. Hofseth & E. Mikkelsen (Eds.), *Viking – Norsk arkeologisk årbok* (vol. LXXII, pp. 211–226). Oslo: Norwegian Archeological Society.

Risbøl, O. (2010). Towards an improved archaeological record through the use of airborne laser scanning. In M. Forte, S. Campana & C. Liuzza (Eds.), *Space, time and place: 3rd international conference on remote sensing in archaeology. BAR International Series* (vol. 2118, pp. 105–112). Oxford: Archaeopress.

Risbøl, O., Bollandsås, O. M., Nesbakken, A., Ørka, H. O., Næsset, E. & Gobakken, T. (2013). Interpreting cultural remains in airborne laser scanning generated digital terrain models: Effects of size and shape on detection success rates. *Journal of Archaeological Science, 40*, 4688–4700.

Risbøl, O., Gjertsen, A. K. & Skare, K. (2006a). *Flybåren laserskanning og kulturminner i skog. Et pilotprosjekt* (NIKU-rapport 03/06). Oslo: NIKU – Norwegian Institute for Cultural Heritage Research.

Risbøl, O., Gjertsen, A. K. & Skare, K. (2006b). Airborne laser scanning of cultural remains in forests: Some preliminary results from a Norwegian project. In S. Campana & M. Forte (Eds.), *From space to place: 2nd international conference on remote sensing in archaeology. BAR International Series* (vol. 1568, pp. 107–112). Oxford: Archaeopress.

Risbøl, O., Gjertsen, A. K. & Skare, K. (2007). *Flybåren laserskanning og kulturminner i skog. Fase 2* (NIKU-rapport 18/07). Retrieved from http://www.niku.no/archive/niku/publikasjoner/NIKU%20Rapport%20pdf/rapp18_Laserskanning.pdf

Risbøl, O. & Smekalova, T. (2001). Archaeological survey and non-visible monuments. *Nicolay Arkeologisk Tidsskrift, 85*, 32–45.

Rundberget, B. (2007). *Jernvinna i Gråfjellområdet. Gråfjellprosjektet, bind 1. Varia* (vol. 63). Oslo: Museum of Cultural History, University of Oslo.

Rundberget, B. (2012). *Jernets dunkle dimensjon. Jernvinna i sørlige Hedmark. Sentral økonomisk faktor og premiss for samfunnsutvikling c. AD 700–1300*. (PhD thesis). University of Oslo, Oslo.

Sittler, B., Schellberg, S., Siepman-Schinker, D. & Weinacker, H. (2006). Airborne laser scanning to generate 3D models of microrelief features for the purposes of forest ecological and archaeological surveys. In T. Koukal & W. Schneider (Eds.), *Conference proceedings from international workshop: 3D remote sensing in forestry* (pp. 281-286). Vienna: University of Natural Resources and Applied Life Sciences.

Smekalova, T. (1993). Magnetic investigation of iron-smelting centres at Snorup, Denmark. *Archaeologia Polonia, 31*, 83–103.

Štular, B., Kokalj, Ž., Oštir, K. & Nuninger, L. (2012). Visualization of lidar-derived releif models for detection of archaeological features. *Journal of Archaeological Science*, 39, 3354–3360.

Trier, Ø. D. & Pilø, L. H. (2015). Archaeological mapping of large forested areas, using semi-automatic detection and visual interpretation of high-resolution lidar data. In *CAA2014. 21st Century Archaeology. Concepts, methods and tools. Proceedings of the 42nd Annual Conference on computer applications and quantitative methods in archaeology* (pp. 81–86). Oxford: Archaeopress.

Vernon, R. W., McDonnell, G. & Schmidt, A. (1999). Medieval iron and lead smelting works: A geophysical comparison. In A. M. Pollard (Ed.), *Geological Society special publication* (vol. 165, pp. 15–34). London: The Geological Society.

Zakšek, K., Oštir, K. & Kokalj, Ž. (2011). Sky-view factor as a relief visualization technique. *Remote Sensing, 3*(2), 398–415.

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A needle in a haystack – an infield survey for iron production sites

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Abstract

This paper provides insight into recent research in North Norway. It is about a pioneer project when geophysical methods were applied for the first time to search for an iron production site in the North. It deals with problems related to the excavating archaeologist's lack of experience in interpreting the data produced by equipment and software developed in the 1980s. Despite the problems faced in detecting and recognising buried structures, applying the method and equipment in such a survey proved successful as two furnaces, two cooking pits and a couple of areas with unidentified activities were found. The survey made it possible to excavate the third iron production site ever found in North Norway that dates to the very beginning of the Iron Age. This indicates that even though there has never been extensive iron production in the North, the technology and know-how were to some degree available, but for some reason were little used.

Introduction

The use of geophysical methods to search for buried signs of past activity has quite long traditions in international archaeology (Campana & Piro, 2008; Gaffney, 2008; Gaffney & Gater, 2003). Such methods have also been employed in Norwegian archaeology (Gustavsen & Stamnes, 2012), but until recently not much when searching for iron production sites. However, this method has been successfully applied at sites in both central and southern Norway (Risbøl & Smekalova, 2001; Stamnes, 2010).

This is an account of recent research on iron production in northern Norway and I will describe and discuss the problems and ultimately the benefit when using a magnetometer in 1999 and 2002 to search for one of the very few north Norwegian iron production sites. Before going into detail, I will briefly outline the background of the project.

Background

The Iron Age in North Norway has for a long time been considered similar to, and a northern extension of, the South Scandinavian Iron Age (Sjøvold, 1962, p. 48). Thus, researchers have concluded that the extensive iron production documented in central and southern Norway must have been part of the Iron Age economy and the way of life also in the North (Bertelsen, 1985, p. 42). However, data to support such a view were lacking as no traces of north Norwegian iron production were discovered before well into the 1990s. This is contrary to the situation in central and southern Norway where research on iron production extends back to the early 1900s (e.g. Kleiven, 1912; Olafsen, 1916; Holme, 1920). See, for example, Larsen (2004, pp. 142–147) for a brief introduction to the research history related to early Norwegian iron production.

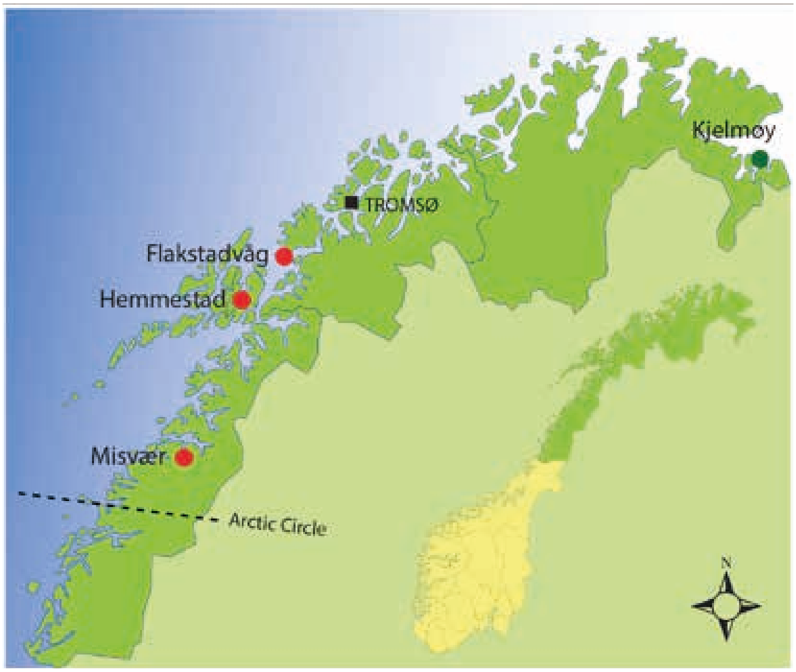

Figure 1. Sites with iron production in North Norway (Graphics: Ernst Høgtun, The Arctic University Museum of Norway)

In 1994, the first north Norwegian site with production slag was documented at Rognlivatnet, close to Misvær in Nordland (Fig. 1). The site is dated to the 1200s and several charcoal pits, two large ones with approximately the same dating, and several smaller ones that are not dated, are found nearby (Bjerck & Stenvik, 1994; Johansen, 2000; Jørgensen, 2010). The site has not been excavated and we have no information about how many or what kind of furnace(s) had been used. Three years later, in 1997, I found another iron production site at Flakstadvåg, on the island of Senja in Troms (Fig. 1). The site was excavated the following year and dated to the Roman Period, close to AD 300. The site was badly eroded by a small stream, but the furnace pit was partly preserved and a great deal of production slag was recovered. Also, iron ore was found in the bog next to the site (Jørgensen, 1998; 1999a; 1999b; 2010; 2011). The excavation covered a less eroded area where most of the slag and the furnace pit were found. However, no details concerning the construction of the furnace or the activities that had taken place next to the furnace were documented. The year after this excavation, the third and last iron production site documented so far was found at Hemmestad Nedre, a farm in Gullesfjord, near Harstad (Figs. 1 and 2). At the site, which was excavated

Figure 2. Hemmestad Nedre; production site in the field on the far side of the road (Photo: Roger Jørgensen)

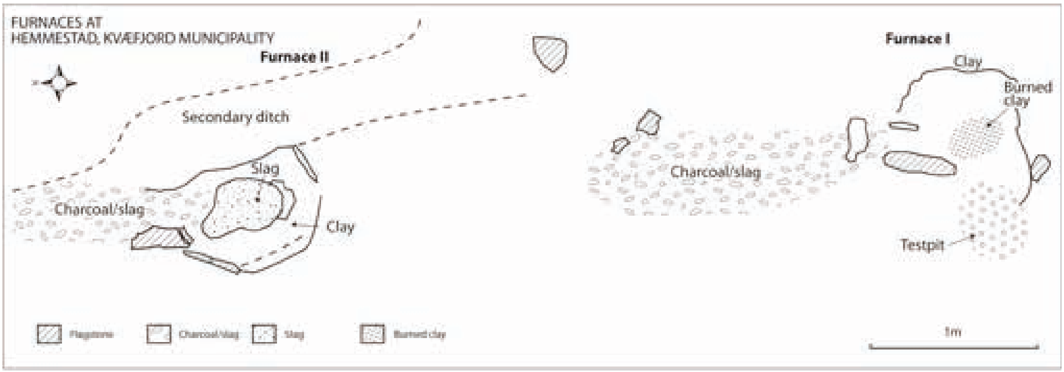

Figure 3. Furnaces at Hemmestad Nedre (Graphics: Ernst Høgtun, The Arctic University Museum of Norway)

Figure 4. Bottom of furnace removed from the pit (Photo: Roger Jørgensen)

in 1999 and 2002, two small, sunken shaft furnaces with slag heaps (Figs. 3 and 4), a charcoal pit and some large cooking pits were found. The two furnaces are dated to the beginning of the Pre-Roman Period, approximately 500 BC (Table 1).

In southern Norway, pine and spruce were the most common types of firewood used in the furnaces during the Early Iron Age. A problem with dating such wood is that these tree species may grow very old and take a long time before they rot (Larsen, 2004, p. 155). Pine is known to be able to live for 700 years and dead trees may take as long as

300 years to decompose (Loftsgarden et al., 2013, p. 61). Thus, the possible margin of error is 1000 years, which may be a serious error when dating any historical site. One way of minimising this problem is, if possible, to select twigs and branches for dating as these represent the younger part of the tree.

There are three ^{14}C dates from the two furnaces and one from the slag heap in front of Furnace I (Table 1). Three of the four dates are based on a mixture of birch and pine, while the fourth, taken deep down inside Furnace II, is based on birch only. Thus, the intermixing of pine in two of the samples at Hemmestad Nedre may be a potential problem. However, as the birch sample produced the second oldest dating, it suggests that the intermixing of pine in the charcoal samples has not seriously affected the dates. This is also supported by the fact that all four dates are relatively close in time. The intermixing of pine as a source of error in ^{14}C dates may not have been as great if the wood came from young trees or close to the cortex, so it seems safe to assume that this must have been the case here.

Table 1. ^{14}C dates from the two furnaces at Hemmestad Nedre (Jørgensen, 2010, p. 37)

Structure	Lab ref.	^{14}C year BP	One sigma	Two sigma
Furnace I	T-14761	2344+69	718-258 BC	751-206 BC
Furnace I	T-14762	2360+89	745-261 BC	765-206 BC
Furnace II	Tua-2662	2351+67	723-363 BC	752-208 BC
Furnace II	Tua-2663	2255+68	392-208 BC	415-106 BC

Considering the huge number of iron production sites found in central and southeastern Norway, it is odd that these three are the only ones known in all of northern Norway. However, this small number of sites is congruent with the situation in northern Finland and northern Sweden, where very few have been found (Bennerhag, 2012; 2018; Bennerhag & Mattson, 2009; Kehusmaa, 1972; Mäkivouti, 1988; Schultz, 1986).

Two of the north Norwegian sites, Rognlivatnet and Flakstadvåg, are situated in the outfield where no agricultural or other disturbances have taken place. At both sites, visible structures made it possible to find and recognise the production sites. At Hemmestad Nedre, slag had been found scattered in a cultivated field with no visible structures indicating where the furnaces had been built. Engaging a specialist using a magnetometer was the only affordable way of pinpointing where to excavate to find remnants of the production site.

Indications of an iron production site

When he was clearing the land about 1950, the farmer at Hemmestad Nedre found two pits, one filled with charcoal and the other with slag. He also spotted signs of a turf house and during ploughing he found a furnace stone of soapstone that he put into the slag pit before covering it with a flagstone. He saved some pieces of slag and burnt clay that he showed me when I arrived at the farm 50 years later. One of the burnt fragments of clay was slightly curved, burnt reddish on the outside and glazed on the inside and there was little doubt that this was a fragment of a shaft furnace.

The initial search for the furnaces

The farmer made the discovery when clearing the land and the supposed location of the site was approximately 150 m from the sea and 10 m above sea level. The now level field measuring about 100 m by 200 m had repeatedly been ploughed and harrowed so no structures were to be seen. Despite many years having passed since the farmer made his discovery, he claimed to remember where the finds were made and agreed to accompany me to the field to pinpoint the spot. At the farmer's guidance, I dug numerous test pits but, except for a few fragments of slag, there were no finds indicating that iron had been produced at the site. It gradually dawned on me that other methods had to be applied to find the exact location of the site and realistically I only had two options, stripping off the topsoil with a machine or employing geophysical search methods. This being a research project without significant funds, stripping the topsoil off the entire field was not a realistic option. Therefore, I contacted the geologist, Richard Binns, a private contractor with a magnetometer who had previously conducted fieldwork for NTNU University Museum and UiT the Arctic University of Norway, and he agreed to help me out.

The 1999 magnetometer search

A two-day search with a Fluxgate Gradiometer (Geoscan FM36) covering an area of 40 m by 60 m was conducted during the summer of 1999 (Binns, 1999) (Fig. 5). A grid was established with measurements 0.5 m apart in the north-south direction and 1.0 m between each line in the east-west direction, in all 4800 readings within this system. The figure illustrates the use of magnetometer FM36 and the sticks indicate where magnetic anomalies were measured.

As the site is only 10 m above sea level, the subsoil has been deposited by the sea and faint outlines of "shores" could be seen on the map produced by the magnetometer. On the one hand, the local search conditions were considered favourable for the method as the

Figure 5. Using the gradiometer (Photo: Roger Jørgensen)

soil did not seem to contain significant amounts of magnetite, but on the other hand the field had recently been fertilised using cow manure that might cause erroneous readings. The report with all the measurements and diagrams from the magnetometer survey could not be prepared before later that summer and to speed up the search, all major

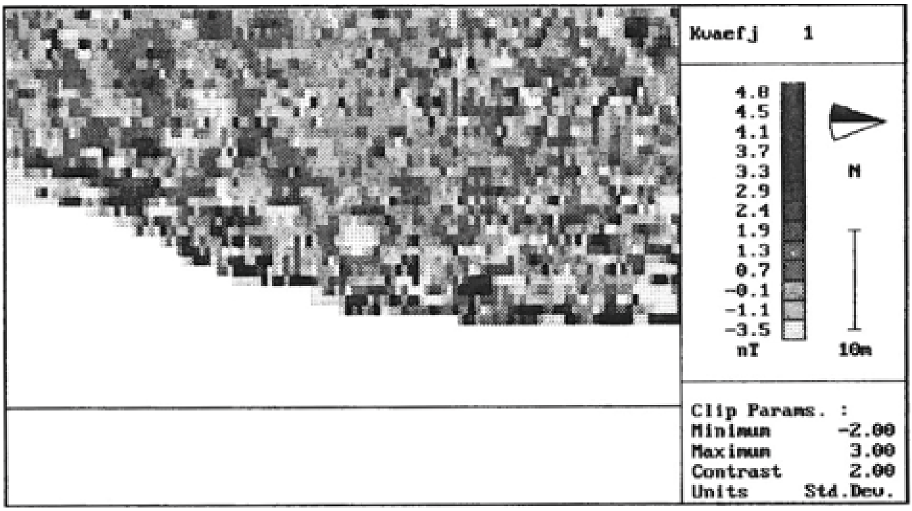

Figure 6. Shade plot displaying magnetic data, fieldwork in 1999

anomalies measured were marked with a stick for immediate examination using spade and trowel. Within the 2400 m^2 mapped area, approximately 30 readings displayed large anomalies indicating past activity. Test pits were excavated at these points, but no finds related to any activity that may have taken place at or near an Iron Age iron production site were found. However, numerous fragments of iron wire, broken tools and parts of machinery were found in the test pits, all finds normally associated with searching with a metal detector in any old field.

In addition to mapping the area within the grid, Binns conducted a free search scan covering a larger area looking for magnetic anomalies, and during this search an area with promising magnetic anomalies was discovered.

The systematic mapping produced several kinds of maps and diagrams displaying magnetic data, all in black and white. These were far from the vivid, colourful and detailed maps of buried structures that today's technology may produce. Three kinds of plots were produced, "shade" (Figs. 6 and 9), "dot density" (Fig. 7) and "trace" (XY traces) (Fig. 8), which proved to be useful in my search. These kinds of plots were

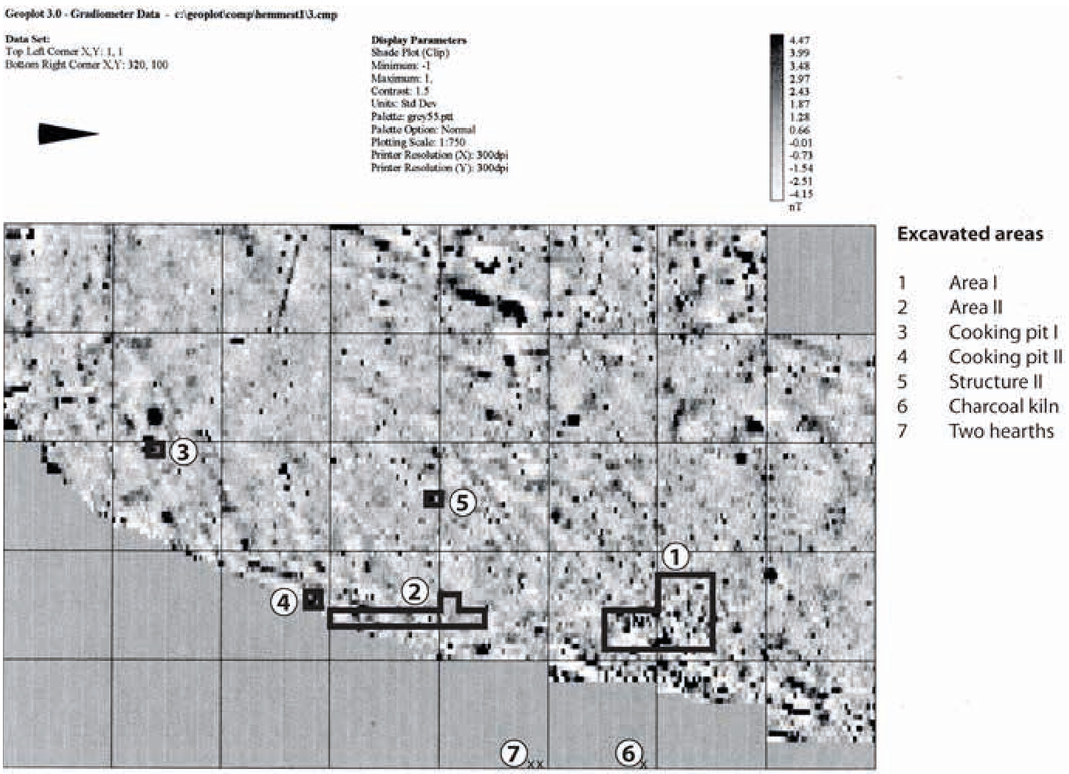

Figure 7. Dot density plot displaying magnetic data, fieldwork in 2002

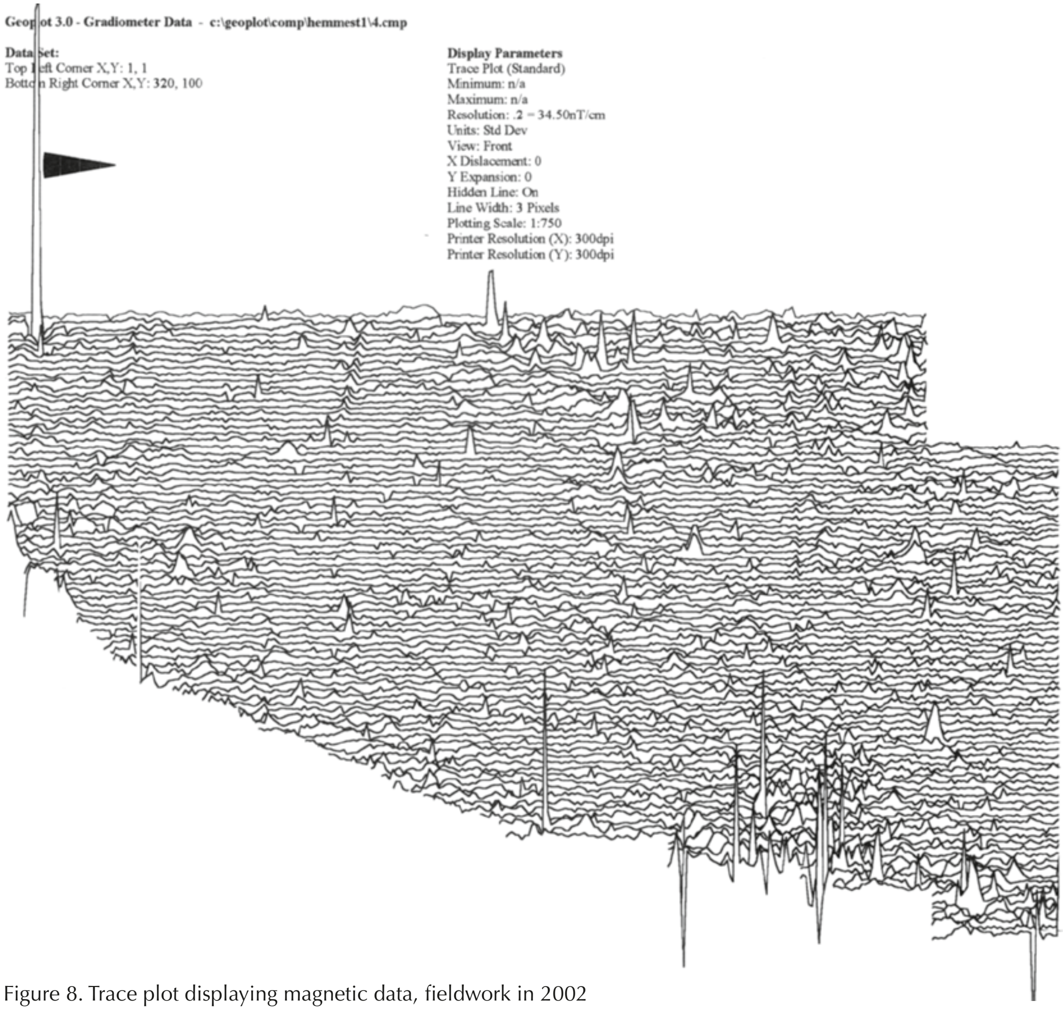

Figure 8. Trace plot displaying magnetic data, fieldwork in 2002

popular options used for displaying magnetic and resistance data in the latter part of the 20th century (Gaffney & Gater, 2003, pp. 107–109), and these black and white plots provided a data set which proved to be crucial in my search. Even though the resolution is not good, the magnetic deviations are in some places particularly pronounced and seem to create patterns indicating structures while in other places single measurements stand out (Fig. 9).

Regardless of the problems extracting relevant data from these diagrams, combining the readings from the mapped area with data from the less systematic scanned area and extensive digging of test pits enabled the excavation conducted later in the summer of 1999. Apart from the test pits dug within the mapped area, numerous pits were opened in the scanned area. In this way, two small furnaces with slag heaps were located and excavated. Also, approximately 250 m^2 of the topsoil were mechanically stripped off to

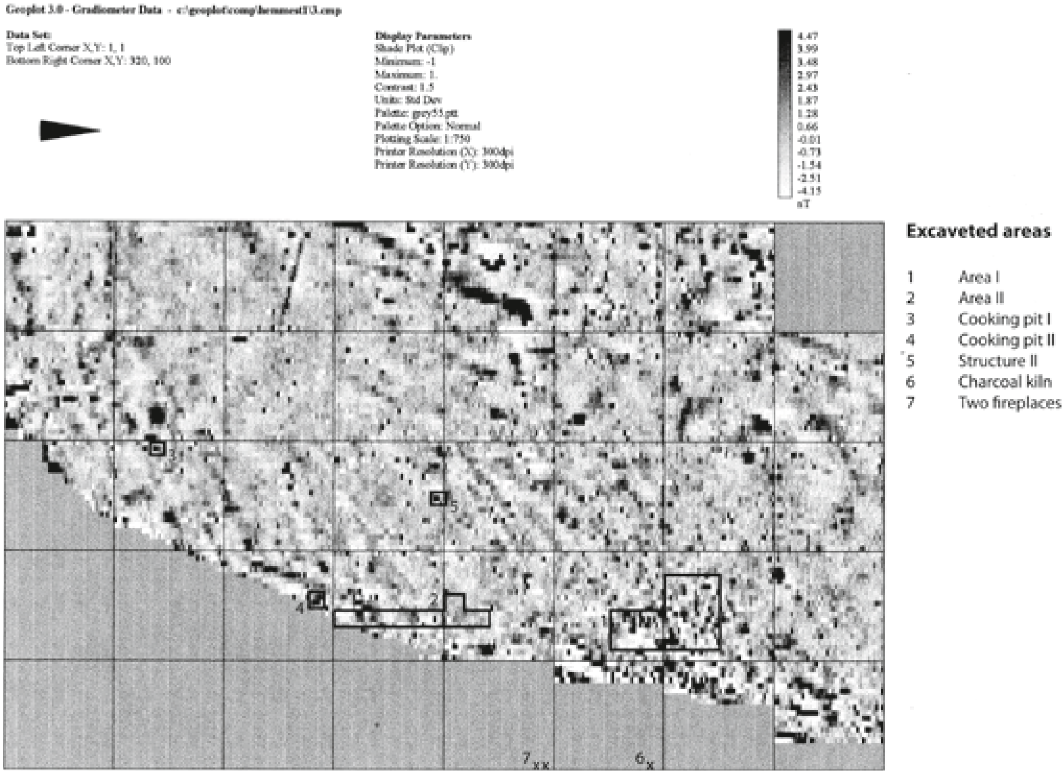

Figure 9. Magnetometer plot from 2002, with excavated areas

uncover more furnaces or structures related to the iron production, but without much success. However, searching for the iron production site with a magnetometer combined with digging test pits proved very successful and it is doubtful that the furnaces would have been located without the use of the magnetometer.

Repeated search in 2002

The discoveries in the field in 1999 were not entirely in agreement with the farmer's tale of what he had discovered 50 years ago. He remembered making the discoveries some distance away from the excavated furnaces and also described two pits with slag and charcoal. Moreover, he had put a furnace stone found when working the field in one of these pits. In the hope of uncovering the two pits and additional furnaces, another magnetometer search was conducted in 2002. The new and larger grid measured 160 m by 100 m and incorporated the area mapped in 1999. The field method and the hardware used were the same, but updated software produced slightly better-quality maps; the contrast was higher thus making the interpretation process easier (Binns, 2003).

Excavations based on the results of this magnetometer mapping revealed no more furnaces, but two cooking pits were documented. One gave a ^{14}Cdate approximately contemporary with the furnaces dated to 500 BC, while the other was dated to the Late Bronze Age. Additionally, a slightly younger unidentified structure of burnt clay and a possible house structure were seen in the plot. Excavations in what appeared to be a house revealed no cultural layers or constructional details consistent with a house. However, a thorough study of the magnetometer data displays lines in the ground parallel with the "house". Hence, what looked like a house structure is probably no more than stones or other shore deposits left behind when the sea retreated due to isostatic uplift. Several areas on the magnetometer plots displayed pronounced magnetic anomalies, but test pits revealed nothing but geological structures.

The plots displayed great differences in the magnetic measurements along the eastern side of the mapped area. This is the transition area between the infield and the outfield where a wire fence once stood. It had long ago disintegrated and parts of the wire were found in the topsoil causing some of the magnetic contrasts shown on figures 6–9. However, quite a lot of slag and burnt shaft fragments were found in the same area, also contributing to the magnetic disturbance.

Continued search for northern iron production

The magnetometer search for an iron production site at Hemmestad Nedre was an early one but not the first to apply such a method to locate an iron production site in Norway. Farbregd (1977) was possibly the first to do so when working on "The Hoset Project" in Nord-Trøndelag in 1973–74. Around the same time as Binns' first magnetometer search at Hemmestad Nedre, Risbøl and Smekalova (2001) successfully searched for iron production sites at Gråfjell in the county of Hedmark.

The fieldwork was conducted 20 years ago, employing technology at least of the same age. My problems recognising signs of past activity in the magnetometer plots were not entirely due to the method, equipment and technology, but perhaps in particular the lack of experience in interpreting the tables and plots. Despite these difficulties, the magnetometer search clearly was a success as we were able to locate a production site with no visible structures.

This was an underfinanced, individual research project with a tiny budget. In accordance with the dominating surveying method at the time, what I had in mind and really would have preferred was to mechanically strip off the topsoil to expose the subsoil surface. Working on a cultivated field, the conditions were well suited for applying this method. However, the lack of financial resources ruled out applying such a rather crude, time-consuming and costly method and this was the reason for turning to the magnetometer survey. This proved to be a fortunate choice as the magnetometer enabled me to locate two furnaces, two cooking pits and a couple of undefined activity areas (Fig. 9). Taking into consideration the technical developments during the last 20 years, it is possible and even likely that a renewed search, not only with a magnetometer but in combination with ground penetrating radar and lidar ("light detection and ranging") would have given a better understanding of the prehistoric activity and of how the iron production site had been organised. Maybe it is time to consider a follow-up project like "Hemmestad Nedre revisited"?

Continued search for iron production sites in North Norway should ideally make use of a combination of methods, traditional as well as "new" geophysical methods. However, this presupposes fairly accurate information about where to look. At present, such information is lacking, but increased use of lidar that covers large areas (Risbøl & Gustavsen, 2016), in combination with automated detection (Trier & Pilø, 2012; Trier et al., 2015) would greatly increase the possibility of documenting more iron production sites in the North. Lidar coverage is getting wider as this is being integrated in public land-use planning and the resolution is improving, thus enhancing this as a tool for archaeological survey. However, there is a practical and an economic downside in applying some of these methods in archaeology. Several methods require the use of highly trained personnel and specialised equipment, making such a joint methodological approach rather costly. However, it is also true that increased emphasis on such methods is likely to reduce costs, for example compared to mechanically stripping off the topsoil. But most important, such a combination of methods is likely to improve the quality of the surveys.

Archaeological field methods are constantly changing as more sophisticated surveying and documentation techniques are being applied. The increased costs related to bringing specialised personnel and equipment into a project may be balanced by increased efficiency and provide new possibilities as demonstrated by my little project at Hemmestad Nedre about 20 years ago.

References

Bennerhag, C. (2012). Samhälle i förändring – järnålder i Norrbottens kustland. *Arkeologi i Norr*, *13*, 45–73.

Bennerhag, C. (2018). *Fantastiska fynd i Vivungi*. Retrieved 3 December 2018 from https://sverigesradio.se/sida/artikel.aspx?programid=98&artikel=6783608

Bennerhag, C. & Mattson, U. (2009). Järnålder i Norrbottens kustland – en analys av teknologiska förändringar i kustsamhället under järnåldern genom tillämpningar av Fornminnesinformationssystemet (fmis). *Bebyggelsehistoria i digitala register*, 58/2009, 46–59.

Bertelsen, R. (1985). Fra den eldste tida til ca. 1500. *Lofoten og Vesterålens historie*. Published by municipalities in Lofoten and Vesterålen.

Binns, R. (1999). *Undersøkelser med Fluxgate gradiometer på Hemmestad, Kvæfjord, Troms* (Report). Tromsø: The Topographical Archive, Tromsø University Museum.

Binns, R. (2003). *Undersøkelser med Fluxgate gradiometer på Hemmestad, Kvæfjord, Troms. Del 2* (Report). Tromsø: The Topographical Archive, Tromsø University Museum.

Bjerck, H. & Stenvik, L. (1994). *Rapport fra befaring 12.7.1994 i forbindelse med nyoppdaget jernvinneanlegg, Rognlivatnet, Skjerstad* (Report). Bodø: Nordland fylkeskommune.

Campana, S. & Piro, S. (Eds.). (2008). *Seeing the unseen. Geophysics and landscape archaeology*. Boca Raton, FL: CRC Press.

Farbregd, O. (1977). Archaeological field work and evidence. *Norwegian Archaeological Review, 10*(1–2), 119–126.

Gaffney, C. (2008). Detecting trends in the prediction of the buried past: A review of geophysical techniques in archaeology. *Archaeometry, 50*(2), 313–336.

Gaffney, C. & Gater, J. (2003). *Revealing the buried past. Geophysics for archaeologists*. Gloucestershire: Tempus Publishing.

Gustavsen, L. & Stamnes, A. A. (2012). Arkeologisk geofysikk i Norge. En historisk oversikt og statusevaluering. *Primitive tider, 14*, 77–93.

Holme, T. N. (1920). Litt om blæstervirksomheten i Norge. *Oldtiden*, 41–57.

Johansen, G. A. (2000). *Trekullproduksjon på Vestvågøya i perioden 1100–1700. Et bidrag til diskusjonen omkring temaet nordnorsk jernvinne og smieaktivitet*. (Master's thesis). University of Tromsø, Tromsø.

Jørgensen, R. (1998). Jernvinna på Flakstadvåg – Nord-Norges første kjente jernproduksjon. In H. E. Eriksen (Ed.), *Årbok for Senja* (vol. 27, pp. 48–57). Senja: Sør-Senja bygde- og historielag.

Jørgensen, R. (1999a). Den tidligste jernutvinning i Nord-Norge. *Ottar, 225*(2), 39–47.

Jørgensen, R. (1999b). Jernvinna på Hemmestad. In Kvæford historielag (Ed.), *Årbok for Kvæfjord* (vol. 13, pp. 2–7). Kvæfjord: Kvæford historielag.

Jørgensen, R. (2010). *Production or trade. The supply of iron to North Norway during the Iron Age.* (PhD thesis). University of Tromsø, Tromsø.

Jørgensen, R. (2011). Prehistoric iron production in North Norway. *Acta Archaeologica, 82*, 97–128.

Kehusmaa, A. (1972). Kemijärvi Neitilä 4. *Helsingin Yliopiston Arkeologian Laitos*, Moniste, 3/1972.

Kleiven, I. (1912). Jønnblåsing og myrmalm. *Syn og segn, 18*, 323–330.

Larsen, J. H. (2004). Jernvinna på Østlandet i yngre jernalder og middelalder – noen kronologiske problemer. In E. H. Hofseth & E. Mikkelsen (Eds.), *Viking – Norsk arkeologisk årbok* (vol. LXVII, pp. 139–170). Oslo: Norwegian Archeological Society.

Loftsgarden, K., Rundberget, B., Larsen, J. H. & Mikkelsen, P. H. (2013). Bruk og misbruk av C^{14}-datering ved utmarks-arkeologisk forskning og forvaltning. *Primitive tider, 15*, 59–69.

Mäkivuoti, M. (1988). An Iron Age dwelling site and burial mounds at Rakanmäki, near Tornio. *Fennoscandia Archaeologica, V*, 35-45.

Olafsen, O. (1916). *Myrmalmsmelting i Norge i ældre tid.* Risør: Erik Gunleiksons forlag.

Risbøl, O. (2009). Fugleperspektiv på kulturminner. Bruk av flybåren laserskanning i arkeologien. In E. H. Hofseth & E. Mikkelsen (Eds.), *Viking – Norsk arkeologisk årbok* (vol. LXXII, pp. 211–226). Oslo: Norwegian Archeological Society.

Risbøl, O. & Gustavsen, L. (2016). *Håndbok. Bruk av luftbåren laserskanning (lidar) i arkeologien*. Retrieved 8 March 2019 from file:///C:/Users/rjo005/Downloads/Luftbaaren_laserskanning.pdf

Risbøl, O. & Smekalova, T. (2001). Archaeological survey and non-visible monuments. *Nicolay Arkeologisk Tidsskrift, 83*(3), 32–45.

Schulz, E.-L. (1986). Ein Eisenverhüttungsplatz aus der Älteren Eisenzeit in Kajaani. *Iskos, 6*, 169–173.

Sjøvold, T. (1962). The Iron Age settlement of Arctic Norway: a study in the expansion of European. Iron Age culture within the Arctic Circle. 1: Early Iron Age (Roman and Migration periods). *Tromsø Museums Skrifter* (vol. 10, no. 1). Tromsø/Oslo: Norwegian Universities Press.

Stamnes, A. A. (2010). *Geofysiske undersøkelser – Jernvinneanlegg på Mokk, Ogndalen i Steinkjer kommune* (Report). Retrieved 1 March 2019 from https://www.dropbox.com/s/uotlef21sbrs06i/RapportMokk.pdf?dl=0

Stamnes, A. A. (2016). *The application of geophysical methods in Norwegian archaeology. A study of the status, role and potential of geophysical methods in Norwegian archaeological research and cultural heritage management*. (PhD thesis). Norwegian University of Science and Technology (NTNU), Trondheim.

Trier, Ø. D. & Pilø, L. (2012). Automatic detection of pit structures in airborne laser scanning data. *Archaeological Prospection, 19*, 103–121. https://doi.org/10.1002/arp.1421

Trier, Ø. D., Zortea, M. & Tonning, C. (2015). Automatic detection of mound structures in airborne laser scanning data. *Journal of Archaeological Science: Reports, 2*, 69–79.

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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

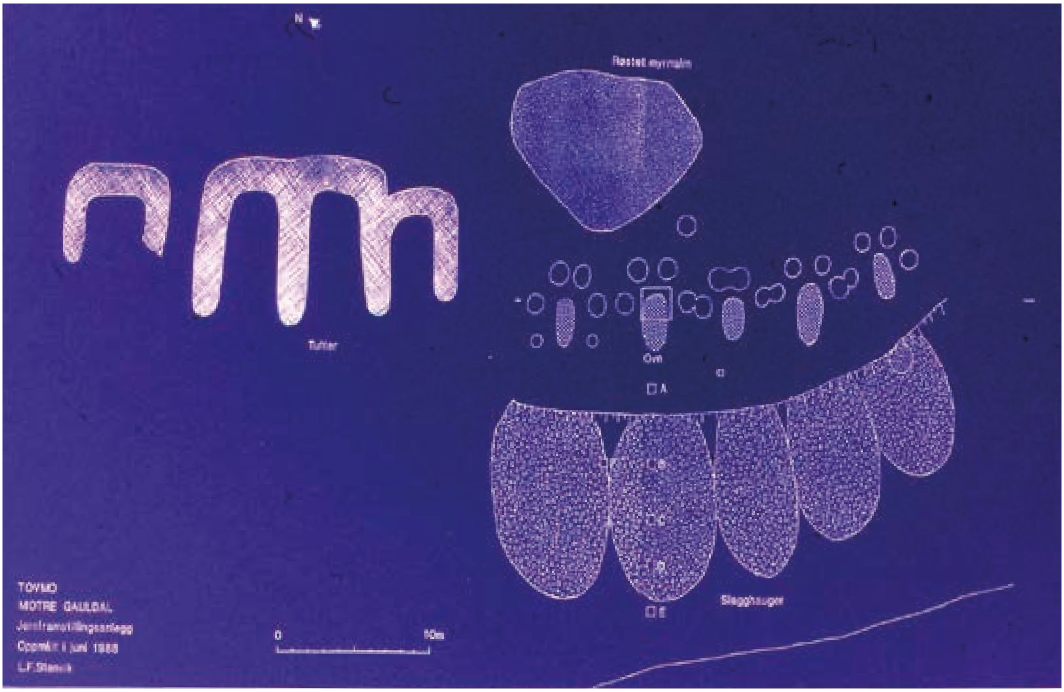

Figure 3. Sketch of the iron production site called Storbekken 1 at Tovmoen in Budalen, made by Stenvik in 1988. The top of the sketch is approximately northeast.

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

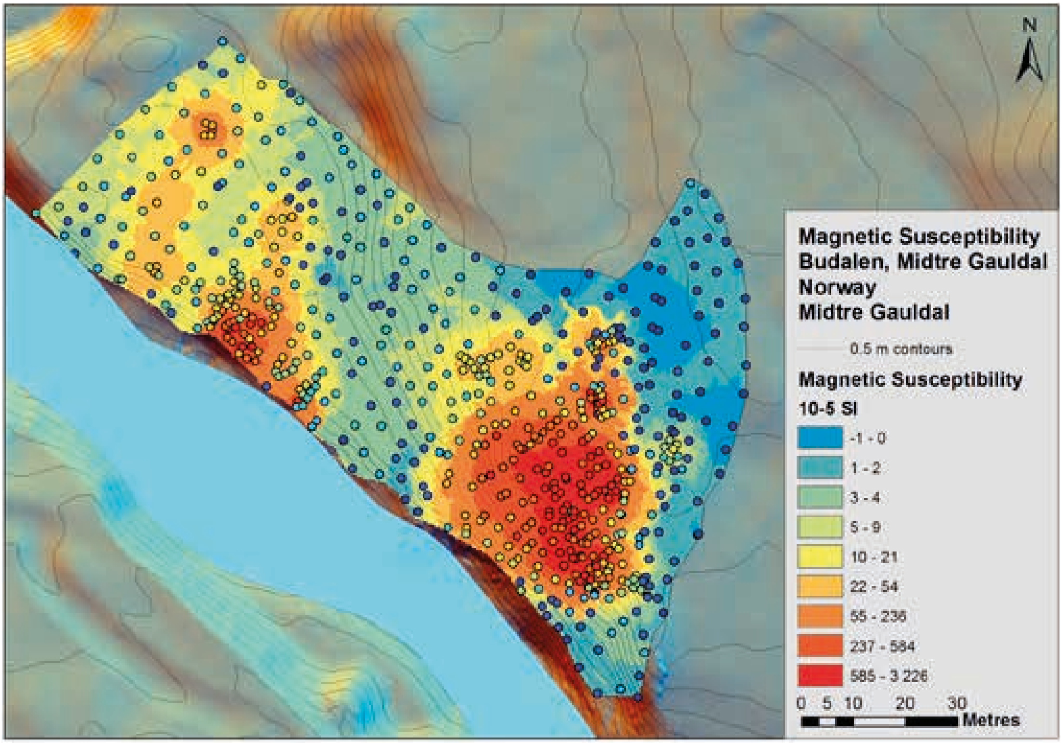

Figure 4. Topsoil volume MS measurements from Storbekken. The Early Iron Age iron production site is in the centre of the image (Storbekken 1). The next area with high readings towards the northwest, close to the stream, is a smaller Viking age iron production site, and far to the northwest is a modern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

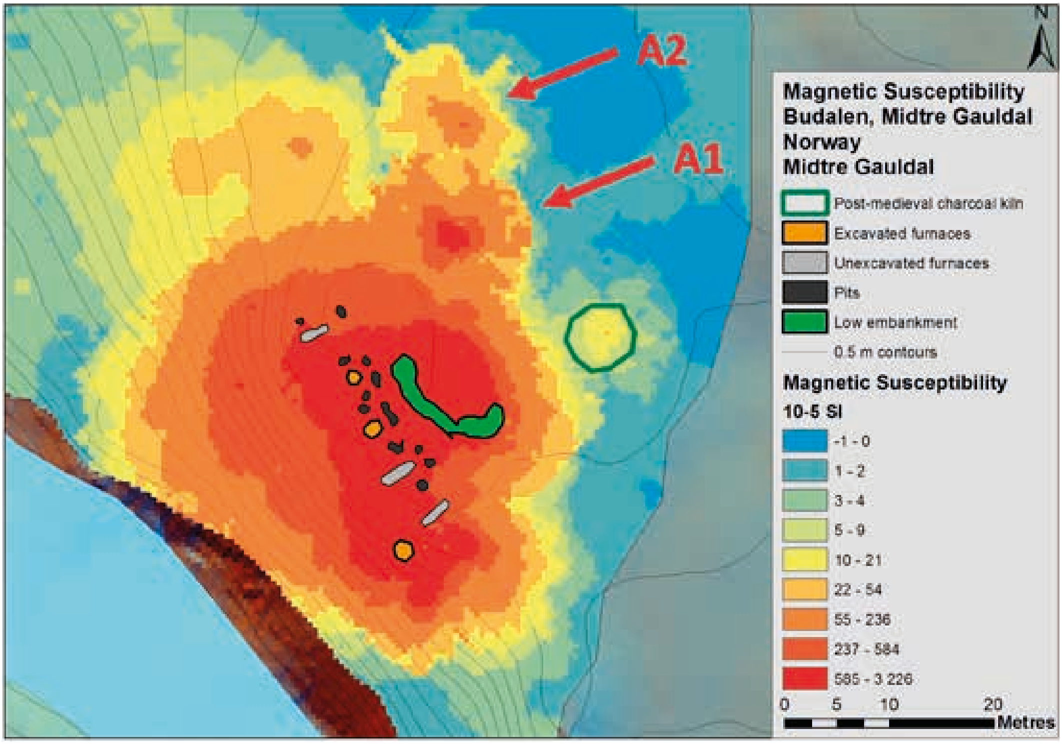

Figure 5. Detail of the topsoil volume MS map. The iron production complex of Storbekken 1 with known archaeology. The slag tips are southwest of the furnaces, down the slope towards the river. Note the hotspots north of the furnace area, and the area of above median readings north-northwest of the northernmost 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.

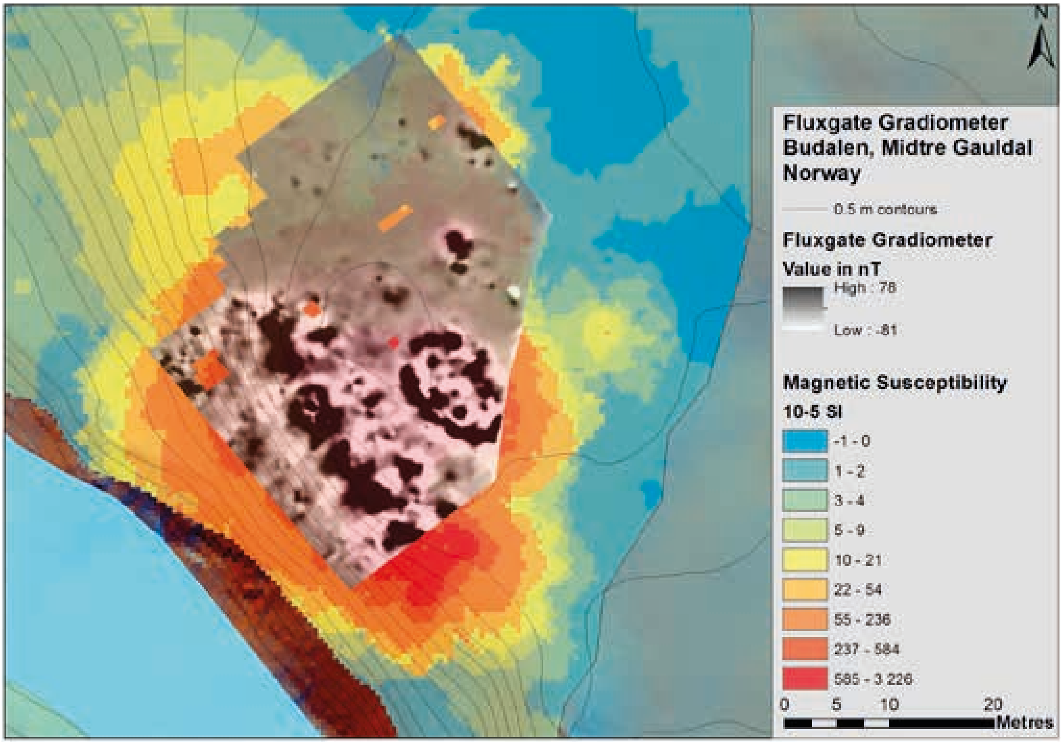

Figure 6. Fluxgate gradiometer survey results from Storbekken 1 overlaid on the topsoil volume MS map.
The gradiometer data are presented at ±1 standard deviation around the mean.

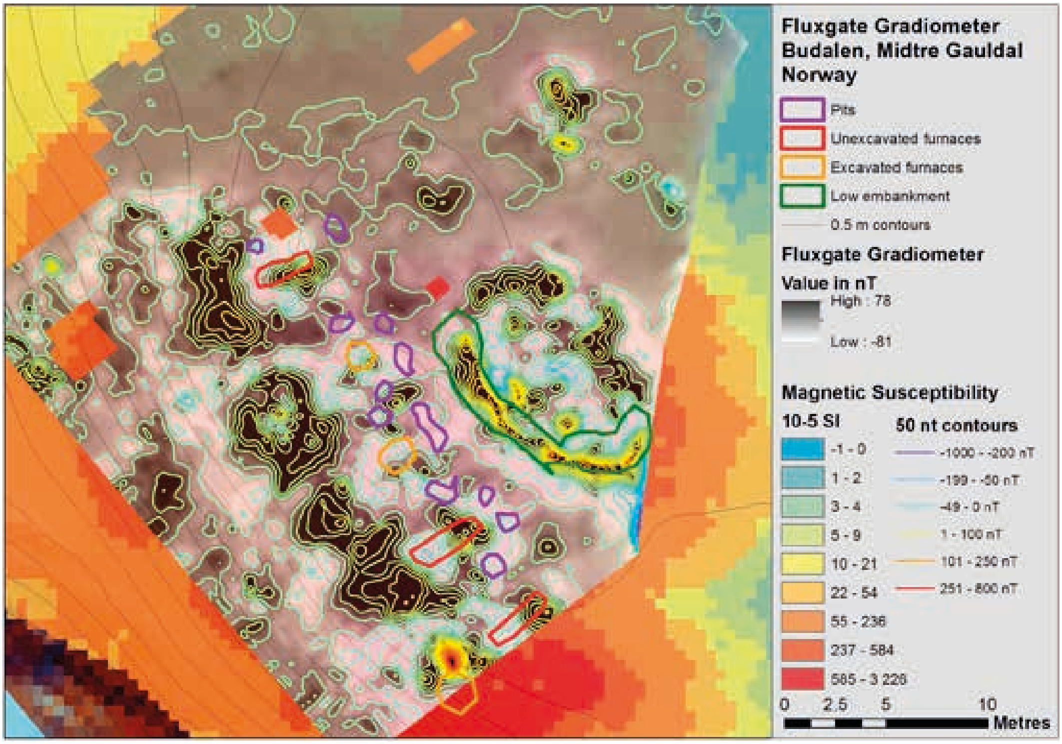

Figure 7. Detailed data plot from Storbekken 1 compared with known archaeological remains. Contour lines every 50 nT, with red lines for positive values and blue lines for negative values.

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

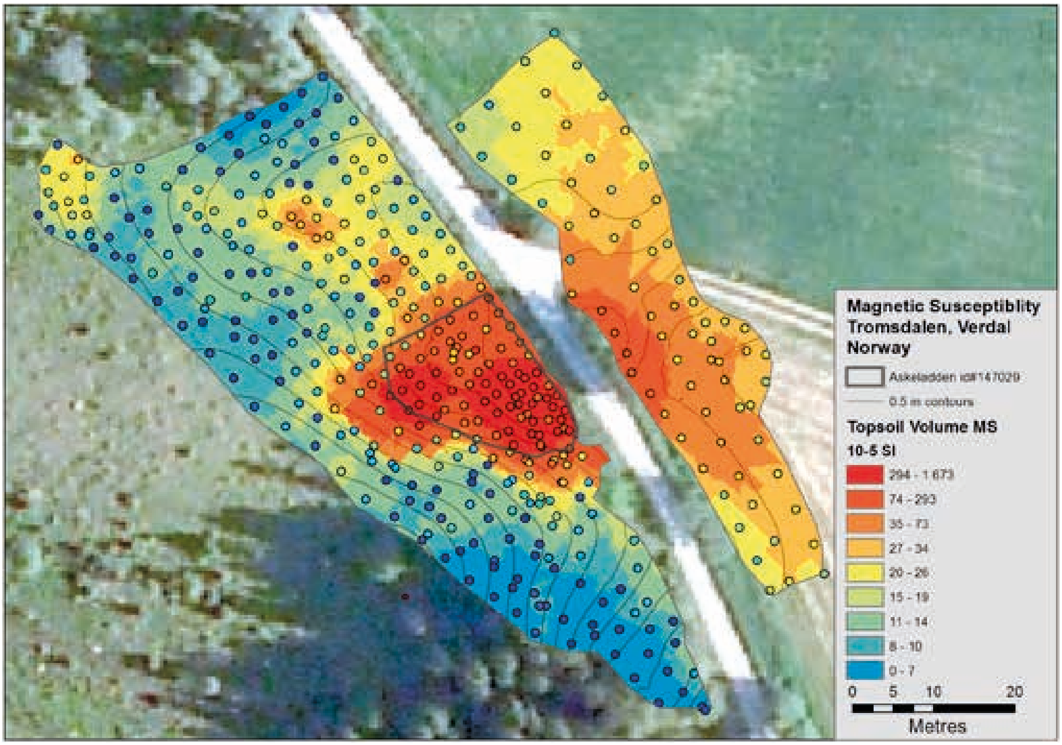

Figure 9. Topsoil volume magnetic susceptibility survey results from Tromsdalen, Verdal in Nord-Trøndelag

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

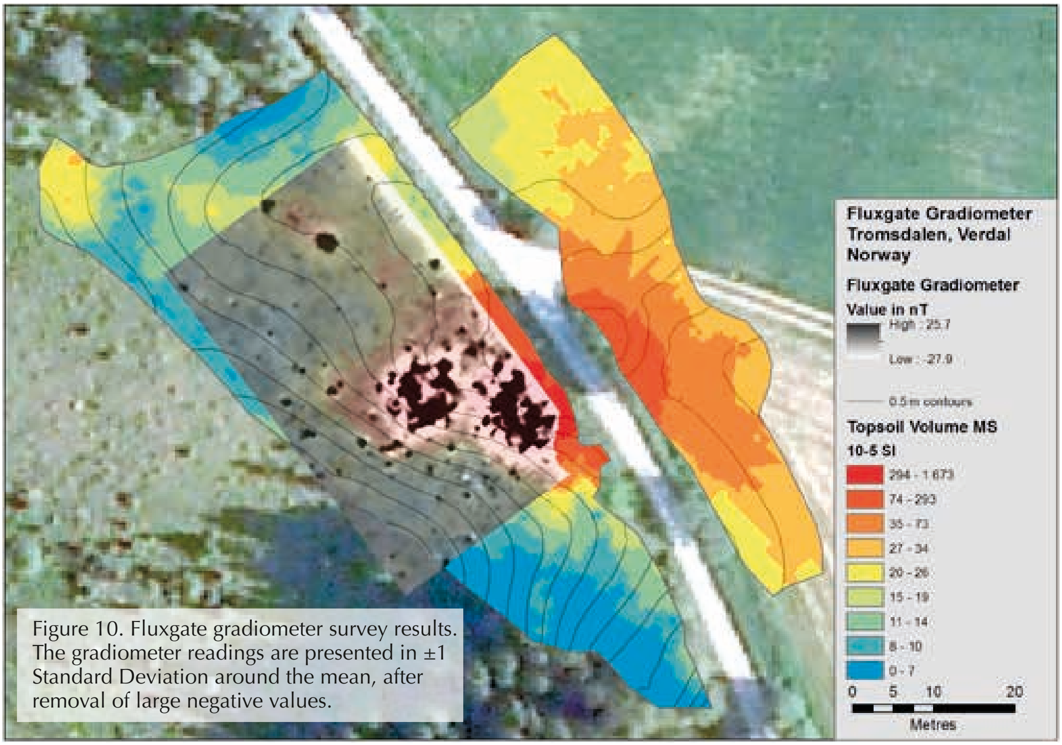

Figure 10. Fluxgate gradiometer survey results. The gradiometer readings are presented in ±1 Standard Deviation around the mean, after removal of large negative values.

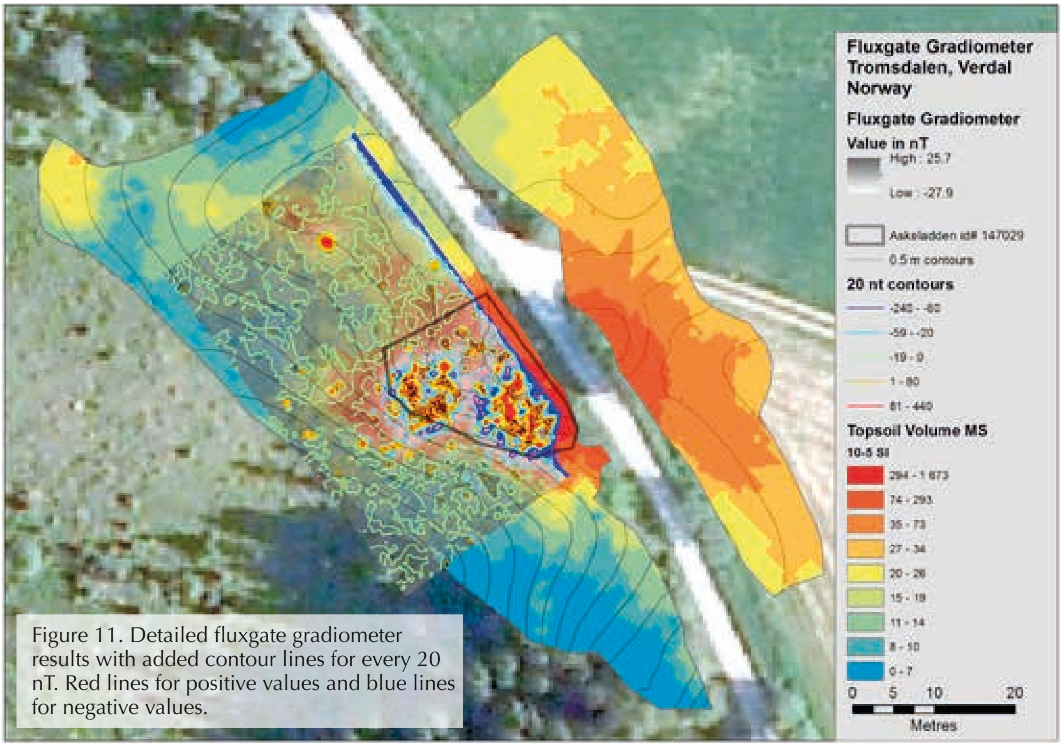

Figure 11. Detailed fluxgate gradiometer results with added contour lines for every 20 nT. Red lines for positive values and blue lines for negative values.

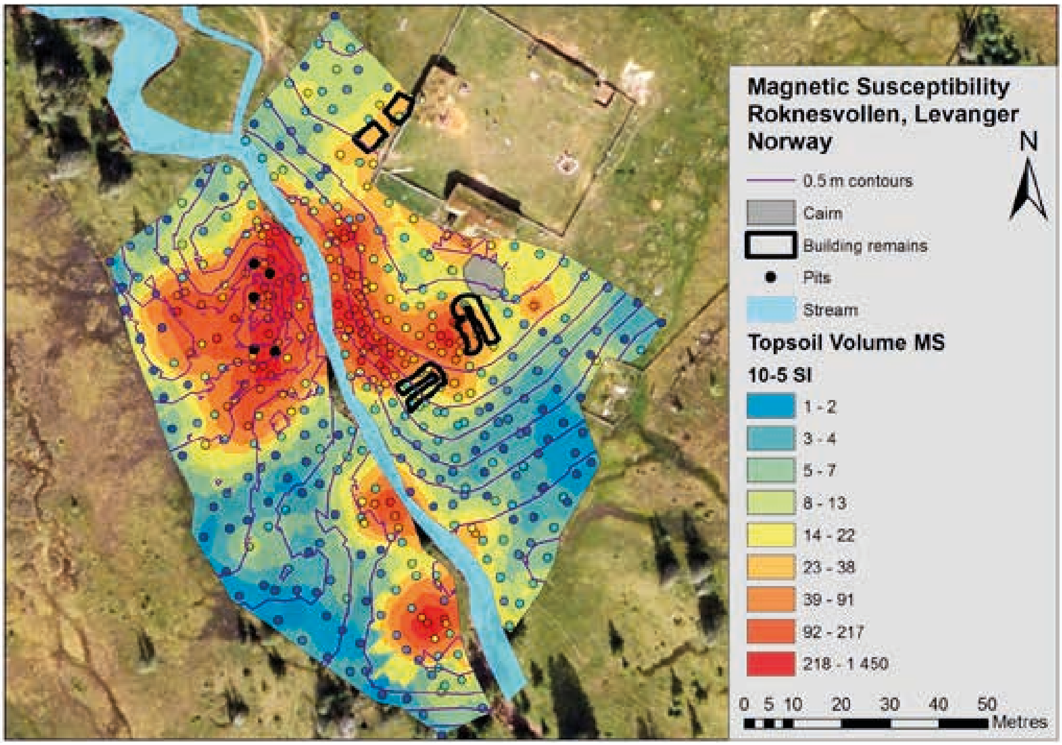

Figure 12. Topsoil volume magnetic susceptibility survey results from Roknesvollen, Levanger, Nord-Trøndelag.

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

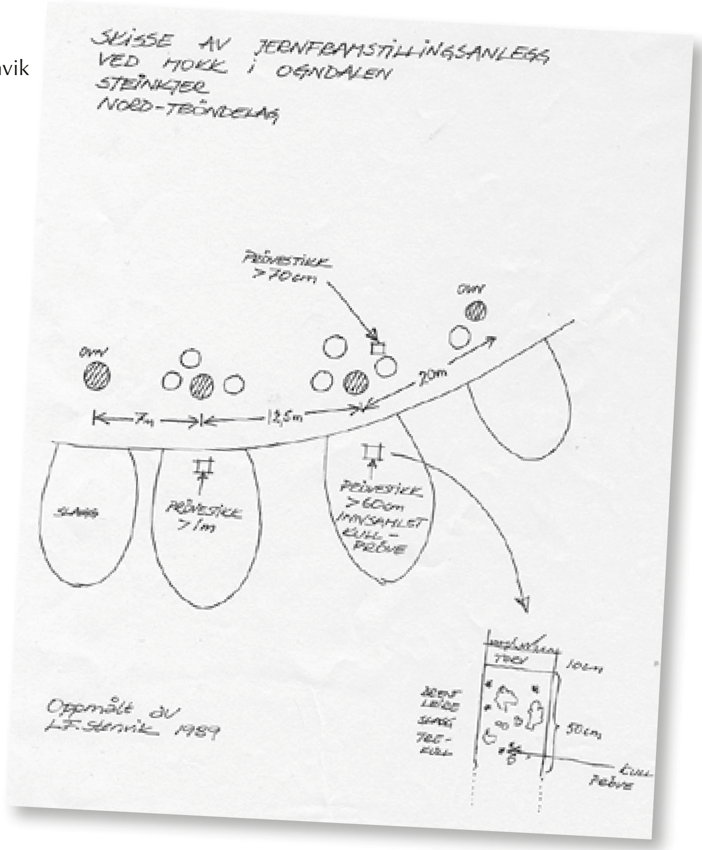

Figure 13. Sketch of the iron production site made by Lars F. Stenvik in 1989.

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:

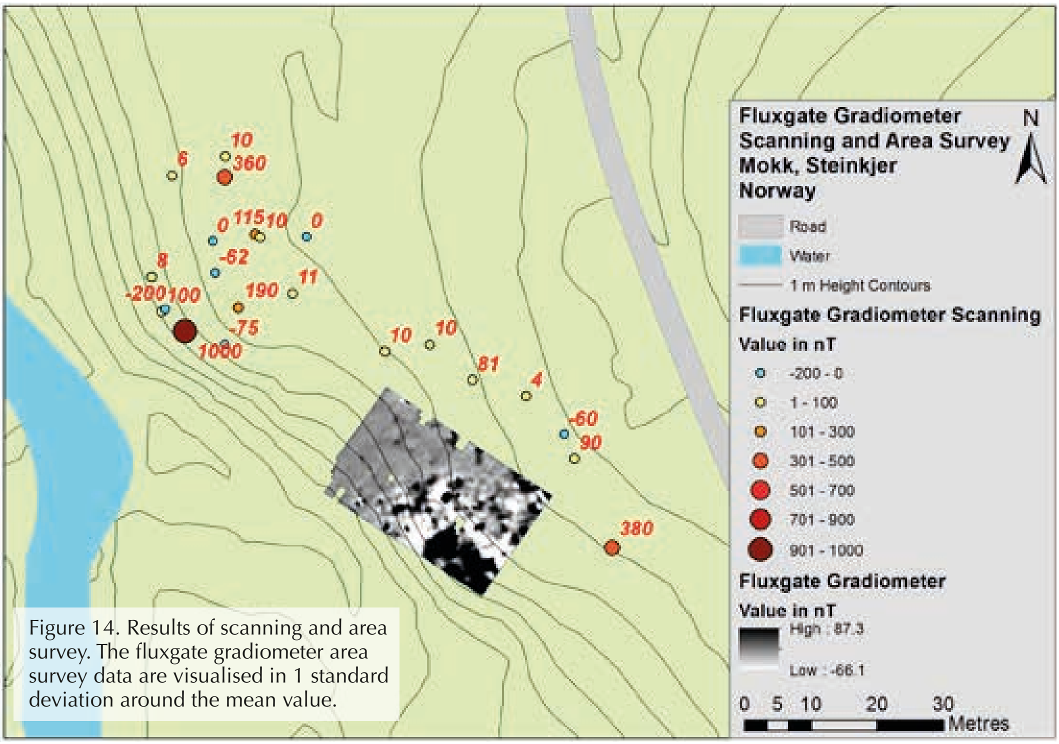

Figure 14. Results of scanning and area survey. The fluxgate gradiometer area survey data are visualised in 1 standard deviation around the mean value.

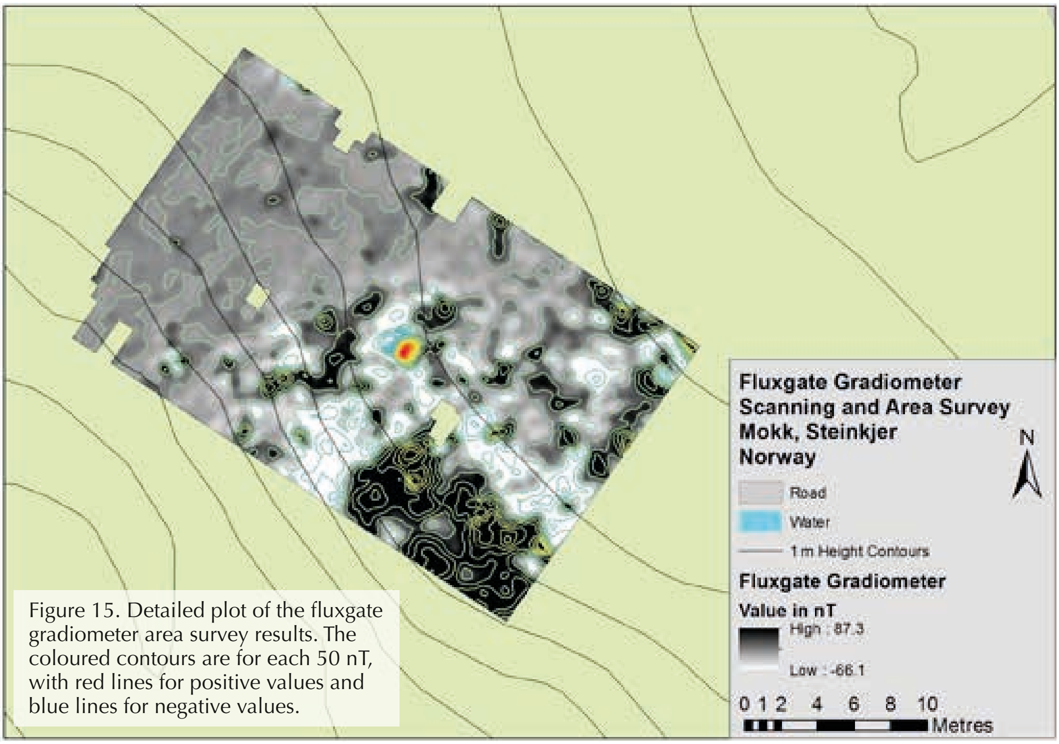

Figure 15. Detailed plot of the fluxgate gradiometer area survey results. The coloured contours are for each 50 nT, with red lines for positive values and blue lines for negative values.

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

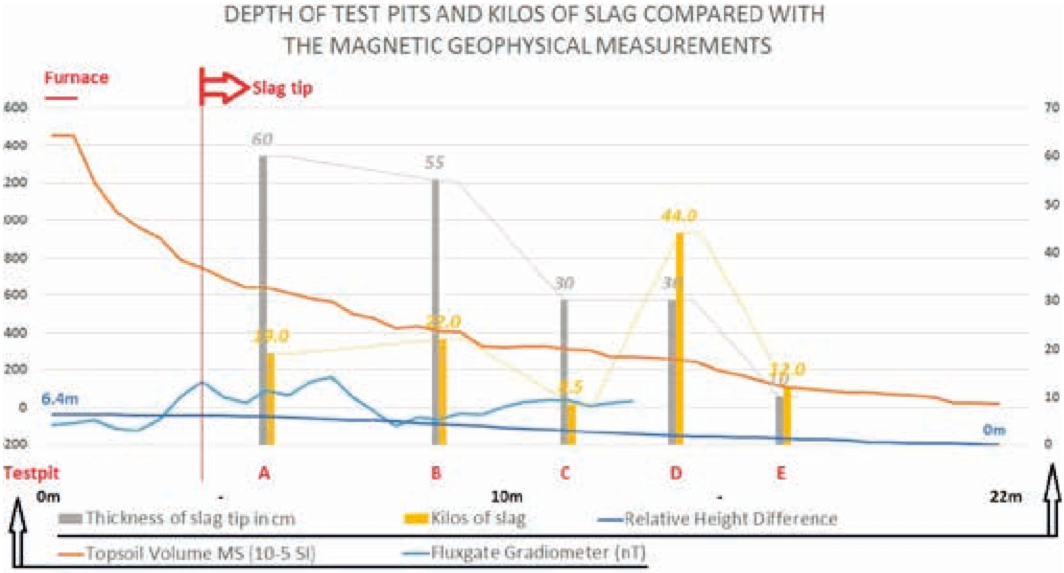

Figure 16. The relationship between the depths of the slag tips and the amount of slag found in test pits, compared with the magnetic geophysical measurements at Storbekken 1. The median MS value was 10.5 10^{-5} SI.

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

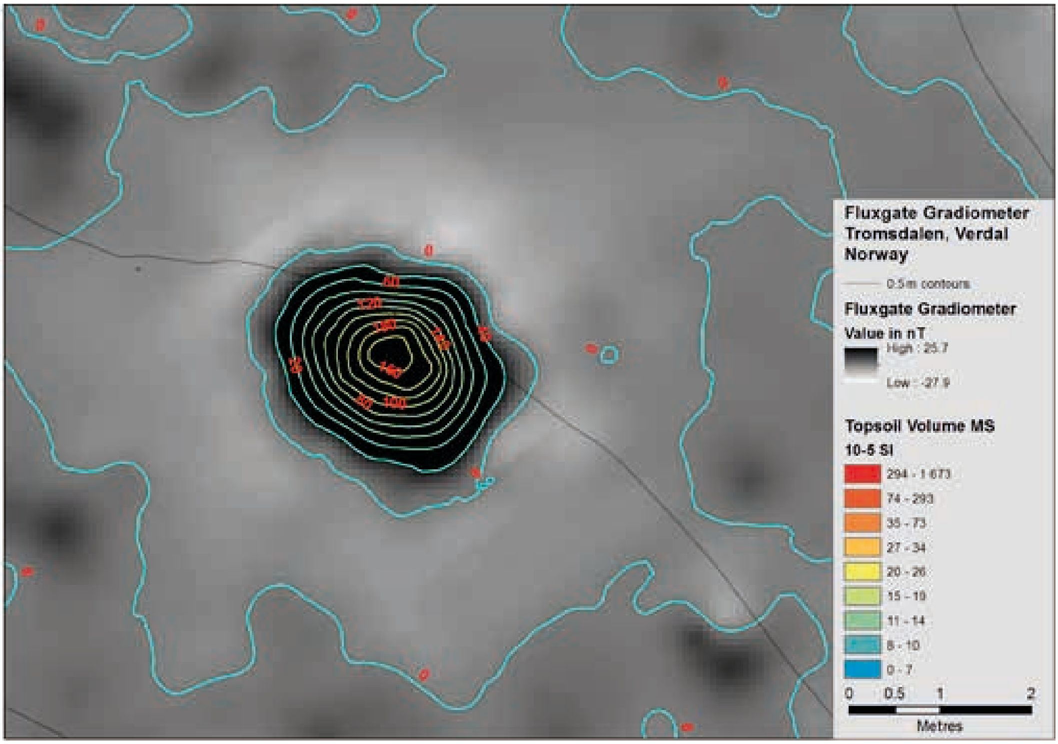

Figure 17. The possible roasting site for iron ore at Tromsdalen. Contours are for every 20 nT, with red lines for positive values and blue lines for negative values.

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).

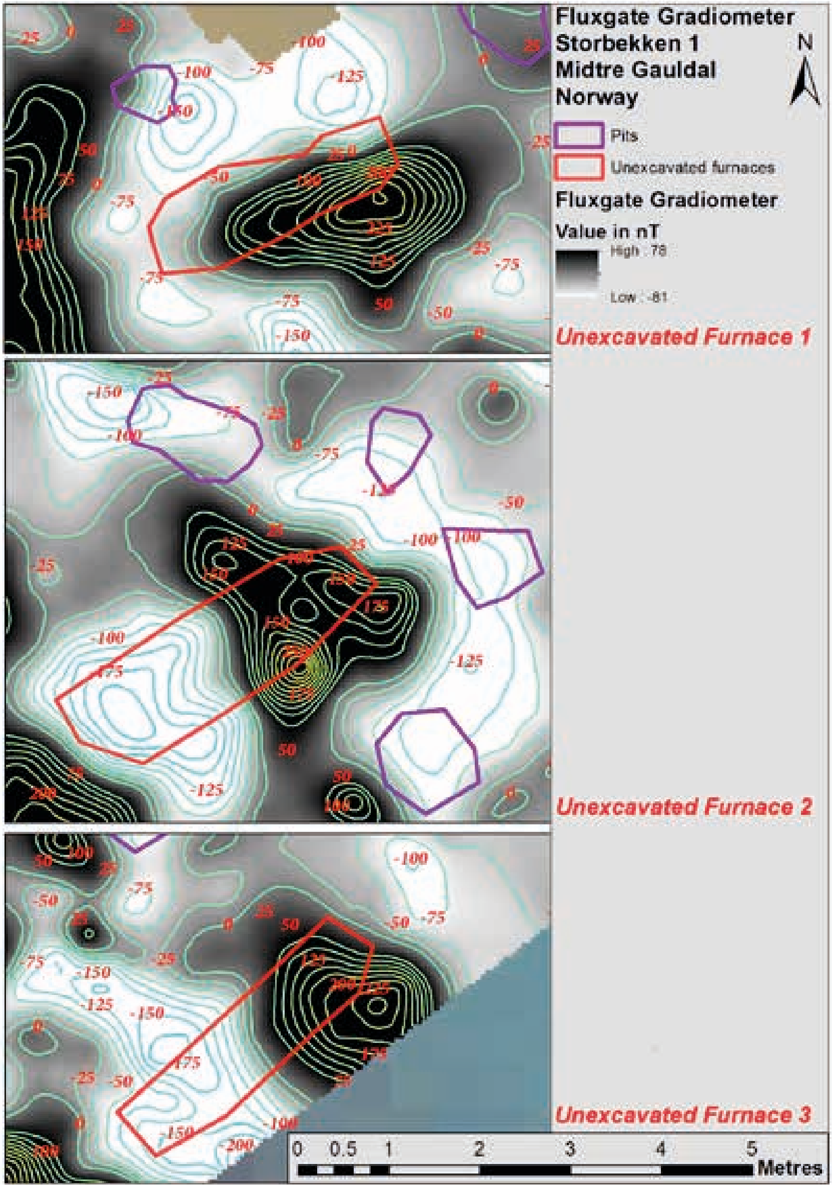

Figure 18. Detailed illustration of the fluxgate gradiometer response of the unexcavated furnaces at Storbekken 1.

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

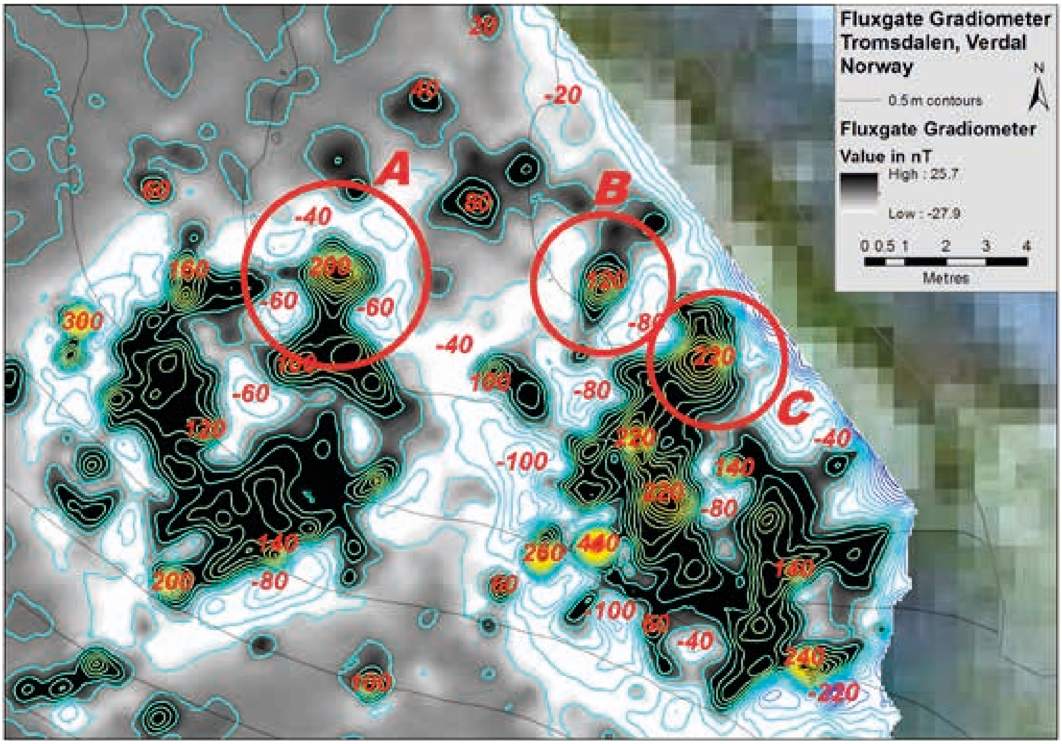

Figure 19. Possible furnaces at Tromsdalen. Fluxgate gradiometer data. The contours are 20 nT apart, with red lines for positive values and blue lines for negative values

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

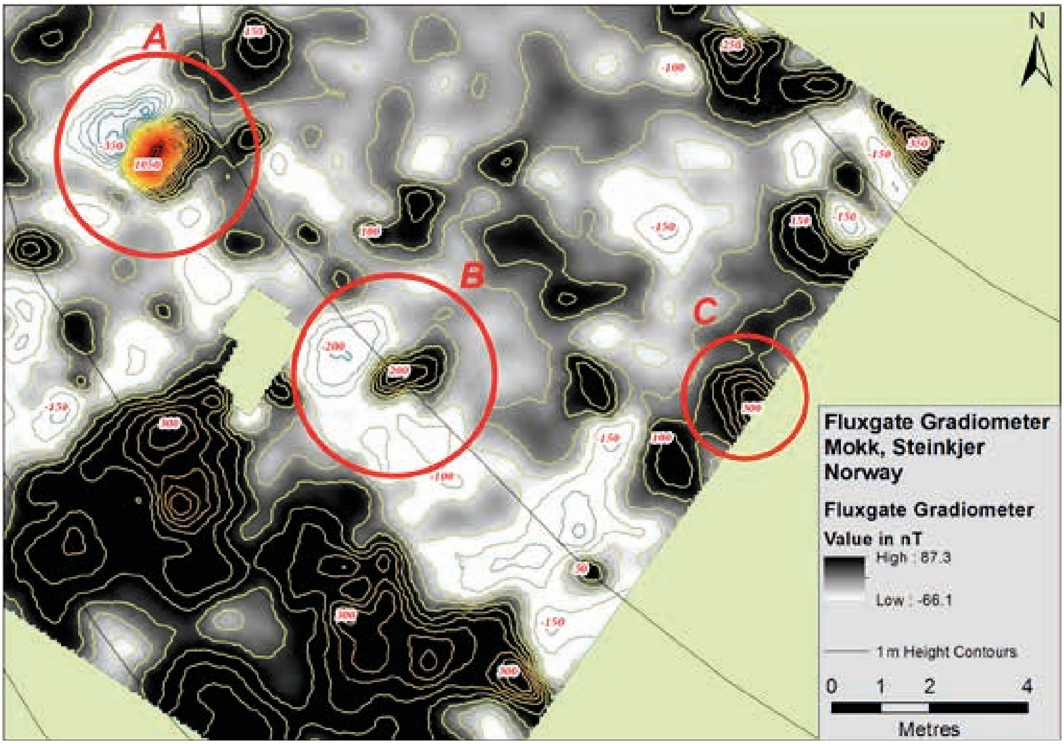

Figure 20. Possible furnaces at Mokk. Fluxgate gradiometer data. The contours are y 50 nT apart, with red lines for positive values and blue lines for negative values

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.

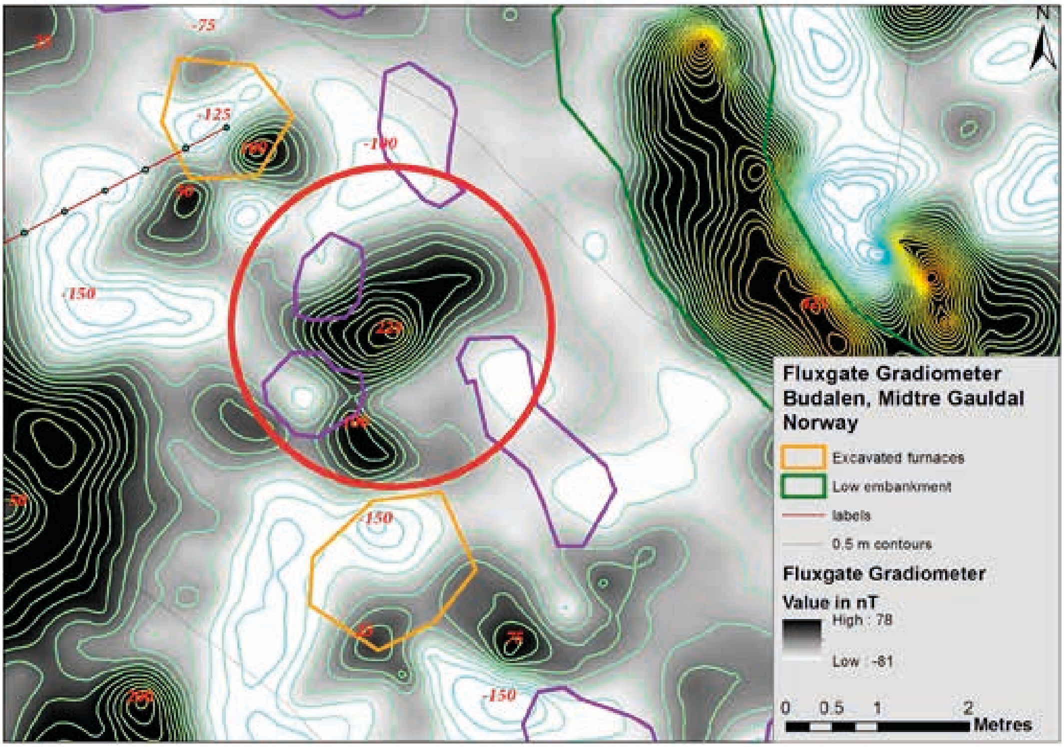

Figure 21. A semi-oval anomaly perpendicular to the edge of the terrace, with a strong maximum reading of 237 nT. This anomaly is situated between the two excavated furnaces. Can this mark a furnace from an earlier phase of activity?

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.

References

Abrahamsen, N., Jacobsen, B. H., Koppelt, U., de Lasson, P., Smekalova, T. & Voss, O. (2003). Archaeomagnetic investigations of Iron Age slags in Denmark. *Archaeological Prospection, 10*(2), 91–100.

Arnkværn, S. (2013). *Arkeologisk rapport. Kulturhistorisk registrering. Tromsdalen, Verdal kommune* (Saksnummer 12/07848). Nord-Trøndelag County Authority.

Aspinall, A., Gaffney, C. & Schmidt, A. (2009). *Magnetometry for archaeologists. Geophysical methods for archaeology*. Plymouth: AltaMira Press.

Batt, C., Fear, S. & Heron, C. (1995). The role of magnetic susceptibility as a geophysical survey technique: A site assessment at High Cayton, North Yorkshire. *Archaeological Prospection, 2*(4), 179–196.

Berre, B. (1999). Heglesvollen år 2000. In Levanger historielag (Ed.), *Årbok 1999* (pp. 65–79). Levanger: Levanger historielag.

Clark, A. (1996). *Seeing beneath the soil. Prospection methods in archaeology.* London: Routledge.

Corney, M., Gaffney, C. F. & Gater, J. A. (1994). Geophysical investigations at the Charlton Villa, Wiltshire (England). *Archaeological Prospection, 1*(2), 121–128.

Crew, P. (1990). Crawcwellt West, Trawsfynydd, Merionetshire. *Archaeology in Wales, 30*, 46–47.

Crew, P. & Crew, S. (1995). Medieval bloomeries in North-West Wales. In G. Magnusson (Ed.), *The importance of ironmaking: Technical innovations and social change, Norberg 1995* (p. 43–50). Stockholm: Jernkonterets Berghistoriska Utskott.

Dalan, R. A. (2008). A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: recent developments and prospects. *Archaeological Prospection, 15*(1), 1–31.

David, A., Linford, N., Linford, P., Martin, L. & Payne, A. (2008). *Geophysical survey in archaeological field evaluation.* Swindon: English Heritage.

Dearing, J. (1999). E*nvironmental magnetic susceptibility. Using the Bartington MS2 system*. Bartington Instruments Ltd.

Espelund, A. (1999). *Bondejern i Norge.* Trondheim: Arketype forlag.

Espelund, A. & Stenvik, L. F. (1993). Ironmaking during the Roman Iron Age in Mid-Norway. The bloomery site Storbekken I in Budalen. In A. Espelund (Ed.), *Bloomery ironmaking during 2000 years* (vol. 3, pp. 123–147). Trondheim: Norwegian Institute of Technology.

Evans, M. E. & Heller, F. (2003). *Environmental magnetism: Principles and applications of enviromagnetics. International geophysics series.* Amsterdam & Boston: Academic Press.

Farbregd, O., Gustafson, L. & Stenvik, L. F. (1985). Tidlig jernproduksjon i Trøndelag. Undersøkelsene på Heglesvollen. *Viking, 48*, 103–129.

Farbregd, O. (1977). Archaeological field work and evidence. *Norwegian Archaeological Review, 10*(1–2), 119–126.

Fassbinder, J. W. E. & Stanjek, H. (1993). Occurrence of bacterial magnetite in soils from archaeological sites. *Archeologia Polona, 31*, 117–128.

Gaffney, C. & Gater, J. (2003). *Revealing the buried bast.* Stroud: Tempus.

Grøtberg, U. T. & Tveiten, O. (2015). Hagleby – utfordringer og muligheter ved et delvis ødelagt materiale. In I. M. Berg-Hansen (Ed.), *Arkeologiske undersøkelser 2005–2006. Kulturhistorisk Museum, Universitetet i Oslo*, pp. 154-171. Oslo: Portal forlag.

Isaaks, E. H. & Srivastava, R. M. (1989). *An introduction to applied geostatistics.* New York: Oxford University Press.

Jørgensen, R. (2010). *Production or trade? The supply of iron to North Norway during the Iron Age*. (Doctoral dissertation). University of Tromsø, Tromsø.

Kallhovd, K. & Larsen, J. H. (2006). På sporet av den eldste jernvinna i indre Agder – et sentralområde med spesialisert overskuddsproduksjon. In D. Skre, H. Glørstad & B. Skar (Eds.), *Historien i fortiden. Festskrift til Einar Østmo på 60-årsdagen. Kulturhistorisk Museum Skrifter* (vol. 4, pp. 237–253). Oslo: Museum of Cultural History, University of Oslo.

Larsen, J. H. (1991). *Jernvinna ved Dokkfløyvatn. De arkeologiske undersøkelsene 1986–1989. Varia* (vol. 23). Oslo: Museum of Cultural History, University of Oslo.

Larsen, J. H. (2009). *Jernvinneundersøkelser. Faglig program, bind 2. Varia* (vol. 78). Oslo: Museum of Cultural History, University of Oslo.

Linderholm, J. (2007). Soil chemical surveying: A path to a deeper understanding of prehistoric sites and societies in Sweden. *Geoarchaeology, 22*(4), 417–438.

Martinsen, J. R. P. & Stene, K. (2017). *En ovn på avveie?* Retrieved 12 February 2019 from http://www.norark.no/prosjekter/skjerka-sektoravgift/en-ovn-pa-avveie/.

Nordlie, E. 2009). *Trøndelagsovner. Arkeologisk forståelse av jernutvinningsteknologi fra eldre jernalder i Midt-Norge*. (Master's thesis). University of Oslo, Oslo.

NTNU University Museum (2013). *Verdal - Kommunedelplan Tromsdalen. Dispensasjon fra kml §3-4 for automatisk freda kulturminner ID 145884-1,2,3,4,5,6,9,10,11,12,13,14,15,16. ID 147599-1,3,4,7. ID 161107, ID 157483-1,2,3. ID 145484-7,8. ID 146750, ID 147614, ID 147606, ID 147611, ID 151840, ID 151841, ID 151842, ID 147617, ID 146732, ID 146746, ID 147620, ID 147029*. Letter to Riksantikvaren dated 04.02.2013, signed by L. F. Stenvik & B. Skar. Trondheim: NTNU University Museum, Norwegian University of Science and Technology (NTNU).

Powell, A. J. (2008). *The magnetic signatures of Medieval and Post-Medieval pyrotechnical industries.* (PhD dissertation). University of Bradford, Bradford.

Powell, A. J., McDonnell, J. G., Batt, C. M. & Vernon, R. W. (2002). An assessment of the magnetic response of an iron-smelting site. *Archaeometry, 44*(4), 651–665.

Prestvold, K. (1999). *Trøndelag i støpeskjeen. Jernproduksjon og sosial organisasjon i Nord-Trøndelag mellom 350 f.Kr. og 500 e.Kr. Gunneria* (vol. 75). Trondheim: NTNU University Museum, Norwegian University of Science and Technology (NTNU).

Risbøl, O., Risan, T., Bjørnstad, R., Fretheim, S. & Rygh, B. H. E. (2002a). *Kulturminner og kulturmiljø i Gråfjell, Regionfelt Østlandet, Åmot kommune i Hedmark. Arkeologiske registreringer 2002, fase 4. NIKU Publikasjoner* (vol. 125). Oslo: NIKU.

Risbøl, O., Risan, T., Kræmer, M. B., Paulsen, I., Sønsterud, K. E., Swensen. G. & Solem, T. (2002b). *Kulturminner og kulturmiljø i Gråfjell, Regionfelt Østlandet, Åmot kommune i Hedmark. Arkeologiske registreringer 2001, fase 3. NIKU Publikasjoner* (vol. 116). Oslo: NIKU.

Risbøl, O. & Smekalova, T. (2001). Archaeological survey and non-visible monuments. The use of magnetic prospecting in outfield archaeology. *Nicolay Arkeologisk Tidsskrift, 85*(3), 32–45.

Risbøl, O., Vaage, J., Fretheim, S., Narmo, L. E., Rønne, O., Myrvoll, E. & Nesholen, B. (2001). *Kulturminner og kulturmiljø i Gråfjell, Regionfelt Østlandet, Åmot kommune i Hedmark. Arkeologiske registreringer 2000, fase 2. NIKU Publikasjoner* (vol. 102). Oslo: NIKU.

Rundberget, B. (2002). *Teknologi og jernvinne – en teoretisk og metodisk tilnærming til jernvinna som kilde for menneskelig kunnskap og handling*. (Cand.philol. thesis). Norwegian University of Science and Technology (NTNU), Trondheim.

Rundberget, B. (2007). *Jernvinna i Gråfjellområdet. Varia* (vol. 63). Oslo: Museum of Cultural History, University of Oslo.

Rundberget, B. (2010). Jernproduksjon i Norge i romertid – en marginal eller sentral ressurs? *Nicolay skrifter*, (3), 36–49.

Schmidt, A. & Marshall, A. (1997). Impact of resolution on the interpretation of archaeological prospection data. In A. G. M. Sinclair, E. A. Slater & A. J. Gowlett (Eds.), *Archaeological Sciences 1995. Oxbow Monographs in Archaeology* (pp. 343–348). Oxford: Oxbow Books.

Smekalova, T. (2006). *Magnetic survey in Hovdem Norway in June 2006. A report*. St. Petersburg: St. Petersburg State University.

Smekalova, T. & Smekalov, S. (2005). *Magnetic survey in Tyin, Sogn Skarvheimen, Oppland, Norway*. St. Petersburg: St. Petersburg State University.

Smekalova, T. & Voss, O. (2002). Field procedures for magnetic investigations of iron-smelting sites with slag pits. In L. C. Nørbach (Ed.), *Prehistoric and medieval direct iron smelting in Scandinavia. Aspects of technology and science* (pp. 223–226, 322–335). Aarhus: Aarhus University Press.

Smekalova, T., Voss, O. & Smekalov, S. L. (2008). *Magnetic surveying in archaeology*. Aarhus: Wormanium.

Solem, T. (1991). Effects of early iron production on vegetation: A study by means of pollen analysis. In A. Espelund (Ed.), *Bloomery ironmaking during 2000 years. Seminar in Budalen 1991* (vol. 1). Trondheim: Norwegian Institute of Technology.

Stamnes, A. A. (2010). *Geofysiske undersøkelser – jernvinneanlegg på Mokk, Ogndalen i Steinkjer kommune.* Trondheim: The NTNU University Museum, Norwegian University of Science and Technology (NTNU).

Stamnes, A. A. (2011). Georadar avdekker fortidsminner. *Spor – populærarkeologisk tidsskrift*, (1), 30–33.

Stamnes, A. A. (2016). *The application of geophysical methods in Norwegian archaeology: A study of the status, role and potential of geophysical methods in Norwegian archaeological research and cultural heritage management.* (Doctoral thesis). Norwegian University of Science and Technology (NTNU), Trondheim.

Stamnes, A. A. & Gustavsen, L. (2014). Archaeological use of geophysical methods in Norwegian cultural heritage management – a review. In H. Kamermans, M. Gojda & A. G. Posluschny (Eds.), *A sense of the past. Studies in current archaeological applications of remote sensing and non-invasive prospection methods. BAR International Series* (pp. 17–32). Oxford: Archaeopress.

Stenvik, L. F. (1991). Iron production and economic "booms" during 2000 years. In A. Espelund (Ed.), *Bloomery ironmaking during 2000 years* (vol. 1, pp. 100–115). Trondheim: NTH.

Stenvik, L. F. (1996). *De arkeologiske undersøkelsene av et jernframstillingsanlegg ved Fjergen i Meråker*. Trondheim: NTNU Vitenskapsmuseet.

Stenvik, L. F. (1997). Iron production in Mid-Norway, an answer to local demand? In H. J. Hässler (Ed.), *Studien zur Sachsenforschung* (vol. 10). Oldenburg: Isensee Verlag.

Stenvik, L. F. (2003). Iron production in scandinavian archaeology. *Norwegian Archaeological Review, 36*(2), 119–134.

Vernon, R. W. (2004). *Application of archaeological geophysical techniques to the investigation of British smelting sites.* (PhD dissertation). University of Bradford, Bradford, Great Britain.

Walach, G., Scholger R. & Cech, B. (2011). Geomagnetic and geoelectric prospection on a Roman iron production facility in Hüttenberg, Austria (*Ferrum Noricum*). *Archaeological Prospection, 18*(2), 149–158.

Wintervoll, J. A. (2010). *Logistikk og transport – en detaljstudie av metallfremstilling i Midt-Norden i romertiden og folkevandringstiden*. (Master's thesis). University of Bergen, Bergen.

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