Full Title: Geoarchaeological evaluation of ground penetrating radar and magnetometry surveys at the Iron Age burial mound Rom in Norway

Short Title: Geoarchaeological evaluation of geophysical surveys in Norway

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Abstract

Following magnetometry and ground penetrating radar surveys, a geoarchaeological field evaluation was carried out at the Iron Age burial mound of Rom in Slagendalen, Vestfold County, Norway, in order to assess the accuracy of the geophysical data interpretation and to investigate specific questions that have arisen during data interpretation. The evaluation was conducted within the framework of an archaeological excavation campaign in 2013, which enabled direct access to the subsurface materials. The archaeological stratification was recorded by laser scanning using a 3D single-surface approach, permitting a virtual reconstruction of the excavated part of the mound and facilitating the comparison between excavation and prospection data. Selected sediment sequences were targeted with in-situ and lab-based measurements for correlation purposes, including magnetic susceptibility, electrical conductivity and water content measurements. Here we present the methodological approach and the results of the geophysical prospection surveys, followed by a geoarchaeological evaluation and a discussion of the impact on the overall archaeological investigation.

Keywords: Geoarchaeology, Geophysics, Magnetometry, GPR, Magnetic susceptibility, Norway

Introduction

Archaeological geophysical prospection has become a frequently used investigation method in archaeology in order to efficiently detect, map and interpret buried structures of archaeological interest (Wynn 1986; Scollar *et al*. 1990; Neubauer 2001b; Linford 2006; Gaffney 2008; Jordan 2009; Fassbinder 2015). The non-invasive nature of this approach allows repeatable investigations of the subsurface without destroying primary data. The use of motorised systems in recent years permits the prospection of areas measuring square kilometres at a high spatial sampling resolution within a reasonable amount of time (Kvamme 2003; Campana 2009; Linford and Linford 2010; Trinks *et al*. 2012; Gabler *et al*. 2013; Trinks *et al*. 2014). Due to these advancements, near surface geophysical prospection methods become exceedingly relevant as cost- and time-efficient tools, not just in the case of archaeological research projects, but also for heritage management, monitoring, protection and rescue or exploration archaeology (Chapman *et al*. 2009; Cowley 2011; Neubauer *et al*. 2012; Bunting *et al*. 2014; Nau *et al*. 2015). In order to further promote this development, however, the corresponding interpretation of the prospection data must provide information as accurate and detailed as possible. Accuracy and level of detail depend on a range of factors, including technical parameters of the measurement systems used, survey design, experience in interpreting geophysical data sets and specific routines applied as well as expertise in local archaeology (Neubauer 2001a; Cowley 2011). By far the most complex and dynamic factor, however, encompasses the physical properties of the subsurface materials and how these respond to different prospection techniques (Scollar *et al*. 1990; van Dam 2001; Cassidy 2008a; Bonsall *et al*. 2014). Local and regional environmental settings including soil types, geology, topography as well as erosion and accumulation processes all influence the quality of prospection data and their interpretation (Kattenberg and Aalbersberg 2004; Becker 2009; Linck and Fassbinder 2014; Fassbinder 2015), yet these effects are rarely fully recognised in studies. At best, this neglect leads to a loss of information and possibly to a drop in the result's accuracy, while in a worst case scenario erroneous interpretations may be produced due to an uncritical evaluation of the prospection data as an accurate depiction of the subsurface conditions. In order to address these issues, a geoarchaeological evaluation of the archaeological geophysical prospection data interpretation can help to better understand the interaction of specific environmental settings with different geophysical techniques, and to build a comparative database for similar archaeological settings and situations.

Precisely such a geoarchaeological evaluation was conducted accompanying the archaeological excavation in 2013 of Rom mound in Slagendalen, Vestfold County, Norway. The excavation followed motorised magnetometry and ground penetrating radar (GPR) surveys carried out in 2012 by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro). Based on the results of the prospection survey, the mound was partially excavated in August 2013 by the Vestfold County Administration (Vfk) and the Museum of Cultural History Oslo (UiO) (McGraw and Bill 2014), attempting to establish the type of burial and the preservation status of the monument. In collaboration with the LBI ArchPro and the Norwegian Institute for Cultural Heritage Research (NIKU) the excavation process was digitally documented throughout using a terrestrial 3D laser scanner. The three-dimensional documentation enabled the later virtual reconstruction of the excavated part of the mound. Besides providing precise data for further archaeological investigations, the resulting volumetric data was used to evaluate the interpretation of the geophysical data. The exposure of soils, sediments and archaeological deposits during the excavation allowed for targeted in-situ geophysical measurements including magnetic susceptibility, electrical conductivity and water content measurements for correlation purposes as well as for the pursuit of specific questions raised during the interpretation process. The study presented here evaluates the general accuracy of the geophysical data interpretation, the amount of detail identifiable in the prospection data sets, and the influence of environmental settings on these data sets. The methodological approach and the results of the geophysical prospection, geoarchaeological evaluation and their impact on the overall archaeological investigation are presented and discussed.

Background

Near-surface geophysical prospection methods are based on the detection of variations in the physical properties of the investigated subsurface materials. The detectability of archaeological and palaeoenvironmental structures is thereby dependent on sufficient measureable contrast between these structures and the host material (Scollar *et al*. 1990; Linford 2006). Different geophysical prospection techniques, such as the commonly used GPR and magnetometry, respond to different physical parameters. The propagation of electromagnetic energy as used in GPR, for instance, is defined by the electric properties of the soil, namely the ground's dielectric permittivity and electrical conductivity, as well as – to a lesser degree – by the magnetic permeability of the medium it traverses. These primary parameters and their interactions with the transmitted electromagnetic pulse have been discussed and addressed in detail by a range of authors (Scollar *et al*. 1990; Leckebusch 2003; Conyers 2013; Cassidy 2008b; Verdonck 2012; Goodman and Piro 2013). Dielectric permittivity thereby "describes the ability of a material to store and release electromagnetic energy in the form of electric charge" (Cassidy 2008a). It is usually expressed dimensionless (εr) as the ratio ($\varepsilon/\varepsilon_0$) between the permittivity of a material (ε) relative to the permittivity of vacuum (ε_0). In most subsurface materials investigated with electromagnetic pulses with a mean frequency between 10 and 1000 MHz, dielectric permittivity is greatly controlled by free and bound water (Cassidy 2008a). The reason for this is the notable difference in the dielectric permittivity values of air (ca. 1 ε_r), freshwater (ca. 80 ε_r) and mineral constituents (ca. 3-8 ε_r), which form major components of mineral soils and sediments (Scollar *et al*. 1990; Annan 2008; Cassidy 2008b; Visconti *et al*. 2014). Magnetic permeability, on the other hand, usually is considered to be only of minor influence for the propagation of electromagnetic energy as long as the amount of ferro-/ferrimagnetic minerals, such as iron, does not exceed approximately 2% (Cassidy 2008a).

This situation is of course different in the case of magnetometer surveys, which aim to detect local variations in the Earth's magnetic field caused by subsurface materials either responding to an applied magnetic field (induced magnetisation – measured with magnetic susceptibility readings) or to magnetic remanence – such as for instance thermoremanent magnetisation (Scollar *et al*. 1990; Neubauer 2001a; Dalan 2006b; Fassbinder 2015). Magnetometry surveys do not distinguish between these two forms of magnetisation but measure the combined "net effect" (Dalan 2006b). While the estimation of remanent magnetisation is a rather cost- and time intensive process, requiring a laboratory environment (Evans and Heller 2003), magnetic susceptibility (MS), in contrast, can quickly and relatively cheaply be measured in-situ as well as in a laboratory (Dearing 1994). MS values of deposits are mainly controlled by the presence or absence of ferrimagnetic minerals, including magnetite, maghemite, hematite and, to a smaller extent, pyrrhotite (Fassbinder 1994; Van Dam *et al*. 2004) and can thus provide basic insights into magnetic mineral composition, indicate different anthropogenic and environmental processes in addition to being a key element in magnetic modelling (Maher 1986; Fassbinder 1994; Dearing *et al*. 1996; Dalan and Banerjee 1998; Maher 1998; Neubauer 2001b; Evans and Heller 2003, Bevan 2016).

Based on these physical principles, water content (respectively dielectric permittivity), electrical conductivity and magnetic susceptibility were chosen as diagnostic elements for general correlation of subsurface materials excavated at the Rom mound with GPR and magnetometry data. A second focus was placed on the targeted investigation of selected phenomena, such as GPR signal attenuation, the abundance of magnetic dipole anomalies, and insufficient contrast observed during the archaeological interpretation of the geophysical prospection data.

Site description

Geographical location and environmental settings

The Rom mound is located in the southern county of Vestfold in Norway, 5.6 km north of the municipal town of Tønsberg, and embedded into Slagendalen – a Viking Age landscape that also accommodates the famous Oseberg ship burial (Brøgger *et al*. 1917; Gansum 1995) (Fig.1). The Slagendalen is a ca. 850 m wide and 6.5 km long river valley, extending roughly in NS direction towards the Oslo Fjord, being flanked on both sides by gently rising slopes with forested hills that ascend to ca. 75 m in the west and ca. 50 m in the east. The rolling topography is described as a "fjärd" landscape (Embleton and King 1970; Bird and Schwartz 1985; Fairbridge 1985; Bird 2010) and as such characterised by more shallow former coastal inlets compared to the steep fjords typical for western and northern Norway. The lowest point of the valley lies at an altitude of ca. 25 m above current sea level, with the Rom mound being situated slightly higher at ca. 27 -28 m. Norway was, and still, is affected by retreating sea-levels caused by post-glacial rebound (Draganits *et al*. 2015). The area around the Rom mound became dry land around 4,000 BC (Sørensen *et al*. 2007) and this process is clearly illustrated by the marine origin of the near surface deposits at the valley bottom (Fig 2b). The mound itself lies on thick marine/fjord deposits, while being surrounded by marine/beach deposits. The area is also influenced by the Ra moraine, a terminal moraine which runs SW-NE towards the coast at Mølen and passes ca. 2km to the west of Slagendalen. Geologically, the area comprises latite, a volcanic equivalent to monzonite, and by rhomb porphyry. The burial mound itself was erected on endostagnic Cambisol (Fig. 2a), a weakly developed soil with periodically reducing conditions (Soil WRB 2006). Today, most of the valley is used for agricultural purposes with large fields covering the majority of the area, thus being well-suited for large-scale motorised geophysical archaeological prospection surveys.

Research history

The archaeological monument at Rom (ID 140556 in Askeladden in the national sites and monuments record) was first discovered by aerial photography in 1990 and subsequently interpreted as a burial mound. In 2001, a test trench (12 × 1m) excavated by UiO and Vfk confirmed this interpretation and revealed a dense stone packing as the mound's core structure as well as traces of a surrounding ring ditch (Brun 2001). The investigation also highlighted that the site was already partially affected by the intense agricultural activity in the valley. Size and structure of the Rom mound as well as the proximity to the Oseberg ship burial (Gansum 1995), rendered the possibility of another ship burial at Rom plausible. In 2003, geophysical prospection surveys conducted by the University of Kiel using GPR and magnetometer measurements provided a first overview of the subsurface structures, further confirming the findings from the aerial interpretation and the test trenching (Lorra *et al*. 2003). In order to learn more about the preservation conditions and current status a coring survey was carried out in 2004 by UiO and Vfk, which revealed fine grained marine clay beneath the mound (Martens 2004) – a material that would favor the preservation of potentially present organic material. In 2009, airborne laser scans (ALSM; 4 ground points/m^2) were conducted by the Norwegian Mapping Authority, and subsequently processed by the LBI ArchPro with a resampled resolution of 0.5 m and visualised as hillshade and local relief model (LRM). The new data highlighted the shallowly preserved superstructure of the mound with a remaining height of ca. 1m (Fig. 3a and b).

Geophysical prospection

In 2012, these earlier results prompted a second, more detailed non-invasive geophysical prospection again using magnetometry, but focusing particularly on high-resolution GPR in order to obtain a clearer view of the mound's internal structure. Surveys were carried out within the framework of the LBI ArchPro Case Study Larvik-Vestfold, conducted as a joint research cooperation between the LBI ArchPro, Vfk, NIKU and the *Gokstad Revitalised* Project, focusing on Viking Age landscapes including the settlement and burial site of Gokstad (Nicolaysen 1882; Gansum 1997; Bill and Rødsrud 2013; Bill *et al*. 2013; Nau *et al*. 2015), the royal burial park of Borre (Nicolaysen 1854; Myhre 1992) and the harbour-, settlement- and burial site of Kaupang (Skre 2007) and its hinterland, all situated in the county of Vestfold. Additional surveys also comprised large-scale investigations of the Slagendalen with the Oseberg mound and the Rom mound. The monument itself was covered with 0.8 ha of magnetometry and a 0.7 ha GPR survey. The fieldwork was carried out between September 24th and 27th 2012. For the GPR survey, a SPIDAR Network GPR array (Sensors & Software) with six transmitter-receiver pairs of PulseEkko Pro 500 MHz antennae in 25 cm cross-line geometry with 50 Hz constant inline sampling interval was used, resulting in ca. 5 -8 cm inline GPR trace spacing, depending on actual driving speed. In order to increase the spatial resolution and to obtain a more detailed picture of the mound's structure, the survey area was covered both in EW and NS directions, resulting in a considerably larger number of individual GPR traces and improved imaging conditions. The magnetometry survey was carried out using eight Förster Ferex CON650 fluxgate type gradiometer probes and a 10 channel EasternAtlas digitizer. The magnetometers were placed with 25 cm cross-line spacing and a 50 Hz constant sampling interval was used for data acquisition, resulting in max. 8 cm inline sample spacing, again depending on actual driving speed. GPR and magnetic data were processed using the LBI ArchPro inhouse *APsoft* software packages *ApRadar* and *ApMag* developed together with ZAMG *ArcheoProspections®*. Data integration, classification and interpretation were carried out in the framework of a Geographical Information System (*ArcGIS 10.2*).

Magnetic surveys confirmed the initial results produced by Kiel University in 2003. Data showed a circular structure (ca. 15 m in diameter) in the centre consisting of strong dipole anomalies, which indicated a stone packing containing highly magnetic rocks of unknown type (Fig. 4a and b). An area of ca. 4 × 4 m located slightly off the centre of the mound and void of magnetic anomalies was interpreted as a possible robber trench. The ring ditch was displayed as weakly negative magnetic anomaly surrounding the actual mound structure with a diameter of ca. 30 m and a width varying from 2 - 4 m. Individual, strong anomalies to the north and west of the mound were interpreted either as pits of archaeological interest, or to have been caused by naturally occurring magnetic boulders as found at the site Berg-Manvik in Vestfold (Berg-Manvik, unpublished results).

The GPR survey conducted in 2012 using the SPIDAR system, which was chosen as primary investigation method, enabled a clear three-dimensional picture of the subsurface (Fig. 5a and b). The increased amount of detail was mainly due to the higher vertical resolution of the 500 MHz antennae operated with the SPIDAR system relative to the 200 MHz antennae used in the survey of 2003. The immediate surroundings of the mound to its south and west displayed several palaeo-meanders belonging to a former dendritic river system. Traces of the palaeochannels were observed between approximately 40 and 180 cm below ground surface (BGS), and partly cut the ring ditch in the south. Between ca. 15 – 20 cm BGS a round structure with a diameter of ca. 15 m appears. At a depth of approximately 40 cm BGS, the diameter increases to a maximum of 21 m, before steadily decreasing to 10 m at a depth of 75 cm BGS. At its SW edge, the otherwise perfectly circular mound structure revealed a disturbance originating either from erosion caused by the nearby palaeochannel, or otherwise possibly due to intensive agricultural activity (i.e. ploughing) in this area.

The interior structure of the central stone packing was characterised by a strongly reflective core area with a diameter of ca. 14 m – 15 m, which corresponds well with the dipole anomalies in the magnetic data, and a lesser reflective periphery with a maximum diameter of ca. 21 m. This difference in amplitude strength was – at the time of data interpretation – potentially attributed to two different sets of rock types used to construct the inner and outer part of the mound’s stone structure. Within the core area of the stone packing, several small, elongated, absorbing features (up to ca. 60 cm length at maximum) were observed and interpreted either as pits, large postholes or possibly caused by individual boulders of igneous rock type (see below). At a depth of ca. 30 cm BGS, a particularly strong reflective area of ca. 5 × 4.5 m correlated well with the “robber trench” observed in the magnetic data. The lack of magnetic anomalies at this spot, while congruent with strong reflections in the GPR data, could only be explained by the removal of a part of the original stone packing. The subsequent back- or in-fill of this disturbance with a material generating even stronger reflective properties was believed to originate from a coarser grain size with a rather loose structure. While the stone packing faded in the GPR data at ca. 90 – 100 cm BGS, the disturbance remains visible down to ca. 160 cm BGS, displaying the conical shape of a pit. Between ca. 30 and 80 cm BGS a weakly reflective, not clearly defined structure is observed surrounding the mound. It is only between ca. 80 and 100 cm BGS that the feature becomes clearly visible and due to its congruence with the negative anomaly in the magnetic data is interpreted as a ring ditch belonging to the grave monument.

Comparing the interpretation results of both techniques, the general picture is largely congruent. Based on the fundamentally different principles of GPR and magnetometry, however, a certain divergence in size and position of the archaeological features could be expected. While GPR detected the entire stone packing of the mound structure, the magnetic data naturally only picked up on the magnetic boulders in the centre of the mound. The ring ditch surrounding the mound, in turn, is shown completely as weak magnetic values, whereas the GPR only indicates parts of its backfill where contrast is sufficient. These findings once again underline the importance of using complementary techniques sensitive to different physical subsurface properties in Norwegian environmental settings.

Methods

The excavation was conducted in a strictly stratigraphical manner with all units being removed in the reverse order of their deposition (Harris 1989). The 3D reconstruction of the Rom mound allowed a highly precise comparison of geophysical data interpretation against the excavated stratification. The virtual reconstruction was based on the 3D single surface recording approach (Doneus and Neubauer 2005) using a Riegl VZ-400 laser scanner. The acquired point clouds were post-processed in *RiscanPro 1.7.6*. and meshed in *Geomagic Studio 2012* to subsequently produce a virtual volumetric representation of every archaeological deposit. Volumes were converted into georeferenced *VRML* files and imported as 3D objects into *ArcScene 10.2* for data integration.

The excavation of the mound allowed access to the stratified archaeological deposits, soils and sediments and enabled detailed sedimentological descriptions as well as measurements of their electrical and magnetic properties. Deposits, soils and sediments were described using selected criteria including stoniness and inclusions from Hodgson and Avery (1976). Stratigraphic observations and archaeological site formation processes were established on-site and followed the principles of archaeological stratigraphy. Colour was described using the Munsell Soil Colour Chart (Munsell 2000). Particle size distribution was determined using a Malvern *Mastersizer 3000* based on laser diffraction measurements conducted at the University of Reading. Particle size classes of a selected sequence were defined based on the International Scale ISO 14688-1. Results were then attributed to a particle size distribution classification (PSDC) using the newly proposed triangle by Blott and Pye (2012) for sand, silt and clay (SSC). PSDC was calculated using the *Microsoft Excel* software *GRADISTAT* of Kenneth Pye Associates Ltd. (http://www.kpal.co.uk/gradistat.html).

MS was measured in-situ using the handheld *Kappa meter SM-30* from *ZH instruments* with an operating frequency of 8 kHz and a pick up coil of 5 cm in diameter (sensor sensitivity: up to 1×10^{-3} SI units). This relatively small measurement volume can lead to over- or underrepresentation of the actual magnetic susceptibility, which was taken into account in the data interpretations (Mazurkevich *et al*. 2009). Laboratory-based MS analyses were conducted at the Vienna Institute for Archaeological Science (VIAS) at the University of Vienna. Samples were dried at room temperature in order to reduce the mass contribution of water and subsequently ground and sieved down to <2mm. The resulting sample material was filled in 10 cm^3 plastic containers and weighed on a KERN 440 precision balance. Volume MS was measured at room temperature with a Bartington MS 2 susceptibility meter using sensor type MS2B at low (0.465 kHz) and high frequency (4.65 kHz) for estimation of frequency dependence. Volume susceptibility measurements were converted to mass specific susceptibility values (in x 10^{-8}/kg), taking into account corrections for the actual sample mass (Dearing 1994).

Volumetric water content (VWC) or apparent dielectric permittivity, respectively, was measured using a 5TE standard capacitance sensor from Decagon Ltd. This sensor produces an oscillating electromagnetic wave at 70 MHz, which is transferred to the surrounding soil by two 5 cm sensor prongs (DecagonDevices 2015). The electromagnetic energy charges the soil according to its dielectric permittivity – the time needed for this process yields the capacitance of the dielectric medium. Capacitance is directly related to dielectric permittivity also taking into account parasitic capacitance inherent to the system as well as the particular sensor geometry (Visconti *et al*. 2014). As described above, dielectric permittivity in turn, is related to water content and here calculated using a third order polynomial known as Topp-equation (Topp *et al*. 1980). Decagon states the error margin at ±1 unit of apparent dielectric permittivity in ranges from 1-40 (soil range) and ±0.03 m^3/m^3 VWC or ±3 % VWC for soils with <10 dS/m (DecagonDevices 2015). At this point it must be noted, however, that the accurate measurement of water content via dielectric methods is extremely complex and refinement of these methods including (soil specific) calibration equations and mixing models present an extensive area of research that is of particular importance in precision agriculture (Topp *et al*. 1980; Wang and Schmugge 1980; Roth *et al*. 1992; Jacobsen and Schjønning 1993; Tran *et al*. 2012; Visconti *et al*. 2014). Temperature, salinity, bulk density and clay content as well as sensor technology used influence the estimation of water content. Particularly measurements with a frequency > 100 MHz require a soil specific calibration (Muñoz-Carpena *et al*. 2006). For the study presented, specific soil calibrations were not conducted; instead, the Decagon in-house calibration for mineral soils was used. The accuracy range of ±1 unit of dielectric permittivity in ranges from 1-40 (soil range) and subsequently ±0.03 m^3/m^3 VWC or ±3 % VWC for soils with <10 dS/m (Visconti *et al*. 2014; DecagonDevices 2015) seemed sufficient for detecting trends throughout the sediment sequences and for correlation purposes intended in this study where contrast is the most essential factor. Volumetric water content is expressed as volume fraction: m^3 water per m^3 soil.

Electrical conductivity was measured likewise using the 5TE capacitance sensor from Decagon via two electrodes sitting on two of the prongs. Values were expressed at 25°C and accuracy ranges within ±10% from 0-7 dS/m. Temperature was measured in °C using a thermistor mounted underneath the sensor overmold (DecagonDevices 2015).

Results and Discussion

Comparison of prospection data interpretation with excavation results

Based on the results of the geophysical prospection, the mound was partially excavated in August 2013 by Vfk and UiO. The 3D documentation of the excavation process was conducted by the LBI ArchPro and NIKU. The excavation trench measured 22 × 3.7 m, crossing the mound structure from its centre partially, including the disturbance towards the surrounding ring ditch (Fig. 4a and 5a). During the excavation process, the trench was extended twice as a response to newly arising questions. In total, 32 stratigraphic units (SU) could be identified and associated with different construction phases (McGraw and Bill 2014) (Fig. 6).

As indicated by the interpretation of the prospection data, the mound itself comprised of a dense stone packing placed over thin layers of fine material including a layer of charcoal that may be connected to cremation rites, and which held the sole artefact found during the excavation: a small golden ring. In the centre of the mound, the area void of magnetic dipole anomalies, respectively the area featuring the strongest reflections observed in the GPR data, emerged as a modern re-use of the grave monument: a century-old, collapsed or backfilled potato cellar – a transformation not uncommon in Norway (Binns 2000; Øhre Askjem 2011; Christer Tonning, personal communication). After being decommissioned, the potato cellar was eventually backfilled with smaller, angular fractions of boulders that slightly differ from the densely packed set of sub-rounded boulders of the initial stone packing of the mound structure. At the bottom of the disturbance, wooden implements were discovered and interpreted as floor construction, used to shield the potato cellar from the moist, underlain by marine sediment. The cellar walls were framed by large, subrounded boulders that might have been part of an original burial chamber of the grave monument. This interpretation however, requires further clarification. Excavations of the surrounding ring ditch showed a multi-phase backfill of ca. 1 m depth, including a layer of charcoal indicating a burning event (Fig. 6).

Following a first general comparison of excavation and prospection data, the archaeological interpretation of the prospection data proved to be accurate, with discrepancies mainly concerning functional aspects. This is well recognizable when comparing the virtually reconstructed excavation against the 2.5D interpretation of the GPR data within a 3D environment (Fig. 7). The modern disturbance caused by the excavation of the potato cellar into the former grave monument indeed presents a later stratigraphic interference and was correctly identified as such. The interpretation of the GPR data correctly identified the reflections in this area as caused by loose backfilled material. Although no ship had been buried in the mound, the geoarchaeological field evaluation raised questions as to if and how geophysical signals would respond to a wooden construction similar to the Gokstad or Oseberg burials.

An evaluation of the interpretation accuracy of the prospection data also needs to consider the technical precision and inherent limits of the survey parameters. The interpretation of the GPR data was based on surveys carried out with a SPIDAR GPR system and a horizontal measurement grid resolution of 25 × 10 cm. The 500 MHz centre frequency of the antenna and a propagation velocity of 8 cm/ns, determined by hyperbola velocity analysis, resulted in a theoretical vertical resolution of ca. 4 cm (Bristow and Jol 2003), though not considering pulse dispersion and attenuation at greater distances (Annan 2008). At Rom, most of the mound structure was located within 50 cm BGS, which might have benefitted the overall accurate time-depth conversion. Time-depth conversion can be problematic due to the laterally and vertically varying physical properties of different subsurface materials and layers and usually ranges within an error margin of ca. ±25 % when based on hyperbolic velocity analysis (Cassidy 2008b). In contrast to vertical or radial resolution, lateral resolution depends – besides velocity and pulse width – from the distance to the antenna and thus can vary greatly across the depth range (Annan 2008).

Stone packing

The stone packing presented the most prominent feature in the geophysical data sets and formed the main element of the mound structure. The GPR data displayed an area of strong reflections, whereas the magnetic data showed strong dipole anomalies that were interpreted as having been caused by magnetic rocks (Trinks *et al*. 2010; Gustafsson and Viberg 2012). Strong dipole anomalies are encountered frequently in Norwegian prospection data sets as a result of the abundant igneous bedrock as well as igneous boulders in this part of the country (Basis: NGU Norges Geologiske Undersøkelse) (Ramberg *et al*. 2008). It was, however, yet unknown to what extent the dipole pattern is relatable to the actual stone packing and what types of rocks create such strong anomalies. Similar questions have been asked by Smekalova *et al.* (2005), who used magnetometry for the investigation of large barrows consisting of granite boulders in Denmark and by Bevan, who studied the geophysical detection of brick pavements (2012) and foundations (1994) and on a more general note analysed dipolar magnetic anomalies (2017). In his studies, Bevan concluded that determining shape and exact location of brick pavements can prove difficult due to the different magnetic properties of individual bricks including for example the varying directions of remanent magnetisation, which often causes brick pavements or magnetic stone packings to cause a heterogeneous, disordered magnetic anomaly. Additionally, variability of induced and remanent parts of magnetisation in individual bricks or boulders leads to complex magnetic anomalies, where the magnetic fields of each brick mutually influence each other, resulting in reduction or increase of the net magnetic moment of the entire anomaly (Bevan 2017, 2012). These observations are also relevant to the stone packing of Rom mound, which is at least partially built using magnetic boulders.

To investigate the stone packing in more detail, every boulder of SU[692] was subjected to magnetic susceptibility measurements using a handheld Kappameter SM-30. In total, 249 specimens were measured and MS values ranged between 0.014 and 120 × 10^{-3} SI units with a mean of 4.4 × 10^{-3} SI (standard deviation: 11.6 × 10^{-3} SI) and a median of 0.31. This descriptive statistics clearly illustrate the generally low MS values of the majority of the boulders while most of the data variability originates from a few extreme outliers (Kurtosis: 41.4, positive skewness: 5.3, no normal distribution). The numbers suggest that the large dipole anomalies are caused by few, highly magnetic boulders (Fig. 8) that mask their magnetically weaker surroundings.

For visual comparison of geophysical and MS data sets and to further highlight the statistical results, the stone packing was mapped in ArcMap based on a georeferenced ortho-photo (Fig. 9). The symbology of the MS values was set to manually defined intervals in order to match the MS classes used for rock type determination (see below).

The magnetogram was visualised within a white-black range of [-32 /+48] nT using 254 grey scale values in order to minimise the size of the dipole anomalies. Figure 9 illustrates that the large dipole anomalies observed in the magnetogram are only partially congruent with high MS values of the numerous and smaller rocks and can be linked to individual specimens only in certain cases. The field intensity of magnetic anomalies depends on a range of factors including size, shape and the position of a rock, the amount of ferro- and ferrimagnetic minerals present, as well as its distance to the sensor (Clark 1990; Neubauer 2001a; Schmidt 2007). It is therefore quite possible for a relatively small-sized rock to create a large dipole anomaly and upon reversion, a large dipole anomaly does not necessarily represent a large source or boulder.

In order to better understand the sources of the strong dipole anomalies, 33 selected boulders were grouped by their MS values into five equally spaced classes (0-10, 10-20, 20-30, 30-40, 40-50) and one > 51 and sub-sampled for rock type identification based on macro- and microscopic observations (Table 1). MS value classes between 0.014-10 × 10^{-3}, 10-20 × 10^{-3} and 20-30 × 10^{-3} SI units contained mainly granite, but also occasionally included metamorphic rock types namely quartzite, orthogneiss and diorite gneiss. MS values between 30-40 × 10^{-3} SI units showed a more varied picture with granite, diorite/gabbro, orthogneiss and amphibolite. Only two samples revealed values between 40-50 × 10^{-3} SI units, that is porphyry and a macroscopically not clearly identifiable magmatic rock. 120 × 10^{-3} SI units as the highest MS value measured originated from a relatively small piece of fine-grained, mafic-ultramafic rock. The abundance of igneous rock types was expected due to the geological history of this part of Norway (Sørensen 1988; Olesen *et al*. 2007; Sørensen *et al*. 2007). Igneous rock originates from processes of melting and cooling, thereby undergoing thermo-remanent processes (Clark 1990; David *et al*. 2008; Gaffney and Gater 2003) and chemical (or crystallisation) remanent processes, dependent on the chemical composition and mineralogical properties (e.g. crystal size and shape), depth, and temperature of crystallisation (Lanza and Meloni 2006). As a result of these processes, igneous rocks often include varying amounts of ferro- and ferrimagnetic minerals, in particular magnetite.

Concluding, visualisation and statistics indicate that the strong dipole anomalies created by the stone packing are caused by individual fragments of igneous rock. The magnetisation of these boulders – mainly granite and other magmatic rocks - results largely from thermo-remanent processes. Differences in the direction of magnetisation, as well as variations in remanent and induced magnetisation of individual boulders ultimately generate a complex pattern of anomalies, which mask the remaining more weakly magnetised stones. Without the possibility of a magnetic “migration”, these anomalies thus must be regarded as a schematic indicator for highly magnetic rocks, rather than an accurate visualisation of the buried stone packing. In order to obtain a more differentiated picture of the dipole anomaly sources, forward magnetic modelling (Bevan 2016) as well as analysing the magnetic mineral composition of the boulders are necessary. Such investigations might also be beneficial for GPR data interpretation, since – theoretically – ferrimagnetic minerals present >2 % could affect the electromagnetic wave propagation (Cassidy 2008a).

The GPR data expectedly showed strong reflections in the area of the stone packing. In its outskirts, however, absorbing areas were interpreted as potential pits backfilled with fine material or even as secondary graves (Fig. 10a). However, during the excavation, these areas turned out to be zones simply void of stones (Fig. 10b). Technically, this means that the majority of the electromagnetic signal propagated further into the subsurface, in contrast to the strong reflections triggered by the rather solid surface of the surrounding stone packing.

Ditch

One of the most interesting finds from an evaluational perspective concerned the ring ditch surrounding the grave monument (Fig. 11a and b). Ditches typically possess enhanced magnetic values mainly due to backfill containing magnetically enriched topsoil, depending on the environmental settings (Le Borgne 1955; Le Borgne 1960; Maher 1986; Fassbinder 1994; Dalan and Banerjee 1998). In Rom, however, the ditch was displayed as a weakly negative magnetic anomaly - a phenomenon frequently observed in Vestfold (Nau *et al*. 2015). This was even more surprising as the excavation revealed a charcoal-rich layer, SU[1450], including burned earth material and cracked stones at ca. 80 cm BGS. In order to investigate the negative anomaly more closely, a preliminary investigation used basic sedimentological descriptions as well as in-situ and lab-based MS measurements. Planar in-situ MS measurements were applied across the ditch over a 6.4 m × 3.0 m area in a 20 x 20 cm grid after removal of the top soil SU[600] using the SM-30 kappameter. The aim was to assess the amount of contrast between ditch filling and surrounding matrix without the masking effects of the topsoil, and to confirm the weakly developed magnetic properties of the ditch (Fig. 12).

Our results support the findings from the magnetic data with very weak MS values around 0.1-0.2 × 10^{-3} for the ditch backfill at the top surface of SU[630], and only slightly increased values between 0.2 and 0.4 SI × 10^{-3} for the surrounding material (Fig. 12). Maximum values cluster around 0.6 SI × 10^{-3}, probably representing the effects of small fragments of magnetic rock inclusions.

The north-western boundary of the ditch is generally identifiable, whereas the south-eastern boundary of the ditch shows a gradual transition, possibly indicating that the ditch is wider than visually distinguishable on the excavated surfaces (Fig. 12). Once the ditch had been excavated, every layer [1 – 5] visible in the profile was targeted with in-situ measurements of MS, GWC and EC in order to characterise the soil and sediments and to correlate them with the geophysical prospection data. Additionally, undisturbed samples were taken from a 1 m core drilled a short distance away from the excavation trench. Volume and mass-specific MS measurements as well as particle size distribution analysis were conducted from sub-samples taken every 10 cm (Fig. 13) along this core.

Mass-specific low frequency MS values ranged between Xlf of ca. 10 and 70 × 10^{-8} m^3/kg. The topsoil shows regular elevated values (> 30 × 10^{-8} m^3/kg), and decreases to around 10 × 10^{-8} m^3/kg between 30 and 70 cm BGS, which stratigraphically corresponds to layers 1 (SU[600]), 2 (SU[630]) and unit 3 (Table 2). It is only at layer 4 (SU[1450]), a more heterogeneous, charcoal-rich layer featuring small stones, some of them fire-cracked, that MS values increase again to ca. 40 × 10^{-8} m^3/kg. Frequency dependence also responds to the charcoal-rich layer with almost 6% indicating the presence of superparamagnetic grains that often are related to burning or magnetically enhanced topsoil (Dearing 1999). The highest mass-specific MS values, however, do not originate from the burning layer itself but are contained in the subjacent layer 5 (40–70 × 10^{-8} m^3/kg) (Fig. 13). Layer 5 is believed to be of shallow marine origin and comprises sandy, clayey silt with orange mottling indicating exposure to varying moisture conditions.

In contrast to the laboratory-based MS measurements, in-situ volume MS measurements generated a different picture and one that matches the archaeological stratification more closely, with a peak in MS values of ca. 100 × 10 $^{-5}$ SI units at ca. 80 cm BGS related to the charcoal layer SU[1450] (Fig. 14). This clear response is most probably attributable to the in-situ measurement of the actual composition of the layer, which – in contrast to the more homogenous material of the layers above - included burned material and fragments of magnetic boulders. Such constituents, which can greatly affect both induced and remanent magnetisation of a layer, are usually excluded in the standardised laboratory sample preparation procedure (Maher 1986; Dearing 1994). Under certain conditions, therefore, when it comes to the evaluation of geophysical prospection data, laboratory-based MS measurements might produce a distorted, unrepresentative picture of the soils and sediments under investigation.

All results considered, the geoarchaeological evaluation could confirm the weakly developed magnetic properties of the ditch backfill in comparison to the surrounding soil material – a contrast potentially insufficient for detection using a gradiometer setup of 0.65 m sensor separation carried 30 cm above the ground surface. Fassbinder (2015) suggested three causes for the formation of a negative anomaly. First, the archaeological material simply displays diminished magnetic properties compared to the surrounding soil matrix as it normally would be the case of e.g. a buried lime stone wall. Secondly, the archaeological feature was immediately backfilled using the excavated material, which consequently weakened its magnetic field intensity due to the fill material being randomised (see also Clark 1990, p. 96). A rapid backfill of the ditch at Rom, however, seems rather questionable, since stratigraphic observations from SU[1412] argue for the ditch being open for at least some time after its construction (see also Fig 11b). The third option explains negative anomalies as the result of a partial dissolution of ferrimagnetic minerals based on humid soil conditions. Gleying and reducing conditions due to permanent or periodical waterlogging usually does not promote the enhancement of magnetic properties (Maher 1986; Evans and Heller 2003; Dalan 2006a; Fassbinder 2015). In contrast, chemical processes related to changing moisture contents and/or a stagnant zone in the soil/backfill can lead to the dissolution of ferrimagnetic minerals, which subsequently – upon re-oxidation – become precipitated as paramagnetic minerals

(Maher 1986; Fassbinder 2015). The Rom mound was erected and cut into endostagnic Cambisol – a relatively young soil with a weakly developed soil structure that is periodically exposed to reducing conditions, which can result in a stagnic colour pattern. This soil type is also characterised by low quantities of illuviated clay, organic matter as well as Al and/or Fe compounds (Soil WRB 2006).

The fine grained marine sediment omnipresent in this part of Norway often can act as a stagnant zone causing periodical waterlogging, particularly in the valley bottoms after extensive rainfall. In-situ and lab-based MS measurements confirmed the weak magnetisation of the soil at Rom, indicating a generally low amount of ferrimagnetic minerals present. Yet, these magnetic depletion processes would also have affected the ditch backfill material. The question thus arises: Why did these processes affect the ditch to a greater extent? Possibly, the concave shape of the ditch added to this effect. In order to further shed light onto this issue, the analysis of MS measurements would clearly need to be supplemented with more data regarding magnetic properties including mineral composition analysis.

While the soils at Rom display magnetic depletion, the subjacent marine sediments are characterised by magnetic enhancement. This marked contrast in induced magnetisation between soils and sediments could also be observed at Gokstad and Sverstad, two other geoarchaeological evaluation studies in Vestfold (geoarchaeological field evaluations, unpublished data). The processes behind this enhancement are not yet fully understood. While gleying and waterlogging in soils can lead to dissolution of ferrimagnetic minerals and consequently to the reduction of induced magnetic properties, marine and perimarine environments seem to promote the formation of iron sulphides, which can be present in the form of paramagnetic mackinaweite and greigite as well as ferrimagnetic pyrrhotite and pyrite (Kattenberg and Aalbersberg 2004). Particularly the ferrimagnetic forms could be responsible for the enhanced MS values observed in Vestfold. Kattenberg and Aalbersberg (2004) argue that these iron sulphides form under reducing conditions and require the presence of Fe(II) and sulphates, both of which can be found in seawater. Iron sulphides can also constitute in estuarine environments, where sulphates form through bacterial decomposition of organic matter. At Rom, these processes could indeed be the reason for the enhanced MS values; however, more detailed studies focusing on the magnetic mineral composition as well as on the contribution of natural remanent magnetisation (Ellis and Brown 1998) would be advisable to better understand the magnetic enhancement of the marine sediments in Vestfold. Alternative explanations for this phenomenon could include detrital remanent magnetisation in marine sediments (Clark 1990) or a possible loss in paramagnetic and diamagnetic components (Maher 1986).

During the archaeological interpretation of the GPR data it was noted that the ring ditch surrounding the burial mound was only visible from ca. 80 - 100 cm BGS – a depth well below the actual stone structure. As such a construction would have been rather unusual, it has been assumed that the visibility of the ditch at higher levels was limited due to insufficient contrast between the ditch backfill and the surrounding soil and sediments. In order to support this hypothesis quantitatively, GWC and EC were measured in-situ using the 5TE capacitance sensor from Decagon. Particle size analysis was conducted on sub-samples taken from the core sample at a 10 cm interval.

The VWC/dielectric permittivity as the most significant physical property for electromagnetic wave propagation shows a slightly increased value of 0.02 m^3/m^3 in the area of SU[1450]. This increase is smaller than the precision range of the moisture sensor (± 0.03 m^3/m^3) and therefore has to be considered with caution when interpreting the data. However, regarding this variation as an indicator for contrast, it correlates well with the GPR data and supports the observations made during the excavation. When comparing the coarser grained SU[1450], which also includes gravels and cobbles up to few boulders, to the upper, finer grained backfill of the ditch, the higher water content seems rather surprising. A possible explanation could point to subjacent layer 5 - comprising possibly shallow marine sandy, clayey silt -, which might act as a stagnant zone and together with the concave shape of the ditch could cause the observed slight increase in water content. Yet, the large clasts, and consequently the unit's heterogeneous composition, should not be underestimated as contributing factor for the strong GRP reflections caused by SU[1450].

Particle size distribution remained relatively constant throughout units [1 - 4], with ca. 10 % clay, 20 % sand and 70 % silt. Changes only occur around ca. 80 cm BGS at the transition to unit [1450], which is in good agreement with the time-depth conversion of the GPR data. In conclusion, the results of the geoarchaeological evaluation confirm the insufficiently low contrast as cause for the invisibility of the ditch above 80 cm depth.

Modern disturbance

Although the burial mound did not contain a boat or ship, the modern potato cellar dug into the monument allowed access to a 2 m profile section without violating stratigraphic principles, and thus provided a unique opportunity to compare structural elements in-situ with their representation in the geophysical prospection data sets (Fig. 15 a and b).

The stratigraphic succession included topsoil layer SU[600], followed by modern backfill SU[900], wooden structure SU[1127], and SU[1092] interpreted as part of the cellar floor, pressed into the underlying moist, clay-rich sediment SU[1214] (Fig. 15a and b), and hence presents many of the elements that would be expected in an actual boat or ship burial. All of these elements were targeted with in-situ measurements for MS, VWC and EC in order to infer more about their geophysical response and to correlate them with the near-surface geophysical prospection data.

Measurements taken in the profile section started only from a depth of below 70 cm BGS, due to the loose structure of the modern backfill above and resulting safety issues. For comparison, a GPR trace was extracted from the radargram at the profile location. Although using a single GPR trace runs the risk of being unrepresentative (Conyers 2015), here it provides a more detailed mode of comparison with regard to external physical soil properties as compared to an entire GPR profile section. The GPR trace shows the typical direct wave and ground wave amplitudes triggered by the antenna - receiver and antenna - ground contact and reflection (Annan 2001) (Fig. 16). After traversing the topsoil layer SU[600], the electromagnetic wave travels through the stony backfill SU[900] of the potato cellar. This heterogeneous unit consists of large, sharp-edged boulders (up to 50 cm in diameter) distributed in a loose structure with considerable pore space in-between. The electromagnetic GPR pulse thus has to pass through solid rock surfaces and voids in quick succession, which generates high amplitude reflections. These profound differences in physical properties compared to the underlying stratigraphy consequently led to stronger reflections in the GPR data as against the actual mound structure. The sharp edges of the boulders created further diffraction of the electromagnetic wave that intensified this effect (Annan 2001), leading to additional scattering in the data. The modern backfill SU[900] is followed by a layer of fine, clay-rich material – a succession well illustrated by the GPR trace - which responds to this distinct difference in physical properties with an increase in amplitude (Fig. 16). The wooden implements (SU[1092]) interpreted as floor construction proved to be of particular interest for the geoarchaeological evaluation, due to the possibility to capture the geophysical response of wooden material in-situ in a burial-like situation, even though Viking Age ships were mainly built from oak, in contrast to the pine used for the cellar implements, and certainly would involve different dimensions (Jensen 1999). The GPR trace did not respond to the wooden material; it seems, however, to be visible in the GPR depth-slices within a range between ca. 80-100 cm BGS as an irregularly shaped anomaly with a small elongated entrance from the south. This is roughly in agreement with the average vertical distance of 10 cm for the planks of SU[1092] and 18 cm for the beams (SU[1195]), which is well in excess of the vertical imaging resolution of the 500 MHz GPR antenna used. The wooden floor construction clearly exemplifies the limits of a functionally correct data interpretation, as well as the necessity for comparative data sets. The possibility of a re-use of the investigated structure was not considered by the geophysical archaeological prospectors and therefore not recognised as such in the data. In-situ measurements of VWC, EC and MS showed a slight but distinct response to the buried wooden material. VWC values responded to the wood being saturated with moisture of the subjacent marine clay-rich layer SU[1214], while the small peak in EC values is attributable to the higher salinity of the sediment. Based on these observations, a buried wooden boat or ship could be detectable by a GPR survey, given that the wooden structure had not disintegrated and its preserved thickness exceeded the vertical resolution of the used GPR antennae. MS measurements responded to the wood, which was rather surprising, since wood is diamagnetic and usually displays weakly negative magnetic properties (Dearing 1994). The slight increase might therefore be explained by a metal inclusion, such as a nail. In this respect, magnetometry naturally does not provide the best prerequisites for detecting a ship or boat burial. Possible indications for a vessel would be derived from ferromagnetic or ferrimagnetic proxies, such as iron nails or other metal objects. This, however, does not provide a guarantee for detection, as seen on the excavation of Viking Age settlement *Heimdaljordet* in Gokstad (Bill and Rødsrud 2013; Macphail *et al*. 2013), where only a small dipole in the magnetometry data marked a boat burial which included a metal sword and iron rivets. In the case of Rom, ferromagnetism would have been most probably masked by the strong dipole anomalies of the magnetic boulders present.

As the GPR pulse travels further downwards, crossing SU[1214], it diminishes both due to energy loss from geometrical spreading as well as attenuation in the wet, fine-grained marine sediment (Doolittle and Butnor 2009; Cassidy 2008b) (Fig 15). This process is in agreement with steadily increasing VWC and EC values. Within the upper zone of SU[1214], however, the subtle increase in reflection amplitudes indicates a different origin of the subsurface material. This observation is further supported by GWC and EC values, which both show similar, short lived peak responses around 1.50 m depth, and is also picked up by the in-situ MS measurements displaying increased values across the same depth range. Sedimentologically, the intense orange mottling suggests variable ground water conditions. A closer look at the radargrams from 2012 - as well as a second, ultra-high resolution GPR survey carried out after the excavation in 2014 -, and the results of their palaeoenvironmental analysis suggests that the burial mound was erected on top of a palaeochannel. Based on this information, this part of the profile interpreted as former channel in-fill. As it was observed and has been discussed in case of the ditch profile, MS values do steadily increase with depth in the marine sediment SU[1214] (Fig 13).

Conclusions and outlook

The geoarchaeological approach to evaluate GPR and magnetic data sets acquired at Rom mound has permitted an assessment of the accuracy of the archaeological data interpretation. General conclusions based on this study with regard to further geophysical studies in Vestfold certainly must highlight the necessity for using complementary methods. The investigation of different physical subsurface parameters not only enhances the probability of detecting buried archaeological features but, more importantly, can enable a detailed interpretation. This was demonstrated in particular by the disturbance of the mound, which could not have been correctly identified as such by either magnetometry or GPR alone.

However, a more targeted approach of each individual geophysical technique depending on the physical properties of the targeted archaeological feature would also enhance the amount of detail identifiable in the data sets. This is demonstrated by the complex magnetic anomaly of the mound structure. In order to map individual boulders based on the magnetic data, distance between sensor and stone packing needs to be reduced whilst spatial sampling must increase. This approach would avoid averaging of the individual magnetic fields created by each boulder and deliver a more detailed view on the structure.

The study also demonstrated that the interpretation of archaeological geophysical prospection data is limited when it comes to the functional aspects of archaeological features. This is a problem inherent to the non-invasive prospection approach, which to a degree can be solved by in-depth knowledge of the local archaeology and close collaboration between interpreters and archaeologists familiar with the survey areas. At Rom, the modern re-use of a burial mound was not considered by the interpreters, yet superficial archaeological features such as burial mounds are part of a landscape changing through time; their archaeological significance is not limited to when they were initially constructed but can extend far beyond this point.

Finally, geoarchaeological evaluations of geophysical prospection data provide feedback on observations and assumptions made during interpretations on a regular basis. These assumptions mostly cannot be verified without access to the subsurface and thus often uncritically find their way into the “common knowledge and experience base”. This point has certainly been illustrated by the partial invisibility of the ditch in the GPR data, and particularly by the unusual magnetic behaviour of the ditch. Conducting and the iterative implementation of geoarchaeological evaluations into the prospection routines also allows a step towards a more critical and testable use of these methods. If performed on a regular basis, geoarchaeological field evaluation will generate valuable knowledge about the influence of environmental settings on a local to regional scale which could be collected in a comparative data base. Such a data base would for example relate the geophysical response of a burial mound to the prevailing environmental settings with regard to survey design and specific equipment used. Recorded components would include soil and sediment type, local geology, topography, climate and weather conditions around the time of the survey as well as geophysical elements such as magnetic susceptibility, dielectric permittivity, electrical conductivity and as well as magnetic signature and radar reflections. Eventually, such a database will enhance the quality of data interpretation in future surveys conducted in such challenging conditions as encountered in Norway and elsewhere.

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Tables

Table 1 Macroscopical identification of magnetic rocks according to MS classes

Magnetic susceptibility classes (x 10^{-7} SI units)	Number of samples	Igneous rocks (n)	Metamorphic rocks
0.014-10	10	Granite (5), Leuco-granite (1)	Quartzpophyr (2), Quarzite (1), Ortho-gneiss (1)
10-20	9	Granite (9)	
20-30	6	Granite (4)	Diorite/Gneiss (1), Ortho-gneiss (1)
30-40	5	Granite (1), Diorite/Gabbro (1)	Amphibolite (1), Orthogneiss (1), Diorite (1)
40-50	2	Porphyr (1), Magmatic rock (1)	
50-120	1	Mafic-ultramafic rock (1)	
	Total = 33		

Table 2 Sedimentological descriptions of the five layers observed in the core sample taken from the ditch (see also Fig 15).

Sample	Corresponding SU unit	Stoniness	Colour (Munsell Code)	Inclusions	Description
Ditch 1	[600]	1% very small, subangular stones, 2% very small, angular	very dark grayish brown (10YR 3/2)		topsoil
Ditch 2		1% very small, angular stones; 25% medium, angular stones	very dark grayish brown (10YR 3/2)		some redoximorphic features (mottling)
Ditch 3		<1% very small, angular stones	black (2.5Y 2.5/1)	some organic material	relatively homogenous, more compact than layer 2
Ditch 4	[1450]	2% very small, angular stones, 25% medium, angular stones	black (7.5Y 2.5/1)	large chunks of charcoal, burned stones showing reddish colour and being porous, unburned cracked	corresponds to stratigraphic unit 1450, a charcoal-rich unit of the backfill; very heterogenous
Ditch 5		10% very small, subangular stones; <1% small, subrounded	very dark grayish brown (2.5Y 3/2)		homogenous, relatively wet, very fine material, redoximorphic