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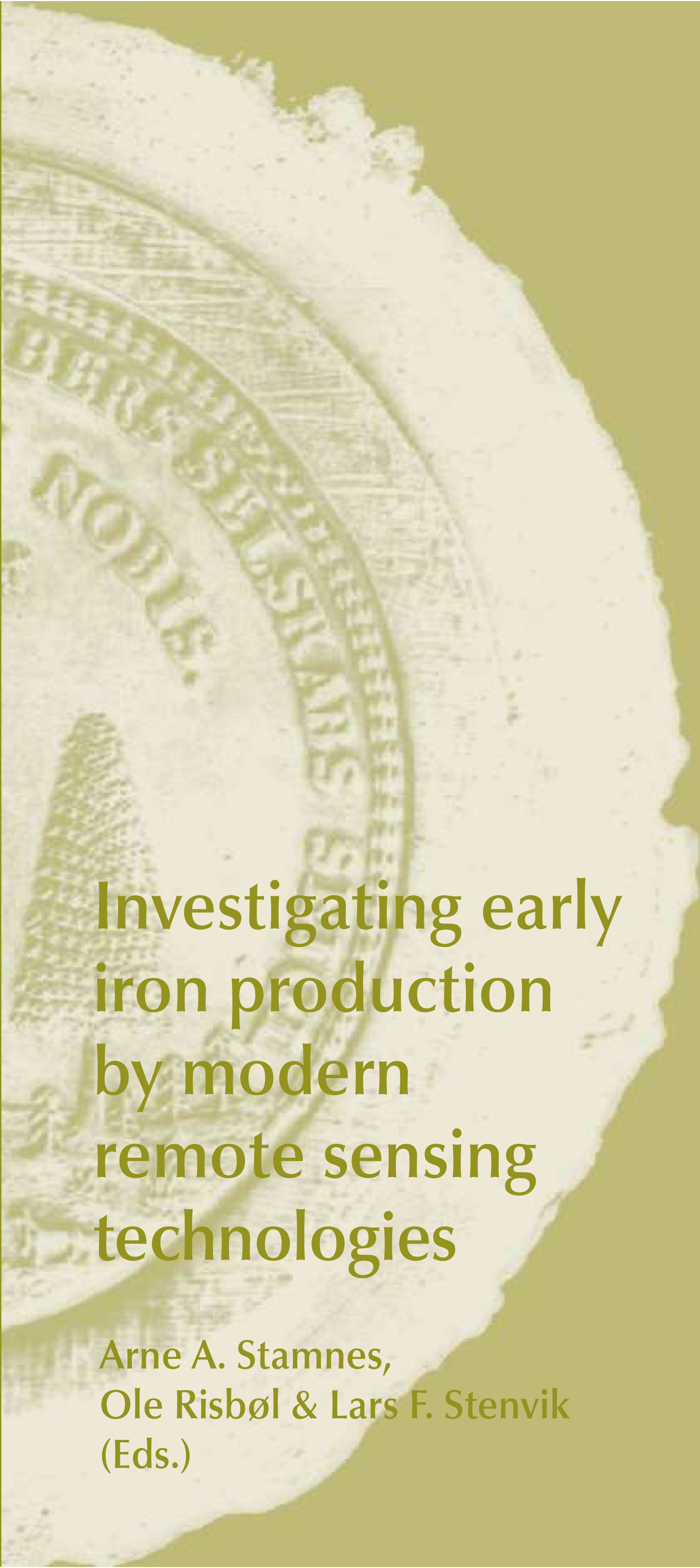

Investigating early iron production by modern remote sensing technologies

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

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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

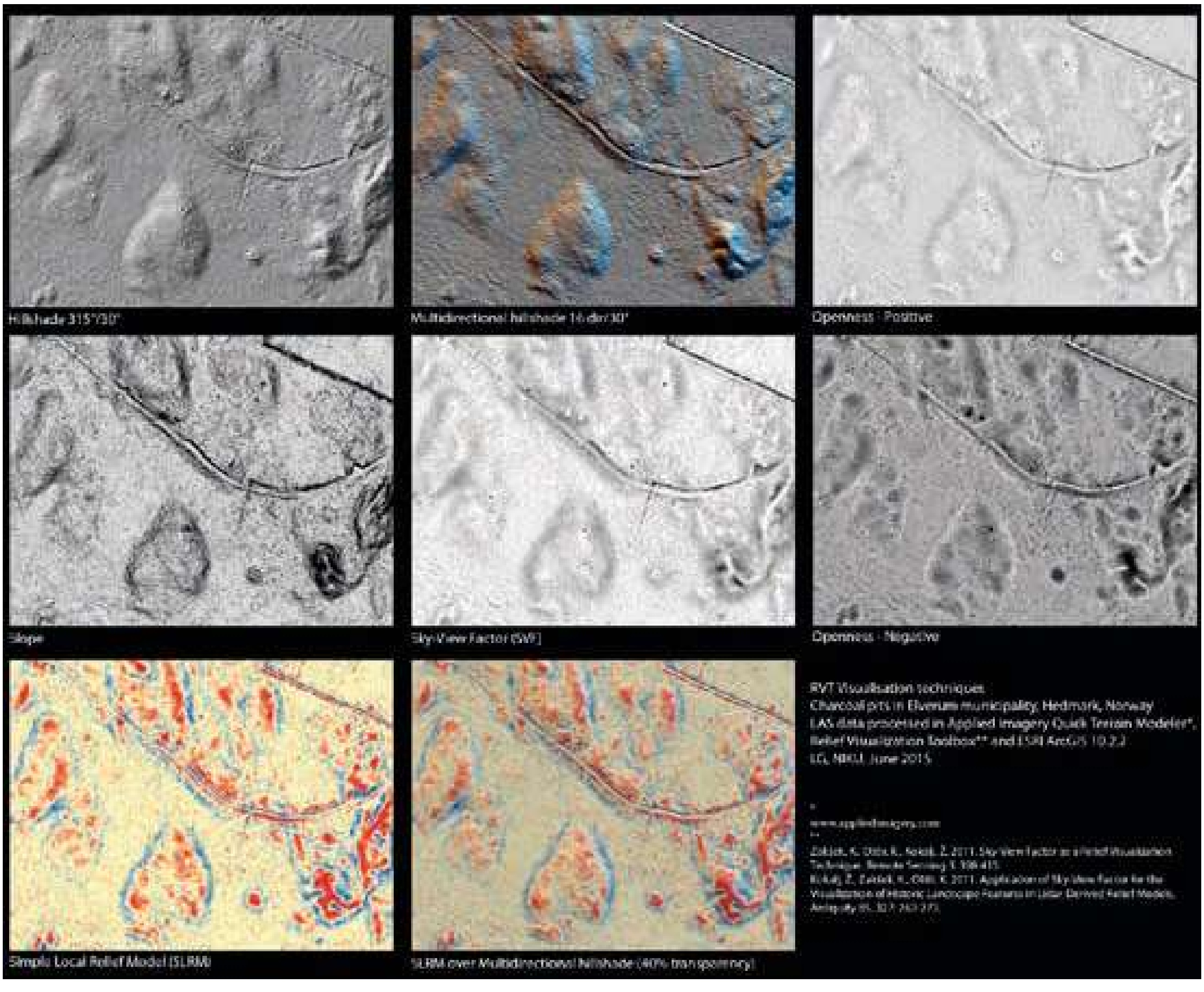

Figure 3. A section of the Elverum study area with examples of common visualisation techniques used for the interpretation of lidar data sets where iron production sites are present. The models were created using a combination of Quick Terrain Modeler, Relief Visualisation Toolbox and ArcGIS 10.2.2.

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

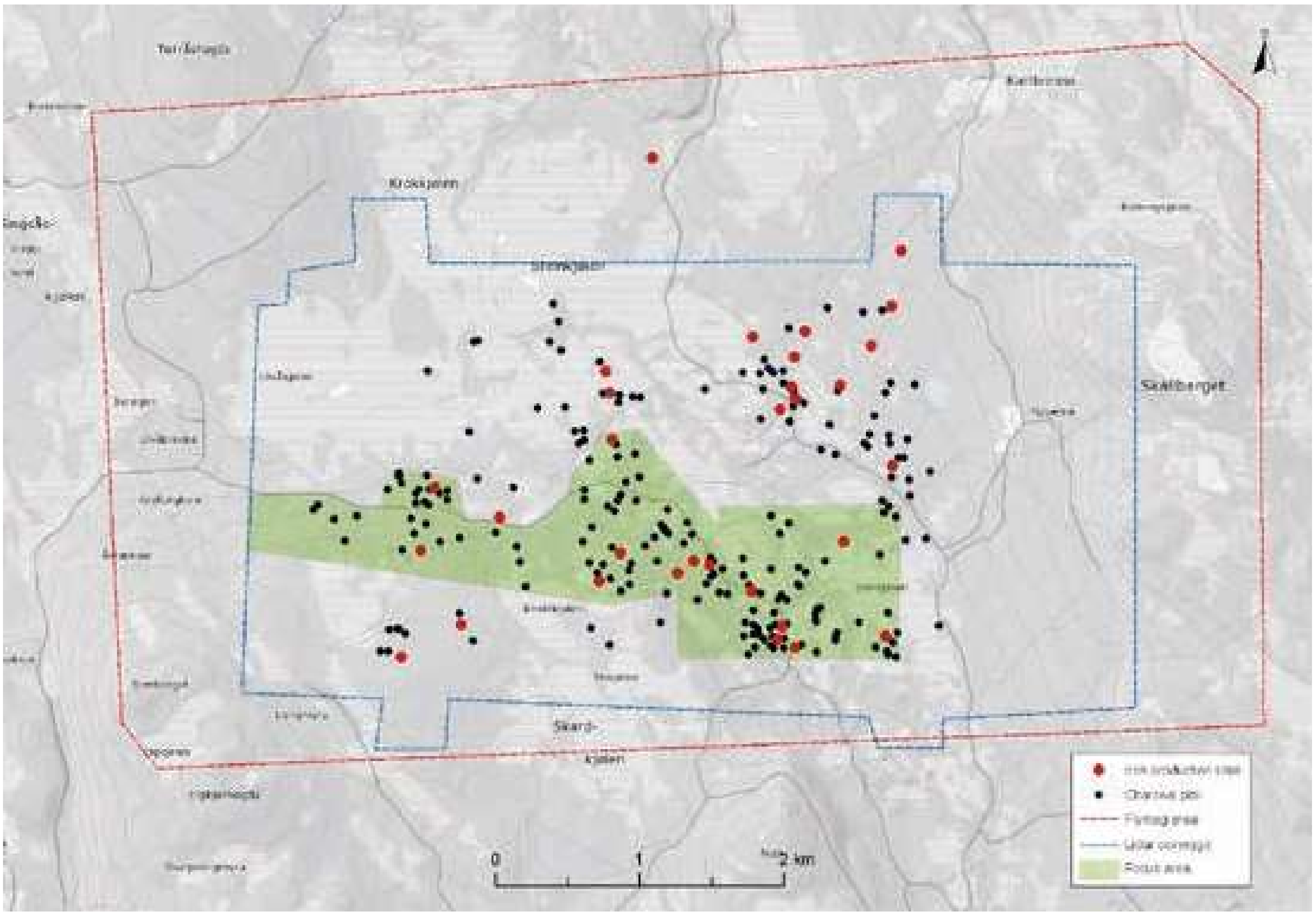

Figure 4. The Elverum case study area showing the distribution of known iron production sites and charcoal pits. The area surveyed using lidar in 2005 is outlined in blue and the area covered by airborne magnetometry is outlined in red. The focus area for the visual interpretation is shaded in green. 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.

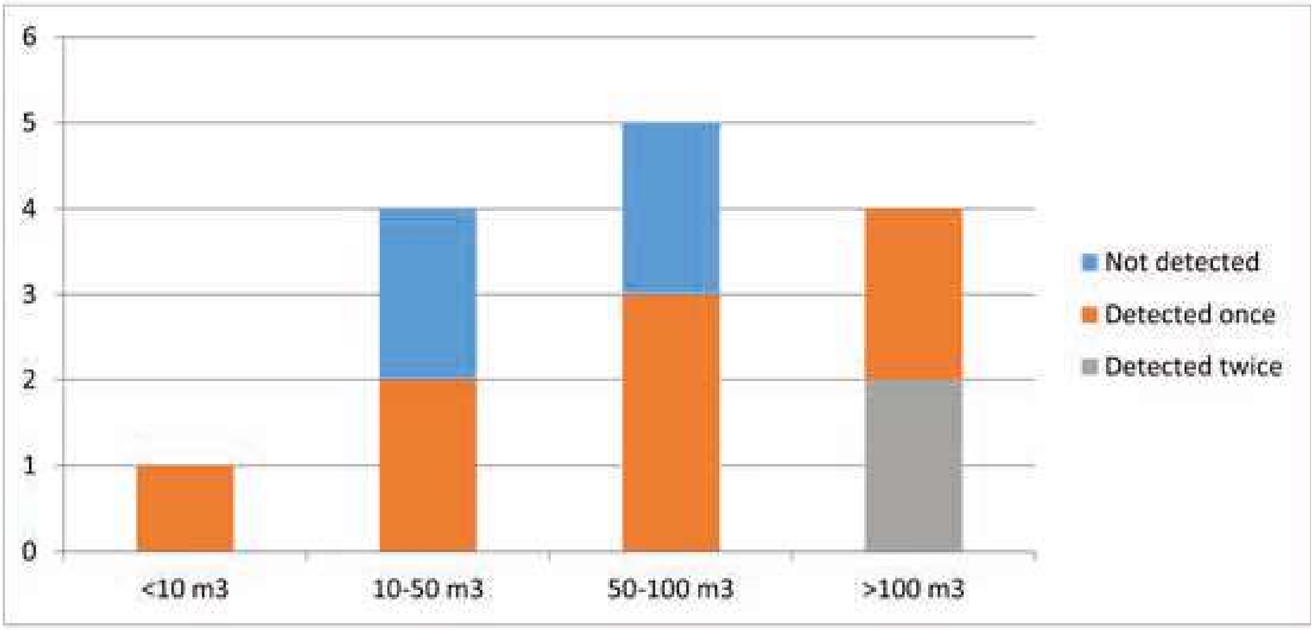

Figure 5. The iron production sites divided into four groups according to their relative size (based on slag volume[11]) and the number of times they were identified by the interpreters.

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.

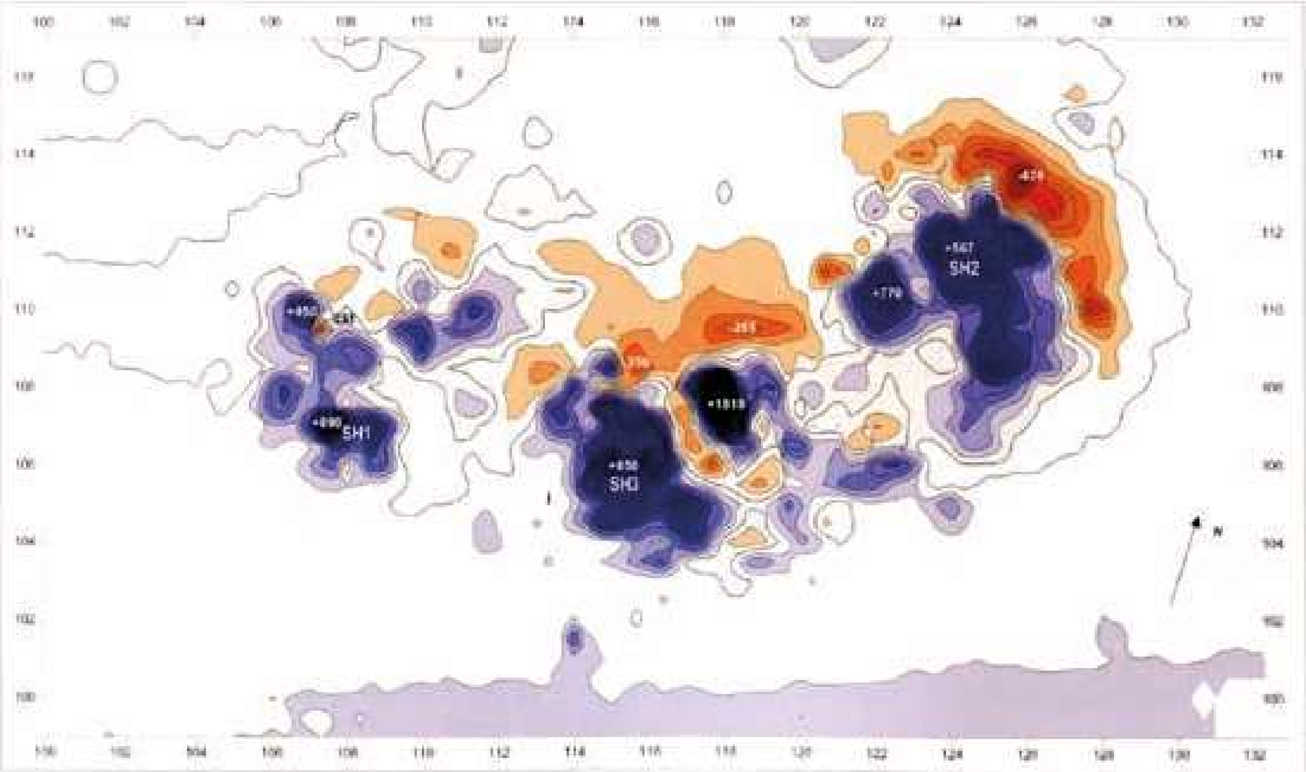

Figure 6. An iron production site similar to the ones in our study area mapped with a handheld magnetometer in 2005 by geophysicist T. Smekalova. SH = slag heap; the dark blue anomalies between slag heaps 2 and 3 are where remnants of the furnaces are situated. After Rundberget (2007, p. 234, Fig. 174).

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.

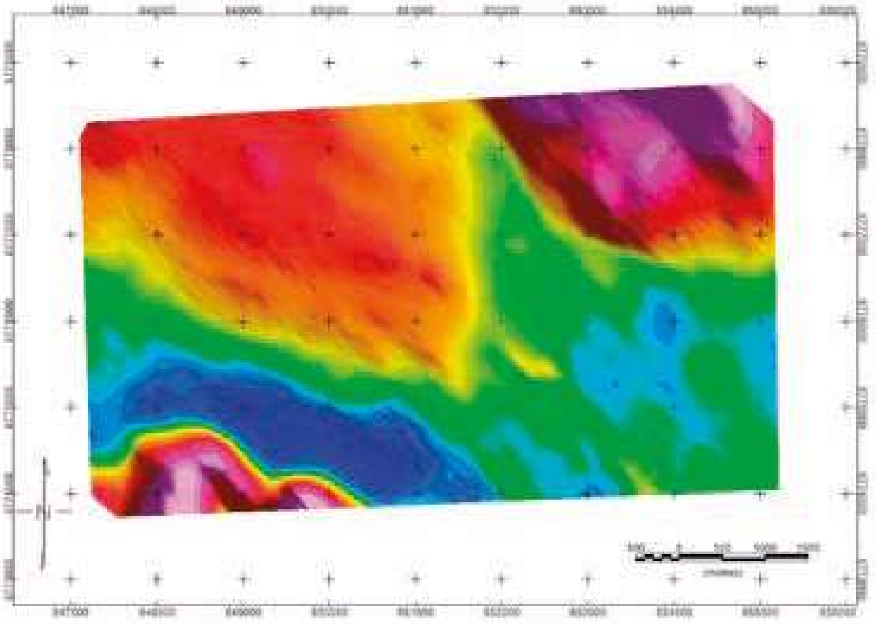

Figure 8: Preliminary map from the airborne magnetometer survey. Red and purple are high relative values, blue is low relative values. There is no scale on the strength of the measurements in this particular example.

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.

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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.

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