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„Investigating the potential of palaeoenvironmental
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Summary

During the last two decades, acquisition of geophysical data has advanced remarkably in terms of speed and resolution allowing for large-scale, high resolution survey approaches and hence the prospection of entire landscapes. The resulting data sets not only include archaeological information such as settlement traces or burials, but also contain palaeoenvironmental information such as palaeochannels or ancient shorelines. To consider this information is important for an encompassing understanding of the area under investigation, yet most studies currently do not focus on this particular type of information.

This thesis aimed to investigate the potential of palaeoenvironmental information for large scale, high resolution geophysical data based on case studies situated in Norway. The first stage encompassed a targeted palaeoenvironmental analysis of magnetometry and GPR data. Designed as a pilot study, this investigation was able to demonstrate the additional benefits of such an approach, yet also identified deficiencies regarding the interpretation process of palaeoenvironmental structures. A second emphasis of this thesis thus concentrated on establishing a workflow for 3D data extraction, visualisation and integration in a GIS environment which proved essential for the correct identification and interpretation of this type of information. A third focus was placed on the significance of incorporating the environmental settings of a study area into the interpretation routines by conducting geoarchaeological evaluations at several case study sites.

This thesis concludes that palaeoenvironmental information plays an essential role in any geophysical prospection and as such must be fully considered. Future research should aim to further implement palaeoenvironmental analysis into the interpretation routines and to better understand the relationship between the environmental settings of a study area and their influence on the geophysical data.

Zusammenfassung

Während der letzten beiden Jahrzehnte hat sich die geophysikalische Prospektion rasant weiterentwickelt, vor allem die Geschwindigkeit und räumliche Auflösung der Datenerfassung hat sich erheblich verbessert. Durch die daraus resultierenden großflächig-hochauflösenden Datensätze können erstmals ganze Landstriche geophysikalisch untersucht werden. Diese Datensätze beinhalten nicht nur archäologische Strukturen wie z.B. Siedlungsspuren oder Bestattungen, sondern auch naturräumliche Informationen, darunter alte Flusssysteme oder verschwundene Küstenlinien. Diese Informationen sind für ein umfassendes Verständnis des jeweiligen Untersuchungsgebietes unerlässlich, werden im Rahmen archäologische Prospektionen derzeit aber selten miteinbezogen.

Basierend auf Fallstudien aus Norwegen untersucht die vorliegende Arbeit daher das Potenzial naturräumlicher Informationen für die großflächig-hochauflösenden archäologisch-geophysikalische Prospektion. Der erste Schritt umfasste dabei eine gezielte Analyse von in Magnetik- und Bodenradardaten enthaltenen naturräumlichen Strukturen. Die Ergebnisse dieser Pilotstudie konnten zeigen, dass das Einbeziehen dieser Informationen einen erheblichen Gewinn für die archäologische Interpretation der Prospektionsdaten darstellt. Es wurden jedoch auch Defizite sichtbar, vor allem im Bereich der detaillierten Interpretation naturräumlicher Strukturen. Ein weiterer Schwerpunkt der Dissertation konzentrierte sich daher auf die Erarbeitung eines Workflows für die dreidimensionale Datenvisualisierung und anschließende Integration innerhalb eines geographischen Informationssystems – ein Ansatz, der sich im Laufe der Arbeit für die Interpretation dieser Art von Information als essentiell herausstellte. Ein dritter Schwerpunkt lag auf der Bedeutung der naturräumlichen Gegebenheiten, darunter Pedologie und Sedimentologie, Geologie, Topographie, Klima etc., eines Untersuchungsgebietes für den Interpretationsprozess. Geoarchäologische Untersuchungen konnten die Relevanz dieses Ansatzes im Rahmen dreier Fallstudien aufzeigen.

Zusammenfassend kann gesagt werden, dass naturräumliche Informationen ein wesentliches Element innerhalb jeder geophysikalischen Prospektion ausmachen und daher entsprechend zu berücksichtigen sind. Weiterführende Forschung sollte sich vor allem darauf konzentrieren, diesen Informationstyp vermehrt in die Prospektionsroutinen zu

implementieren, sowie den Einfluss naturräumlicher Gegebenheiten auf die geophysikalischen Daten besser zu verstehen.

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The case studies presented in this thesis derive from two research projects: The Gokstad Revitalized Project led by the Museum of Cultural Heritage (MCH) at the University of Oslo and the Vestfold Project jointly conducted by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), Kulturarv Vestfold fylkeskommune (Vfk) and the Norwegian Institute for Cultural Heritage Research in Oslo (NIKU). I am very grateful that I was given access to this data and so was able to use it for my research. I would like to thank in particular Jan Bill (Director Gokstad Revitalised Project, MCH), Terje Gansum (Vkf) and Knut Paasche (NIKU).

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Geoarchaeological fieldwork was conducted during the excavations of Rom in Slagendalen and *Heimdaljordet* in Gokstad. I am very grateful to the Museum of Cultural Heritage (MCH), University of Oslo for giving me the opportunity to collect this much needed data. I am also thankful to both excavation teams, in particular to Christian Løchsen Rødsrud, Jessica Leigh McGraw, Magnar Mojaren (all MCH), Julie Karina Øhre Askjem (Vfk) and Rebecca Cannell (University of Bournemouth). Coring work was conducted mainly during the geophysical

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The research topic of my thesis focuses on different disciplines including geophysics, archaeology and digital archaeology as well as the earth sciences and as such requires an interdisciplinary approach. The diverse expertise available among the research staff of the LBI ArchPro provided an excellent environment for such an endeavor. I would like to thank the entire team, but in particular Erich Nau, Mario Wallner, Alois Hinterleitner, Geert Verhoeven, Christine Markussen and Immo Trinks for their time and advice. Two members of the LBI have contributed in particular to chapter IV: “3D visualisation and integration of palaeoenvironmental information extracted from large-scale, high-resolution archaeological GPR data – Examples from Norway”: Juan Torrejón Valdelomar has contributed the impressive 3D reconstruction of the Gokstad landscape; Georg Zotti has programmed the conversion tools required for the proposed workflow and was always up for discussions about 3D visualisation of GPR data.

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Declaration of Publications

The following articles and conference papers have been published related to this thesis

Publications

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The following contributions to scientific conference have been made related to this thesis

Conference Sessions, Presentations and Posters

CAA Computer applications & Quantitative methods in Archaeology international conference, 14th– 16th March 2016, Atlanta, USA, Session Organizer: Differing perspectives: The wide world of geophysical prospection

NSGG Near surface geophysical group meeting 6th December 2016, London, UK, Presentation: What on earth is this? Non-archaeological information in large-scale, high resolution geophysical prospection data

CAA Computer applications & Quantitative methods in Archaeology international conference, 29th March – 2nd April 2016, Oslo, Norway, Presentation: A geoarchaeological approach to selected issues in Norwegian archaeological geophysical prospection

The XI Nordic Conference on Application of Scientific Methods in Archaeology SMIA XI, 20th – 23rd October 2015, Helsinki, Finland, Presentation: A geoarchaeological approach to selected issues in Norwegian archaeological geophysical prospection

The X Nordic Meeting on Stratigraphy, 20th – 23rd October 2015, Helsinki, Finland, Presentation: Stratigraphic excavation and 3D reconstruction at Rom burial mound, Vestfold County, Norway

11th International conference on Archaeological Prospection, 15th – 19th September 2015, Warsaw, Poland, Presentation: Geoarchaeology as essential supplement for large-scale, high-resolution archaeological geophysical prospection – the case study Gokstad in Norway

CAA Computer applications & Quantitative methods in Archaeology international conference, 30th March - 3rd April 2015, Siena, Italy, Presentation: Interdisciplinary investigation of the burial mound at Rom in Vestfold County, Norway

CAA Computer applications & Quantitative methods in Archaeology international conference, 22nd -25th April 2014, Paris, France, Presentation: Landscape Tomography: *Creating a work flow for 3D visualization of palaeoenvironmental information contained in large scale, high resolution GPR data sets*

10th International conference on Archaeological Prospection, 29th May – 2nd June 2013, Vienna, Austria, Presentation: Large scale, high resolution archaeological geophysical prospection: a source for palaeoenvironmental reconstruction

19th EAA Annual Meeting, European Association of Archaeologists, 4th-8th September 2013, Pilsen, Czech Republic, Presentation: *Geophysical prospection as a landscape analysis tool*

Table of Contents

Introduction	1
Aims and Objectives	2
Structure of the thesis	3
 Chapter I	 5
1.1 Archaeological prospection	5
1.2 Geophysical prospection	7
1.3 Magnetometry	10
1.4 Ground penetrating radar	19
1.5 Large scale-high resolution approach	27
 Chapter II	 33
2.1 Palaeoenvironmental information	33
2.2. Environmental settings	37
2.2. Case study areas	48
2.2.1 The Vestfold Project	49
2.2.2. Gokstad	53
2.2.3. Oseberg/Slagendalen	59
2.2.4. Kaupang	66
 Chapter III	 73
Palaeoenvironmental analysis of large-scale, high-resolution GPR and magnetometry data sets: the Viking Age site of Gokstad	73
3.1. Introduction	73
3.2. Background	75
3.3. The archaeological site of Gokstad	76
3.4. Methods	81
3.5. Results	84
3.5.1. Palaeo-coastal information	85
3.5.2. Buried bedrock	94

3.5.3. Hydrological information.....	96
3.5.4. Palaeo-topographic information.....	101
3.6. Discussion and Conclusions	108
Chapter IV.....	119
3D visualisation and integration of palaeoenvironmental information extracted from large-scale, high-resolution archaeological GPR data – Examples from Norway	119
4.1. Introduction.....	119
4.2. 3D Visualisation of GPR Data in Archaeology.....	121
4.3. Methodology.....	123
4.4. Software for 3D visualisation of GPR data	128
4.5. Case study sites	129
4.5. 3D data visualisation.....	132
4.6. GIS Data integration.....	143
4.6.1. Investigating archaeological landscapes.....	144
4.6.2 The burials in Slagendalen.....	147
4.6.3 Rom mound.....	149
4.6.4 3D reconstruction	150
4.7 Discussion and Outlook.....	152
Chapter V.....	155
<i>In-situ</i> and laboratory-based magnetic susceptibility measurements at the archaeological site of <i>Heimdaljordet</i> , Gokstad.....	155
5.1 Introduction.....	155
5.2 Background	159
5.2.1 Complementary archaeological geophysical prospection techniques.....	159
5.2.2 Magnetic susceptibility measurements	160
5.3 The study site <i>Heimdaljordet</i>	161
5.4 Fieldwork.....	166
5.5 Methods.....	170
5.6 Results.....	171
5.6.1 Profiles.....	173
5.6.2 Archaeological features.....	176
5.7 Discussion.....	179

Chapter VI.....	185
Testing an approach for geoarchaeological field evaluations of magnetic and GPR data interpretation.....	185
6.1 Introduction.....	185
6.2 Background and approach.....	189
6.3 Methodology.....	191
6.4 Results.....	197
6.4.1 Magnetometry related evaluation techniques	201
6.4.2 GPR related evaluation techniques.....	204
6.5 Discussion.....	206
 Chapter VII.....	 211
Geoarchaeological evaluation of ground penetrating radar and magnetometry surveys at the Iron Age burial mound Rom in Norway.....	211
7.1 Introduction.....	211
7.3 Site description	213
7.3.1 Geographical location and environmental settings.....	213
7.3.2 Research history	214
7.3.3 Geophysical prospection	216
7.4 Methods.....	221
7.5 Results and Discussion	223
7.5.1 Comparison of prospection data interpretation and excavation results.....	223
7.5.2 Specific questions addressed.....	228
7.5.3 Ditch.....	234
7.5.4 Modern disturbance.....	241
7.6 Conclusions and outlook	244
 Chapter VIII	 247
Discussion and conclusions	247
8.1 Introduction.....	247
8.2 Conclusions drawn from the case studies.....	247
8.2.1 Targeted palaeoenvironmental analysis of geophysical prospection data	247
8.2.2 3D visualisation and integrative interpretation approach of GPR data	249

8.2.3 Geoarchaeological evaluation at <i>Heimdaljordet</i>	250
8.2.4 Testing an <i>in-situ</i> geoarchaeological evaluation approach.....	252
8.2.5 Geoarchaeological evaluation at Rom	253
8.3 Assessing characteristics and impact of palaeoenvironmental information on geophysical prospection surveys	254
8.3.1 Environmental settings and geoarchaeological evaluation	255
8.3.2 Palaeoenvironmental structures and patterns	258
8.3.3 The situation in Vestfold	260
8.4 Future research avenues	262
8.4.1 Palaeoenvironmental analysis of geophysical data.....	262
8.4.2 Role of Geoarchaeology in Geophysical Prospection.....	263
8.4.3 Methodological aspects.....	266

List of Figures

Fig. 1.1	First aerial picture of Stonehenge taken from a balloon (P. H. Sharpe, public domain)	6
Fig. 1.2:	Active and passive methods in archaeological geophysical prospection, (based on Neubauer, 2001b)	7
Fig. 1.3	The three columns that constitute a comprehensive interpretation of archaeological geophysical data: Geophysical expertise, local archaeology and environmental settings	9
Fig. 1.4	Different types of magnetisation (based on Neubauer, 2001b)	11
Fig. 1.5	Motorised magnetic multi fluxgate gradiometer array pulled by an all-terrain-vehicle (ATV)	15
Fig. 1.6	Workflow diagram for magnetic data processing and interpretation. Modified from Gaffney et al., Figure 1 (2016)	17
Fig. 1.7	Magnetogram of Rom mound with clearly visible stone packing of consistent of igneous rock	18
Fig. 1.8	State-of-the-art motorised multichannel GPR array pulled by an ATV	23
Fig. 1.9	Workflow diagram for GPR data processing and interpretation	24
Fig. 1.10	Grey-scale image of GPR depth slice 40-60 cm below ground surface (BGS) of Rom mound. The dark area in the middle of the radargram evidences strong reflections created by a stone packing	25
Fig. 1.11	Example of volume-rendered GPR data of a survey area in Jutland, Denmark using Voxler 4. Pink areas illustrate the rolling topography of a dune field	26
Fig. 1.12	GPR data sets from large scale, high resolution geophysical prospection carried out at Gokstad, Norway	28
Fig. 1.13	Workflow for grid-free positioning during motorised archaeological geophysical prospection. Modified from Gaffney et al., Figure 1 (2016)	30
Fig. 1.14	Example of an integrated data interpretation in a GIS environment based on prospection data from <i>Heimdaljordet</i> in Gokstad, Norway	32
Fig. 2.1	GPR data from <i>Heimdaljordet</i> in Gokstad, Norway, demonstrating the presence of palaeoenvironmental structures next to archaeological features. The pattern indicates buried beach deposits (see also chapter III)	34
Fig. 2.2	Palaeoenvironmental structures and patterns as contained in archaeological geophysical prospection data are essential in understanding different environments (PE) developed over time	36
Fig. 2.3	Fig. 2.3 Periglacial features known as ice polygons pseudomorphs become clearly visible in magnetic data sets from the Roman site Carnuntum in Austria. ArchPro Carnuntum/Mario Wallner	39
Fig. 2.4	Environmental settings are significant for planning and design of archaeological geophysical prospection surveys	45
Fig. 2.5	Influence of environmental information on a technical level. Persistent precipitation softens the ground and leads to small-scale flooding	46

Fig. 2.6	Environmental factors such as local weather around the time of data acquisition, as well as physical and chemical processes in the subsurface materials are influencing the outcome of an archaeological geophysical prospection survey	46
Fig. 2.7a	GPR data (40-45 cm BGS) of <i>Heimdaljordet</i> in Gokstad showing settlement traces and burial mounds	47
Fig. 2.7b	Note the absence of these archaeological features in the corresponding magnetic data	47
Fig. 2.8	Topographic map displaying the location of Vestfold County and the three case study areas Gokstad, Oseberg/Slagendalen and Kaupang in Norway, ca. 40 km southwest of the capital Oslo. Basemap: © kartverket www.kartverket.no	49
Fig. 2.9	Aerial orthophoto (2011, basis: Norge I Bilder, Norwegian Map authorities, Geovekst and Municipalities, resolution 10 cm) of the case study area Gokstad gives a good impression of the densely populated Vestfold County. Increasing urban development necessitates suitable heritage management strategies	50
Fig. 2.10	Bar diagram illustrating the increasing use of geophysical prospection in Norway since the 1990ies. Modified from Gustavsen & Stamnes (2014)	51
Fig. 2.11	On-going sea-level retreat in the south of Norway. Location of the Younger Dryas Ra moraine in orange. Blue isolines represent current crustal uplift rates in mm/year - based on (Dehls et al., 2000) - resulting from postglacial rebound (from Draganits et al 2015)	52
Fig. 2.12	Excavation of the Gokstad ship burial in 1880. Public Domain, Wikipedia/ www.gaia.no	55
Fig. 2.13	Landscape around Gokstad with the field <i>Heimdaljordet</i> in the front and the Gokstad mound encircled in the back. View towards north. Source: Google Earth. September 09, 2015. Accessed February 26, 2017	56
Fig. 2.14	Large scale, high resolution GPR data sets of the Gokstad study area	57
Fig. 2.15	Large scale, high resolution magnetometry data sets of the Gokstad study area	58
Fig. 2.16	The excavation of the Oseberg mound was carried out in 1904-1905. Public Domain, Museum of Cultural History, UiO/Olaf Væring	60
Fig. 2.17	Large scale, high resolution GPR data sets covering almost the entire Slagendalen, which also accommodates the Oseberg mound (red circle)	62
Fig. 2.18	Large scale, high resolution magnetometry surveys covering almost the entire Slagendalen, which also accommodates the Oseberg mound (red circle)	63
Fig. 2.19	Landscape of Slagendalen with Basberg in the front and Oseberg mound in the back. View towards North. Source: Google Earth. August 19, 2015. Accessed February 15, 2017	65
Fig. 2.20	Landscape of Slagendalen with Rom burial mound in the front. View towards North-northeast. Source: Google Earth. August 19, 2015. Accessed February 15, 2017	66
Fig. 2.21	Drawing of the Viking Age landscape around the trading post Kaupang with reconstructed sea-levels around 800 AD. 800 AD. Flemming Bau, Vikingskibmuseet i Roskilde	67
Fig. 2.22	Reconstruction of the Viking Age trading post at Kaupang. Flemming Bau, in: (Skre, 2007a)	67
Fig. 2.23a	GPR depth slice (40-45 cm BGS) overlying DTM (source: Norwegian Mapping authority, 0.5 m resolution) with reconstructed shoreline during the Viking Age at Kaupang based on sea-level data (+ 3.6 m) from Sørensen et al. (2007)	68

Fig. 2.23b	Today's shoreline shows the silted up coastal inlet – a result of the still on-going postglacial rebound	68
Fig. 2.24	Large scale, high resolution magnetic surveys at Kaupang and its hinterland	70
Fig. 3.1	Location of Gokstad in Vestfold County, Norway, among other prominent Viking Age landscapes including Kaupang, Oseberg/Slagendalen and Borre (basemap: ©kartverket www.kartverket.no , resolution 20 x 20 m)	72
Fig. 3.2	Map of local topography of the Gokstad study area (Basis: Norge I bilder, Norwegian Map Authorities, Geovekst and Municipalities, dtm Sandefjord 2008, 0.5 m resolution) with the Gokstad ship burial (red circle) and the Viking Age settlement and burial site <i>Heimdaljordet</i> (red polygon) marked. The structures of archaeological interest, which were newly mapped by geophysical archaeological prospection surveys during the <i>Gokstad revitalised</i> project are indicated	73
Fig. 3.3	Surficial deposits in the Gokstad study area (red rectangle) (basis: NGU, Norges Geologiske Undersøkelse, http://geo.ngu.no/kart/losmasse). Blue and violet areas illustrate sediment cover influenced by marine and intertidal processes caused by changing sea-levels. The Ra moraine (marked in green) runs ca. 4 km north-west of Gokstad	77
Fig. 3.4	Aerial orthophoto (2011, basis: Norge I Bilder, Norwegian Map authorities, Geovekst and Municipalities, resolution 10 cm) of the Gokstad study area illustrating densely populated areas surrounded by agriculturally used land and partly forested bedrock outcrops. The study area encompasses approx. 2.5 km ² , where GPR (red) and magnetometry (blue) survey areas cover every accessible field. In certain areas measurements were impossible due to wet ground conditions or crops	78
Fig. 3.5	Acquired GPR data sets covering 454 hectares in the neighbourhood of the Gokstad mound (red circle). Clearly visible at a depth of 60-80 cm BGS are extensive palaeochannel systems in the lowlands (outlined in blue). The slope areas (outlined in red) and <i>Heimdaljordet</i> (outlined in green) display non-archaeological structures and patterns, whose sources and origins are still only poorly understood	79
Fig. 3.6	Magnetometry data sets covering 403 hectares in the vicinity of the Gokstad mound (red circle). While lowlands (outlined in blue) and <i>Heimdaljordet</i> (outlined in green) generally contain a small number of anomalies, the sloping fields (outlined in red) contain large, long-wavelengths dipolar magnetic anomalies	80
Fig. 3.7	GPR survey using a 16 channel 400 MHz MIRA with a Leica GPS for data positioning in the immediate neighbourhood of the Gokstad mound	82
Fig. 3.8	GPR depth-slice (ca. 60-80 cm BGS) of <i>Heimdaljordet</i> displaying rectangular and round features interpreted as parts of a Viking Age settlement and a burial site. The southern part of this area is covered in a striking pattern of alternating strongly reflecting and absorbing layers	85
Fig. 3.9	Palaeoenvironmental interpretation illustrating beach deposits cut by a stratigraphically younger palaeochannel with integrated archaeological features in the west	87
Fig. 3.10	Sea-level reconstructions based on raster classification of topographic data (5 m DTM) for the Gokstad area from 4,000 BC until AD 800. Dashed square indicates the location of Fig. 3.11	88
Fig. 3.11	Calculated shore line range, based on present day topography, for the Viking Age (3.4 – 4.0 m above current sea-level (Sørensen et al. 2007) at <i>Heimdaljordet</i> illustrate that the settlement has been built close to the shoreline	89
Fig. 3.12	The radargram above clearly illustrates the fine, slightly dipping layers interpreted as beach sediments composed of sandy material. The grain size distribution of core sample 4006	

reveals alternating layers with varying amounts of fine and coarse clastic sediment, which are visible in the GPR as reflective and absorbing properties. Limited congruence between the radargram and the observed stratigraphic units is caused by the maximum vertical resolution (at best 5cm given a 400 MHz GPR pulse and an assumed velocity of 8 cm/ns) of the electromagnetic wave (Bristow and Jol, 2003) 92

- Fig. 3.13 Palaeochannel systems 1, 2 and 3 superimposed onto an aerial orthophoto taken in 1956 (basis: Norge I Bilder, Norwegian map authorities, Geovekst and Municiplaities, resolution 20 cm), before the stream courses were regulated. Note the slight differences between locations of the palaeochannels based on the geophysical prospection data sets and stream courses in 1956 (pink line) caused by lateral channel migration 94
- Fig. 3.14a Palaeochannel system 1 featuring two tributary channels is easily identifiable in the GPR depth-slice (60-80 cm BGS), where it overlaps with remains of *Gokstad nedre* burial mound 96
- Fig. 3.14b The meandering channel system is only faintly visible in the magnetometry data set of the same area 96
- Fig. 3.14c Integration of archaeological and palaeoenvironmental information based on GPR and magnetometry surveys 96
- Fig. 3.14d Interpretation of the modern drainage pipe installed after 1956, which is clearly visible in the magnetic data as linear anomaly with alternating polarization (most likely ceramic pipe) 96
- Fig. 3.15a GPR depth slice displaying the intersection of palaeochannel system 1 with the burial mound *Gokstad nedre* at 65 – 70 cm BGS 98
- Fig. 3.15b 3D volume rendering of the corresponding GPR data color-coded according to depth, which supports the superposition of the ditch surrounding the burial mound compared to the palaeochannel 98
- Fig. 3.16 The radargram shows both the ring ditch and the grave of *Gokstad nedre* burial mound. Note the intersection of the eastern ditch section with the palaeochannel. The magnification shows congruence of core stratification (4019) and reflectors at the boundaries of ditch and palaeochannel, before the electromagnetic energy attenuates in the finer, moist marine sediment 99
- Fig. 3.17a Magnetic data image on the sloping areas in the western part of the Gokstad survey area shows large dipole anomalies caused by magnetic bedrock (outlined in red) 102
- Fig. 3.17b The same bedrock is displayed in the GPR data as absorbing areas (outlined in red). A strongly reflective band indicates erosion and accumulation processes. Several core locations (4022-4024, 4026) for evaluation purposes were defined based on the GPR data. Note also the archaeological structures detected in the GPR data sets, which are tentatively interpreted as settlement structures 102
- Fig. 3.17c The slope model highlights the topographic relation of the pattern observed in the geophysical data 103
- Fig. 3.17d Palaeoenvironmental interpretation of the features observed in the geophysical data as buried shallow bedrock, colluvium and weathering horizons 103
- Fig. 3.18 The radargram illustrates the undulating buried palaeo-topography consisting of shallow buried bedrock that is covered by colluvium. The stratification of cores 4022-4024 supports this finding. The position of cores 4022 and 4023 on the radargram is schematic 106
- Fig. 3.19 3D reconstruction of the Gokstad area with sea-level reconstruction (at 3.6-4.0 m asl) and integrated archaeological and palaeoenvironmental features (view towards southwest). This study resulted in different zones emerging with a concentration of archaeological remains at

the Viking Age shoreline (green), while structures in the dried up fjärd (blue) so far seem to have been limited to few burial mounds. The slope areas (red) provide a more complex picture with settlement traces possibly dating to the Viking Age, that have yet to be subjected to more detailed archaeological investigations. A use for activities that only left elusive physical traces in this zone, such as pasturing or agriculture, might present an additional option

		109
Fig. 4.1	Input-Output diagram for 3D visualisation of GPR data	123
Fig. 4.2a	Point-based data visualisation of subset A of the beach deposits in Gokstad in CloudCompare	125
Fig. 4.2b	The data set consists of points with coordinates derived from the source data grid and a color representing the data value	125
Fig. 4.3	Arbitrary slicing and colour adjustment in CloudCompare. This 3D visualisation required 3.95 GB of memory in CloudCompare compared to 6.43 GB visualised as Volrender in Voxler 4 for the same data set	126
Fig. 4.4a	Location of all three case studies in the county Vestfold, Norway with 3D views (Google earth) of the respective test data sets at each site	129
Fig. 4.4b	Basberg	129
Fig. 4.4c	Rom	129
Fig. 4.4d	Gokstad features two test data sets. Viking Age settlement <i>Heimdaljordet</i> with the beach deposits are in the front, while the data set including the palaeochannel lies in the back	129
Fig. 4.5	GPR amplitude map 75-80cm Below Ground Surface (BGS) overlain by the interpretation of burial mounds and settlement traces. The beach deposits in the south are outlined in yellow. Subsets a and b are marked by black rectangles, individual profiles are highlighted in white and numbered 1, 2 and 3 (see also Fig. 6)	133
Fig. 4.6	Profile 3 shows a sequence similar to profile 1. The laminated beach foreshore sediment, however, seems to directly overly marine sediment. Vertical exaggeration 2	134
Fig. 4.7	Profile 2 of subset b demonstrates how multiple sections through the beach deposits and the palaeochannel can be used to understand the complex subsurface stratification at <i>Heimdaljordet</i> . Vertical exaggeration 1.5	135
Fig. 4.8	Profile 1 illustrates a sequence of laminated beach foreshore sediment, overlain by possible fluvial or backshore sediment and cut by a stratigraphically younger palaeochannel. Vertical exaggeration 2	136
Fig. 4.9a	GPR amplitude map (70-75 cm BGS) with the subset outlined in red	137
Fig. 4.9b	Top view of the same extent using volume rendering and locations of profiles 1 and 2. Note the modern pipe, which regulates the stream since 1956, as well as the amount of detail in the course of the river. The legend refers to the arbitrary scalar values of the initial grey-scale images	137
Fig. 4.10	Profile 1 shows details of the palaeochannel infill and the modern pipe. It also displays an archaeological feature interpreted as pit or dwelling that was erected at the stream margins and shows a distinctively rectangular shape. Vertical exaggeration 1.5	138
Fig. 4.11	Profile 2 shows details of the palaeochannel infill and the modern pipe. Vertical exaggeration 1.5	138

Fig. 4.12	GPR amplitude map (45-50 cm BGS) displaying beach ridges, overlain by the 2D interpretation of the burial mounds and a dense patterns of drainage ditches. The red rectangle marks the subset subject to 3D visualisation	139
Fig. 4.13	Volume rendering of subset with integrated polylines (shapefiles) from 2D interpretation. The dense drainage network was rendered transparent and thus no longer disturbs the interpretation process. Vertical exaggeration 1.5. Red line marking the location of Profile 1 in Fig. 4.15	140
Fig. 4.14	Limited integration of ALS data with archaeological interpretation and volume rendered GPR data from Kaupang in Voxler 4. Vertical exaggeration 1.5	141
Fig. 4.15	Profile 1 highlights different depositional events in the internal structure of the beach ridges, shallow buried bedrock and burial mounds. The disturbing modern drainage ditches have been digitally removed. Vertical exaggeration 1.5	142
Fig. 4.16	Input-Output diagram for the integration of isosurfaces into ArcScene. Note the iterative approach of 3D interpretation before data are further converted for import into the GIS	145
Fig. 4.17a	GPR amplitude map (50-55cm BGS) from a subset of Basberg showing most likely burials along a reflective band. Red arrows mark the view direction for image b	146
Fig. 4.17b	View towards north-west. Integration of burials and band visualised as cleaned isosurfaces in ArcScene together with a DTM of the Basberg area. The 3D view shows features detected with GPR below the current surface	146
Fig. 4.18a	Location of Basberg in the Slagen Valley close to Tønsberg and ca. 4 km northwest of the current sea border	147
Fig. 4.18b	Isosurfaces of burials and band integrated with topographic, reconstructed sea-level and soil data	147
Fig. 4.18c	Isosurfaces with reconstructed relative sea-level at 15.8 m above current sea-level based on calculations for 2000 BC	147
Fig. 4.18d	Isosurfaces with reconstructed sea-level at 12.5 m above current sea-level based on calculations for 1000 BC. Based on these additional data sets, data integration yields a <i>terminus post-quem</i> for the graves between 2000 and 1000 BC. Sea-level data are based on Sørensen et al. (2007)	147
Fig. 4.19a	Colour-coded isosurfaces displaying Rom burial mound and a close-by palaeochannel from the Slagen creek integrated with topographic data (DTM, 0.5 m)	148
Fig. 4.19b	View from underneath today's surface (rendered semi-transparent). Note the proximity of the palaeochannel and today's course of the river	148
Fig. 4.20	Isosurfaces integrated with manual interpretation of Rom burial mound and topographic data. View towards northeast	149
Fig. 4.21a	Surface model in 3ds Max based on ALS data (0.5m resolution)	150
Fig. 4.21b	Addition of isosurfaces for the river model and shape files from the 2D interpretation of Gokstad nedre burial mound in ArcMap 10.2	150
Fig. 4.21c	Modelling of river and sea-level	150
Fig. 4.21d	Adding vegetation. The generated virtual model follows the guidelines established in the London Charter (Denard, 2009) and the principles of Seville (Archaeology, 2011). Special attention is provided to scientific transparency and traceability	150

Fig. 4.22	3D reconstruction of the Gokstad landscape during the Viking Age. The river is bordered by vegetation and runs in close vicinity of Gokstad mound and Gokstad nedre mound towards the shoreline in the south, where a trading post is located. Bedrock outcrops are sparsely wooded, the area to the east (left) shows indications of marshy conditions. The valley bottom is used for sheep pasture, as these animals are known to be relatively salt-tolerant (Macphail et al., 2013)	151
Fig. 5.1	Location of the study site <i>Heimdaljordet</i> in Gokstad at the western side of the Oslo Fjord, Vestfold County, Norway amid other important Viking Age sites	154
Fig. 5.2a	Aerial photograph of the Gokstad area with the site <i>Heimdaljordet</i> situated ca. 500 m south of the Gokstad mound (both marked in red)	155
Fig. 5.2b	Map of the same area	155
Fig. 5.3	GPR depth-slice (70-75 cm BGS) displaying the <i>Heimdaljordet</i> study site with its settlement traces in the western part and burial mounds in the north-eastern part	156
Fig. 5.4	Magnetogram of the <i>Heimdaljordet</i> study site. Note the lack of settlement traces and burial mounds as detected in the GPR data	157
Fig. 5.5	The entire region around Gokstad is covered mainly by marine sediments as a result of post-glacial rebound and subsequent sea-level retreat. The red rectangle marks the image section of Fig. 5.2	160
Fig. 5.6	Soil map of the study site <i>Heimdaljordet</i> . Most of the area is covered by periodically water saturated stagnosol. Red rectangles are marking the location of trench 1 and trench 2	162
Fig. 5.7	Archaeological and palaeoenvironmental interpretation based on the high-resolution GPR data with settlement traces in the west, burial mounds in the north-east and beach deposits cut by a palaeochannel in the south-east	163
Fig. 5.8	Based on the interpretation map the location of excavation trench 1 was chosen. Trench 2 investigated the location of a sword hilt discovered in the course of metal detector surveys. Note the location of core 7670 in an area undisturbed by archaeological structures and the location of profile HDSS4 in trench 2	164
Fig. 5.9	<i>In-situ</i> volume susceptibility measurements in trench 1 after removal of top soil using a Bartington susceptibility meter and a MS2D probe	166
Fig. 5.10	Preliminary map of the archaeological structures identified in trench 1 at <i>Heimdaljordet</i> . The ditches interpreted as building plots are marked with grey fill. Most of the linear structures running from south-west to north-east are plough marks. Compare also to Fig. 5.11a. (from Gokstad revitalised project/ Christian Løchsen Rødstrud)	167
Fig. 5.11a	Ortho-photo of excavation trench 1 which focused on a rectangular arrangement of ditches, presumably Viking Age property plot boundaries, detected by high resolution GPR measurements. The photo displays archaeological features embedded into the subsoil as seen after topsoil removal. Note also the disturbance by modern drainage ditches visible in the trench. Locations for MS measurements from profile (yellow bars) and core (yellow points) samples are marked	168
Fig. 5.11b, c	Sample locations HDSS1 and HDSS2 taken from profiles of trench 1. Volume susceptibility was measured <i>in-situ</i> at a 2 cm interval (red points) and included the transition to subsoil. Material for mass specific susceptibility measurements was sampled at an approximately 10 cm interval from top to bottom (HDSS1-1, HDSS1-2 etc.: green ovals) and was taken to the laboratory for further analysis. HDSS3 with four subsamples followed the same principle, yet any photographic documentation was unintentionally destroyed	168

Fig. 5.12a	Oblique photo of the boat grave in excavation trench 2. The picture clearly shows the remains of a small, decayed vessel together with indications of iron panning at the transition between top- and subsoil (Macphail et al., 2013)	169
Fig. 5.12b	Sample location HDSS4 taken from the profile of trench 2. The measurement of volume susceptibility <i>in-situ</i> was prohibited by the unfavourable weather conditions. Material for mass specific susceptibility measurements was sampled at an approximately 10 cm interval from top to bottom (HDSS4-1, HDSS4-2 etc.: green ovals) and was taken to the laboratory for further analysis	169
Fig. 5.13	Sequence of integrated data including at (a) 70-75 cm BGS with the outline of trench 1	171
Fig. 5.13b	Magnetic data with the outline of trench 1	171
Fig. 5.13c	GPR data interpretation of features targeted in trench 1	171
Fig. 5.13d	GPR data interpretation superimposed with results from the planar <i>in-situ</i> volume MS measurements	171
Fig. 5.13e	Ortho-photo of trench 1 after removal of topsoil with building plots clearly visible	171
Fig. 5.13f	Ortho-photo superimposed with the planar <i>in-situ</i> volume MS measurements	171
Fig. 5.14	Profile samples HDSS1-HDSS4 of topsoil and transition to subsoil with mass specific susceptibility values in $10^{-8} \text{ m}^3\text{kg}^{-1}$ (left) and volume specific susceptibility values in 10^{-5} SI (right)	174
Fig. 5.15	Core samples showing topsoil and transition to subsoil with volume specific susceptibility values in 10^{-5} SI (core 7670) and archaeological features with mass specific susceptibility values in $10^{-8} \text{ m}^3\text{kg}^{-1}$ (cores 7874, 7941)	177
Fig. 5.16	Magnetogram processed with settings to enhance the visibility of the archaeological features. The superimposed ditches as interpreted based on the GPR data reveal a number of strong magnetic anomalies that might indicate thermoremanently magnetised material	183
Fig. 6.1	Location of the study site Gokstad among other prominent Viking Age landscapes in the Province Vestfold, Norway	186
Fig. 6.2	The study area of Gokstad with the well-known Gokstad burial (Macphail et al., 2013; Nicolaysen, 1882) to the east, the newly mapped Viking Age settlement and cemetery <i>Heimdaljordet</i> to the south-east (Bill and Rødstrud, 2013; Nau et al., 2015). In the west, on the field of the <i>Sverstad</i> farmstead, the test trench with the profile was dug during a geoarchaeological field evaluation of geophysical prospection data. Source: ©Kartverkert, www.kartverkert.no	187
Fig. 6.3	The hand-held kappa meter SM-30 used to measure volume MS in the field	192
Fig. 6.4	Moisture sensor with custom-made steel piercer	195
Fig. 6.5	GPR depth slice 65-70 cm BGS displaying the two clearance cairns as strongly reflective features targeted during the geoarchaeological field evaluation. The profile location was selected based on an area free of disturbance from drainage ditches and archaeological features	197
Fig. 6.6	Magnetometry data with the locations of the two clearance cairns. Clearance cairn 512 was completely obscured due to shallowly buried magnetic bedrock – a problem frequently occurring in Norway. In the middle of the dipole anomaly, data could not be acquired due to obstacle blocking the survey path	198

Fig. 6.7	Clearance cairn 512 with the exact position of the profile. The profile was dug mechanically in an undisturbed location down to ca. 1.60 m below surface, where ground water started to intrude	199
Fig. 6.8	Comparison of lab-based processed and unprocessed sample material with <i>in-situ</i> measurements collected every 10 cm. Note the difference in scale of each measurement technique	201
Fig. 6.9	Comparison of grain size distribution, gravimetric water content, volumetric water content and electrical conductivity collected along the profile	204
Fig. 7.1a	The Rom mound located in Slagendalen near the western shore of the Oslo Fjord, ca. 200 km SSW of Oslo	211
Fig. 7.1b	Oblique aerial photo with the Rom mound showing as a negative crop mark	211
Fig. 7.2a	Soil and	212
Fig. 7.2b	Sediment map of the area surrounding the Rom mound. The monument is situated on endostagnic cambisol developed on thick marine/fjord deposits. Basis: NGU (Norges Geologiske Undersøkelse)	212
Fig. 7.3a	Hillshade visualisation of the ALS data	213
Fig. 7.3b	Local-relief model displaying the remaining state of preservation of the Rom mound relative to the current topography	213
Fig. 7.4a	Magnetogram (10 × 10 cm resampled pixel resolution) of Rom mound with red rectangle marking the 2013 excavation trench	216
Fig. 7.4b	Archaeological interpretation of the magnetic prospection data	216
Fig. 7.5a	GPR depth-slice 40-60 cm BGS (10 × 10 cm resampled resolution) of the Rom mound with red rectangle marking the 2013 excavation trench	218
Fig. 7.5b	GPR data interpretation of depth-slice 40-60 cm BGS	218
Fig. 7.6	3D explosion model of the excavated stratification at Rom mound. Three main structures could be identified: the mound structure itself, the surrounding ring ditch and the modern disturbance	222
Fig. 7.7a	Comparison of the virtually reconstructed archaeological stratification of Rom mound with 2.5 D GPR data interpretation (80-200 cm BGS) in ArcScene 10.2. Red arrows illustrate view directions for 7.7b and 7.7c	223
Figure 7.7b, c	demonstrate the interpretation accuracy of the ring ditch as observed in the GPR data. Note the congruence between SU[1450] and GPR interpretation at ca. 80 cm BGS, where the ditch first becomes visible in the GPR data	223
Fig. 7.8	Radargrams displaying sections through the entire mound structure from NW – SE	224
Fig. 7.8a	This radargram was obtained using a SPIDAR GPR system in 2012. The lower 25 × 10 cm measurement grid resolution and GPR trace sampling rate of 0.2 ns resulted in a coarser, less detailed picture of the subsurface	224
Figures 7.8b, c	In contrast, show a radargram obtained from the second survey in 2014 using a high-definition 400 MHz MIRA. The image also displays the trench previously excavated in 2013. This data enables a much clearer imaging of the subsurface structure and highlights the presence of several palaeochannels based on the higher measurement resolution of 2-6 × 12 cm, resulting in a resampled image of 8 × 8 cm together with a high GPR trace sampling interval of 0.16 ns. Note the slightly different scales of figures 7.8a and 7.8b, 7.8c	224

Fig. 7.9	Comparison of high and ultra-high definition GPR surveys. 7.9a shows depth-slices 25-30 cm BGS conducted with a SPIDAR GPR system. 7.9b: The same depth-slices acquired with the MIRA system displays a far more detailed and clearer image of the subsurface, including a kind of rim at the outskirts of the stone packing. 7.9c Depth-slice at 60-75 cm BGS collected with the SPIDAR GPR. 7.9d The corresponding depth-slice acquired with the MIRA system features a lining interpreted as part of the potato cellar, which is barely visible in the corresponding SPIDAR image 7.9c	225
Fig. 7.10	Distribution curve of the 249 specimens tested for MS illustrates that the data are not normally distributed and thus support the hypothesis that the large anomalies are caused by only few highly magnetic boulders	227
Fig. 7.11	MS of specimens measured at the top surface of SU[692], overlying large magnetic dipole anomalies	228
Fig. 7.12a	GPR interpretation of depth slice 40-60 cm BGS with stones and absorbing features	231
Fig. 7.12b	Mapped stone packing from SU[692] illustrates the limited congruence between actual stones and strong reflections. The “absorbing” features emerge as areas void of stones	231
Fig. 7.13a	3D Explosion model of the ditch backfill surrounding the burial monument with associated stratigraphic sequence	232
Fig. 7.13b	Top surface of SU[492] displaying the increase in clast inclusions and the presence of charcoal at its base. Northern ditch profile illustrates the stratification of the ditch fill	232
Fig. 7.14	Planar MS measurements on the top surface of SU[630] clearly illustrating low MS values compared to the north-western flank of the ditch. The south-eastern edge of the ditch appears more gradually expressed in the MS data	233
Fig. 7.15	Results from the laboratory-based analyses of undisturbed core sample material taken from ditch backfill	235
Fig. 7.16	Results from the <i>in-situ</i> measurements from the ditch backfill exposed during the excavation. Image shows the northern ditch profile	236
Fig. 7.17a	3D Explosion model of the modern disturbance cutting through the prehistoric burial monument with corresponding stratigraphic sequence	239
Fig. 7.17b	Vertical section cutting through the disturbance caused by the modern potato cellar	239
Fig. 7.18	Results from the <i>in-situ</i> measurements taken from the vertical section through the modern disturbance	240
Fig. 8.1	Flow diagram of the systematic implementation of environmental aspects into the archaeological geophysical prospection routine	262

List of Tables

Table 3.1a	Measurement specifications for the GPR surveys conducted	81
Table 3.1b	Measurement specifications for magnetic surveys conducted	81
Table 3.2	Sediment descriptions of evaluation cores and observed layers	91
Table 3.3	Sediment descriptions of evaluation cores and observed layers	99
Table 3.4	Sediment descriptions of evaluation cores and observed layers	105
Table 4.1	Description of test sites and overview about selected 3D visualisation modes, data integration and 3D reconstruction	130
Table 5.1	Mass specific MS measurements from cores 7874 and 7941. Note the low contrast between samples taken from archaeological features and the subsoil, in which they are embedded	180
Table 6.1	Sedimentological description and stratigraphic observations of the layers discovered at <i>Sverstad</i>	200
Table 7.1	Descriptive statistics of MS values acquired from the stone packing	227
Table 7.2	Macroscopical identification of magnetic rocks according to MS classes	230
Table 7.3	Sedimentological descriptions of the five layers observed in the core sample taken from the ditch	234

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 (Fassbinder, 2015; Gaffney, 2008; Jordan, 2009; Linford, 2006; Neubauer, 2001b; Scollar et al., 1990; Wynn, 1986). 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 (Campana, 2009; Gabler et al., 2013; Kvamme, 2003; Linford and Linford, 2010; Trinks et al., 2014, 2012). 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 (Bunting et al., 2014; Chapman et al., 2009; Cowley, 2011; Nau et al., 2015; Neubauer et al., 2012).

These data sets do not just contain archaeological structures such as burial grounds or settlement traces, but also include different types of palaeoenvironmental information abundant on different levels of the archaeological geophysical prospection routine. Such information commonly is not considered in particular, because in most cases the focus of geophysical surveys remains on the archaeology. Palaeoenvironmental information, however, constitutes an important part of the overall information contained in large scale, high resolution geophysical prospection. The research presented here will thus concentrate on the analysis of palaeoenvironmental information and investigate the potential it has on archaeological geophysical prospection.

Aims and Objectives

Following from the above, the main objective of this thesis was to investigate the potential of palaeoenvironmental information for large scale, high resolution geophysical prospection data sets and to assess how it affects the resulting archaeological interpretation.

Since no study so far particularly focused on palaeoenvironmental information, it became necessary to set up a pilot study as a first step within this thesis. Based on large scale, high resolution magnetometry and GPR data sets, three initial research questions were targeted:

- What type of palaeoenvironmental information is contained in large scale, high resolution geophysical prospection?
- How can this information be analyzed?
- How does this information impact the archaeological interpretation of large scale, high resolution geophysical prospection?

Results of this pilot study quickly identified two further areas of research that needed to be addressed in this thesis. First, the nature of palaeoenvironmental structures and patterns as identified in the pilot study differs substantially from those of archaeological features and therefore demands for new ways of visualization and integrative analysis prior to and during interpretation. And secondly, the significance of palaeoenvironmental information in archaeological geophysical data is not limited to the structures and patterns visible in the data sets. The consideration of palaeoenvironmental information such as pedological, geological and geomorphological characteristics of a study area is essential to further enhance the interpretation of archaeological geophysical data on a qualitative level.

Structure of the thesis

Based on these insights, the research project presented here was organized thematically and structured into a general introduction to the research topic and eight chapters. This includes two introductory chapters at the beginning, followed by five chapters focusing on different aspects of the influence palaeoenvironmental information can have on large scale, high resolution archaeological geophysical prospection. Finally, a closing chapter discusses conclusions drawn from the case studies, the general impact of palaeoenvironmental information on archaeological information as well as future research avenues.

The introduction establishes the research topic and outlines the thematic structure of the thesis. Chapter I introduces the field of archaeological geophysical prospection and gives a general overview about the geophysical techniques used in this study, magnetometry and ground penetrating radar (GPR), including their basic physical and measurement principles, state-of-the-art measurement systems and current use in archaeology, as well as applied data processing and interpretation routines. Techniques used for geoarchaeological evaluation including magnetic susceptibility (MS), electrical conductivity, water measurement as well as sediment and soil descriptions will be introduced separately in the respective chapters V-VII (see below). This is followed by a section discussing characteristics and particular issues encountered in large scale, high resolution archaeological geophysical prospection approaches.

Chapter II discusses the term palaeoenvironmental information and its significance for the encompassing interpretation of archaeological landscapes. It also stresses the significance of considering the environmental settings of a study area for analyzing and extracting palaeoenvironmental as well as archaeological information contained in archaeological geophysical prospection data together with the relevant environmental factors and physical and chemical processes. The second part of chapter II is dedicated to generally introduce the case study areas in Norway, county Vestfold: Gokstad, Oseberg/Slagendalen and Kaupang. Environmental settings relevant for the perspective research questions for each case study site are presented together with the individual research chapters.

As mentioned above, chapter III constitutes of a pilot study focusing on a palaeoenvironmental analysis of the Viking Age landscape of Gokstad using large scale, high

resolution magnetometry and GPR data sets. These data sets are systematically analyzed and interpreted regarding palaeoenvironmental structures and patterns. A particular emphasis is placed on the implications for the archaeological interpretation as well as on a general assessment of this approach's benefits and limitations.

Chapter IV addresses methodical questions of how to extract, visualize and interpret palaeoenvironmental information within an integrative approach that takes into account their special nature. Using different test data sets from the archaeological landscapes of Gokstad, Oseberg and Kaupang, a workflow for integrated 3D analysis and interpretation of palaeoenvironmental structures and patterns within a GIS environment was developed using the 3D volumetric data visualization Voxler (Golden Software).

Chapters V-VII focuses on the potential of palaeoenvironmental information for the geoarchaeological evaluation of geophysical prospection results. This research tests time- and cost-efficient *in-situ* techniques that aid in the qualitative assessment of geophysical prospection results. For that purpose, case studies accessible through excavations at *Heimdaljordet* and *Sverstad* in Gokstad and Rom in Slagendalen were selected. By measuring soil/sediment properties diagnostic for the signal response of magnetometry and GPR such as MS, water content/dielectric permittivity as well as electrical conductivity while generally taking into account the environmental settings of the study area, it was possible to gain valuable insights into the sources of archeological and palaeoenvironmental anomalies, structures and patterns. Eventually, this approach aided in better understanding the influence of environmental settings onto the geophysical techniques used as well as in enhancing the accuracy of interpretation results.

Chapter VIII, finally, is used to draw conclusions from the research chapters, to critically discuss the role of palaeoenvironmental information in geophysical prospection and to suggest future research avenues for this direction.

Chapter I

1.1 Archaeological prospection

Today, archaeological prospection - remote sensing and geophysical prospection - presents an integral part in archaeological research (Scollar *et al.* 1990, 2). This, however, has not always been the case.

The beginnings of archaeological prospection are grounded in the 1920ies, when the first of the archaeological prospection methods – aerial photography - evolved from military aerial reconnaissance (Fig. 1.1). First systematic aerial photography surveys were carried out in the 1920ies and 30ies by pioneers such as O.G.S. Crawford, who focussed not just on the detection but also on the interpretation and mapping of the discovered archaeological features (Crawford, 1929, 1924). Digital ortho-rectification of oblique aerial images presented a further step in this direction (Scollar *et al.*, 1990). Otto Braasch proved the abilities of this prospection method by discovering more than 20.000 archaeological sites in the southern Germany during nine years of systematic aerial surveys (Braasch, 1983).



Fig. 1.1 First aerial picture of Stonehenge taken from a balloon (P. H. Sharpe, public domain)

The digitalisation in photography, computer-based photogrammetry as well as the use of global navigation satellite system (GNSS) have greatly impacted remote sensing. In particular the development of new techniques such as airborne laser scanning (ALS) (Doneus et al., 2013, 2008), airborne laser bathymetry (ALB) (Doneus et al., 2013) and airborne imaging spectroscopy (AIS) (M. Doneus et al., 2014) during the last decades further increased the potential for systematic large-scale prospection and monitoring of archaeological sites and landscapes (Scollar et al., 1990), (Gaffney, 2008).

Remote sensing surveys have contributed extensively to the detection of new and the mapping and monitoring of already known archaeological sites. However, more precise information about for example the specific type of a site or its preservation status requires a different approach: geophysical prospection (Neubauer, 2001a).

1.2 Geophysical prospection

Archaeological geophysical prospection has emerged from the much larger field of geophysics used for earth exploration in the Earth sciences and during the last 50 years developed into an independent field of research (Batayneh, 2011). Electrical resistivity represented the first geophysical prospection method used in archaeology, applied in a survey in 1946 by Atkinson (1953). This was followed by the rise of magnetometry in the 1950ies and ground penetrating radar in the 1970'ies and 80ies (for more details see chapters 1.3 and 1.4 below)

Archaeological geophysical prospection uses ground-based, non-invasive and therefore re-measurable techniques for the detection, mapping and interpretation of archaeological structures, sites and landscapes (Gaffney and Gater 2003; Schmidt et al., 2015). All of these prospection techniques are based on the small-scale recording of physical properties of the subsurface. Local variations or anomalies detected allow for conclusions on archaeological structures and deposits. The success of archaeological geophysical prospection, however, is entirely dependent on sufficient measurable contrast between archaeological structures and surrounding subsurface material (Linford, 2006; Neubauer, 2001a).

Archaeological geophysical prospection encompasses a range of different techniques, which can be divided in active and passive methods (Fig. 1.2). Active methods provoke a reaction from the subsurface by sending out a signal, while passive techniques, in contrast, measure particular physical properties of the targeted subsurface materials (Neubauer, 2001a).

ACTIVE	PASSIVE
<i>Ground-penetrating radar</i>	<i>Magnetometry</i>
<i>Electrical conductivity</i>	<i>Gravimetry</i>
<i>Seismic</i>	<i>Geothermal</i>
<i>Sonar</i>	<i>Radiometry</i>
<i>Geoelectromagnetic</i>	

Fig. 1.2 Active and passive methods in archaeological geophysical prospection, (based on Neubauer, 2001b)

Different techniques thereby respond to different physical properties, which is why an approach using complementary techniques has proven in many cases to yield the best prospection results (Watters, 2009). The choice of techniques for a survey thus is fundamental for its outcome and depends on several factors including prevailing environmental settings, individual research questions as well as time and budget considerations.

Yet, archaeological geophysical prospection does not only comprise data acquisition, even though a suitable survey design plays a decisive role. Targeted data processing and in particular data interpretation that addresses the research question and translates the geophysical data into results comprehensibly to non-specialists are essential for a successful geophysical study.

It is, however, important to stress that archaeological geophysical prospection does not yield a complete picture of all archaeological structures in the investigated subsurface. Sensors do only respond to particular physical properties and, as mentioned above, archaeological structures will become visible only if there is sufficient contrast between them and the surrounding subsurface (Kvamme, 2003).

The amount of detail an archaeological geophysical prospection can provide determines the level of interpretation that is possible. This generally depends on the sensitivity of the sensors and the measurement resolution (Neubauer, 2001a). Apart from a suitable survey design, an encompassing data interpretation requires knowledge of local archaeology, expertise in interpreting geophysical data as well as the consideration of the environmental settings such as geology and pedology of a survey area. Only if these three elements are equally considered, a comprehensive interpretation will be possible (Fig. 1.3).

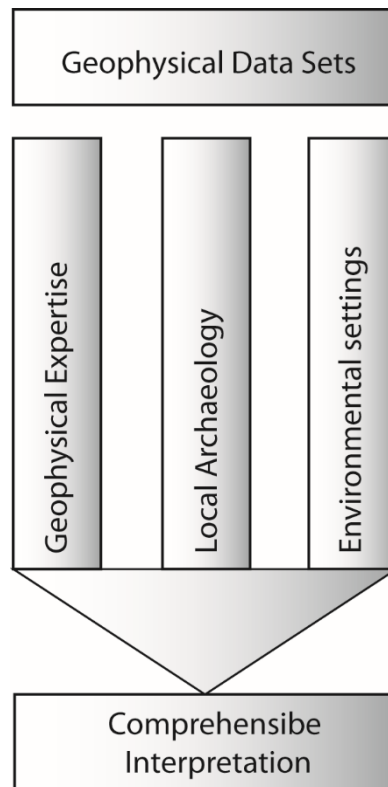


Fig. 1.3 The three columns that constitute a comprehensive interpretation of archaeological geophysical data: Geophysical expertise, local archaeology and environmental settings

During the last few decades, new technical developments such as the motorisation of multi-sensor/antenna systems (Leckebusch 2003; Linford 2006; Gaffney 2008; Trinks et al. 2010), have been able to demonstrate the potential of archaeological prospection not only to locate and map archaeological features, but to address a whole set of new research questions regarding analyses and interpretation of archaeological landscapes.

The following section will focus on the underlying physical principles of individual techniques used in this thesis and address recent developments within these techniques in more detail.

1.3 Magnetometry

Physical background

Magnetism is based on the movement of electrically charged particles and conveyed by magnetic fields shaped as dipoles. These fields are generated by electric currents that give rise to magnetic moments of elementary particles such as for example negatively charged electrons which circle around a positively charged atomic nucleus. Electrons possess an additional magnetic moment generated by a spin around their vertical axis and thus display a larger magnetic moment than positively charged protons or neutrons. Consequently, the magnetic moment of any atom is the sum of its individual magnetic moments and the interaction of strength and direction of any arising magnetic fields. The same applies to solid materials, whose magnetic properties are deriving from the magnetic moments of their individual atoms and their interactions with each other. All solid materials can be classified as one of five types of magnetism based on their magnetic properties: diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic (Neubauer, 2001a)

In contrast to all other types of magnetism, which are caused by their electron's spins, diamagnetism is generated by the electron's orbiting. If a magnetic field is applied to these materials, the direction of the arising, small magnetic moments is opposite to that of the external magnetic field resulting in a weakly negative MS. Diamagnetic materials particularly relevant for archaeological magnetic surveys are for example water and quartz.

Paramagnetic materials do possess permanent magnetic moments that - without the application of a magnetic field - are aligned in such a way that their net magnetic moment is zero (Fig. 1.4). When a magnetic field is applied to paramagnetic materials, the magnetic moments align with the external field and thus intensify the overall magnetisation which becomes weakly positive. Examples for paramagnetic materials are the minerals lepidocrocite and ferrihydrite (at room temperature). In ferromagnetic materials, unpaired electron spins are aligned to each other within domains due to a phenomenon known as long-range ordering. While the alignment within a domain gives rise to a magnetic field, the net magnetic moment of ferromagnetic material is zero due to the interaction of the domains with each other leading to randomisation (Aspinall et al., 2008). The situation is different in the presence of an external field, such as for example the Earth magnetic field,

which causes the domains to align with it and thus creates a net magnetic moment. Ferromagnetic material possesses a “magnetic memory” meaning that a part of the magnetisation remains in the material even after the magnetic field has been lifted. This part is called magnetic remanence. Examples for ferromagnetic materials are iron, cobalt and nickel (Nave, 2016).

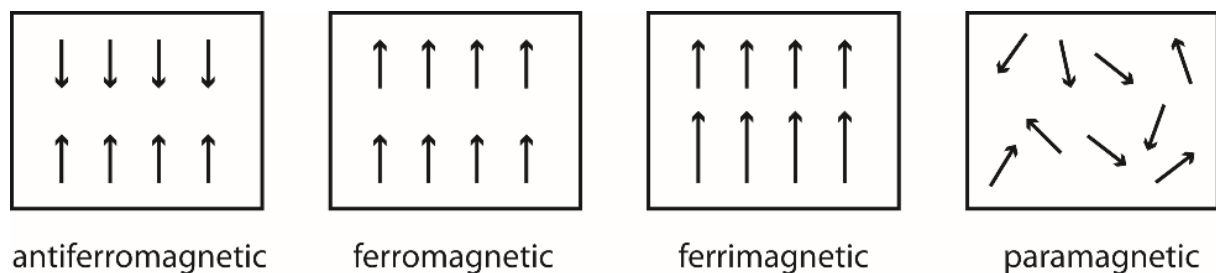


Fig. 1.4 Different types of magnetisation (based on Neubauer, 2001b)

Antiferromagnetic materials such as goethite and haematite show magnetic moments or electron spins that are oriented in opposite directions, resulting in a net magnetic moment of zero. However, rising temperature weakens this ordering of magnetic moments and eventually breaks it up entirely at a point known as Néel temperature. As a consequence, the material becomes paramagnetic showing a weakly positive MS. Ferrimagnetic materials behave in a similar way, showing the same alignment of magnetic moments as antiferromagnetic materials. The difference lies in the diverging quantities of alignment directions (1/3 to 2/3) and as a result, ferrimagnetic materials become magnetised. Just as antiferromagnetic materials, ferri – as well as ferromagnetic materials are temperature-dependent. These types of magnetism can gain a magnetic remanence at room temperature, but become paramagnetic above their individual Curie temperatures. The most significant ferrimagnetic materials regarding magnetic prospection are magnetite and maghemite, which are highly susceptible to magnetic fields (Evans and Heller, 2003; Kattenberg, 2008; Neubauer, 2001a).

The Earth's magnetic field

Following the same principle, the main component of the Earth magnetic field is thought to be generated by electrical currents resulting from turbulent convection currents in the liquid outer core. Over-simplified, the earth magnetic field can be understood as a field mainly generated by a dipole at the centre of the Earth. Much smaller parts in the range of 1-2 % are contributed by rocks in the earth's crust as well as by temporal inconsistent external fields caused through ionised particles in the magnetosphere. The main magnetic field or dipole field changes constantly due to magnetic secular variation, a phenomenon caused by spatial and temporal variations of the convection cells as well as by differences in rotation between core and mantle. The intensity of the earth magnetic field, measured in Ampere per meter (A/m), is constantly changing on different temporal and intensity scales. These cyclic diurnal variations range between 20 and 50 nT (Tesla measures the flux) and are caused by the sun's activity throughout the day. Smaller variations known as pulsations and micro pulsations display even smaller amplitudes between 0.001-50 nT within a temporal range of 0.2s - 10min (Neubauer, 2001a).

The method of magnetometry

Magnetometry is based on the capacity to measure the strength of localised, spatial variations of the earth magnetic field using a magnetometer (Aspinall et al., 2008). Archaeological structures often show enhanced magnetic properties due to different processes including heating, edaphic and pedological processes (Kattenberg, 2008) (see also below). As all other archaeological geophysical prospection methods, magnetometry is dependent on sufficiently measurable contrast between archaeological structures and surrounding subsurface material. Challenges for the detection of buried archaeological structures using magnetometry present diurnal variations and pulsations of the earth magnetic field mentioned above. Since the intensities of these variations are able to exceed the magnitude of buried archaeological features, they can seriously impair the detection of archaeological structures. A solution to this issue is presented by gradiometer configurations, in which two sensors are arranged along a line of known distance. This approach is based on the fact that the intensity of magnetic fields diminishes inversely

proportional to the third power of distance (Neubauer, 2001a). Ideally, thus, the top sensor is mainly influenced by the earth's magnetic field, while the bottom sensor registers potential magnetic fields generated by archaeological structures in the subsurface due to a shorter distance to the ground surface. By distracting top from bottom reading, the diurnal variations and pulsations are diminished and the survey will produce a clearer picture of the subsurface. In Europe, magnetic inclination requires gradiometers to be carried vertically, in contrast to equatorial areas, where sensors are oriented horizontally (Fassbinder, 2015; Kattenberg, 2008).

The development of magnetic measurement devices

Magnetometry is one of the most widely used geophysical prospection methods in archaeology (Neubauer, 2001a). Based on the discovery of thermo-remanent magnetism in burned clay made during the 19th century (Folgheraiter, 1896), magnetometry became the focus of research in archaeological geophysical prospection during the 1950ies – a development that triggered further research and resulted in important observations for the use in Archaeology: This must include conclusions by Le Borgne (1955) on increased susceptibility in topsoil when compared to the underlying subsoil as well as Belshé's investigation of the potential for dating ovens by using the directions of magnetic streamlines as well as first experimental field studies using ASKANIA Torsionswaagen for (very time-consuming) data acquisition (Belshé 1956). Around the same time, Aitkens and Hall recognised the applicability of a precession proton magnetometer and developed such a tool at the Research Labs for Archaeology and the History of Arts (RLAHA) at Oxford. The new proton magnetometer presented a great improvement with a sensitivity of 1 nT and a measuring time of only 5 seconds (Aitken, 1958; Aitken et al., 1958).

In the late 1950ies, Scollar, who already had worked with electrical resistivity in Germany, recognised the necessity to address the natural fluctuations of the Earth's magnetic field (Neubauer, 2001a). This observation resulted in the first prototype of a differential proton magnetometer (Scollar et al., 1990). During the 1960'ies and 70'ies, the development of magnetic prospection was driven by new data acquisition tools such as the first fluxgate gradiometer (Allred, 1964) and the rubidium magnetometer (Ralph, 1964). Finally, the

development of a fluxgate magnetometer system with incorporated data logger especially for archaeological purposes by GEOSCAN RESEARCH led to a further spread of magnetic prospection in Archaeology (Neubauer, 2001a).

However, attention did not only concentrate on the development and application of new measurement tools. An additional focus was placed on the improvement of computer-based data processing including an essentially automated acquisition process as well as computer-based data analysis (Neubauer, 2001a). Advancements in this field were particularly based on the work of Scollar and Aitkens, as well as Aitken's student Linington (Linington, 1971, 1970, 1969, 1968; Scollar et al., 1986; Scollar and Krückeberg, 1966). Integrated image data processing, standardised digital image visualisation, as well as different algorithms for a better data processing and the enhancement of models and simulations presented important new tools in order to better understand and interpret prospection data. Besides considerable advancements in the field of measurement systems and data processing, ground breaking research occurred also concerning the understanding of the magnetic properties of soils and sediments and formed a third focus in the development of geomagnetic prospection in archaeology (Graham and Scollar, 1976; Mullins, 1974; Tite and Mullins, 1971).

In 1982, Bavaria in Germany incorporated geophysical prospection into the heritage management strategy using a differential proton magnetometer initially developed by Scollar and a caesium gradiometer (Fassbinder and Linck, 2015). In 1983, a digital image processing system enabled the integration of aerial and prospecting data (Becker, 1996; Fassbinder and Irlinger, 1999; Neubauer, 1990).

Research especially targeted on geomagnetic prospection in Vienna and Munich played a decisive role in further developments. H. Friesinger directed a special research area called "Neue Wege der Frühgeschichtsforschung", which included the adaptation of a VARIAN caesium gradiometer (ZAMG) for archaeological purposes (Neubauer, 2001a). An additional research venue focussed on 3D modelling and interpretation of from magnetic data. This progress was made possible by the development of affordable field-based digital image processing system as well as by the use of new processing algorithms (Eder-Hinterleitner et al., 1996; Neubauer and Eder-Hinterleitner, 1998).



Fig. 1.5 Motorised magnetic multi fluxgate gradiometer array pulled by an all-terrain-vehicle (ATV)

State-of-the-art magnetic systems and their use in Archaeology

As mentioned above, a range of sensors based on different physical principles were developed in the field of magnetometry in order to measure the strengths of magnetic fields. Today, mainly two types prevail: optically pumped magnetometers such as caesium vapour sensors, which measure the total magnetic field intensity as well as fluxgate sensors, which measure only one component of the magnetic field, either vertical or horizontal (Fig. 1.5). Even though the last years have seen an increase in the use of caesium vapour devices, most magnetic surveys in archaeology these days are conducted using fluxgate sensors in gradiometer array mostly due to practical reasons: Fluxgate gradiometers are light weight and affordable. The physical principle of a fluxgate sensor is based on alternating magnetic saturation and unsaturation (Gaffney, 2008).

Fluxgate sensors as used for the studies reported in this thesis consist of two metal cores, which are surrounded by a set of two primary (drive) wires wound in opposite directions as well as a set of secondary (sense) wires, which are wound around the primary wires, again in

opposite directions to each other as well as with regard to the primary wires. If the primary wires are energised by an alternating current, the metal cores begin to fluctuate between states of magnetic saturation and unsaturation, consequently exhibiting low and high magnetic permeability. This process generates a magnetic field, which is registered by the second set of wires, the sense wires. In a magnetically neutral background, input and output currents will cancel each other out due to inversely arranged coils. If the fluxgate is exposed to an external magnetic field such as the earth magnetic field, however, saturation of the cores will require less effort when in alignment with the external field and more effort when opposed to its direction. As a result, input current and induced output current generated by the fluctuating magnetic field will be thrown out of balance. This magnitude in phase shift is proportional to the external field's strength and polarity – a relation that allows to determine the magnetic field's strength (Kattenberg, 2008; Scollar et al., 1990).

Data processing and interpretation

Magnetic data processing encompasses several stages using specific software such as ApMag (Fig. 1.6). Once data acquisition is finished, data restoration and pre-processing is initiated. This stage includes a verification of the position data quality, a correction of the sensor drift/shift as well as compensation of Earth's magnetic field variations and of the vehicle's influence.

The following stage includes data processing and georeferencing. Track and sensor positions are calculated and subsequently resampled on a georeferenced regular grid. Based on this grid, data are further processed using de-spiking, various filters and measuring line annealing as needed, which ultimately yields 2D raster files for visualisations known as magnetograms (Fig. 1.7). Magnetograms are visualised as grey-scale raster images based on the conversion of magnetic values to 256 grey-scales or as float tiffs where every pixel displays a processed magnetic values. Once magnetograms are generated, they can be imported into a GIS and enhanced in an multi-stage iterative cycle using procedures such as de-spiking, median filter, edge enhancement, Gaussian smoothing and high/low pass filtering.

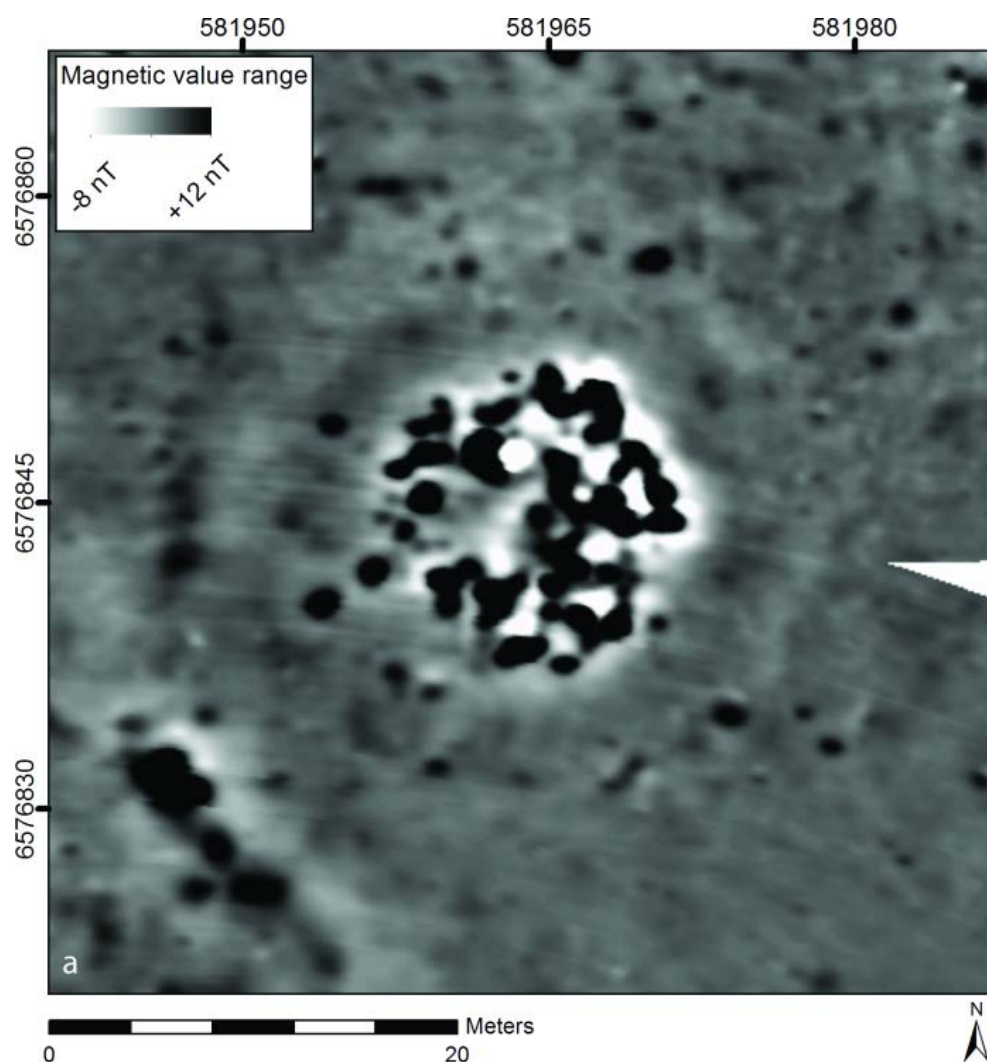


Fig. 1.7 Magnetogram of Rom mound with clearly visible stone packing of consistent of igneous rock

Interpretative mapping based on magnetic data is mainly conducted manually in a GIS environment resulting in thematic 2D maps. However, semi-automated approaches are increasingly used for pre-interpretation of anomalies in order to manage large scale data sets. Tools applied to this task are raster classification as well as more sophisticated approaches using specific software such as Trimble eCognition Suite (<http://www.ecognition.com/suite>) currently being developed by the LBI ArchPro.

Interpretative mapping includes drawing and editing of archaeological and palaeoenvironmental features and feature classification in a spatial database. However, in-depth data interpretation also involves the use of 3D modelling of magnetic data in order to investigate probable sources for the measured anomalies and thus enhance knowledge and interpretation quality for future surveys as well as to generate 3D content based on the two-dimensional magnetic data (Neubauer and Eder-Hinterleitner, 1998). Based on the results of this approach, spatial and spatio-temporal analysis can be conducted, which eventually lead to thematic or chronological archaeological interpretation maps.

1.4 Ground penetrating radar

Physical background

The principle of GPR is based on the emission of an electromagnetic wave into the ground by a transmitter. Electromagnetic waves are generated by the oscillatory motion of electrically charged particles. In addition to the electrical field, a magnetic field is produced. Electrical and magnetic fields thereby move perpendicular to and in phase with each other. As soon as they are generated, electromagnetic waves are self-perpetuating. The frequency of the electrical current's oscillation (measured in cycles per second) generates waves of different wavelengths. A higher frequency results in a shorter wavelength with subsequently less penetration depth but a higher resolution, whereas lower frequencies generate waves of longer wave length resulting in greater penetration depth and lower resolution. Once emitted, the radar signal or waves will travel an infinite distance through air or space unless they encounter a medium that either reflects, absorbs or attenuates them. If, through this

process, either the magnetic or electric part is lost, the wave stops propagating and ceases (Annan, 2008; Conyers and Goodman, 1997).

The method of GPR

The GPR method is based on the recording of the time an electromagnetic wave needs to travel from a transmitter to a physical discontinuity or interface encountered in the subsurface and back to a transmitter. This time span represents a proportion of the travel distance and can be used to calculate the depth of said interface. Electromagnetic waves are usually generated by applying an electrical current onto a copper wire or plate placed in an antenna. After emission, a part of the electromagnetic signal known as air wave travels directly from transmitter to receiver; the remaining part enters the subsurface where it propagates in the form of an elliptical cone. At the interface between adjacent layers with different physical properties, a part of the electromagnetic wave is reflected while the residual part continues to traverse the subsurface until its energy dissipates and eventually the signal ceases (Conyers and Goodman, 1997).

Arrival time and amplitude of each reflection is recorded by a receiver, digitized and stored in a computer. All reflections received at the same location are combined in a trace. By moving the transmitter-receiver channel along a profile, traces can be bundled to sections or radargrams. The interpolation of all adjacent radargrams generates a 3D data cube, which subsequently can be cut into horizontal time or depth slices (see also below) (Annan, 2008; Conyers and Goodman, 1997; Leckebusch, 2003a).

Penetration depth as well as vertical and lateral resolution of a GPR survey is governed by the radiation characteristics of the antennas used, the frequency of the emitted electromagnetic pulse as well as by the physical properties of the subsurface materials. For archaeological purposes, commonly 400-500 MHz antenna frequencies are used, resulting in a penetration depth of several meters dependent on the traversed media.

Among the physical properties, dielectric permittivity represents the most important parameter for GPR surveys. Simplified, it determines how much resistance an electromagnetic field encounters when travelling through a medium. The difference in

dielectric permittivity between two adjacent subsurface layers thus controls the strength of reflection. Dielectric permittivity is also used to calculate the propagation velocity of an electromagnetic wave in m ns^{-1} using the following formula: $v = c/\sqrt{\epsilon_r}$ (m ns^{-1}) with $c = 0.3\text{m ns}^{-1}$ as the speed of light and ϵ_r as the dielectric permittivity, assuming that the magnetic properties of the material can be neglected (Conyers and Goodman, 1997; Takahashi et al., 2012).

The development of GPR measurement devices

GPR entered the field of archaeological geophysical prospection around the 1970'ies and 1980'ies. Although radar detection and ranging (radar) technology was known since the beginning of the 20th century, it was not used until the 1970ies to locate buried objects and thereafter was widely applied by soil scientists and hydrologists as a geotechnical tool to investigate soil units, bedding planes as well as depth and nature of groundwater tables (Conyers and Goodman, 1997).

Throughout the 1980ies and 90ies, a number of successful GPR prospections were carried out, but the data often remained unprocessed. Additionally, the then inability of differentiating archaeological from geological features limited the use of GPR in archaeology (Lawrence B Conyers, 2015). Some of the best practise examples of GPR surveys at that time were conducted in Japan, benefitting from faster computer processors and special software programs (Goodman et al., 1995, 1994; Goodman and Nishimura, 1993; Imai et al., 1987). The situation changed when in the early 1990ies computers became faster and thus better equipped to process GPR data. This improvement allowed the development of a new set of tools able to collect reflection data as digital files and storing large amounts of data for later processing and analysis. Particularly the work of Dean Goodman led to many important GPR acquisition and data-processing techniques, which included amplitude slice maps, computer-simulated 2D models and 3D reconstructions of buried features (Goodman et al 2006; Goodman and Piro 2013; Novo et al 2013).

State-of-the-art GPR systems and their use in Archaeology

The use of GPR in archaeology has spread slower than other archaeological geophysical prospection techniques such as earth resistance or magnetometry. The reasons for this may relate to the complexity of GPR surveys regarding the operation of the systems and especially the data processing. In the past, these challenges might have led to GPR data being misinterpreted and, in some cases, caused the rejection of the technique altogether (Gustavsen and Stamnes, 2014).

In order to increase efficiency in the field, motorised multichannel GPR systems have been developed by specialised companies allowing rapid surveys with a high spatial sampling density (Fig. 1.8). Power supply, data logging and positioning system are incorporated in the vehicle.

A recent development presents the application of stepped-frequency GPR systems using multichannel antenna arrays of different frequencies which provide both the maintenance of a standard resolution and a greater penetration depth (Linford and Linford, 2010; Soldovieri and Orlando, 2009).



Fig. 1.8 State-of-the-art motorised multichannel GPR array pulled by an ATV

Data processing and interpretation

The processing of GPR data encompasses several stages (Fig. 1.9). Its procedures are more complex and time-intensive compared to the processing of magnetic data. Specifically designed software such as well-known programs GPR slice (<http://www.gpr-survey.com/>), ReflexW (<http://www.sandmeier-geo.de/reflexw.html>) and ApRadar provide a range of tools and filters for data restoration and pre-processing. This stage includes trace interpolation, band-pass frequency filtering, spike removal, dewow filter, average-trace-removal, amplitude gain correction, amplitude balancing and Hilbert transformation in order to eliminate and compensate for errors deriving mainly from signal and positioning deficiencies and rough ground conditions while at the same time enhancing the visibility of archaeological structures and deposits according to the research questions (Leckebusch, 2003a).

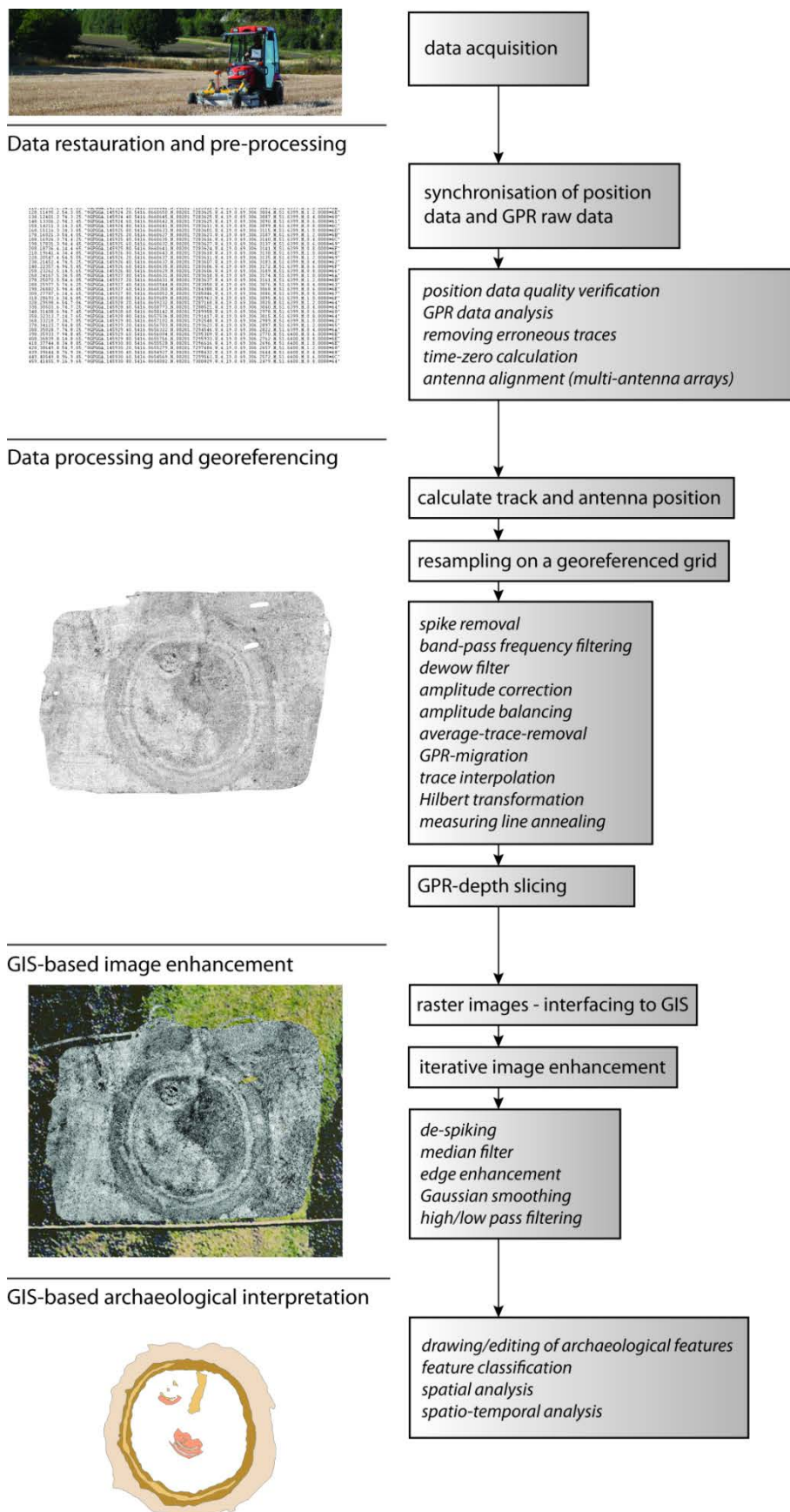


Fig. 1.9 Workflow diagram for GPR data processing and interpretation

The next stage entails the interpolation of reflection traces recorded at each measurement position to form a 3D data volume. These volumes are subsequently cut into horizontal slices in order to visualise reflections occurring at the same planimetric position at a specific time (ns) or depth (m) (Goodman et al., 1995). A conversion of time to depth, however, is only possible, if the velocity of the GPR signal is known. Velocity can be estimated relatively using hyperbolae, common mid-point or move-out analyses. The absolute depth of buried features is dependent on the changing velocity as the signal traverses different media in the subsurface (Dalan et al., 2011). If the surveyed area shows pronounced changes in terrain, GPR data need to be topographically corrected in order to compensate for positioning errors, while the much simpler process of topographic adjustment includes terrain data within the 3D data cube. (Goodman et al., 2006; Leckebusch and Rychener, 2007). Time and depth slices can be visualised as both colour and grey-scale raster images (Fig. 1.10).

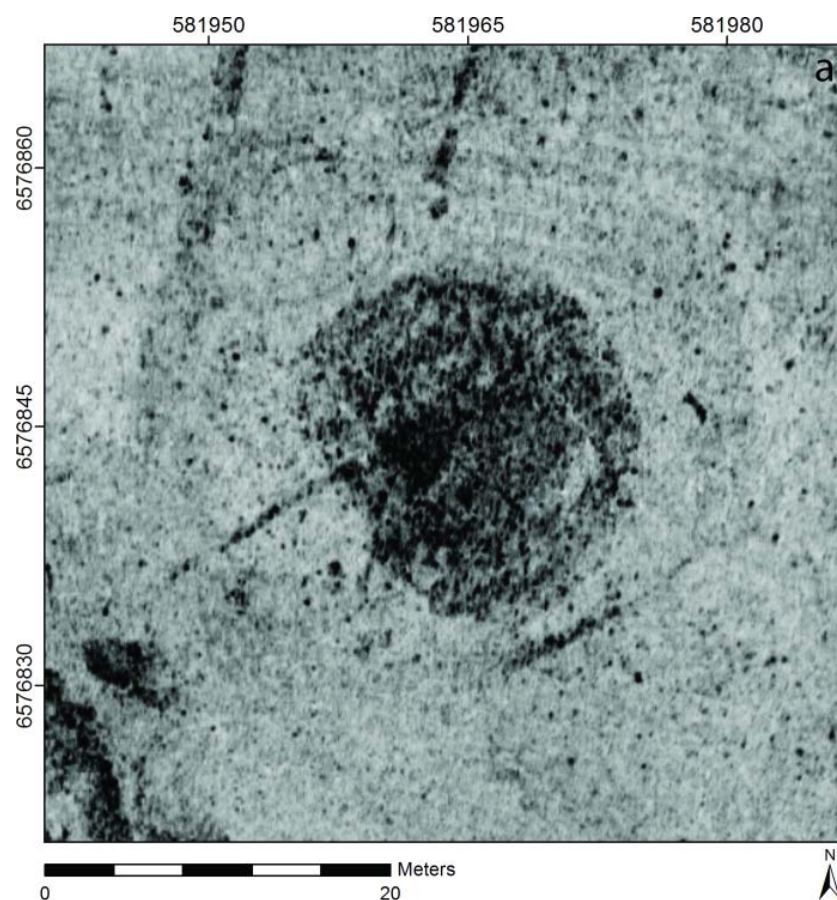


Fig. 1.10 Grey-scale image of GPR depth slice 40-60 cm below ground surface (BGS) of Rom mound. The dark area in the middle of the radargram evidences strong reflections created by a stone packing

Similar to the interpretation of magnetic data, interpretative mapping of GPR data is carried out mostly manually in a GIS environment, at times using semi-automated approaches. There are differences though, based on the particular nature of the two archaeological geophysical prospection techniques. GPR surveys yield three-dimensional data and thus can be analysed in 2D and 3D. Traces, consisting of numerous reflections, are bundled and plotted in a 2D section of the subsurface along the profile measured. Known as radargrams, these sections allow to investigate “the basic raw” reflections (Lawrence B. Conyers, 2015). However, the suitability of radargrams for mapping archaeological structures is limited, thus making time or depth slices the method of choice for the interpretative mapping of GPR data. Yet, time and depth slices still are a two-dimensional representation of an actually three-dimensional data set. In order to exploit their full potential, GPR data require a multi-dimensional analysis approach using individual traces, time or depth slices, volume rendering and integrated iso-surface extraction (see also the 3D visualisation and integration approach presented in chapter IV of this thesis) (Lawrence B Conyers, 2015; Watters, 2009) (Fig. 1.11).

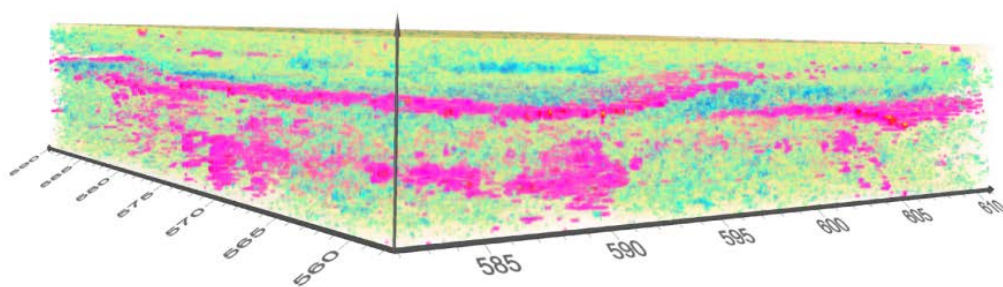


Fig. 1.11 Example of volume-rendered GPR data of a survey area in Jutland, Denmark using Voxler 4. Pink areas illustrate the rolling topography of a dune field

1.5 Large scale-high resolution approach

Within the last few decades, technical developments in the field of archaeological prospection have advanced remarkably. One of the most significant improvements is the motorization of geophysical measurement devices. Today, surveys are increasingly carried out using effective multi-sensor and multi-antenna arrays being towed by either ATV's or off-road vehicles or pushed by mini tractors (Conyers and Leckebusch, 2010; Dabas, 2008; Gaffney, 2008; Gaffney et al., 2012; Gallo et al., 2009; Nau et al., 2015; Neubauer et al., 2011; Schneidhofer et al., 2016; Trinks et al., 2010b). This development has led to the acquisition of ever larger areas in a short amount of time consequently enabling archaeological geophysical prospection on a landscape scale (Linford and Linford, 2010; Trinks et al., 2012) (Fig. 1.12).

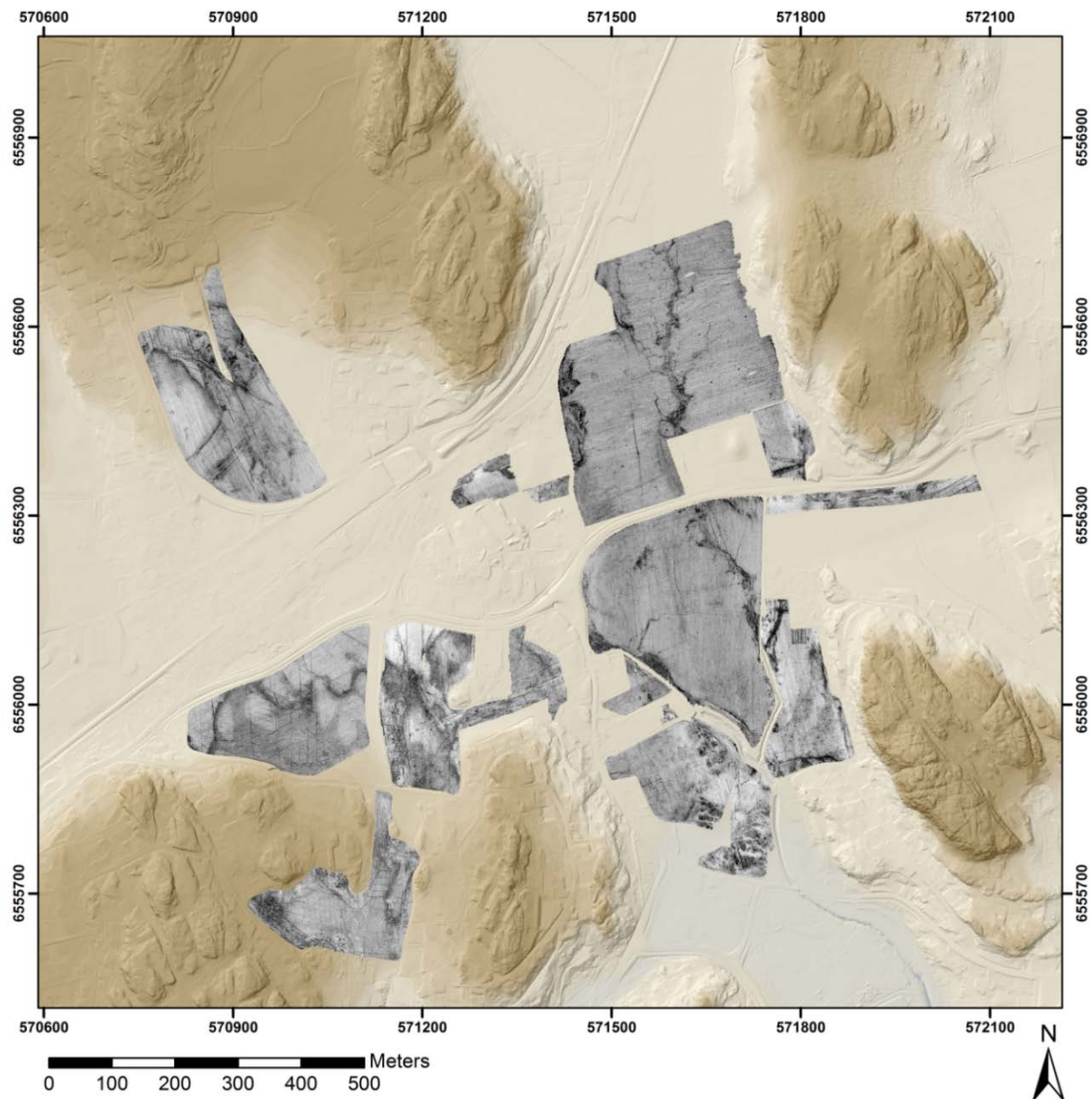


Fig. 1.12 GPR data sets from large scale, high resolution geophysical prospection carried out at Gokstad, Norway

The prospection of large areas, however, has been conducted before, albeit using hand-held systems and hence took years to cover archaeological landscapes (Neubauer et al., 2012; Powlesland et al., 2006). The decisive element of this new approach, thus, is the fact that besides entailing a higher measurement speed, motorization additionally provides high resolution data through the use of multi-sensors and multi-antenna arrays. Naturally, this influences the efficiency of the geophysical surveys: With greater speed, more area can be surveyed in less time while providing high resolution (Neubauer, 2001a).

In order to benefit from this greater efficiency, however, precise and accurate measurement positioning is necessary. Until recently, positioning in archaeological geophysical surveys was conducted using a pre-set grid with data acquisition along parallel profiles – a method still in use when performing a survey using a hand-held measurement system. Motorised systems, in contrast, are based on a grid-free positioning system, which allows a more independent and rapid data collection. Measurement carts are either tracked by a robotic total station or carry a rover antenna mounted on the antenna box as part of a real time kinematic global positioning system (RTK-GPS) (Fig. 1.13). A base station sends real time correction providing centimetre accuracy to the rover. The resulting position data needs then to be synchronised with the raw data of the actual survey, which is achieved using an electric pulse-per-second signal (PPS). This process is complex and presents one of the most challenging tasks in motorized geophysical prospection. However, even though the highest resolution possible is preferable for any prospection survey, appropriate spatial resolution should be chosen dependent on the research question and dimension of expected archaeological features (Conyers and Leckebusch, 2010; Gaffney, 2008; Neubauer, 2001a).

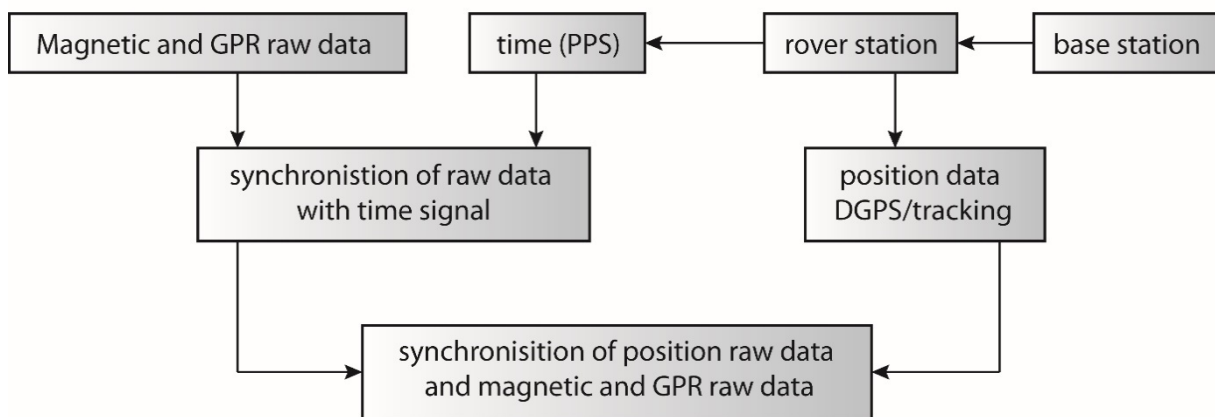


Fig. 1.13 Workflow for grid-free positioning during motorised archaeological geophysical prospection. Modified from Gaffney et al., Figure 1 (2016)

At present, among the most widely used geophysical prospection methods in archaeology are magnetometry and ground penetrating radar. Motorized magnetic systems can carry multiple sensors and cover – depending on the measurement speed – up to 25 ha per day. Measurement speed is based on the ground conditions and the minimum resolution aimed for (Trinks, 2011). Motorised GPR devices are slower, but currently still achieve between five and eight ha per day (Gabler et al., 2013). More detailed information on the particular measurement devices used on the individual case studies will be given in the respective chapters III-VII.

Large scale, high resolution data acquisition produces vast data sets that – in the case of GPR – can quickly reach quantities of up to a terabyte. In order to process data sets of this size, specific soft- and hardware to handle such quantities is required. But it is not just acquisition

and processing of large scale, high resolution geophysical data that demands new strategies. The sheer amount of archaeological structures potentially present in for example several square kilometers of geophysical data necessitates a well-thought-out interpretation approach in order to fully exploit the potential of this data and avoid creating a data tomb. Such an approach must include the storage of data and meta data in a data base. Mapping and interpretation in an integrated GIS environment using complementary data sets as well as additional external data considering environmental settings and excavation data (Fig. 1.14) are essential. In recent years, efforts for semi-automated feature extraction have been undertaken to with varying degrees of success in remote sensing (Lambers and Traviglia, 2016) and archaeological geophysical prospection (Conyers and Leckebusch, 2010; Leckebusch et al., 2008). This endeavor will most likely be further pursued in the years to come.

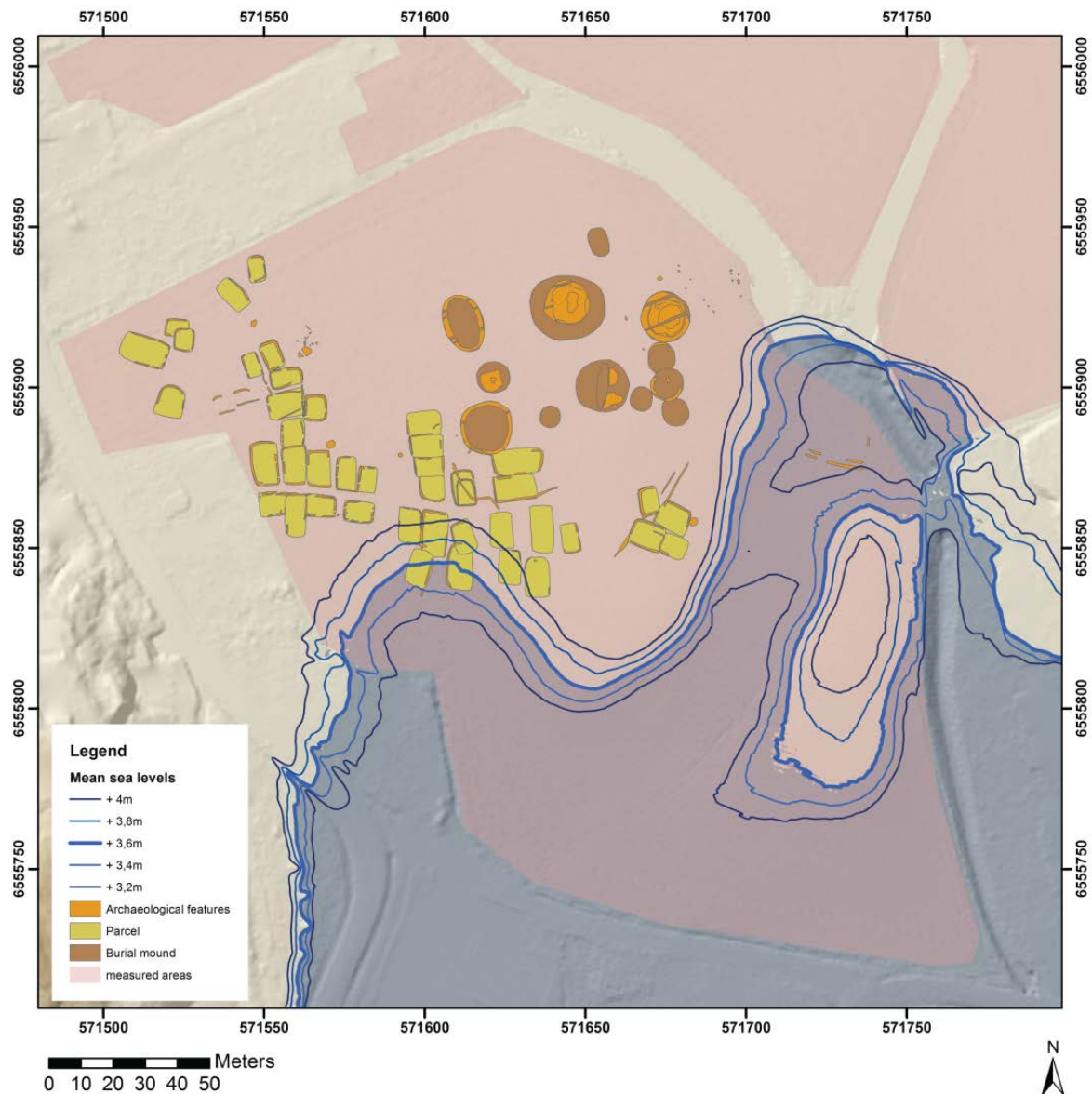


Fig. 1.14 Example of an integrated data interpretation in a GIS environment based on prospection data from *Heimdaljordet* in Gokstad, Norway

Today, studies increasingly focus on archaeological investigations at landscape-scale – not least, because large scale geophysical prospection and remote sensing devices are available, and thus can provide the necessary data sets in order to be able to undertake systematic investigations of this scale (Gaffney et al., 2012; Powlesland et al., 2006). This increased interest in the study of archaeological landscapes naturally also leads to an increased interest for the palaeoenvironmental elements of said landscapes.

Chapter II

2.1 Palaeoenvironmental information

Archaeological geophysical data sets do not just provide information on archaeological remains; they also contain extractable palaeoenvironmental information. If correctly interpreted, structures and patterns originating from natural processes can yield insights into the landscape development.

Typical examples for a palaeoenvironmental structure abundant in geophysical data sets are palaeochannels (Fig. 2.1). These types are often easy to identify and in most cases quite relatable to the archaeological interpretation: Such remnants of former hydrological systems might relate to the choice of settlement locations, subsistence strategies as well as trade routes and transportation (Brown, 1997).

The significance of types such as ice polygon pseudomorphs, root pits, beach deposits or shallow buried bedrock is more subtle and can provide information on past climate, palaeotopography, erosion and accumulation processes and palaeoecology.

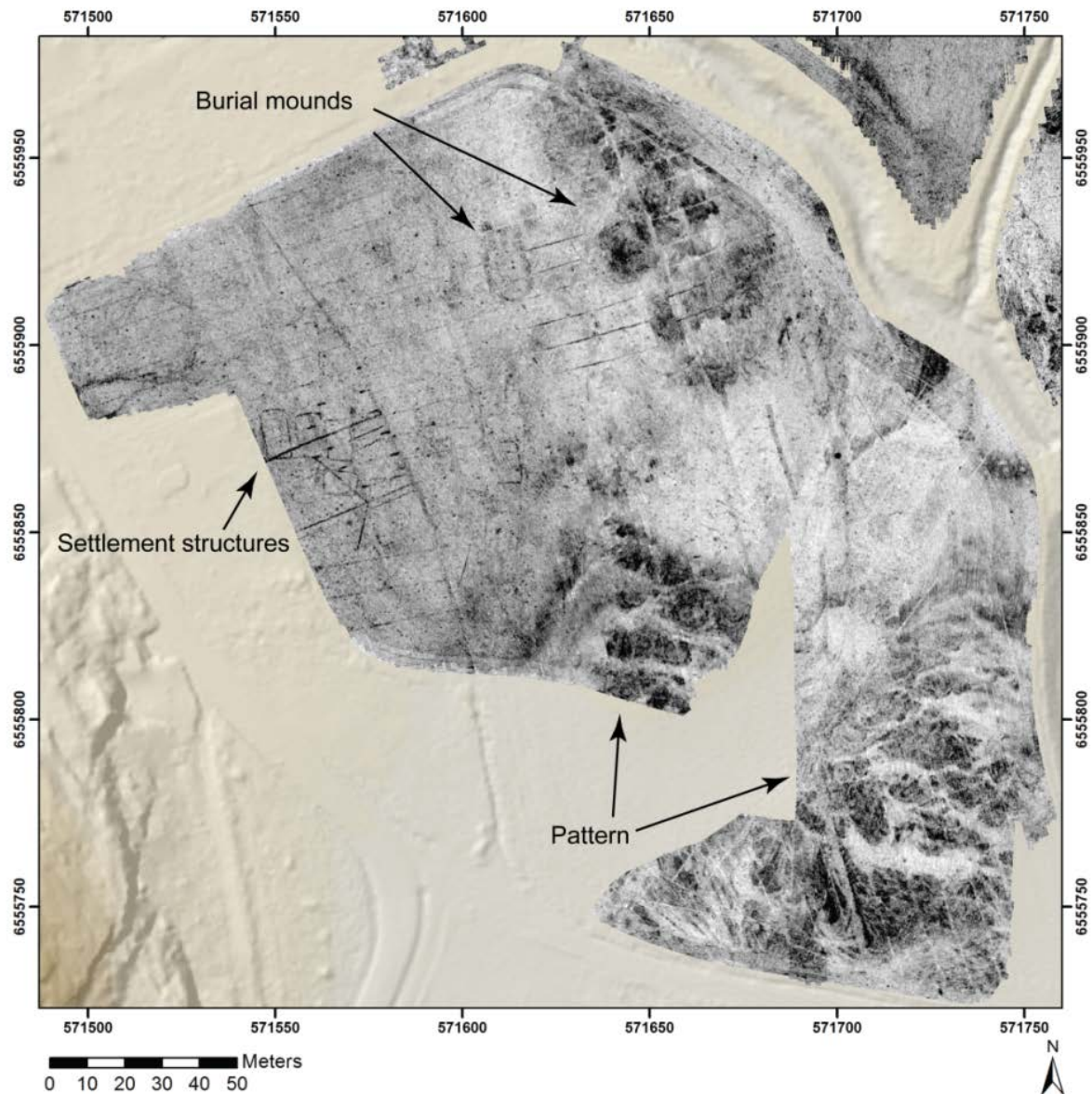


Fig. 2.1 GPR data from *Heimdaljordet* in Gokstad, Norway, demonstrating the presence of palaeoenvironmental structures next to archaeological features. The pattern indicates buried beach deposits (see also chapter III).

Even though the importance to understand the amount of influence palaeoenvironmental information holds on a study area and how this information affects archaeological geophysical prospection is widely accepted, palaeoenvironmental information has been handled differently in studies. While some regarded it as important contribution and included it extensively (Conyers, 1995; Fitch et al. 2005; Gaffney 2008; Leopold et al. 2010; Wegmann et al. 2012), many did not particularly emphasize it.

Investigating archaeological landscapes

For the interpretation of large scale, high resolution archaeological geophysical prospection data, the extraction of palaeoenvironmental information plays a particularly important role (Fig. 2.2). As mentioned before, research in archaeology focuses more and more on the investigation of archaeological landscapes. The concept of archaeological landscapes and the definition of what constitutes an archaeological landscape are still subject to much debate in the archaeological research community. These discussions are fuelled by different research perspectives and concepts of space and at the same time have entailed different approaches in landscape archaeology (Ashmore and Knapp, 1999; Lawrence B Conyers, 2015; Fleming, 2006; Ingold, 1993; Llobera, 2007; Lock and Molyneaux, 2006). Fields such as cultural ecology, historical ecology as well as approaches including site catchment studies and the investigation of micro-landscapes (Kruk 1973) used the term of “archaeological landscapes” as early as the 1970ies (Bintliff, 1992, 1977; Clark, 1989; Higgs, 1975). The concept of landscapes is thereby not confined to the historical disciplines but can also be found in for example geography and ecology. Detailed work about the existing definitions and originations of the concept of the “archaeological landscape” can be found in Heilen (1999), Anschuetz et al. (2001), Heilen (2005) and Hu (2011). In the study presented here, the term “archaeological landscape” is used to describe a study area constituent of cultural and environmental elements, which is investigated for the role these elements played in the way humans interacted with their surroundings (Hu, 2011). People always have been adapting to their environments and exploiting the resources these environments offered, both in terms of subsistence strategies as well as in socio-cultural ways. Thus, understanding palaeoenvironmental systems and relating them to the archaeological information is invaluable in understanding the human past (Butzer, 1982; French, 2002).

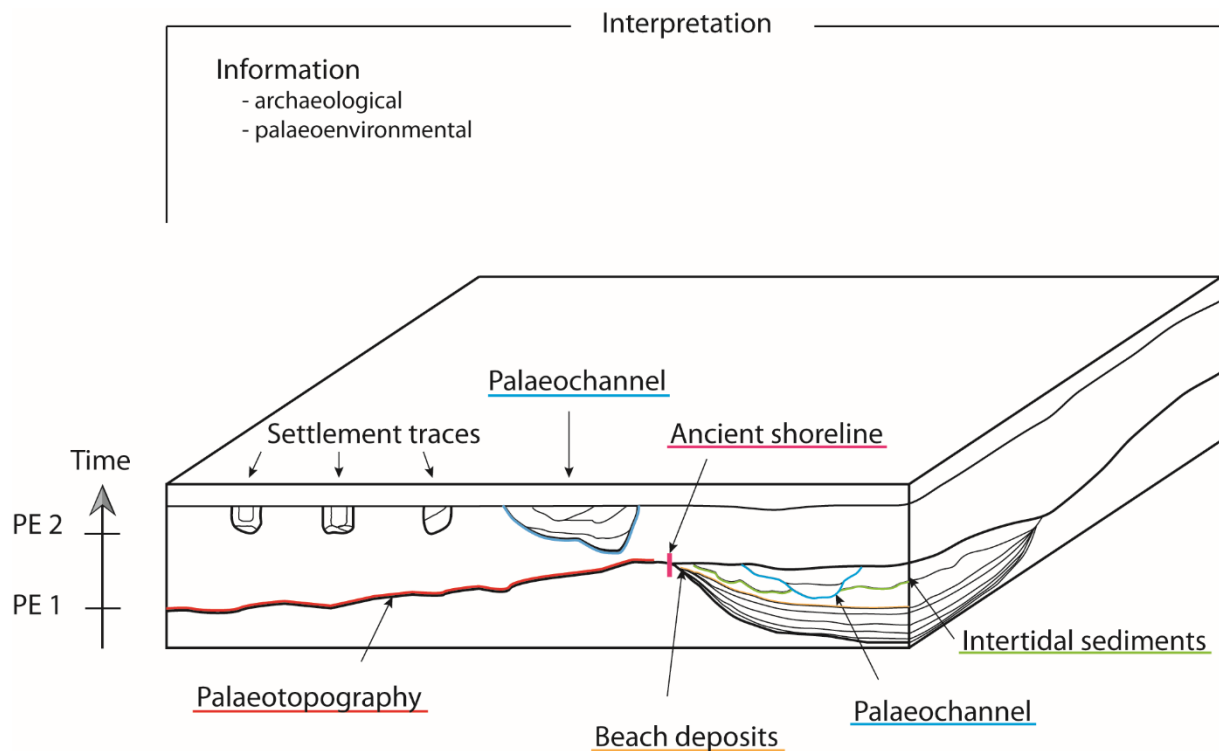


Fig. 2.2 Palaeoenvironmental structures and patterns as contained in archaeological geophysical prospection data are essential in understanding different environments (PE) developed over time.

Among other techniques, large scale, high resolution magnetometry and GPR provide a resourceful data base for these regionally scaled investigations, which – due to their size – tend to include a substantial amount of palaeoenvironmental structures and patterns (Schneidhofer et al., 2016). Even though such structures are also present in smaller scaled surveys, identification and recognition of their significance within the archaeological landscape can be problematic.

The interpretation of an archaeological landscape as defined above based on archaeological prospection data sets, which includes the extraction and use of palaeoenvironmental information, however, requires an encompassing understanding of the prevailing environmental settings and their interaction with each other in any given study area.

2.2. Environmental settings

Different environments are the result of complex and dynamic systems produced by a wide variety of factors that can influence a geophysical prospection survey. This includes the geological history of a survey area, its prevailing sediment/soil types and structures, the type of vegetation present, geomorphological processes, animal activity such as bioturbation, climate, and not least human impact (Grotzinger et al., 2011). The interrelation between these factors turns the considerations of environmental settings in archaeological geophysical prospection into a complex endeavor. An overview over the most important factors will be given below. Physical and chemical processes and their influence on magnetometry and ground penetrating radar surveys are discussed in the respective case studies in chapters V-VII, which focuses on geoarchaeological evaluation of geophysical prospection results.

Environmental factors

Sediments and soils present the most important palaeoenvironmental factors in any archaeological geophysical survey. Their relevant physical and electromagnetic properties determine the degree of contrast in relation to the targeted archaeological features that is so vital to the success of every prospection method.

Sediments are divided into clastic, biogenic and chemical types based on the processes involved in their formation. Clastic sediments are defined as rock and mineral material broken down by weathering and subsequently transported by wind, water, ice or gravity. These different modes of transportation can be further classified into for example (river), lacustrine (lake), marine (sea), aeolian (wind) or glacial (ice). Clastic sediments are further classified by their grain sizes and/or mineralogical composition.

Soils, in contrast, are the product of weathering and different interacting soil forming factors in the course of time including climate, relief, organisms and available parent material. Chemical and mineralogical composition of the parent material, which can be either bedrock or sediment, is primarily responsible for the formation of specific soil types with typical characteristics (Grotzinger et al., 2011). Soils largely constitute of rock fragments, minerals,

organic matter, organisms, gases and liquids. Physical properties such as texture, structure, chemical and mineralogical composition, density, porosity, color as well as individual soil horizons aid in determining between different soil types (Blume et al., 2010; Gupta et al., 2008) and dictate the response of certain soil types to individual geophysical techniques (see below).

The geomorphological properties of a study area play another significant factor in archaeological geophysical prospection. Geomorphology studies the classification and formation of different landforms and the processes that create them in the course of time (Cordova, 2017). A thorough understanding of the geomorphological processes active in a study area is central to correctly identifying and interpreting palaeoenvironmental as well as archaeological information contained in geophysical data sets. These processes operate on different spatial and temporal scales. Good examples for continental processes spanning tens of thousands of years are glaciation/de-glaciation during the Quaternary. Fluvial processes might alter terrain on a continental to regional level, while some erosion and accumulation activities such as landslides and mass movements can occur during relatively short-lived events in the range of days to month while modifying the landscape only on a local scale (Grotzinger et al., 2011).

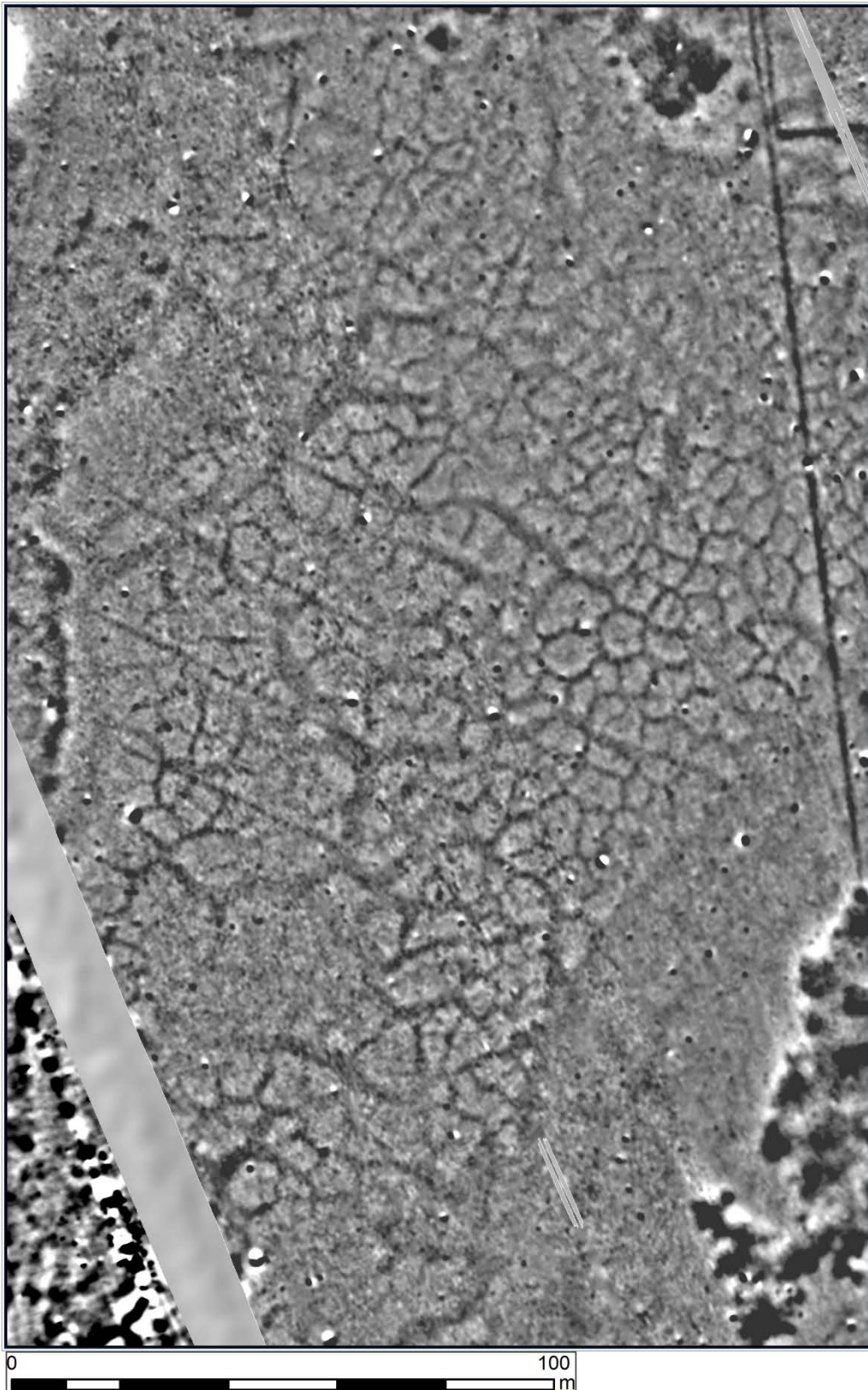


Fig. 2.3 Periglacial features known as ice polygons pseudomorphs become clearly visible in magnetic data sets from the Roman site Carnuntum in Austria. ArchPro Carnuntum/Mario Wallner

Climate presents another palaeoenvironmental factor significant for archaeological geophysical prospection and is largely controlled by longer-term changes of atmospheric conditions. It is determined by monitoring a range of meteorological variables including temperature, humidity, wind, precipitation and atmospheric pressure over a certain period of time – usually 30 years. Weather, in contrast, considers the same variables over a shorter amount of time within a smaller spatial context (Grotzinger et al., 2011). As described above, climate plays a significant role in the development of soils and the distribution of sediments in a given area. On an interpretative level, climate is also partly responsible for the formation of structures such as periglacial features (Fig. 2.3).

On a technical level, obviously, the vegetation cover of a study area influences the choice of survey design. Densely forested areas generally complicate the conduction of archaeological geophysical surveys or – when it comes to motorized approaches – often render them impossible, mainly due to issue regarding accurate positioning. Furthermore, vegetation cover affects the soil and can alter its physico-chemical parameters such as pH, water content and bulk soil chemistry, which are significant for geophysical techniques (see below) (McBride 1994, Gurevitch et al. 2006). Vegetation cover is also an important factor regarding stratification as it can prevent or at least limit erosional processes. However, areas thickly permeated by for example tree roots can negatively affect the outcome of a geophysical survey.

Besides palaeoenvironmental factors, human activities naturally present a considerable factor in the shaping and development of an archaeological landscape and thus are of significance for geophysical prospection surveys. Past and present agricultural use is the most accounted for human activity and is significant for geophysical prospection at all three levels. Especially modern farming methods contribute extensively toward destruction of archaeological and palaeoenvironmental information. Plowing actively damages the upper part of the soil and with it any archaeological and palaeoenvironmental structures. Subsequent erosion contributes to this process. Local and regional scaled drainage systems can prompt a change in the physical properties of soils and sediments and influence preservation and detectability of features. Pasture impacts vegetation type and growth and influences the physic-chemical properties of soils and sediments. These factors are especially

important when it comes to a qualitative assessment of the archaeological geophysical prospection data (see below).

Physical and chemical processes

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 dependent on sufficient measureable contrast between these structures and the surrounding material (Linford, 2006; Scollar et al., 1990). If this contrast is not adequately pronounced, because physical properties of archaeologically relevant features are almost identical to those of the surrounding matrix, archaeological information will remain undetected (Neubauer, 2001b).

Physical properties and in particular the electromagnetic properties, in turn, are influenced by various physical and chemical processes in the subsurface materials. Different geophysical prospection techniques, such as GPR and magnetometry, are influenced by 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 by the magnetic permeability of the medium it traverses. The radar wave is thereby reflected at the interface of two superimposed layers showing different physical properties – soils and sediments, bedrock, rocks, building material or organic matter. The reflection amplitude, however, does not actually present a measurement of the physical properties of these different materials, but indicates the degree of difference between two adjacent units (Conyers 2004). These primary parameters and their interactions with the transmitted electromagnetic pulse have been discussed and addressed in detail by a range of authors (Cassidy, 2008a; Conyers, 2013; Goodman and Piro, 2013; Leckebusch, 2003b; Scollar et al., 1990; Verdonck, 2012). Dielectric permittivity thereby “describes the ability of a material to store and release EM energy in the form of electric charge” (Cassidy, 2008b). It is usually expressed dimensionless (ϵ_r) as the ratio (ϵ/ϵ_0) between the permittivity of a material (ϵ) relative to the permittivity of vacuum (ϵ_0). In most low-loss materials investigated using electromagnetic pulses with a mean frequency between 10 and 1000 MHz, dielectric permittivity is greatly controlled by free and bound

water (Cassidy, 2008b). The reason for this is the notable difference in the dielectric permittivity values of air (ca. $1 \epsilon_r$), freshwater (ca. $80 \epsilon_r$) and mineral constituents (ca. $3-8 \epsilon_r$), which form major components of mineral soils and sediments (Annan, 2008; Cassidy, 2008a; Scollar et al., 1990; Visconti et al., 2014). Naturally, the amount of water present in any subsurface material depends on environmental factors such as climate as well as local weather conditions before and during a geophysical survey (Grotzinger *et al.* 2008). It is also dependent, however, on the hydraulic conductivity, which characterises how free water moves through soils and sediments based on their permeability and saturation.

Permeability, in turn, relates to grain size distribution, compaction, cementation, porosity and structure of pore space, as well as relative abundance of liquid and gas phases. Pore space is measured by the porosity of a soil as a volume or in per cent (Blume et al., 2010). Water content is also connected to the electrical conductivity of a material. If rich in soluble salts such as ions Na^+ , K^+ , Ca^{2+} , Mg^{2+} and Cl^- , electrical conductivity will increase upon increasing water content (Shi and Wang, 2005). This can ultimately result in attenuation of an electromagnetic signal and its dissipation in moist materials before reaching features of archaeological interest (Leckebusch 2003). Bound water, on the other hand, refers to water adsorbed onto the surfaces of clay particles based on a difference in electric charges. Due to the larger surfaces of the clay particles and the smaller pores, clay-rich sediments and soils retain more water than coarser grained materials and subsequently have a different dielectric permittivity leading to different reflection properties.

Not just the strength of the reflection, but also the propagation velocity of the electromagnetic radar wave and its reflection pattern depend on these changes in physical and chemical properties of the subsurface material. Mineral composition, variations in water content and salinity as well as changes in bulk density of superimposed layers all contribute to reflection, attenuation or absorption of the initial radar signal (Van Dam & Schlager 2002; Leckebusch 2003). Magnetic permeability needs to be considered since the carrier wave on which the signal travels is *electromagnetic* (Van Dam & Schlager 2000). However, it usually is thought 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 2009a).

The situation is different with magnetometry which aims to detect local variations in the Earth's magnetic field. These variations originate from subsurface materials showing contrasting magnetic properties caused by either magnetic remanence or induced magnetisation. Induced magnetisation describes the degree, to which a material can be magnetized when exposed to an external magnetic field (Rinita A. Dalan, 2006; Fassbinder, 2015; Neubauer, 2001a; Scollar et al., 1990). Magnetic remanence, in contrast, describes the magnetisation of a material once the magnetic field is removed, for instance thermo-remanent magnetization. Magnetic surveys measure the combined "net effect" (Rinita A. Dalan, 2006). While the estimation of remanent magnetisation is a rather cost- and time intensive process, requiring a laboratory environment (Evans and Heller, 2003), induced magnetisation or MS, in contrast, can quickly and relatively cheaply be measured *in-situ* as well as in a laboratory (Dearing, 1994) (Dalan & Banerjee 1998, Tite & Mullins 1971) provided that subsurface materials are accessible.

Magnetic properties of soils depend on mineralogical composition and grain size of different iron compounds, which are naturally determined by parent material as well as effects of weathering and pedogenesis (DeJong *et al.* 2005). In simple terms, iron oxides typically present the main contributors in well drained soils, whereas waterlogged soils often are dominated by iron sulphides. (Tite & Mullins 1971) (for more details on magnetic enhancement and depletion processes in subsurface materials, see chapter 5.7.)

The soil type and its characteristic properties concerning redox processes, water saturation and mineralogical and chemical composition are relevant for magnetic surveys, since these processes can lead to dilution or loss of iron oxides and a very weak magnetization of archaeological features and/or leveling of the contrast between magnetic anomalies and surrounding material.

The main contribution to MS in soils or sediments, even if only present in low quantities, derives from ferrimagnetic minerals, such as magnetite (Fe_3O_4) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) (Maher 1998), in some cases also pyrrhotite (Fe_{1-x}S ($x = 0$ to 0.2)) (Mullins 1977) and greigite (Fe_3S_4) (Stanjek et al. 1994) (Fassbinder, 1994; Van Dam et al., 2004) and thus can provide basic insights into magnetic mineral composition, indicate different anthropogenic and palaeoenvironmental processes and plays a key element in magnetic modelling (Dalan and Banerjee, 1998; J. A. Dearing et al., 1996; Evans and Heller, 2003; Fassbinder, 1994; Maher,

1998, 1986; Neubauer, 2001b). If soils are poor in ferrimagnetic minerals, they usually show low MS values caused by weakly magnetised components, such as clays enriched in Fe, or iron oxides containing mostly Fe^{3+} bearing oxides, such as haematite (Fe_2O_3), goethite ($\alpha\text{-Fe}^{3+}\text{O}(\text{OH})$), ferrihydrite ($\text{Fe}_2\text{O}_3 \cdot 0.5\text{H}_2\text{O}/\text{Fe}_2\text{O}_3 \cdot 1.4\text{H}_2\text{O}$) and lepidocrite ($\gamma\text{-FeO}(\text{OH})$) (Maher 1988). For ferrimagnetic conversion, however Fe^{2+} is required (Maher 1998).

The MS within a soil profile is decreasing vertically, with most soils showing an accumulation of ferrimagnetic minerals in the topsoil (LeBorgne 1955, 1960a, 1960b). This vertical decrease is caused by complex and partially counter-acting processes, such as the *in-situ* formation of iron minerals, their transport and dissolution, as well as the weathering input on iron to form either ferric or non-ferric minerals (Maher 1988). In terms of archaeology, human-induced processes, such as burning activities (hearth fires, ovens, clay-fired bricks and ceramics) enhance the magnetic remanence of subsurface materials, which consequently also adds to the degree of magnetisability of these materials (Le Borgne 1955) making such processes significant for the detection of archaeological remains.

Environmental settings and geophysical prospection

As mentioned above, most archaeological geophysical prospection surveys need to consider environmental settings out of necessity. Basic knowledge of the study area's topography, ground conditions, past and current status of vegetation growth as well as insights into soil type and local geology is required when planning the technical aspects of a survey (David et al., 2008). These parameters will ultimately influence the choice of techniques, and consequently specify types of sensors including their precision as well as lateral and vertical resolution, penetration depth in connection with expected depth of targets and the size of the predicted archaeological features (Gaffney, 2008; Jordan, 2009; Linford, 2006). Since these considerations will affect survey design, naturally this must happen in preparation of and in some cases during the survey to adapt to a change in conditions (Fig. 2.4).

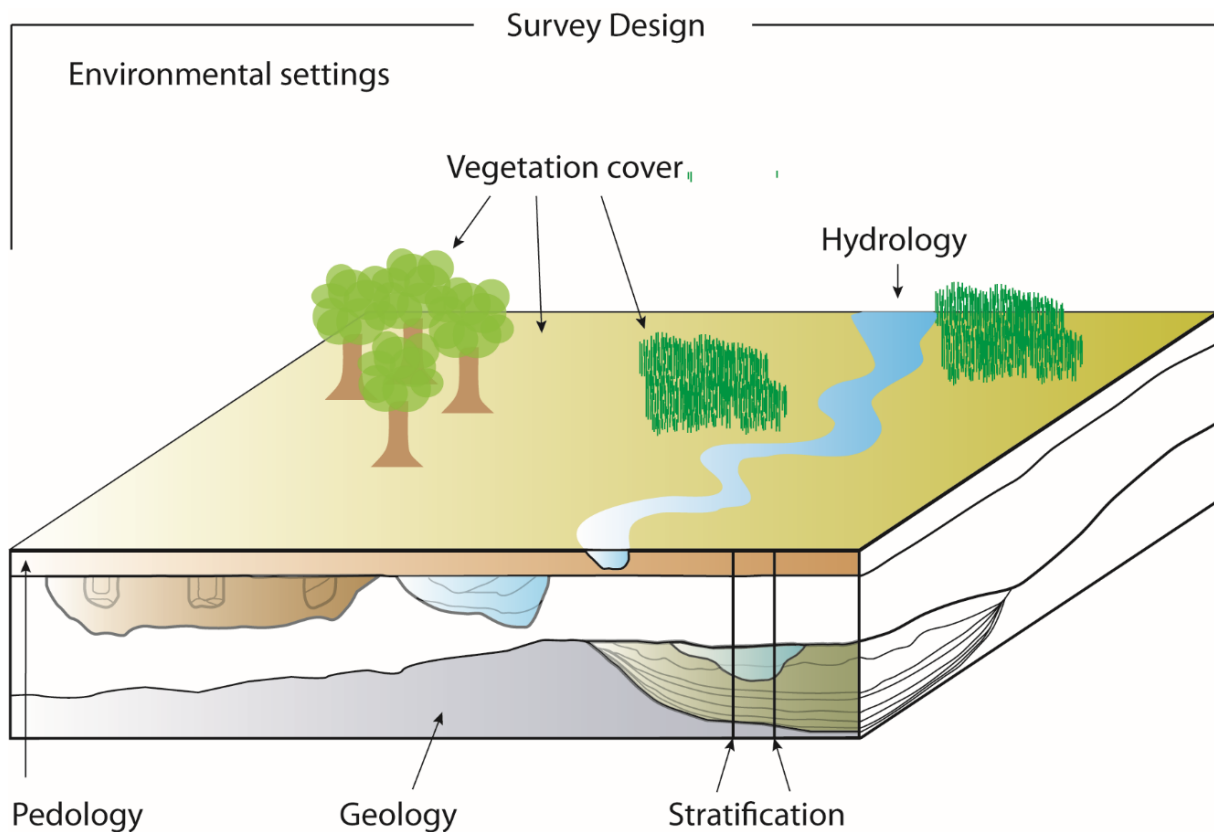


Fig. 2.4 Environmental settings are significant for planning and design of archaeological geophysical prospection surveys

Environmental settings such as steep terrain or forested areas obviously limit the choice of methods. However, more detailed preliminary investigations of soil and sediment type present, expectable stratification and/or erosion and accumulation zones are necessary to fully factor in the influence of environmental settings into survey design and measurement approach (Fig. 2.5). This influence is for example evidenced by the dynamic processes of dilution and loss of iron oxide concentrations in water-saturated and periodically water saturated soils and sediments which can lead to low magnetic contrast (Fig. 2.6) (Kattenberg and Aalbersberg, 2004). Moist, fine grained earth material usually results in increased electromagnetic signal attenuation and subsequently to a lower penetration depth in GPR surveys (Cassidy, 2008b).



Fig. 2.5 Influence of environmental information on a technical level. Persistent precipitation softens the ground and leads to small-scale flooding.

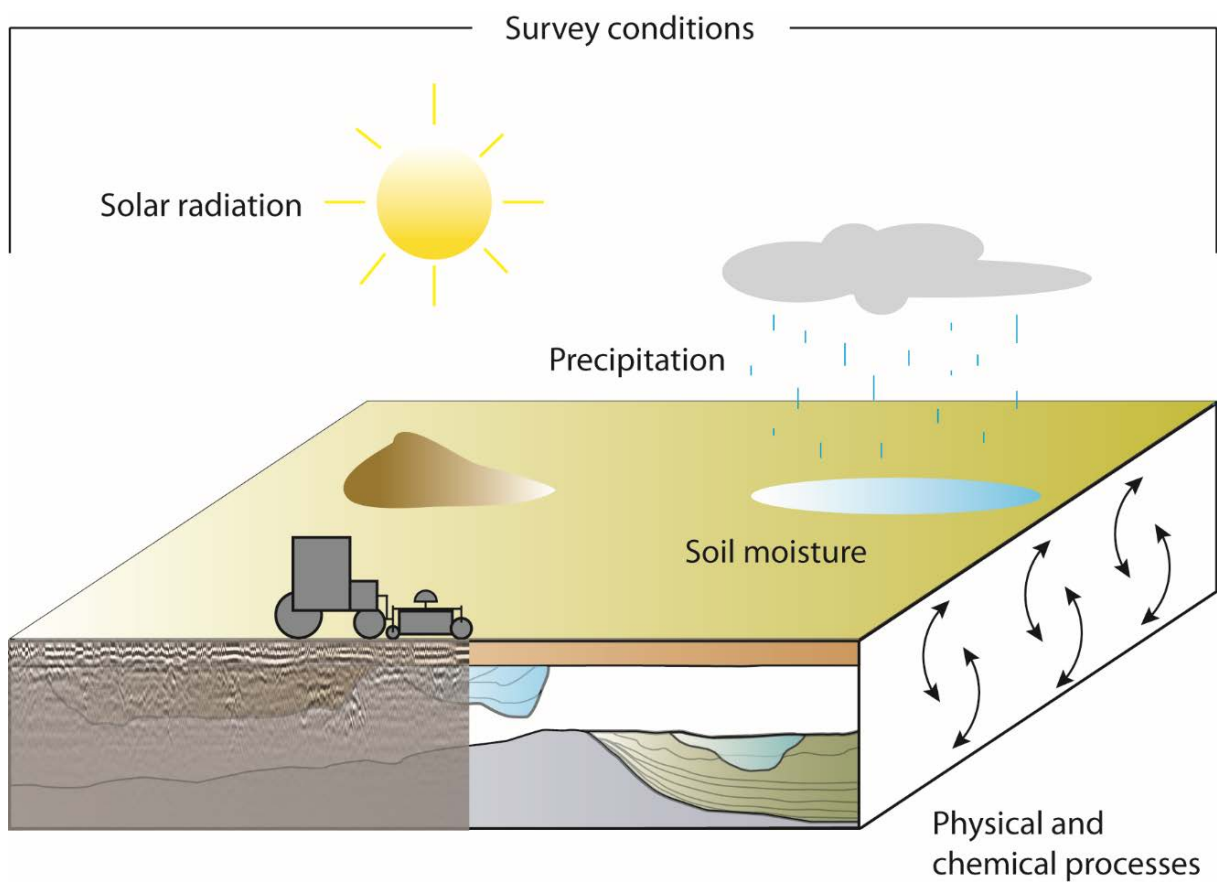


Fig. 2.6 Environmental factors such as local weather around the time of data acquisition, as well as physical and chemical processes in the subsurface materials are influencing the outcome of an archaeological geophysical prospection survey

Closely linked to the technical level is the consideration of environmental settings on a qualitative level. Qualitative in this respect relates to questions of reliability and accuracy regarding the archaeological interpretation of geophysical data and is most apparent by the following example: Many archaeological geophysical data sets show areas void of any archaeological structures, where sensors did not record a significant difference in the physical properties of the subsurface materials. Typically, these areas are simply interpreted as “free of archaeology” and not further considered (Fig. 2.7). From a qualitative perspective, however, such areas might only appear to be empty for one of the following reasons: archaeological features could be buried beneath colluvium and therefore situated beyond penetration depth or sensor sensitivity. Alternatively, archaeological features might have been destroyed by erosional processes. And finally, features might be undetectable due to insufficient contrast between the physical properties of archaeological structures and surrounding earth materials.

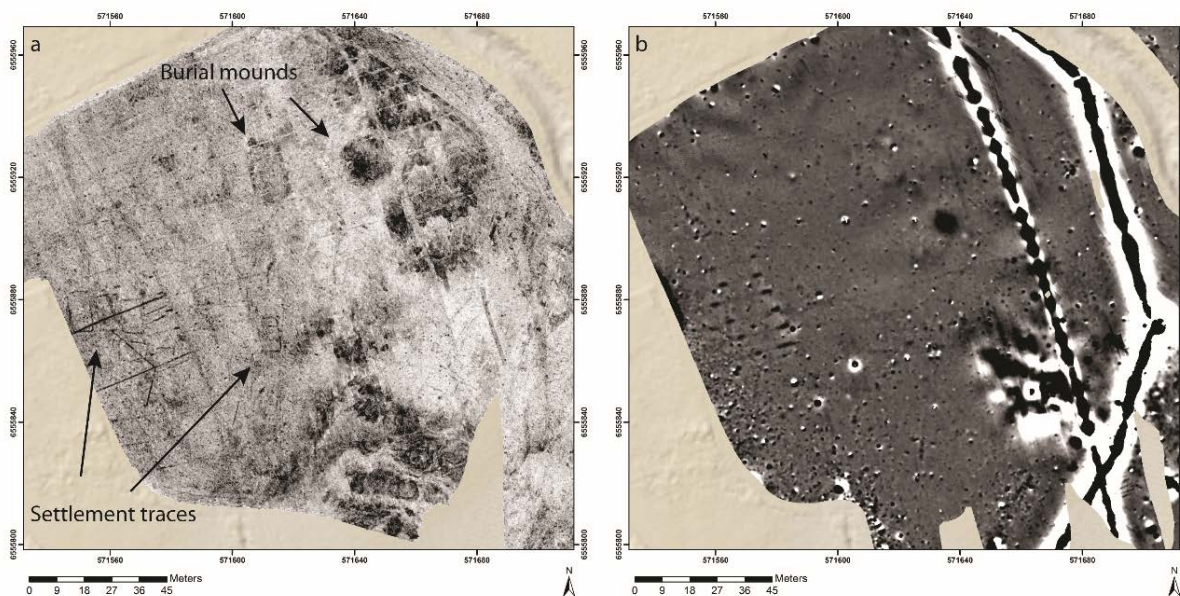


Fig. 2.7a GPR data (40-45 cm BGS) of *Heimdaljordet* in Gokstad showing settlement traces and burial mounds. 2.7b Note the absence of these archaeological features in the corresponding magnetic data

While these considerations are not new and might be incorporated into an experienced interpreter's analysis, they are rarely ever explicitly stated in reports and studies let alone further investigated. Unfortunately, this leads to perceiving geophysical data sets and the resulting interpretation maps as an accurate depiction of the subsurface – a fact that is particularly problematic for archaeologists not familiar with the analysis of geophysical data. To disregard the qualitative aspects of geophysical survey data can impede attempts of implementing geophysical prospection firmly into heritage management as here, accuracy of the interpretation is of utmost importance. This issue only intensifies when dealing with large scale data sets, which cover vast areas and therefore potentially include a wider variety of different and changing environmental settings.

2.2. Case study areas

The thesis includes three different case study areas including Gokstad, Kaupang and Oseberg/Slagendalen, which are all located in Vestfold County, Norway (Fig. 2.8).



Fig. 2.8 Topographic map displaying the location of Vestfold County and the three case study areas Gokstad, Oseberg/Slagendalen and Kaupang in Norway, ca. 40 km southwest of the capital Oslo.

Basemap: © kartverket www.kartverket.no

2.2.1 The Vestfold Project

Vestfold is the smallest of Norway's 19 counties and situated approximately 40 km southwest of Oslo, on the western side of the Oslo fjord, a (Fig. 2.8). Vestfold is densely populated and, due to its better climatic and soil conditions compared with the northern counties, is to a large part used for agriculture. Consequently, extensive parts of Vestfold constitute of developed areas or farmed land (Fig. 2.9), in contrast to the counties inland and in the north, which are characterized by mountainous regions or are densely forested. As a result, Vestfold is well suited for large scale, motorized archaeological geophysical prospection.



Fig. 2.9 Aerial orthophoto (2011, basis: Norge I Bilder, Nowegian Map authorities, Geovekst and Municipalities, resolution 10 cm) of the case study area Gokstad gives a good impression of the densely populated Vestfold County. Increasing urban development necessitates suitable heritage management strategies

Archaeological geophysical prospection experienced a rather difficult start since first introduced to Norway in 1968 with the numbers of surveys considerably increasing since early 2000 (Fig. 2.10). Factors responsible for this trend include a lack of complementary survey approaches using more than one technique as well as often poor quality data acquisition and processing routines (Gustavsen and Stamnes, 2014). The main element

complicating archaeological geophysical prospection in Norway, however, seems to be the challenging environmental settings that prevail in this country.

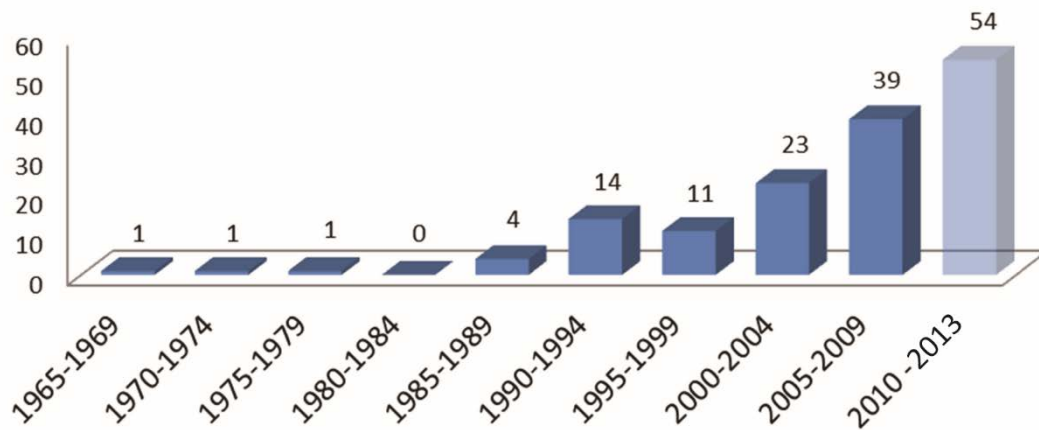


Fig. 2.10 Bar diagram illustrating the increasing use of geophysical prospection in Norway since the 1990ies. Modified from Gustavsen & Stamnes (2014)

Geologically, Norway is dominated by the Caledonian orogeny and was shaped strongly by Quaternary glaciations and de-glaciation as well as – in the most recent history – by retreating sea-levels based on post-glacial rebound processes. During the Last Glacial Maximum (LGM), which ended around 19000 BP, when a third of the northern hemisphere was covered by thick ice-shields, the landmasses were pressed down into the crust by the weight of the ice. When the glaciers started to melt, this weight slowly lifted causing the landmasses to rebound, which led to a sea-level retreat. This process is still on-going today, at decreasing rates (Draganits et al., 2015) (Fig. 2.11). As a consequence, areas in Vestfold are covered by sediments providing unfavorable conditions for magnetometry and GPR surveys including fine-grained sediments and very heterogeneously mixed soils. Additionally, the bedrock in the area of Vestfold was formed by volcanic processes resulting in the formation of mostly igneous rock – a challenge for magnetic surveys. Apart from environmental settings, modern disturbance in the form of dense drainage systems, installed

to enhance the quality of the often wet soils, poses another challenge for archaeological geophysical prospection in Vestfold.



Fig. 2.11 On-going sea-level retreat in the south of Norway. Location of the Younger Dryas Ra moraine in orange. Blue isolines represent current crustal uplift rates in mm/year - based on (Dehls et al., 2000) - resulting from postglacial rebound (from Draganits et al 2015)

This was the initial situation, when in 2010 the LBI ArchPro teamed up with its Norwegian partners, the Norwegian Institute for Cultural Heritage Research (NIKU) and the Vestfold fylkeskommune county Archaeology (Vfk) to start the Vestfold Project (<http://lbi-archpro.org/cs/vestfold/index.html>).

The aim of this project was twofold: First, to adapt to and successfully apply large scale, high resolution archaeological geophysical prospection in Norway despite the challenging environmental settings. Second, to investigate prominent Iron Age and Viking Age sites in Vestfold on a landscape scale including Gokstad (Nicolaysen, 1882) and Oseberg/Slagendalen (Gansum, 1995), Kaupang and its hinterland as well as Borre (Myhre, 1992; Nicolaysen, 1854) based on the newly acquired large scale, high resolution geophysical data. This was particularly important due to ongoing threats through extended infrastructure and development work in this highly populated part of Norway. Ultimately, both aims should contribute to establish the method of large scale, high resolution archaeological geophysical prospection for the systematic use in archaeological heritage management. Surveys started in 2011 and comprised motorised high resolution magnetic multi-sensor and multi antenna GPR surveys. The high resolution of these measurement instruments ensured an outstanding level of detail visible in the subsurface images and thus enabled a comprehensive analysis and interpretation of the prospection results.

In the following sections, the case study areas Gokstad, Oseberg/Slagendalen and Kaupang will be presented together with an overview on their archeological history and significance in the Iron and particularly in the Viking Age. More detailed information of relevant local environmental settings will also be given in the respective chapters.

2.2.2. Gokstad

The archaeological site of Gokstad includes one of the most prominent Viking Age ship burials of Norway: the Gokstad mound. The mound showed a height of up to 6 m, a diameter of ca. 50 m while covering roughly 4200 m². It was excavated in 1880 by Nicolay Nicolaysen and revealed a remarkably well-preserved ship (Nicolaysen, 1882) (Fig. 2.12). The

burial is dated using dendrochronology to around 900-905 AD (Bonde and Christensen, 1993) and included a very tall ca. 40 year old male displaying an abnormal physique. Based on the ship as well as the extraordinary grave goods, which included rare import goods, the buried man is assumed to have been of high social status. The Gokstad ship itself was designed for voyages on high-sea and built around ten years before it was buried. The vessel is 23.5m long, 5.2 m wide and designed for 16 oarsmen on each side. The structure of the mound included a trench dug into anaerobic marine sediments, in which the ship was placed and covered by moss, bundles of hazel and clay mixed with sand. These materials provided excellent preservation conditions for the organic materials of which the ship and many of the grave goods were built. Still during the Viking Age around ca. 935 AD, the Gokstad ship burial was reopened and looted – an event not uncommon during the Viking Age and evidenced for similar burials such as the Oseberg ship burial in Slagendalen (see below). After a second excavation in 1905, the remains of the Gokstad man were reburied and the mound was eventually reconstructed in 1929 and made publicly available. In 2007, the grave was re-opened once more and the human remains recovered for further scientific analyses (Museum of Cultural History Oslo, 2016a; Nicolaysen, 1882).



Fig. 2.12 Excavation of the Gokstad ship burial in 1880. Public Domain, Wikipedia/www.gaia.no

Until very recently, archaeological findings were sparse in the landscape surrounding the grave monument, limited to a Bronze Age causeway (Skjelsvik et al., 1958), few further burial mounds and archaeological traces found in the nearby area *Heimdaljordet*, some 500 m to the south of the Gokstad mound (Gansum, 1997; Hinsch, 1945) (Fig. 2.13).

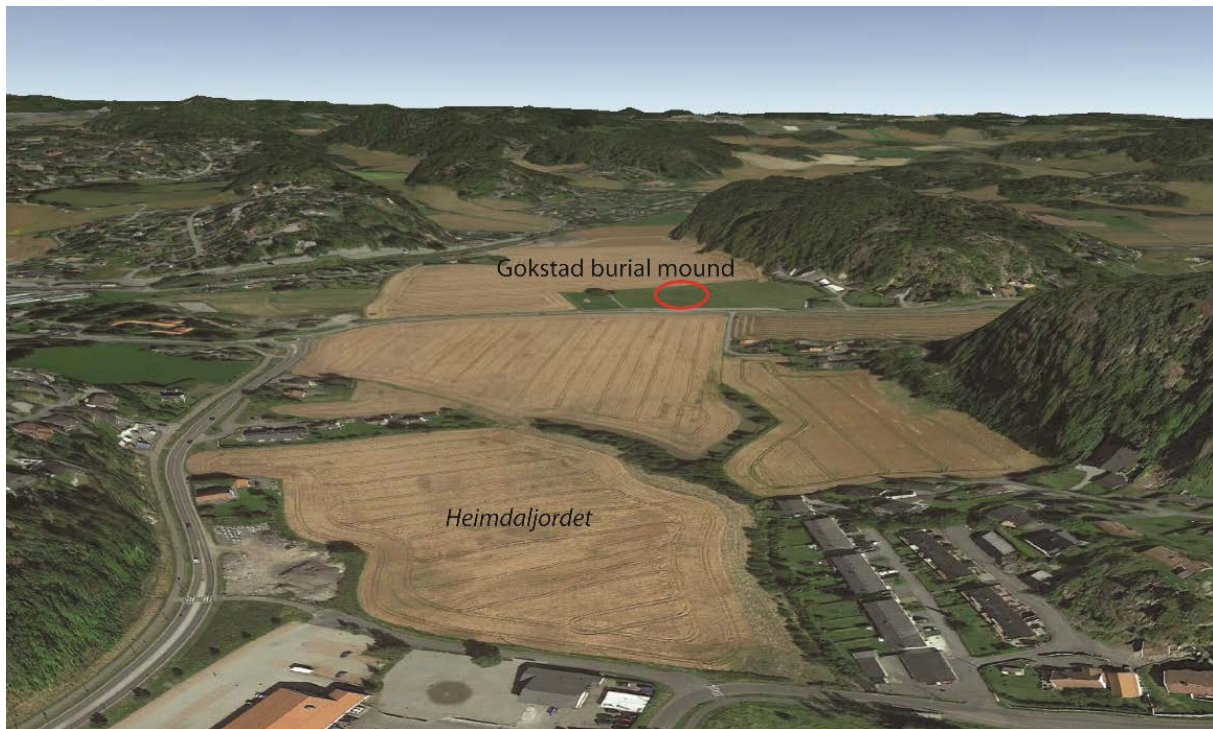


Fig. 2.13 Landscape around Gokstad with the field *Heimdaljordet* in the front and the Gokstad mound encircled in the back. View towards north. Source: Google Earth. September 09, 2015. Accessed February 26, 2017

In order to learn more about the context in which the burial mound once was set, the *Gokstad revitalized project*¹ was initiated in 2009 by the Museum of Cultural History (MCH) Oslo. The project's interdisciplinary research agenda comprised a variety of fields, including anthropology, geoarchaeology and history. In September 2011, a first campaign of archaeological geophysical surveys was carried out jointly by ZAMG, NIKU, Vfk and the Vienna Institute for Archaeological Science (VIAS). This eventually led two additional campaigns conducted by the LBI Archpro, Vfk and NIKU in 2012 again using motorized magnetometry and GPR in a wider survey area surrounding the Gokstad ship burial.

The aim of these large scale, high resolution prospection surveys was to produce detailed subsurface maps of the accessible area surrounding the Gokstad mound and to search for further buried archaeological remains. Of particular importance was the area at *Heimdaljordet*, where top soil stripping during rescue excavations in 1996 had revealed potential settlement traces (Gansum, 1997). Surveys were carried out in two campaigns in

¹ <http://www.khm.uio.no/english/research/projects/gokstad>

April/Mai and September 2012 (Fig. 2.14 and 2.15). This approach proved successful and yielded a detailed map of the settlement at *Heimdaljordet*, a number of newly discovered burial mounds south and west of the Gokstad mound as well as few settlement structures on the slope areas (Bill and Rødstrud 2013; Nau et al. 2015).

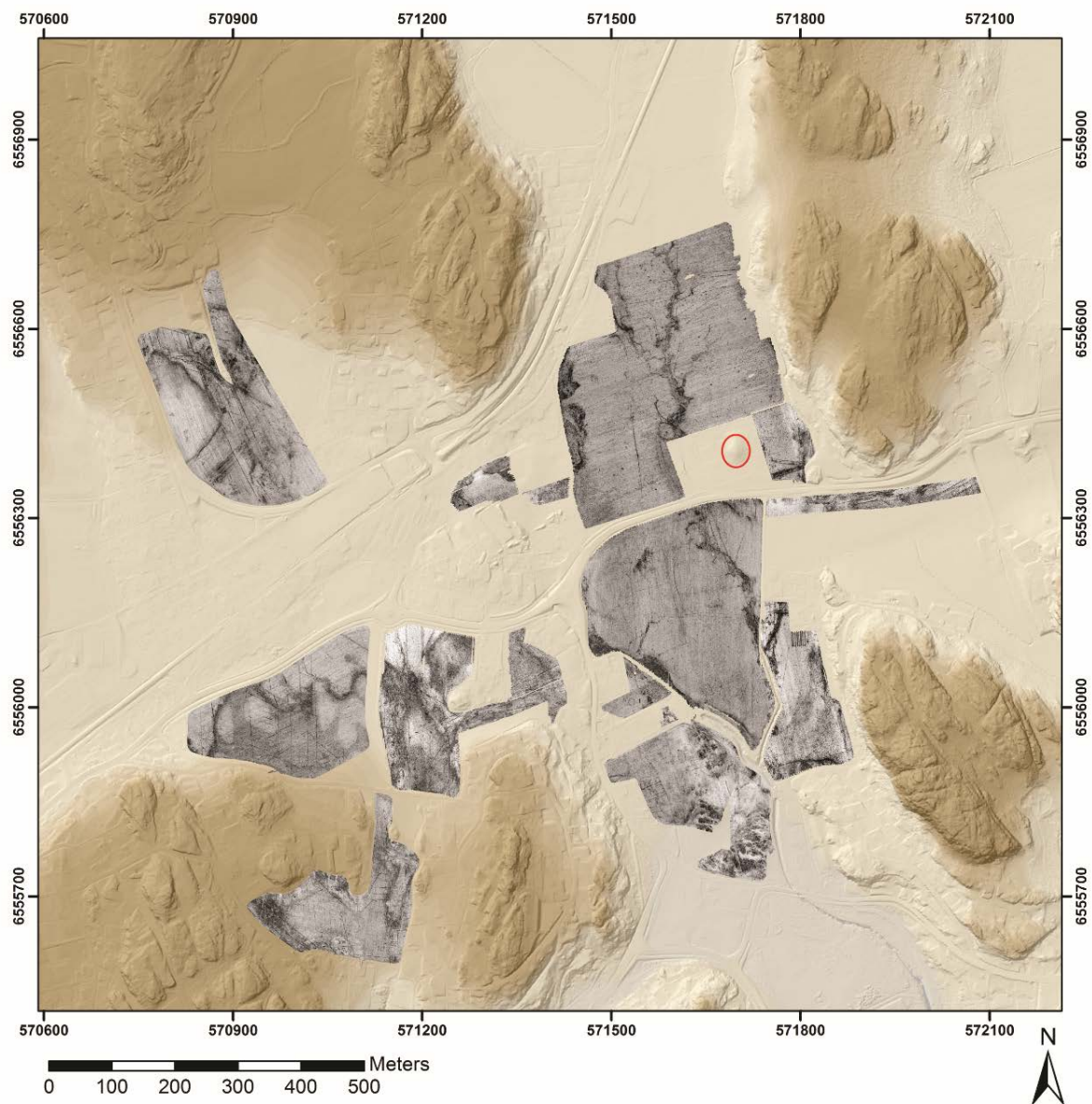


Fig. 2.14 Large scale, high resolution GPR data sets of the Gokstad study area

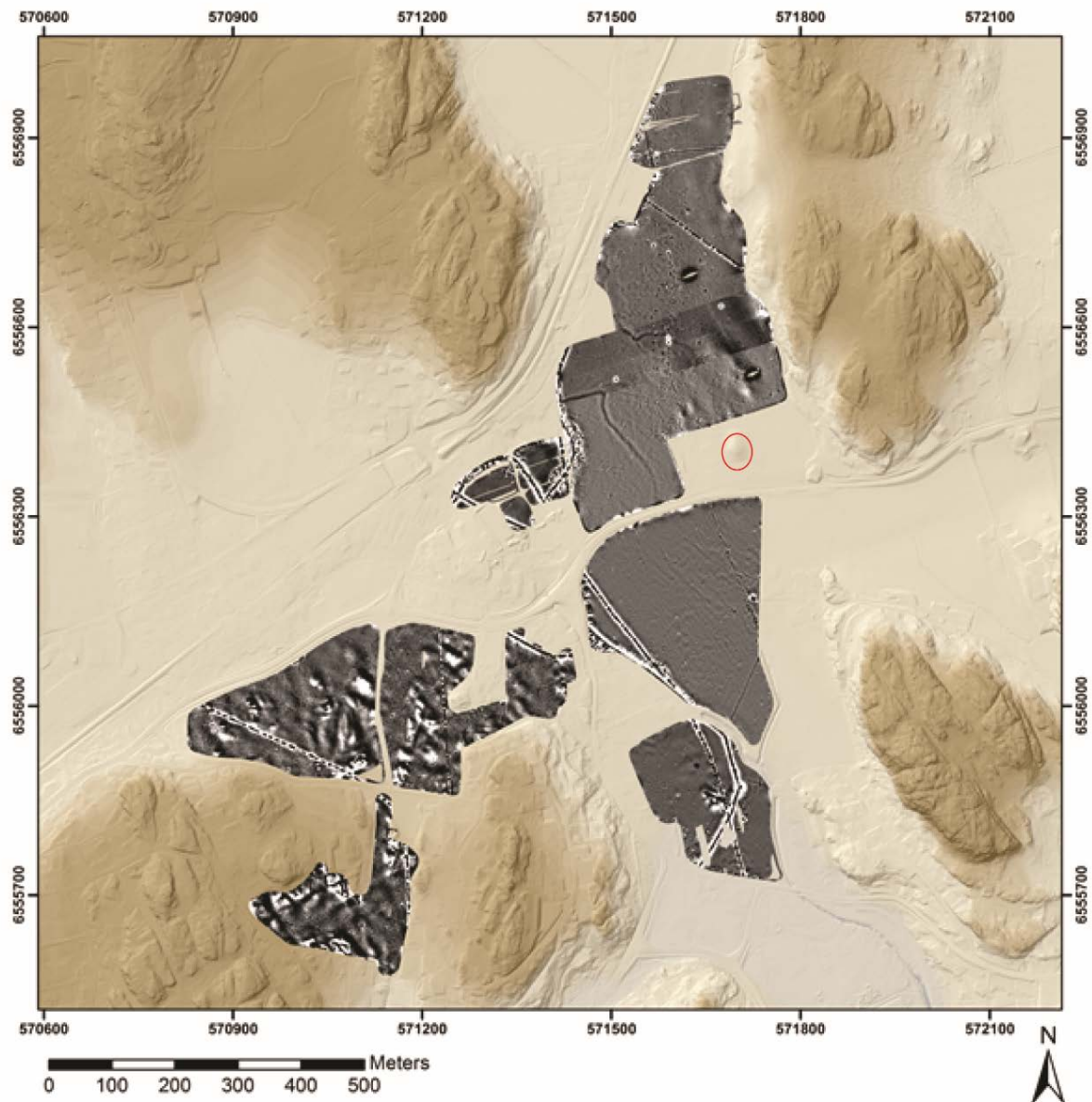


Fig. 2.15 Large scale, high resolution magnetometry data sets of the Gokstad study area

Apart from distinct archaeological structures, the geophysical data sets also displayed numerous structures and patterns of presumably natural origin, which generally are not investigated in much detail. In the case of Gokstad, however, the intensity and scale of these structures together with Norway's diverse and dynamic geomorphological history (Ramberg et al. 2008) raised questions regarding their origin and specifically their implications for the archaeological record.

In this thesis, Gokstad represents the main case study area. Large scale, high resolution data sets covering roughly half a square kilometre at Gokstad was used in a pilot study which aimed at the first analysis that specifically targeted potential palaeoenvironmental information in a study area (see chapter III). Smaller sub sets of the Gokstad case study area, namely the Viking Age settlement of *Heimdaljordet* (chapter V) and a field called *Sverstad* (chapter VI), were used for a geoarchaeological evaluation of the geophysical data as well as its natural background signal based on diagnostic palaeoenvironmental parameters. Additional sub sets were used to develop and test work flows for three-dimensional visualisation of GPR data to extract palaeoenvironmental information (chapter IV).

2.2.3. Oseberg/Slagendalen

Slagendalen, which translates into valley of the river Slagen, is situated 5.6 km to the north of municipal capital Tønsberg, and about 200 km south of Norwegian's capital Oslo. The gently sloped valley runs almost exactly north-south and is framed by forested hills on both sides. Today, the area is populated by small villages and scattered farmsteads, which accounts for it being used mainly agriculturally. At the southern part of this landscape, the Oseberg ship burial is situated, marking one of the most significant and well-known archaeological sites of the Scandinavian countries (Brøgger et al., 1917; Gansum, 1995).



Fig. 2.16 The excavation of the Oseberg mound was carried out in 1904-1905. Public Domain, Museum of Cultural History, UiO/Olaf Væring

Discovered in 1903 by laymen, the Oseberg ship burial was soon identified as a remnant from the Viking Age based on the fine wood carvings recovered in a first investigation. In 1904, the monument was properly excavated during the summer month by archaeological pioneer Gabriel Adolf Gustafson (Fig. 2.16). Results showed that the Oseberg ship was the burial site of two women, one elderly (ca. 70-80 years) and one middle-aged (ca. 50 years). The burial was dated via ^{14}C dates between 680 and 900 AD. While historical context and social status of the dead remain unknown, archaeological excavations revealed much information about the ship itself. Similar to the Gokstad ship, large parts of the ship were persevered in the more than 1000 years since its burial, due to the structure being set into

moist, marine sediments and covered by turf, which aided in preserving most of the organic materials, also including rare organic grave goods even though the burial seemed to have been robbed soon after interment. The ship was designed as a row and sail boat and had space for 30 oarsmen, built mainly from oak, while deck planks and mast were made of pine. Dendrochronological analyses yielded felling dates for the wood of around 820 AD in the south-west of Norway. It took 21 years to restore the ship to its current shape, which today is on display in the Viking Age ship museum in Oslo (Brøgger et al., 1917; Holck, 2006; Museum of Cultural History Oslo, 2016b; Sæjörg Walaker Nordeide, 2011; Sæjörg Walaker Nordeide, 2011).

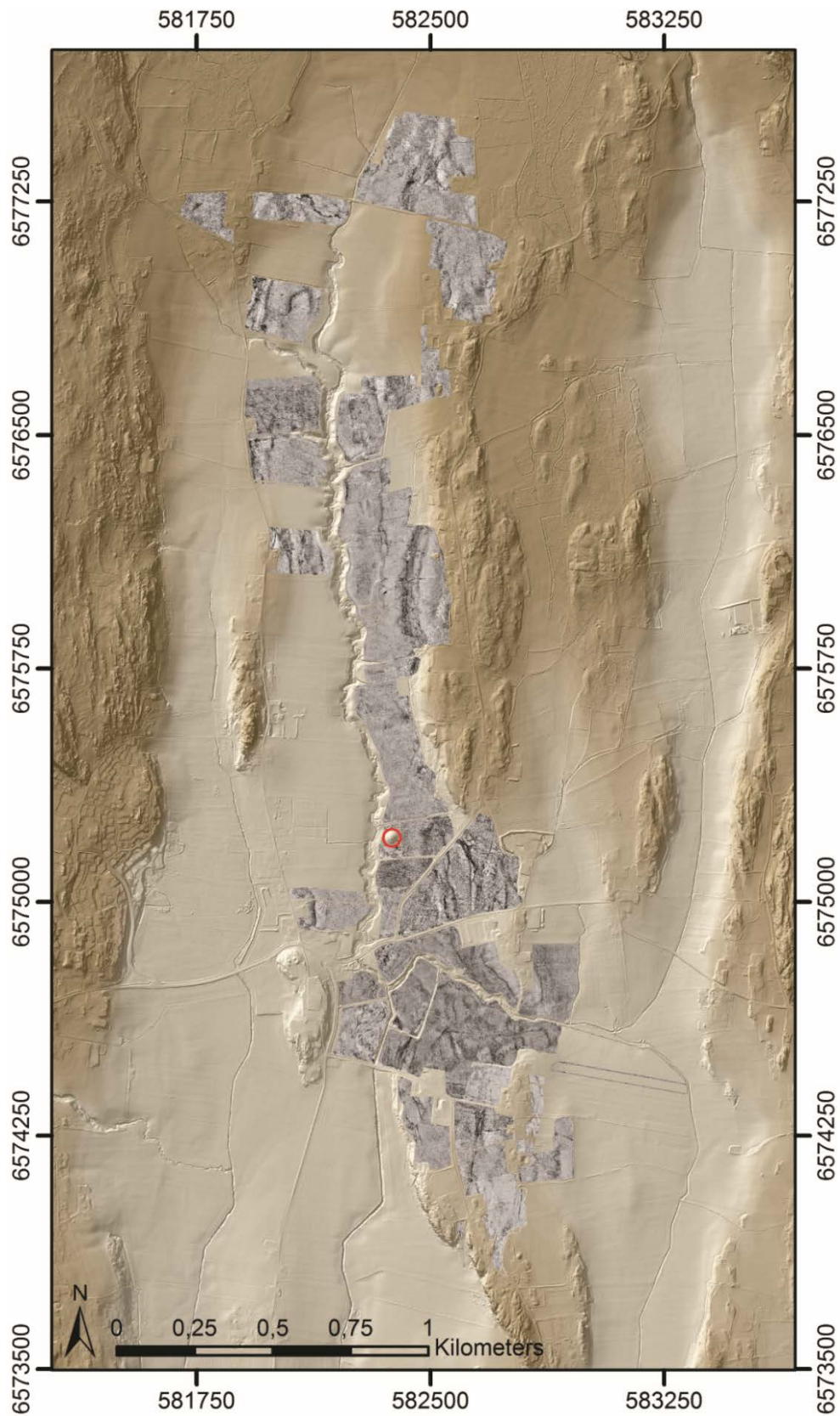


Fig. 2.17 Large scale, high resolution GPR data sets covering almost the entire Slagendalen, which also accommodates the Oseberg mound (red circle)

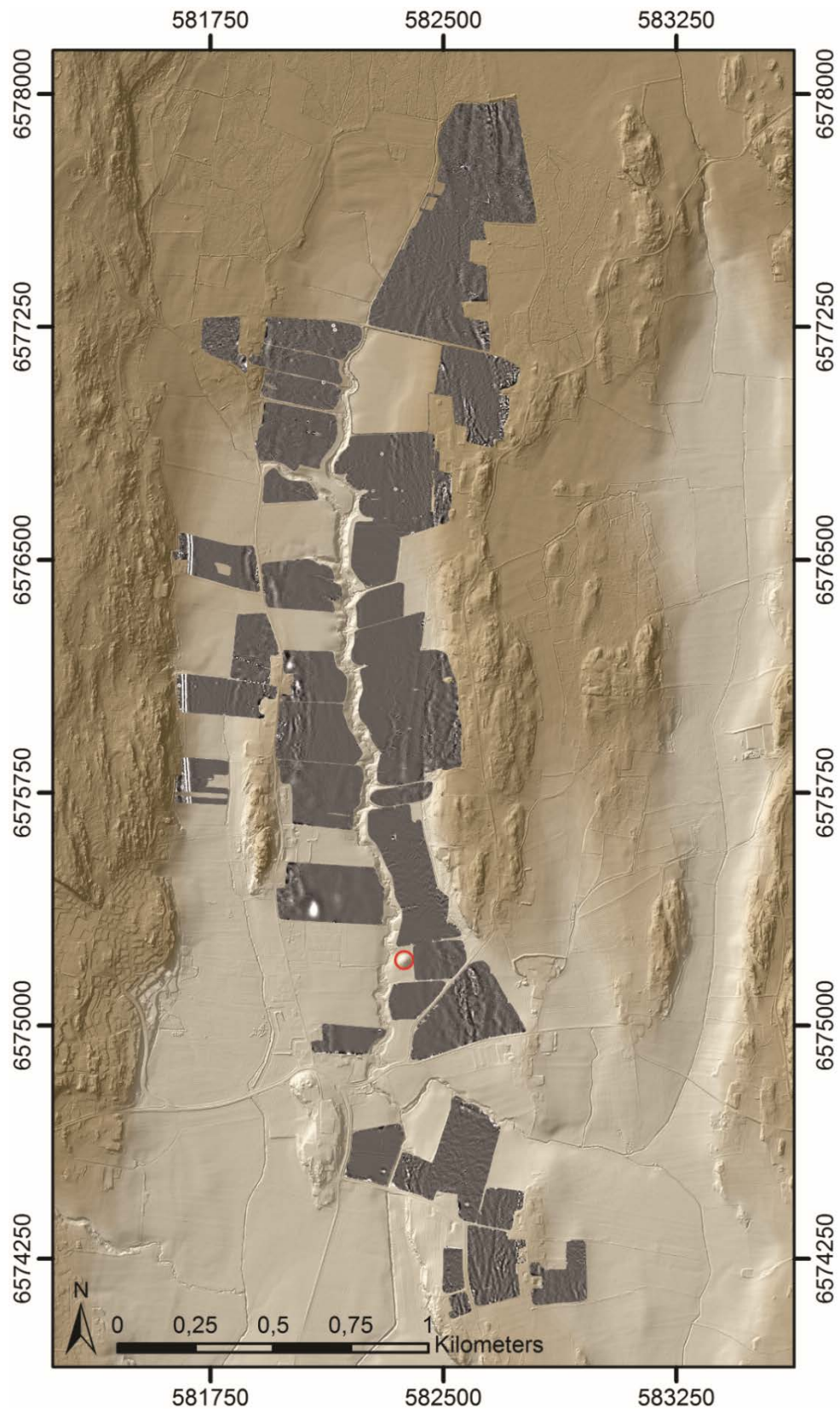


Fig. 2.18 Large scale, high resolution magnetometry surveys covering almost the entire Slagendalen, which also accommodates the Oseberg mound (red circle)

Until recently, this exceptional monument was regarded as a relatively isolated spot in the landscape of the Slagendalen, among just few other known burial mounds including Kaltvet (ID 76844), 26 burial mounds at Rom Søndre (ID 61689) and a small mound at Rom Östre (ID 22248) (McGraw and Bill, 2014). This fact aroused interest and was the reason why the Slagendalen was included as a case study area into the Vestfold Project. Complementary geophysical prospection surveys started in 2012 led by the LBI ArchPro and were jointly conducted by Vfk and NIKU. The aim was to prospect the entire Slagendalen in order to get a more complete and comprehensive picture of this archaeological landscape (Fig. 2.26). A particular focus was directed at the Viking Age and the context of the Oseberg ship burial. During several campaigns between 2012 and 2015, an area of 115 ha could be prospected with GPR (Fig. 2.17), while 145 ha were investigated using magnetometry (Fig. 2.18). Preliminary results include a range of previously unknown archaeological sites, among them a large number of burial mounds as well as settlement traces from the Nordic Iron Age and possibly the Viking Age.

For this thesis, two case study areas were selected from Slagendalen: Rom Vestre burial mound and the Basberg area.

The area of Basberg is located in the south of Slagendalen ca. 1.5 km south of the Oseberg mound (Fig. 2.19). Surveys in Basberg yielded an interesting distribution along a large scale palaeoenvironmental pattern and thus proved suitable to test three-dimensional visualisation and integration of GPR data in Chapter IV.

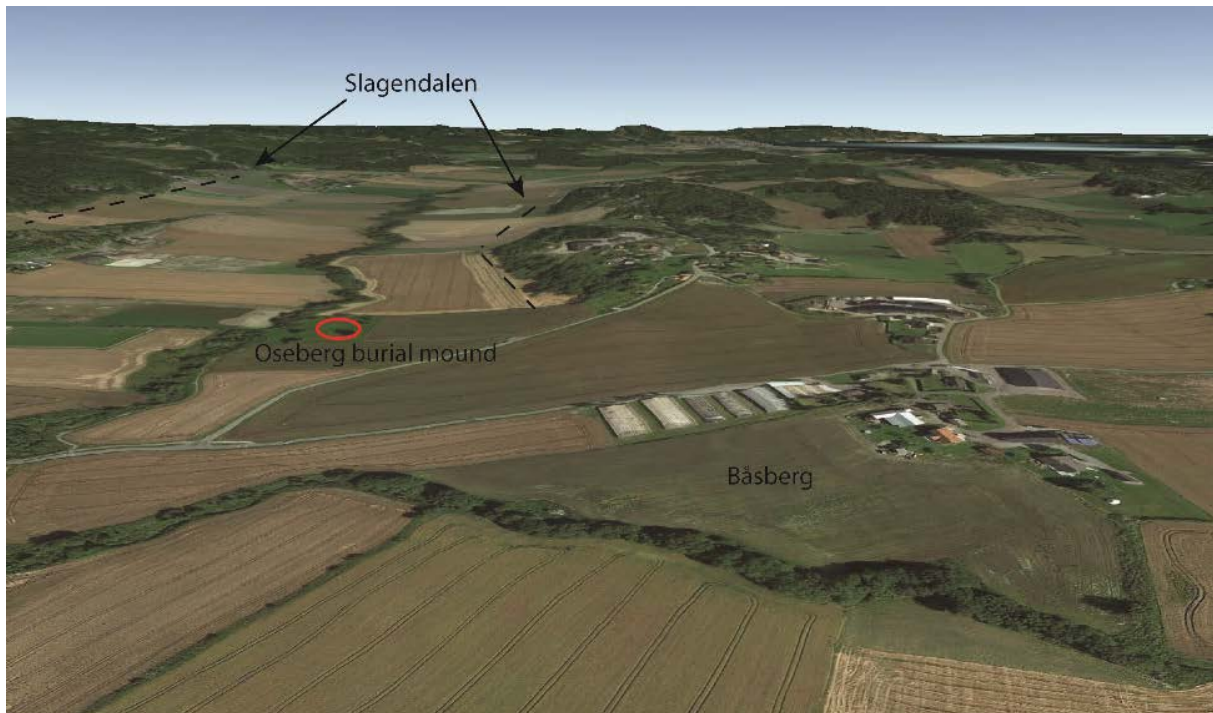


Fig. 2.19 Landscape of Slagendalen with Basberg in the front and Oseberg mound in the back. View towards North. Source: Google Earth. August 19, 2015. Accessed February 15, 2017

Rom Vestre, a large burial mound situated ca. 1.7 km northwest of the Oseberg ship burial, was first discovered in aerial pictures in 1991, followed by several intrusive, small-scale archaeological investigations including coring and test-trenching during the early 2000s (Fig. 2.20). In order to get a more complete picture of the mound, the LBI ArchPro conducted several high-resolution surveys using different settings of GPR devices. In 2013, the mound was partially excavated, which enabled access to the subsurface and allowed to evaluate the interpretation of the archaeological geophysical prospection as well as the impact of the palaeoenvironmental information onto the survey quality (chapter VII) (McGraw and Bill, 2014).

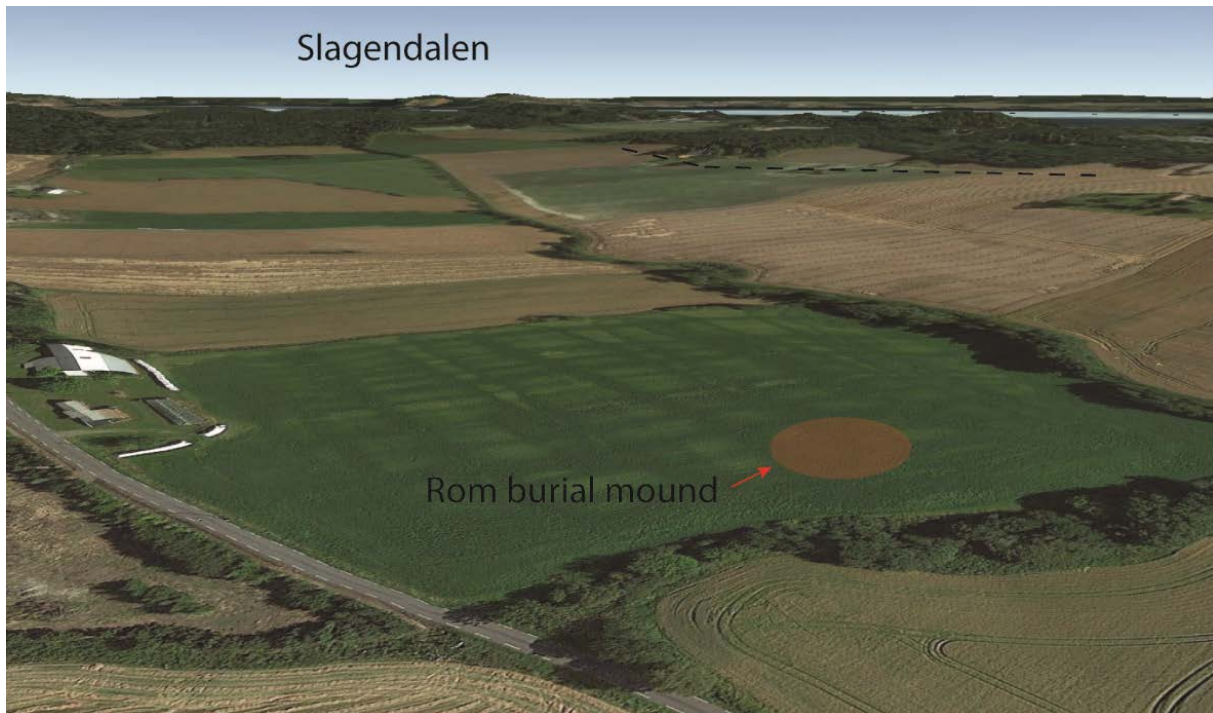


Fig. 2.20 Landscape of Slagendalen with Rom burial mound in the front. View towards North-northeast.
Source: Google Earth. August 19, 2015. Accessed February 15, 2017

2.2.4. Kaupang

Kaupang is interpreted as Norway's first protourban settlement dated to the Viking Age and used as an important harbor and trading post (Fig. 2.21). It started to rise in significance in the late 700's AD and – according to results of several excavations – reached its climax in trading during the 9th century AD (Fig. 2.23). Just outside of the settlement to both the southwest and northeast along the then shoreline lie extensive grave fields with numerous burials (Fig. 2.29). Similar settlements have been found along the coasts of Scandinavia at strategic points and include well known sites Birka in Sweden (Ambrosiani, 2013; Trinks et al., 2010b) and Hedeby in Germany (Maixner, 2010; Schietzel, 2014). Kaupang probably persisted until the beginning of 900 AD based on the youngest burial dated so far. Reasons for its decline are still subject to debate but could have been caused by sea-level retreat rendering the harbor useless or a change of trading routes due to political reasons (Skre, 2007b).

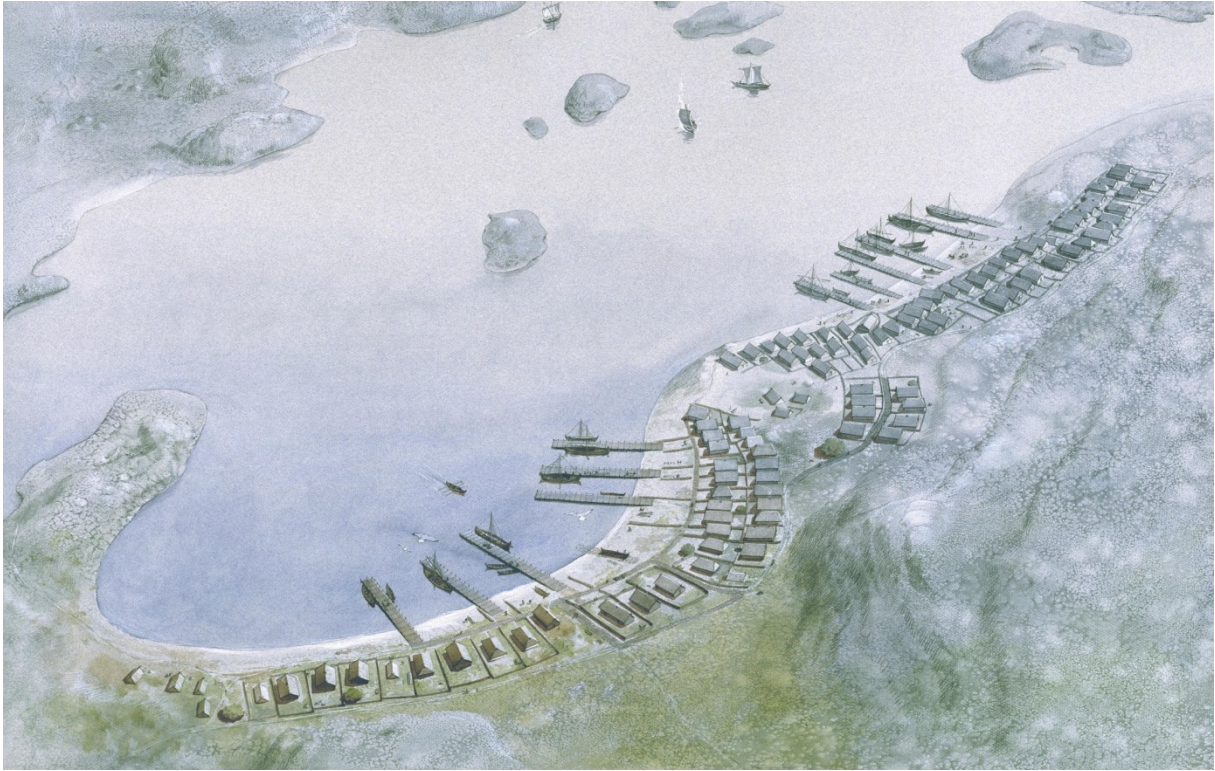


Fig. 2.21 Drawing of the Viking Age landscape around the trading post Kaupang with reconstructed sea-levels around 800 AD. Flemming Bau, Vikingskibmuseet i Roskilde



Fig. 2.22 Reconstruction of the Viking Age trading post at Kaupang. Flemming Bau, in: (Skre, 2007a)

As mentioned before, Norway's landscape is very much characterised by geomorphological processes connected to the last ice-age and Kaupang and its surroundings are no exception. Based on regional sea-level curves, the shoreline at Kaupang during the Viking Age was located ca. 4m above the current sea-level – a fact that needs to be considered when interpreting the archaeological landscape especially with regard to its function as a trading centre relying on access to the sea (Fig. 2.23a) (Sørensen et al., 2007).

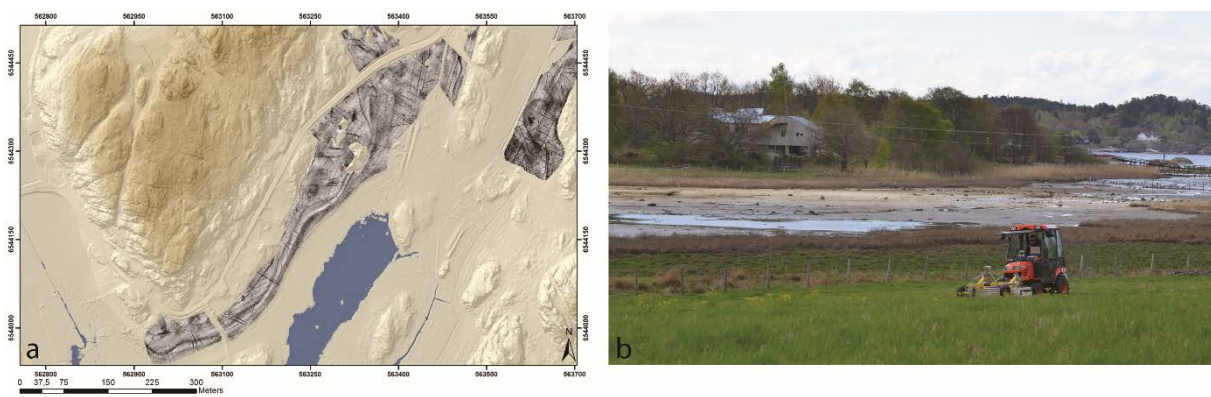


Fig.2.23a GPR depth slice (40-45 cm BGS) overlying DTM (source: Norwegian Mapping authority, 0.5 m resolution) with reconstructed shoreline during the Viking Age at Kaupang based on sea-level data (+ 3.6 m) from Sørensen et al. (2007). 2.23b Today's shoreline shows the silted up coastal inlet – a result of the still on-going postglacial rebound.

Today, Kaupang is located in Vestfold county, close to Larvik, on a gentle slope ca. 100 m inland of the small coastal inlet Kaupangskilen and ca. 700m from the actual coast (Fig. 2.23b). While the lower area towards the coast is protected as cultural heritage and used mainly for pasture, the upper area is developed and covered by farms and houses. Excavations in the 19th and 20th century targeted the settlement as well as the cemeteries at Kaupang and allowed small insights into the structure of the trading post as well as the recovery of finds evidencing valuable import goods.

Despite several excavation campaigns since its discovery in 1956, not much was known about Kaupang's hinterland. One question in particular aroused interest, and that concerned the existence of a possible "royal estate", as is evidenced in Hedeby and Birka (Ambrosiani,

2013; Trinks et al., 2014). Connected to this, some historians believe Kaupang to be the important port Skiringssal, which first is mentioned by Ottar, a trader visiting King Alfred the Great in 880 AD. They connected a possible royal estate to be located at the farm *Huseby* in the area Tjøllingvollen, Lunde. This hypothesis was supported by the fact that – in terms of archaeology - relatively little was known from Kaupang's surroundings (Skre, 2007b).

In addition to Oseberg/Slagendalen, Kaupang became one of the focal points of the Vestfold Project in 2010. The aim was to investigate the internal structure and the extent of the settlement and its cemeteries as well as to understand its connection to the hinterland in Tjøllingvollen during the Viking Age. Surveys were conducted in several campaigns from 2011-2014 using complementary prospection techniques for encompassing results. Magnetic surveys covered 156 ha in Kaupang itself as well as in the hinterland in Tjøllingvollen (Fig. 2.24), while GPR surveys measured 109 ha.

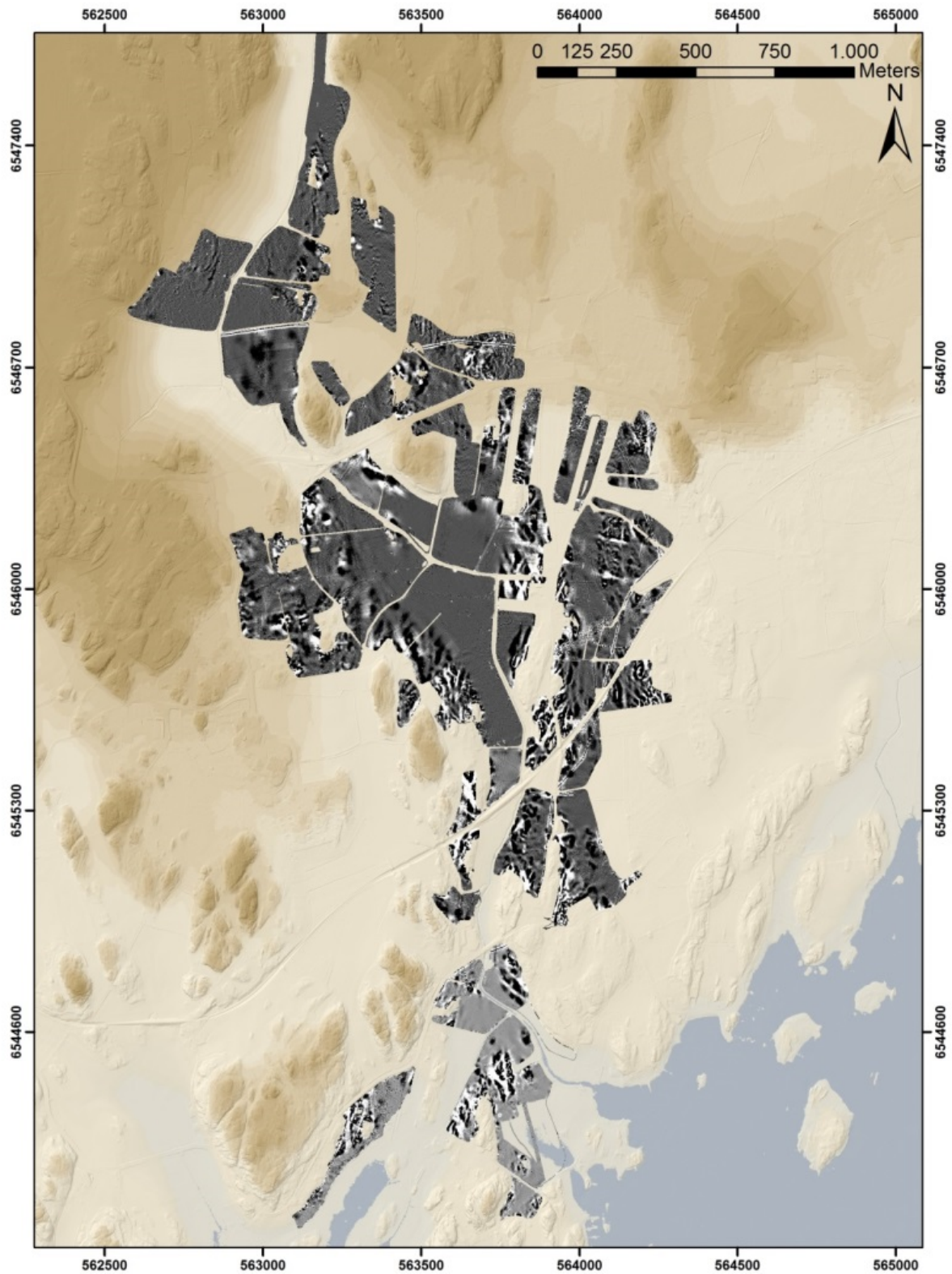


Fig. 2.24 Large scale, high resolution magnetic surveys at Kaupang and its hinterland

In this thesis, Kaupang was mainly used for testing 3D visualisation approaches as well as for comparative purposes. In the southwestern-most part of the Kaupang survey area, several previously unknown burial mounds were discovered in a GPR data set. A sub set of this area was used in order to develop and test a workflow for integrated three-dimensional visualisation and integration (Chapter IV).

Chapter III

Palaeoenvironmental analysis of large-scale, high-resolution GPR and magnetometry data sets: the Viking Age site of Gokstad

3.1. Introduction

As already discussed in chapter II, the interdisciplinary research agenda of the Gokstad revitalised project focused on the Gokstad mound itself and its surrounding landscape using amongst other techniques large scale, high resolution geophysical prospection (Fig. 3.1).

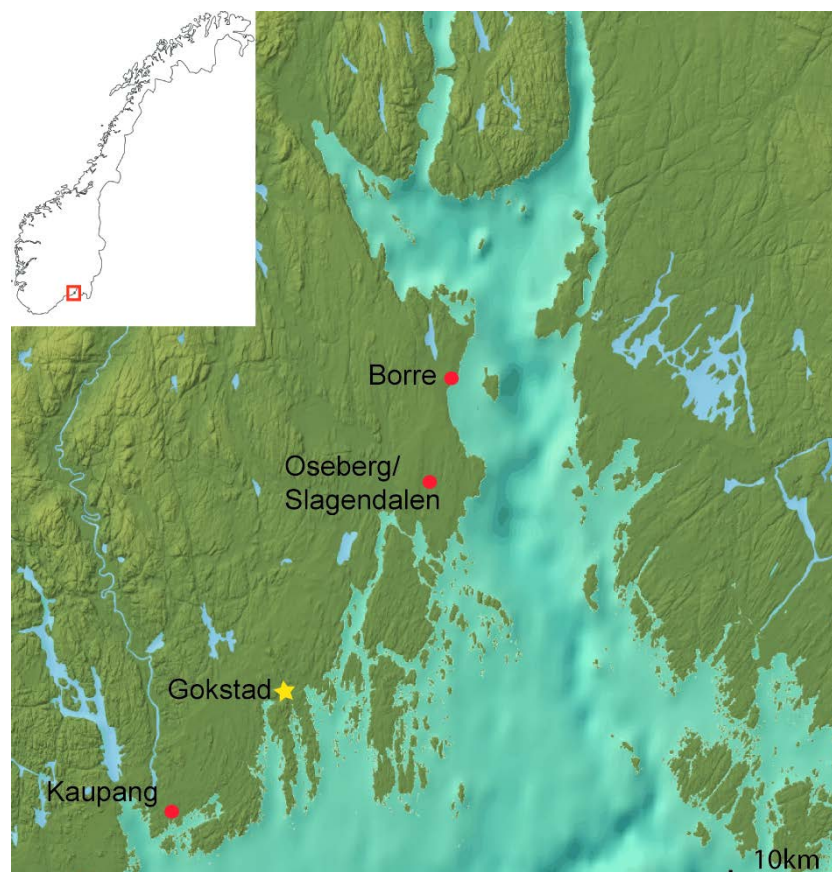


Fig. 3.1 Location of Gokstad in Vestfold County, Norway, among other prominent Viking Age landscapes including Kaupang, Oseberg/Slagendalen and Borre (basemap: ©kartverket www.kartverket.no, resolution 20 x 20 m)

The resulting magnetometry and GPR data sets proved to hold a substantial amount of non-archaeological information and were thus selected to be analysed specifically for palaeoenvironmental information. Designed as a pilot study, this analysis also explores methodological approaches regarding identification and visualisation of palaeoenvironmental structures and patterns. Subsequent geoarchaeological investigations including augering and sedimentological analyses test the accuracy of the derived interpretations. Finally, impact and potential benefit of the palaeoenvironmental analysis on the archaeological interpretation of the Gokstad area are discussed.

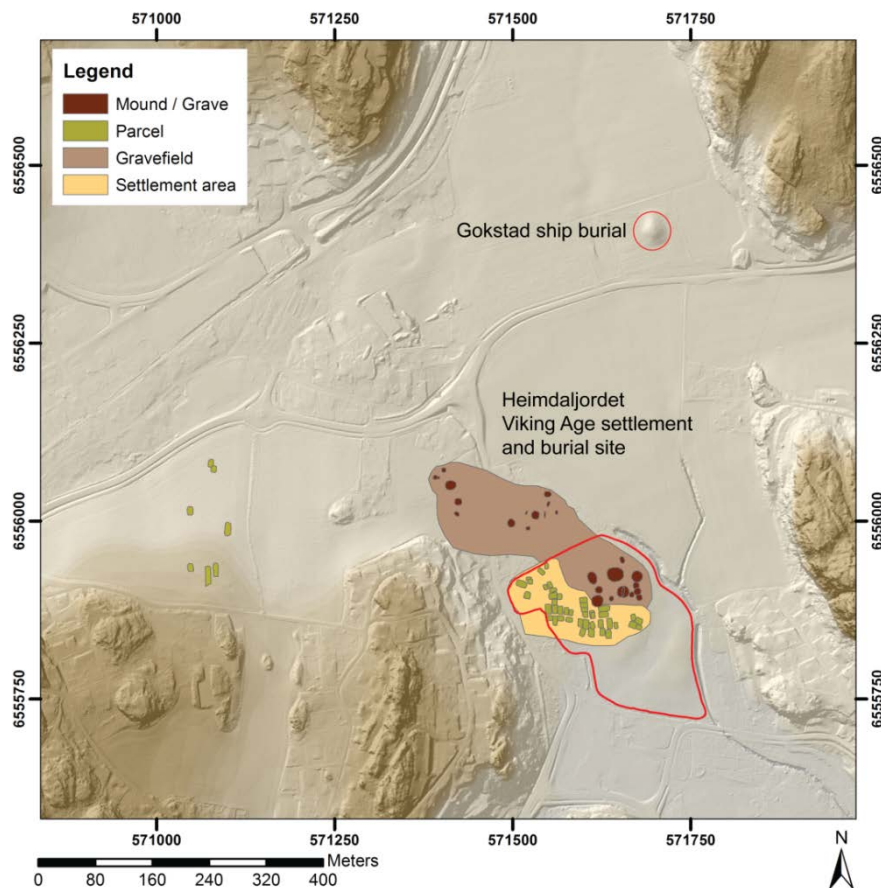


Fig. 3.2 Map of local topography of the Gokstad study area (Basis: Norge I bilder, Norwegian Map Authorities, Geovekst and Municipalities, dtm Sandefjord 2008, 0.5 m resolution) with the Gokstad ship burial (red circle) and the Viking Age settlement and burial site *Heimdaljordet* (red polygon) marked. The structures of archaeological interest, which were newly mapped by geophysical archaeological prospection surveys during the *Gokstad revitalised* project are indicated

3.2. Background

Palaeoenvironmental information on archaeological sites and their surroundings has become an integral part for the comprehensive understanding of archaeological landscapes (Butzer 1982; French et al. 2005). It is unquestioned that a holistic approach using a range of different methods is required in order to be able to understand the complex development of archaeological sites at the scale of landscapes (Courty et al. 1990; Brown 1997; Dincauze 2000; French 2002; Bell and Walker 2005; Rapp and Hill 2006; Denham 2008; Goldberg and Macphail 2009; Benedetti et al. 2011). Space- and airborne remote sensing techniques, such as satellite imagery, aerial photography, airborne laser scanning (ALS) and spectral imaging, have long been used for this purpose, offering large-scale overviews of study sites as well as exploiting proxies, such as differences in elevation, vegetation growth or electromagnetic signatures (Donoghue and Shennan 1988; McHugh et al. 1988; Brivio et al. 2000; Challis and Howard 2006; Doneus et al. 2008; Siart et al. 2008; Derooin et al. 2011; Lasaponara and Masini 2011; Doneus et al. 2013). In contrast, ground-based archaeological geophysical surveys, including magnetometry, earth resistance and GPR, are generally not focused on the extraction of palaeoenvironmental information, causing this aspect often to be disregarded by archaeological projects (Gaffney, 2008). Nevertheless, geophysical techniques have been used targeted for the investigation of alluvial, wetland or cave sequences (Bates & Bates 2000; Weston 2001; Challis & Howard 2006; Bates et al. 2007; Mansfield 2007; Armstrong 2010). The reasons for palaeoenvironmental information being used so little in archaeological studies might include its complexity, the lack of appropriate visualisation methods, as well as data sets that have been insufficient in size for the understanding of geomorphological features and formation processes.

Recently, studies have started to recognize the potential offered by palaeoenvironmental information derived from geophysical data sets (Fitch et al. 2005; Gaffney 2008; Leopold et al. 2010; Wegmann et al. 2012). This trend is partially attributable to an increased interest in archaeological landscapes, but also due to a rapid technological development concerning large-scale, high-resolution geophysical archaeological prospection. Motorization of measurement devices and grid-free positioning systems using RTK GNSS for efficient data positioning enables multi-sensor arrays to cover large areas at high-resolution (Leckebusch 2003; Linford 2006; Gaffney 2008; Trinks et al. 2010). The resulting large-scale, high-

resolution geophysical data sets offer the potential to consider palaeoenvironmental information as an important element for the understanding of the archaeological landscapes. However, a particular approach in order to specifically extract this information has not yet been undertaken. Earth science disciplines such as geology (Jongmans and Garambois 2007; Kneisel et al. 2008; Burke et al. 2008; Dam 2012; Proulx-McInnis et al. 2013), geomorphology (Schrott and Sass, 2008), sedimentology (Neal 2004; Hickin et al. 2009) and soil sciences (Lunt et al. 2005; Saey et al. 2013a) have since long applied geophysical techniques as part of their investigations, and the methodologies used have proven to be useful to certain extent as well for geophysical archaeological prospection data sets. Their survey parameters, however, differ substantially from archaeological prospection surveys by often much larger scale at considerably lower spatial sampling resolution, by a general preference for 2D profiles as well as by data processing not designed for archaeological purposes. In recent years, electromagnetic induction methods have advanced significantly, with great potential for the non-invasive investigation of past land surfaces (Conyers et al. 2008; De Smedt et al. 2011; De Clercq et al. 2012; Saey et al. 2013); these methods are, however, currently not used regularly for archaeological purposes.

3.3. The archaeological site of Gokstad

Gokstad is located in the province of Vestfold in southern Norway, approximately 1.5 km west of today's coastline just outside Sandefjord at ca. 4 – 15 m height above current sea-level. The topography in southern Norway was shaped by the last glaciation and processes related to subsequent de-glaciation. Caused by the weight of the Scandinavian Ice shield, the crust in this area was isostatically pressed in the mantle (Ramberg et al. 2008). Since the end of the Last Glacial Maximum around 20000 years ago, melting ice resulted in some 125 ±5m global sea level rise (Chappell and Shackelton, 1986). In central parts of Scandinavia, this global sea-level rise was outnumbered by crustal uplift related to post-glacial rebound due to unloading from the former Scandinavian Ice shield, which led to a sea-level retreat (Pugh 2004, Ekman 2009). Crustal uplift has gradually slowed down but is still active today in the area of Gokstad at ca. 2 mm per year (Olesen et al. 2004).

During the Viking Age, sea-levels retreated slightly more rapidly at a rate of ca. 3.5 mm per year in the area of Larvik (Sørensen et al. 2007). The subsequent shoreline displacement rate is strongly controlled by the distance to the centre of the former ice masses (Ekman, 2009) and can vary locally depending on many parameters including topography, type of sediment and especially tectonic movements (Draganits et al. in press). Prøsch-Danielsen (2006) even claimed to be able to reconstruct an alternation of transgression and regression. Thus, coastal marine deposits in lower areas may comprise fine-grained sediments. Once the sea-level retreated, these deposits became exposed to coastal reworking processes prior to transforming into salt marshes, and finally dry land-processes and their sediments, which cannot easily be distinguished based on sediment maps (2011 NGU, Løsmasser) (Fig. 3.3). The local geology around Gokstad consists of igneous intrusive rocks, mainly monzonite and quartz monzonite. About 10 km to the north, rhombporphyry prevails, while 10 km to the east syenite and quartz syenite predominates (<http://geo.ngu.no/kart/berggrunn>). The Gokstad area is additionally influenced by the Ra moraine, which runs in a distance of ca. 4 km to the north-west and parallel to the coast, until reaching the sea at Mølen. It is a terminal moraine composed of glacial till formed during the Younger Dryas period (ca. 12.800 – 11,500 years ago BP) (Mangerud et al. 2011), including unsorted material of size fractions ranging from clay to boulders (Ramberg et al. 2008). Today, the topography in this part of Norway is characterised by shallow, dry fjärds (Fairbridge 1985; Embleton & King 1970; Bird & Schwartz 1985; Bird 2010, fig. 8.1.1.) delimited by large bedrock outcrops. These outcrops can partially be covered by soils and sediments; at higher altitudes and in locations with steeper gradients the bare rock is usually exposed.

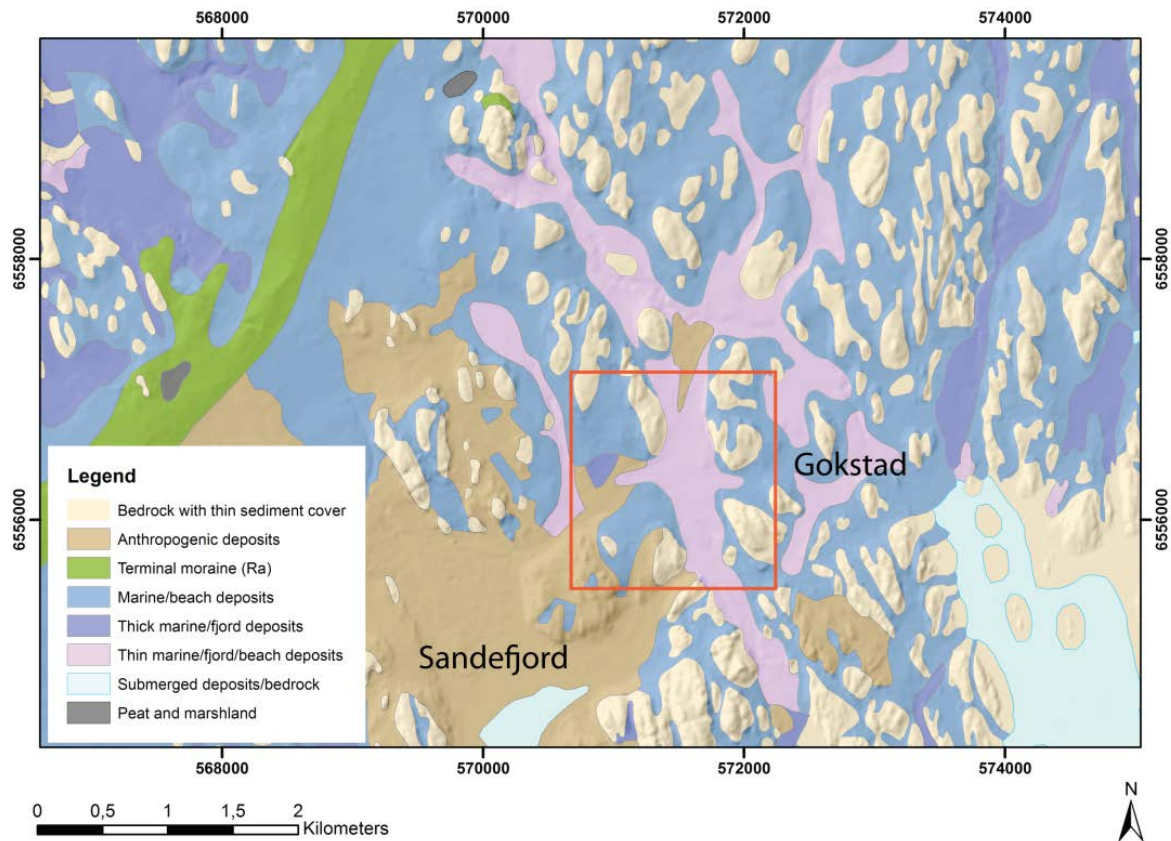


Fig. 3.3 Surficial deposits in the Gokstad study area (red rectangle) (basis: NGU, Norges Geologiske Undersøkelse, <http://geo.ngu.no/kart/losmasse>). Blue and violet areas illustrate sediment cover influenced by marine and intertidal processes caused by changing sea-levels. The Ra moraine (marked in green) runs ca. 4 km north-west of Gokstad

Concerning soils, lowlands are frequently covered by stagnosols (<http://wms.skogoglandskap.no/cgi-bin/jordsmonn>), which are characterised by a stagnant zone preventing the water from draining, as well as redoximorphic properties caused by the repeating cycles of reducing and oxidising conditions. To a lesser extent, albeluvisols can be found in the floors of valleys on top of fluvial sediments. In contrast, the slope areas show more oxidised conditions with cambisols on steeper terrain and umbrisols forming close to the bedrock outcrops (Soil WRB, 2006). Today, the area around Gokstad is to a large extent used for agriculture (Fig. 3.4). Deep-ploughing and extensive drainage systems are needed particularly in the lowlands for the cultivation of the often wet soils. The consequences are thick plough layers and ground disturbances caused by a dense network of buried pipes that complicate the interpretation of the near-surface geophysical prospection data sets.

However, these fields permit access and survey with efficient motorised geophysical prospection systems – a prerequisite for large-scale, high-resolution geophysical archaeological prospection.

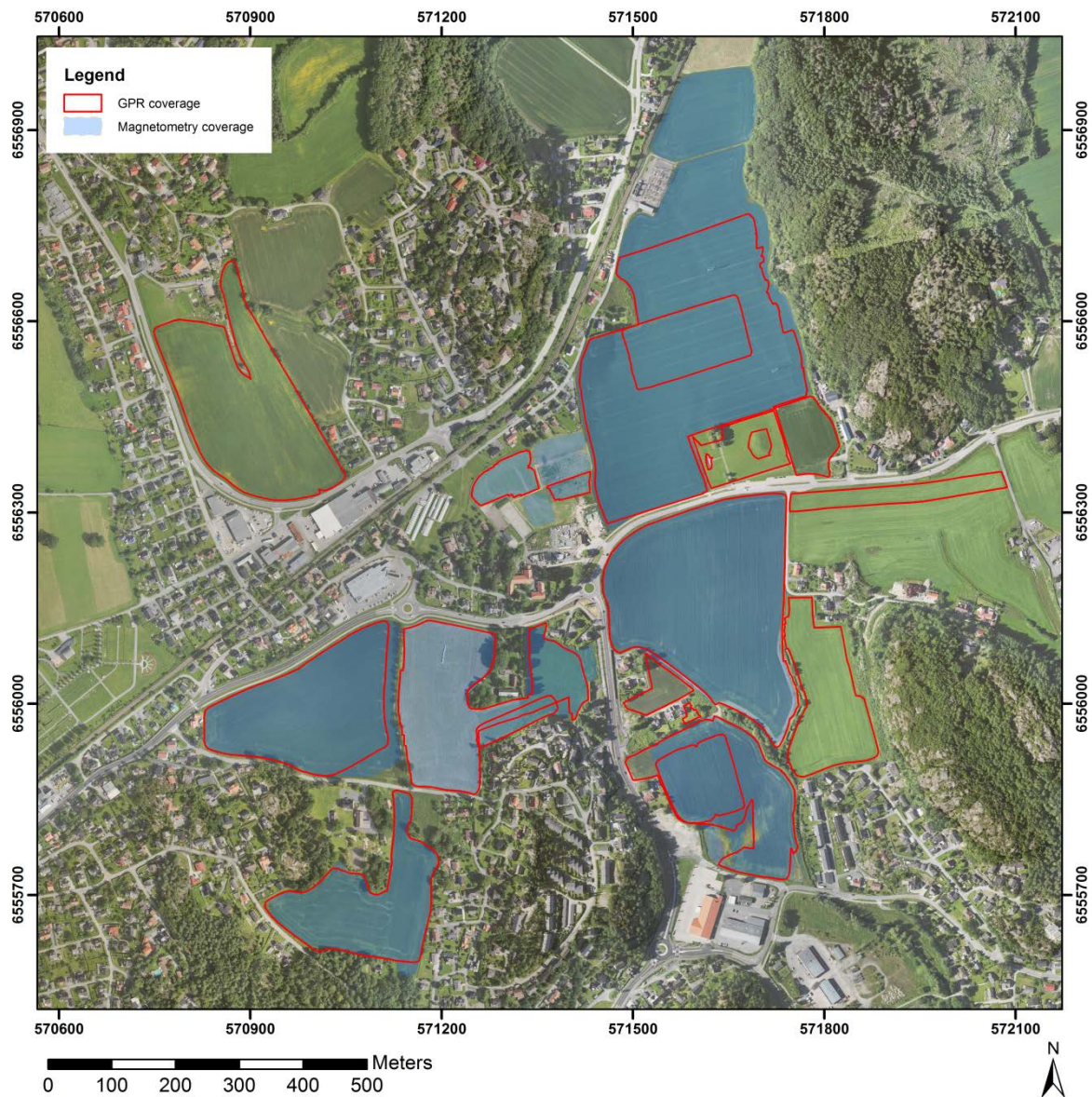


Fig. 3.4 Aerial orthophoto (2011, basis: Norge I Bilder, Norwegian Map authorities, Geovekst and Municipalities, resolution 10 cm) of the Gokstad study area illustrating densely populated areas surrounded by agriculturally used land and partly forested bedrock outcrops. The study area encompasses approx. 2.5 km², where GPR (red) and magnetometry (blue) survey areas cover every accessible field. In certain areas measurements were impossible due to wet ground conditions or crops

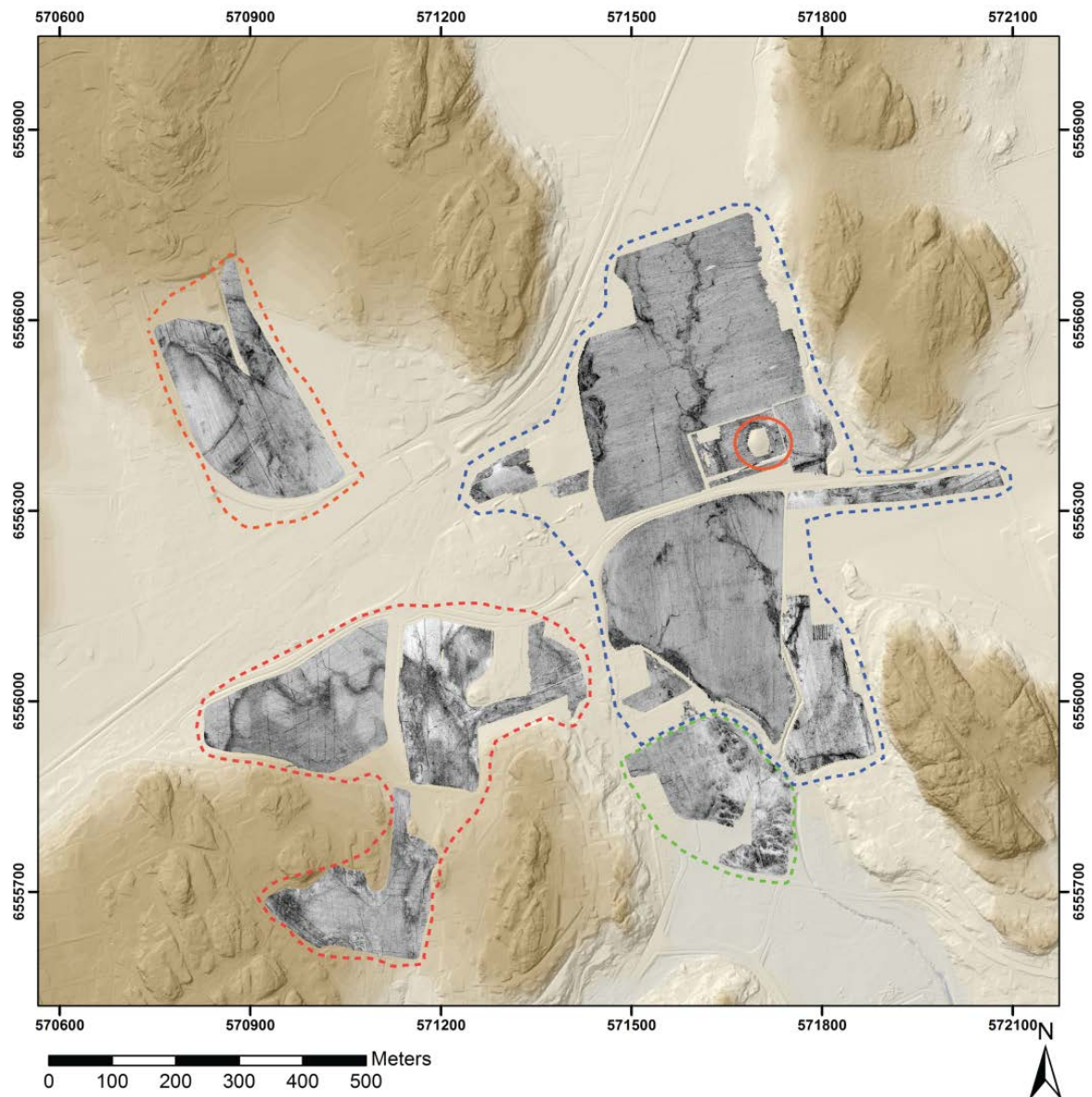


Fig. 3.5 Acquired GPR data sets covering 454 hectares in the neighbourhood of the Gokstad mound (red circle). Clearly visible at a depth of 60-80 cm BGS are extensive palaeochannel systems in the lowlands (outlined in blue). The slope areas (outlined in red) and *Heimdaljordet* (outlined in green) display non-archaeological patterns, structures and features, whose sources and origins are still only poorly understood

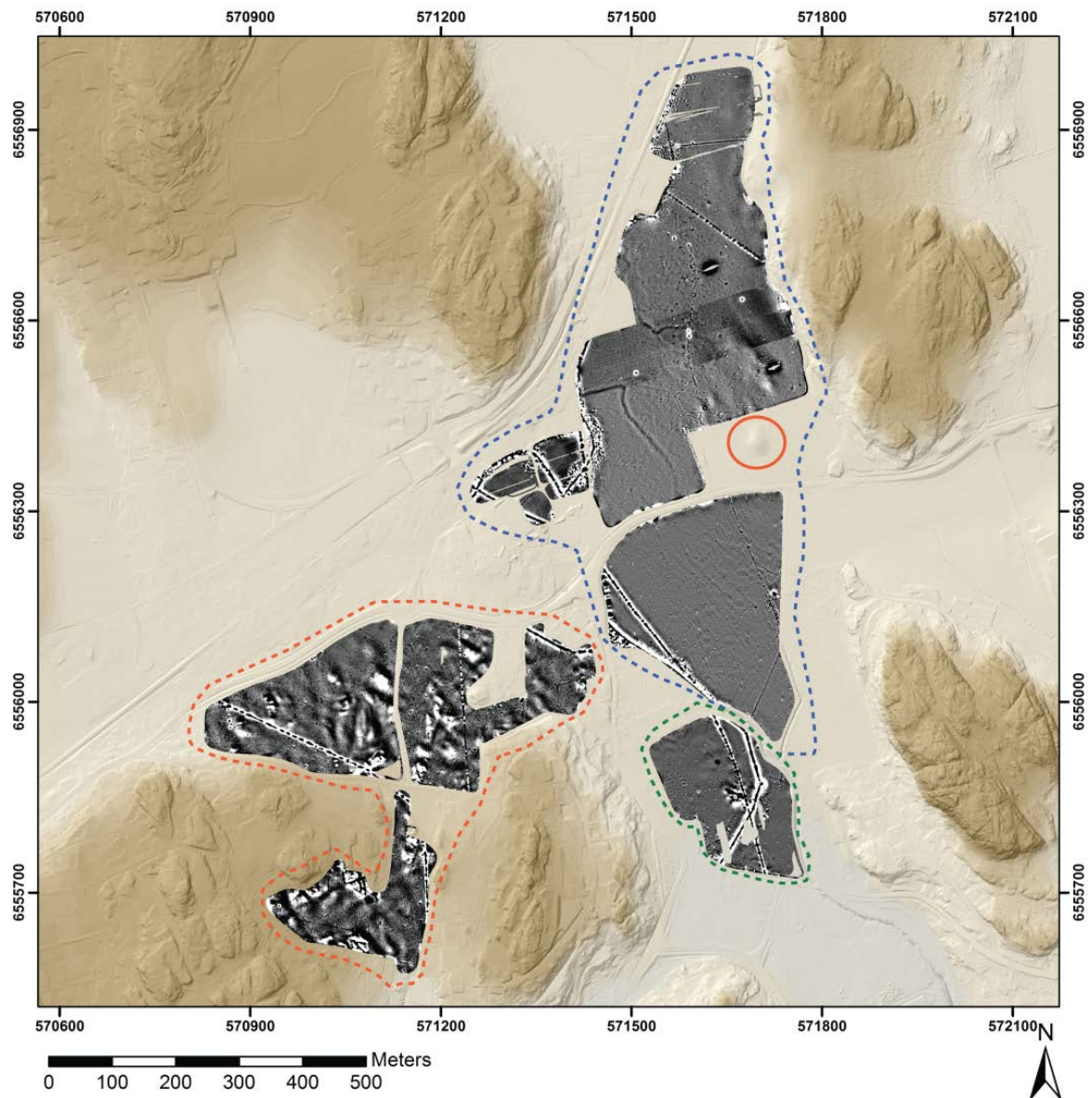


Fig. 3.6 Magnetometry data sets covering 403 hectares in the vicinity of the Gokstad mound (red circle). While lowlands (outlined in blue) and *Heimdaljordet* (outlined in green) generally contain a small number of anomalies, the sloping fields (outlined in red) contain large, long-wavelengths dipolar magnetic anomalies

3.4. Methods

Magnetometry and GPR surveys were conducted over the course of three fieldwork campaigns conducted in September 2011 as well as in April and September 2012. A total area of 45.4 hectares (Fig. 3.5) and 40.3 hectares (Fig. 3.6) was surveyed with GPR and magnetics, respectively. All applied geophysical survey systems were state-of-the-art

motorised systems pulled by an All-Terrain-Vehicle (ATV) or pushed by a small tractor while using different GNSS real-time kinematic positioning systems with 5 Hz position update rates and few centimetres position accuracy. Data were recorded with position information assigned in the ETRS89/UTM zone 32N coordinate system. Measurement control, data acquisition and navigation in the field were provided by different software products (Gabler et al. 2013) (Table 3.1).

Table 3.1a Measurement specifications for the GPR surveys conducted

System	Antenna type	Antenna Frequency	Nr. of Channels	Measurement frequency	Stacks	Resolution	Resampling rate	GPS System	Survey Speed	Acquisition software
SPIDAR	PulsEKKO Pro 500	500 Mhz	6	50 Hz	4	25 x 8 cm	25 x 10 cm	Javad TRIUMPH-1	≤ 15 km/h	SPIview
MIRA	MALÅ 400 Mhz Antenna	400 Mhz	16	50 Hz	4	8 x 4 cm	8 x 8cm	Leica GPS1200	≤ 10 km/h	MIRAsoft

Table 3.1b Measurement specifications for magnetic surveys conducted.

Sytem	Sensor type	Sensitivity	Nr. of Sensors	Measurement frequency	Resolution	Resampling rate	GPS System	Survey Speed	Aquisition Software
Förster PNC	FerexCON650	0.1 ntesla	10	50Hz	25 x 10 cm	10 x 10cm	Javad TRIUMPH-1	≤ 30 km/h	Förster DataServer
EasternAtlas	FerexCON650	0.1 ntesla	8	50Hz	25 x 10 cm	10 x 10cm	Javad TRIUMPH-1	≤ 30 km/h	LoggerVIS

The applied GPR devices included a six channel SPIDAR array from *Sensors & Software* and a 16 channel 400 MHz MALÅ Imaging Radar Array (MIRA) from *MALÅ Geoscience*. The higher spatial sampling resolution of the MIRA system was exploited on areas holding a large potential for buried archaeology and previously registered archaeological features (Fig. 3.7).



Fig. 3.7 GPR survey using a 16 channel 400 MHz MIRA with a Leica GPS for data positioning in the immediate neighbourhood of the Gokstad mound

GPR data sets were processed and visualized using the in-house ApRadar software (ZAMG *ArcheoProspections*® / *LBI ArchPro*) developed by Alois Hinterleitner. Applied filters included trace interpolation, time-zero corrections, band-pass frequency filtering, spike removal, de-wow filters, average-trace-removal, amplitude-gain corrections, amplitude balancing and Hilbert transformation. Data were interpolated into a georeferenced 3D data block and subsequently sliced into depth-slices of 5, 10, 20, 30, 40 and 50 cm thickness and displayed as grey-scale TIFF images. For time-to-depth conversion a constant velocity of 8cm/ns was used based on moveout hyperbola velocity analysis and fitting carried out in *ReflexW*. The velocity of the GPR signal, however, is dependent on the spatially variable physical properties of the subsurface and therefore may vary laterally and vertically ($\pm 50\%$).

Magnetometry data sets were acquired using an eight channel Förster PNC system and a 10-channel EasternAtlas EAL digitizer system both mounted on non-magnetic trailers. Data sets were processed and visualized using the in-house ApMag software (ZAMG *ArcheoProspections*® / *LBI ArchPro*) developed by Alois Hinterleitner. Filters applied included

line-shift and sub-grid balancing, displacement corrections, spike removal, noise reduction, data interpolation, band-pass filter, as well as adaptable background removal for suppression of the disturbing effects caused by the survey tow-vehicle. Additionally images were Wallis filtered to minimize the geological influence and to enhance image contrast. Subsequently optimized sets of georeferenced grey-scale images using different magnetic data clip-off ranges were produced. It should be noted, that the geophysical prospection data were processed for archaeological purposes. GPR and magnetometry data sets were integrated with aerial photographs, ALS data, soil maps, geological maps and historical cartographic maps in the framework of a geographical information system (*ESRI ArcGIS 10.2*) for analysis and interpretation. Selected GPR data were three-dimensionally visualised using *AVS/Express 7.3*. Two-dimensional analysis of selected radargrams was conducted in *ReflexW*. Sea-level reconstructions for the Viking Age are based on raster classification of modern topographical data (2008 by the Norwegian Mapping Authority with 0.5 m resampling rate) and assume mean sea-levels during the Viking Age between 3.4 – 4.0 m above current sea-level based on Sørensen et al. (2007). For geoarchaeological evaluation of the identified palaeoenvironmental structures and patterns, additional sedimentological data were collected by augering conducted during three fieldwork campaigns in 2012 and 2014. Cores 4019, 4022-24 and 4026 were recovered using a gouge auger with 2.5 cm diameter, while core 4006 was retrieved with a soil core sampler with 5 cm diameter. Analyses included stratigraphic observations and sediment descriptions in the field (Hodgson and Avery, 1976) as well as grain size distribution using a *mastersizer 3000* based on laser diffraction measurements conducted at the University of Reading. Grain size classes were defined based on the International Scale ISO 14688-1. These data were further analysed and visualised using *Rockworks 15* software.

3.5. Results

Palaeoenvironmental analysis and interpretation of GPR and magnetic data sets revealed palaeo-hydrological, palaeo-topographical and palaeo-coastal information. Anomalies,

structures and patterns are described in detail below. The interpretations of the geophysical prospection data were evaluated by augering at selected locations.

3.5.1. Palaeo-coastal information

In the southern part of *Heimdaljordet*, close to the newly discovered traces of a Viking Age settlement and corresponding burial mounds, the high-resolution GPR data showed a striking irregular curved and banded pattern of alternately strongly reflecting and absorbing areas, beginning at a depth of approximately 20 cm, just underneath the by ploughing mixed topsoil, and remaining partially visible down to a depth of 2.4 m (Fig. 3.8).

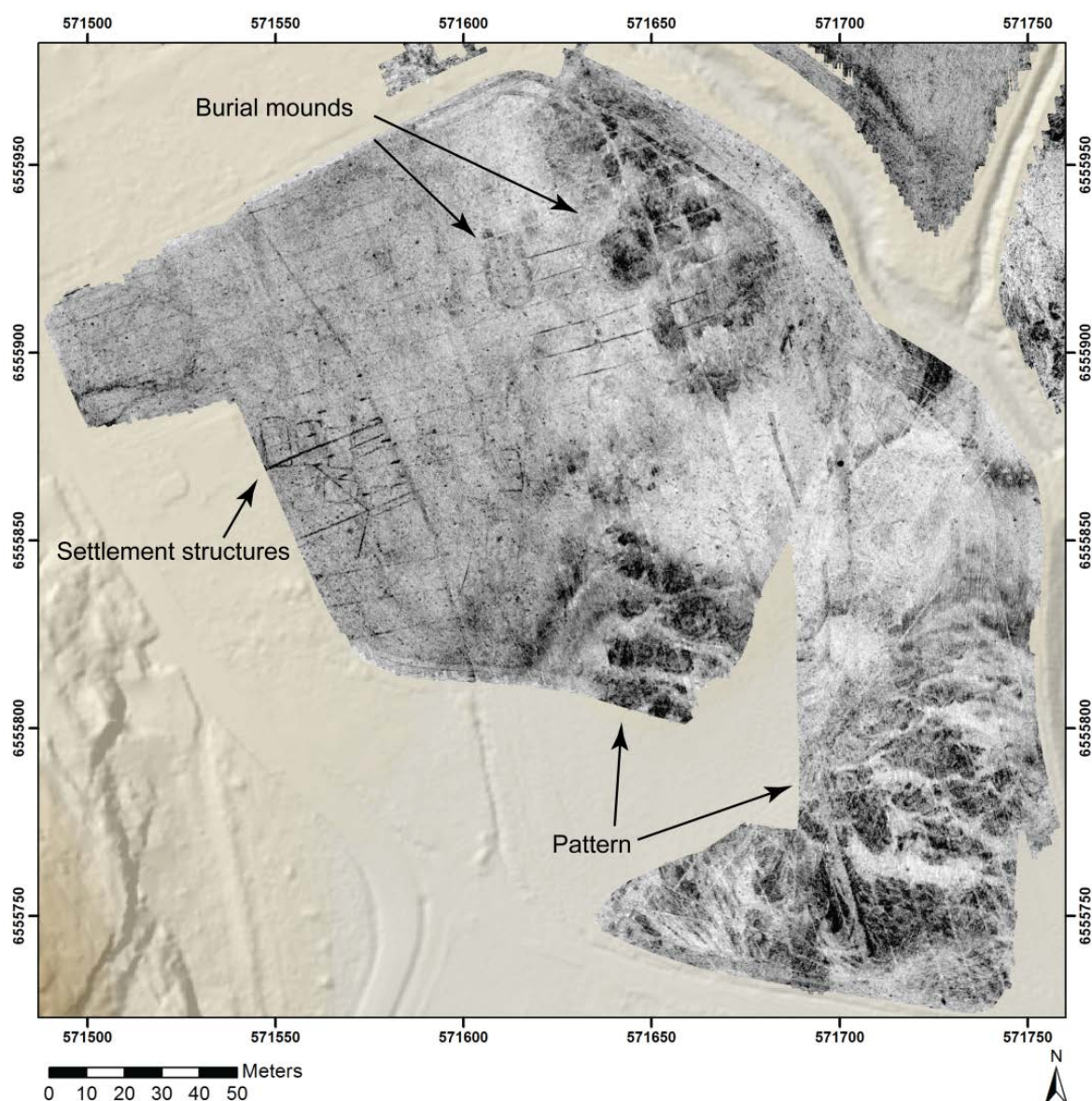


Fig. 3.8 GPR depth-slice (ca. 60-80 cm BGS) of *Heimdaljordet* displaying rectangular and round features interpreted as parts of a Viking Age settlement and a burial site. The southern part of this area is covered in a striking pattern of alternating strongly reflecting and absorbing layers

This pattern covers an area of ca. 1.7 ha with relatively clear boundaries towards the northern part of *Heimdaljordet*. Boundaries towards the south, east and west cannot be established based on the data available, but presumably the pattern is continuing in these directions. In the north-eastern area, a small meandering stream (ca. 3 m width) cuts through these deposits (see below). Between ca. 20-40 cm below BGS, the pattern shows irregular ramified areas of absorbing nature embedded in a reflective matrix. This pattern

intensifies with depth and is well developed between 60 and 80 BS cm. Between 80 and 100 cm BGS the pattern transforms into a more banded appearance and eventually, between 100 and 120 cm BGS, the ramifications dissolve into very fine curved layers of absorbing and reflective nature. This process is particularly noticeable when viewing the GPR depth-slices in quick succession in form of an animated slide-show, which also demonstrates a southwards dipping of these layers towards today's shoreline. Such movement usually occurs when layering in the subsurface deviates from the current topography, leading to the depth-slices cutting through the former surface gradient. Although this behaviour could be suppressed by applying topographic correction to the GPR data, it yields information about the palaeo-topography. These observations, its geomorphological location in the valley and slightly above present day coastline, together with the fact that the magnetometry data did not pick up this pattern, aided in the interpretation of the finely banded sediments as sandy beach deposits (Fig. 3.9).

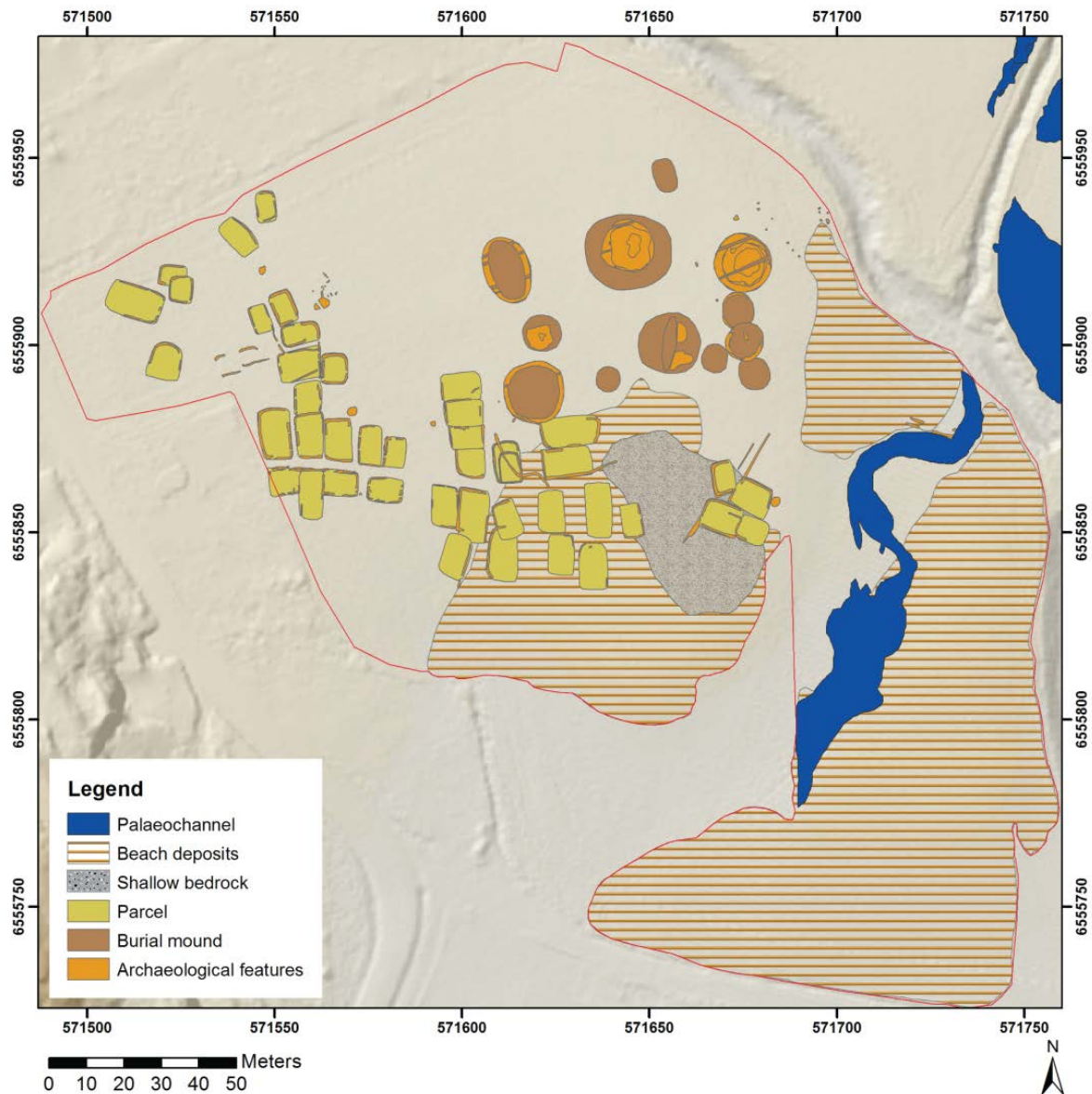


Fig. 3.9 Palaeoenvironmental interpretation illustrating beach deposits cut by a stratigraphically younger palaeochannel with integrated archaeological features in the west

The presence of arenosol at this location, which forms on sandy deposits, further supports this interpretation (IUSS 2006, 2007 Skog og landskap, WMS Jordsmonn). In order to preliminary test these findings, a simplified sea-level reconstruction based on raster classification was applied to the topography model at *Heimdaljordet* using an assumed mean sea-level of 3.6 m for the Viking Age (ca. AD 800) (Sørensen et al. 2007), which shows an overall match between modelled Viking Age shoreline and the observed pattern. Based on

these findings, the pattern was interpreted as palaeo-beach deposit displaying an alteration of fine and coarse sandy material (Fig. 3.10 and 3.11).

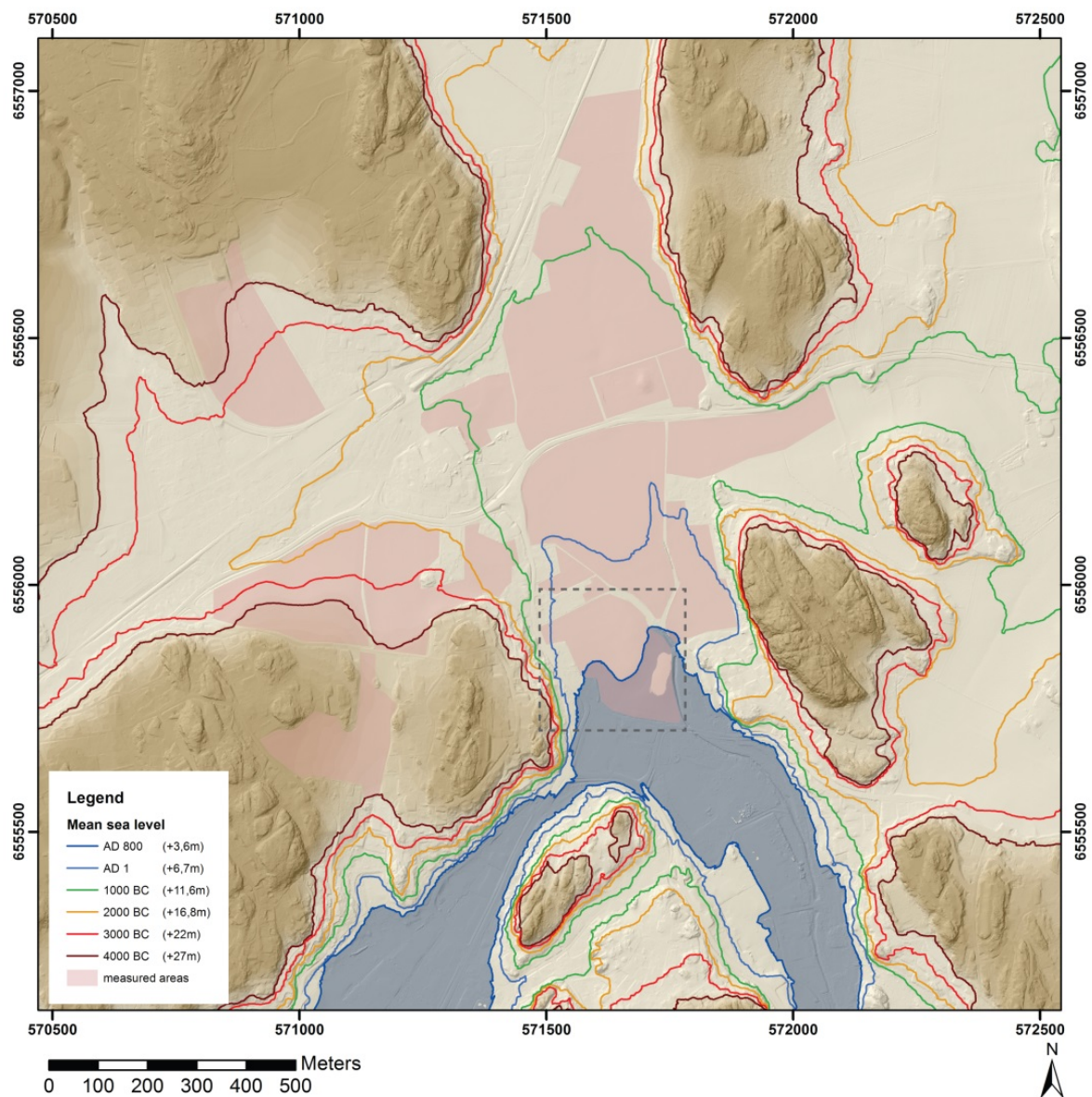


Fig. 3.10 Sea-level reconstructions based on raster classification of topographic data (5 m DTM) for the Gokstad area from 4,000 BC until AD 800. Dashed square indicates the location of Fig. 3.11

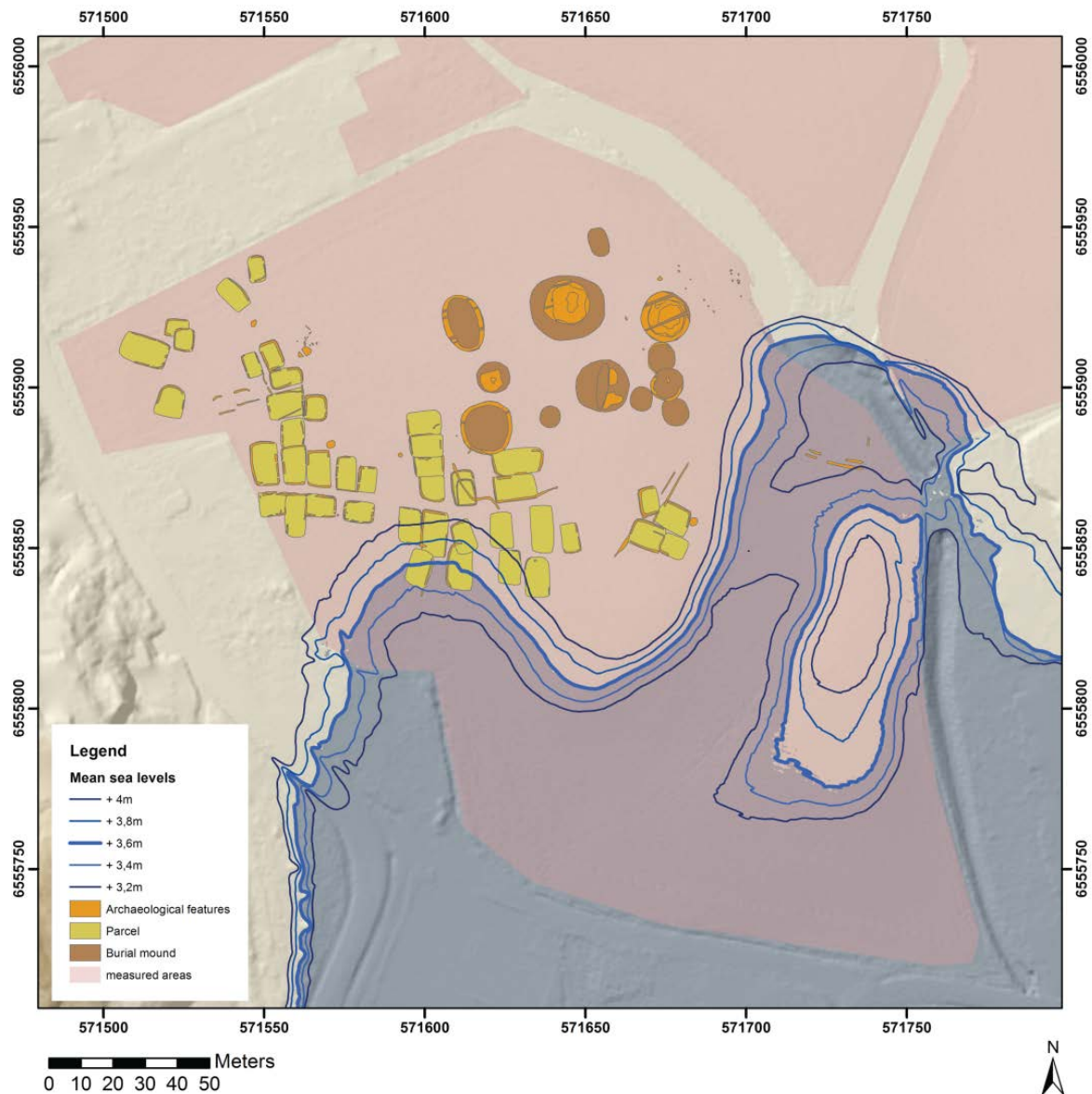


Fig. 3.11 Calculated shore line range, based on present day topography, for the Viking Age (3.4 – 4.0 m above current sea-level (Sørensen et al. 2007) at *Heimdaljordet* illustrate that the settlement has been built close to the shoreline

For evaluation purposes, a core sample (4006) was retrieved from a location amidst the observed coastal deposition pattern down to a depth of 2.40 m (Fig. 3.12). In total, 22 different layers were observed, with some units as thin as 1 cm (Table 3.2). Texture varied from very fine, well sorted to coarse, poorly sorted sands. Boundaries appeared sharp and units were easily distinguishable. Plant macrofossils discovered in unit 5 were broadly identified as marsh plants, indicating change from marine to terrestrial conditions. Grain size

distribution of material <2 mm confirmed the alternation of coarser and finer grain size fractions in successive layers, and together with a varying amount of organic material correlates with the reflective and absorbing properties observed in the GPR data set. Surprisingly, units 16, 18 and 19 are very heterogeneous with unit 19 containing clearly visible persevered plant material. Units 5, 7, 11 and 16 contained material >2 mm and therefore could not be measured using the laser granulometer. Since the amount of sample material was too small to yield statistically significant results for the sieving method, grain size distribution was estimated based on macroscopical examination aided by a hand lens and grain-size distribution chart.

Table 3.2 Sediment descriptions of evaluation cores and observed layers

Core	Unit	Thickness (cm)	Texture	Upper Boundary	Sorting	Stoniness	Moist colour	Comments
4006	1	0-23	silty sand	sharp, straight	/	1%, very small stones, subangular	dark olive brown (2.5Y 3/3)	topsoil
	2	23-31	fine sand	sharp, straight	/		very dark greyish brown (2.5Y 3/2)	topsoil, heterogeneous, lenses of humic material, mottled
	3	31-54	silty sand	sharp, straight	/		very dark greyish brown (10YR 3/2)	heterogeneous, lenses of medium sand
	4	54-64	medium sand	sharp, straight	well sorted		dark greyish brown (2.5Y 4/2)	beach deposit
	5	64-65	macrofossils	sharp, straight	/		black (10YR 2/1)	intertidal deposit, plant macro fossils,
	6	65-70	coarse sand	sharp, straight	well sorted moderately		dark olive brown (2.5Y 3/3)	beach deposit
	7	70-96	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit
	8	96-100	fine sand	sharp, straight	well sorted moderately		dark grey (2.5Y 4/1)	beach deposit
	9	100-108	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit
	10	108-109	fine sand	sharp, straight	well sorted moderately		dark olive brown (2.5Y 3/3)	beach deposit
	11	109-112	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit
	12	112-113	fine sand	sharp, straight	well sorted moderately		dark olive brown (2.5Y 3/3)	beach deposit
	13	113-118	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit, thin layer of Fe precipitation at the boundary to beach deposit, fine laminations indicating different depositional
	14	118-128	fine sand very fine	sharp, straight	well sorted very well		dark olive brown (2.5Y 3/3)	
	15	128-140	sand	sharp, straight	sorted moderately		black (2.5Y 2.5/1)	beach deposit
	16	140-160	coarse sand very fine	sharp, straight	sorted very well		dark greyish brown (2.5Y 4/2)	beach deposit, heterogeneous, lenses of fine sand (2.5Y 2.5/1)
	17	160-175	sand	sharp, straight	sorted moderately		black (2.5Y 2.5/1)	beach deposit, some mottling
	18	175-218	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit, heterogeneous, some lenses of fine sand (2.5Y
	19	218-219	fine sand	sharp, straight	well sorted moderately		black (2.5Y 2.5/1)	beach deposit
	20	219-221	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit
	21	221-222	fine sand	sharp, straight	well sorted moderately		black (2.5Y 2.5/1)	beach deposit
	22	222-240	coarse sand	sharp, straight	sorted		dark greyish brown (2.5Y 4/2)	beach deposit

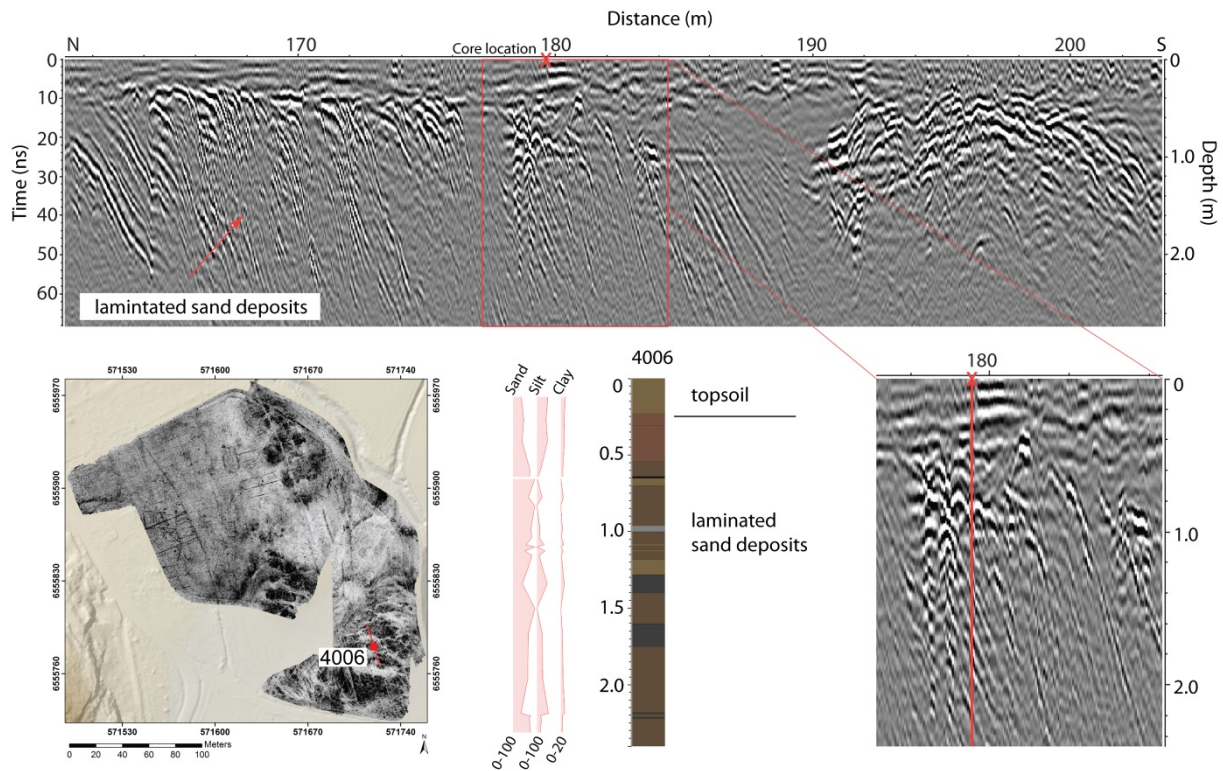


Fig. 3.12 The radargram above clearly illustrates the fine, slightly dipping layers interpreted as beach sediments composed of sandy material. The grain size distribution of core sample 4006 reveals alternating layers with varying amounts of fine and coarse clastic sediment, which are visible in the GPR as reflective and absorbing properties. Limited congruence between the radargram and the observed stratigraphic units is caused by the maximum vertical resolution (at best 5cm given a 400 MHz GPR pulse and an assumed velocity of 8 cm/ns) of the electromagnetic wave (Bristow and Jol, 2003)

Results of the coring and sedimentological analyses support the findings from the palaeoenvironmental analysis. The integration of both data sets identifies the pattern as beach sediments, probably beach face deposits, which are a part of the foreshore sediments of a beach, characterised by gently sea-ward dipping ($2-10^\circ$) and parallel lamination (Komar, 1998). The fine lamination seen in the GPR data sets represent the alternation between coarse and fine sands, which speaks for different depositional events of varying energy, possibly reflecting changes in clastic input, wind direction and wave strength (Yoshiki, 2005). The lower units seem to have been formed by a different process as is indicated by the higher organic content and especially the preserved plant remains. A local marine transgression cannot be ruled out and more detailed investigations on this matter are currently being conducted (Cannell, forthcoming; Macphail et al. 2013). The irregular pattern

displayed in the upper 60 cm, however, demands a different interpretation and might be connected to backshore sediments, the formation of successive berms caused by the marine regression and subsequent marshland formation. Sea-level oscillations by storm actions and/or high tides as well as an estuarine situation, where fluvial sediments intermix with beach deposits (Syvitski and Shaw, 1995) only present two possible scenarios that could have led to the observed irregular pattern. Further investigations, including the study of organic and water content, geochemical analyses, but especially macro- and microfossil analyses are required in order to investigate the palaeoenvironmental history of this part of the coast in more detail.

3.5.2. Buried bedrock

Buried bedrock describes a solid dense rock, covered under shallow (< 3 m) overburden comprising unconsolidated sediment and soil. In the study area buried bedrock is relatively abundant on the sloping fields, but also present in the lowlands. In the GPR data sets, buried bedrock almost always is coated by a thin, strongly reflective band, believed to originate from a strong reflection of the electromagnetic wave at the transition between solid bedrock and unconsolidated sedimentary material. When measuring across the feature, this strong reflection virtually coats the geological body, appearing as contour lines of the bedrock's shape in 2D GPR depth-slices. The actual rock itself is characterised by an absence of reflections due to its relative homogeneity, and the reflection of a large amount of the electromagnetic energy at its surface. Buried bedrock is easily detectable in a depth-slice animation by its glassy, bubbly appearance. In the geomagnetic data sets, buried bedrock can create strong magnetic dipole anomalies (e.g. red area in Fig. 3.6) while masking large areas – a frequent issue encountered in Norway. The geology in the Gokstad area consists of monzonite and quartz monzonite, which can contain magnetite and iron ore (1 %) as accessory minerals (Sørensen, 1988).

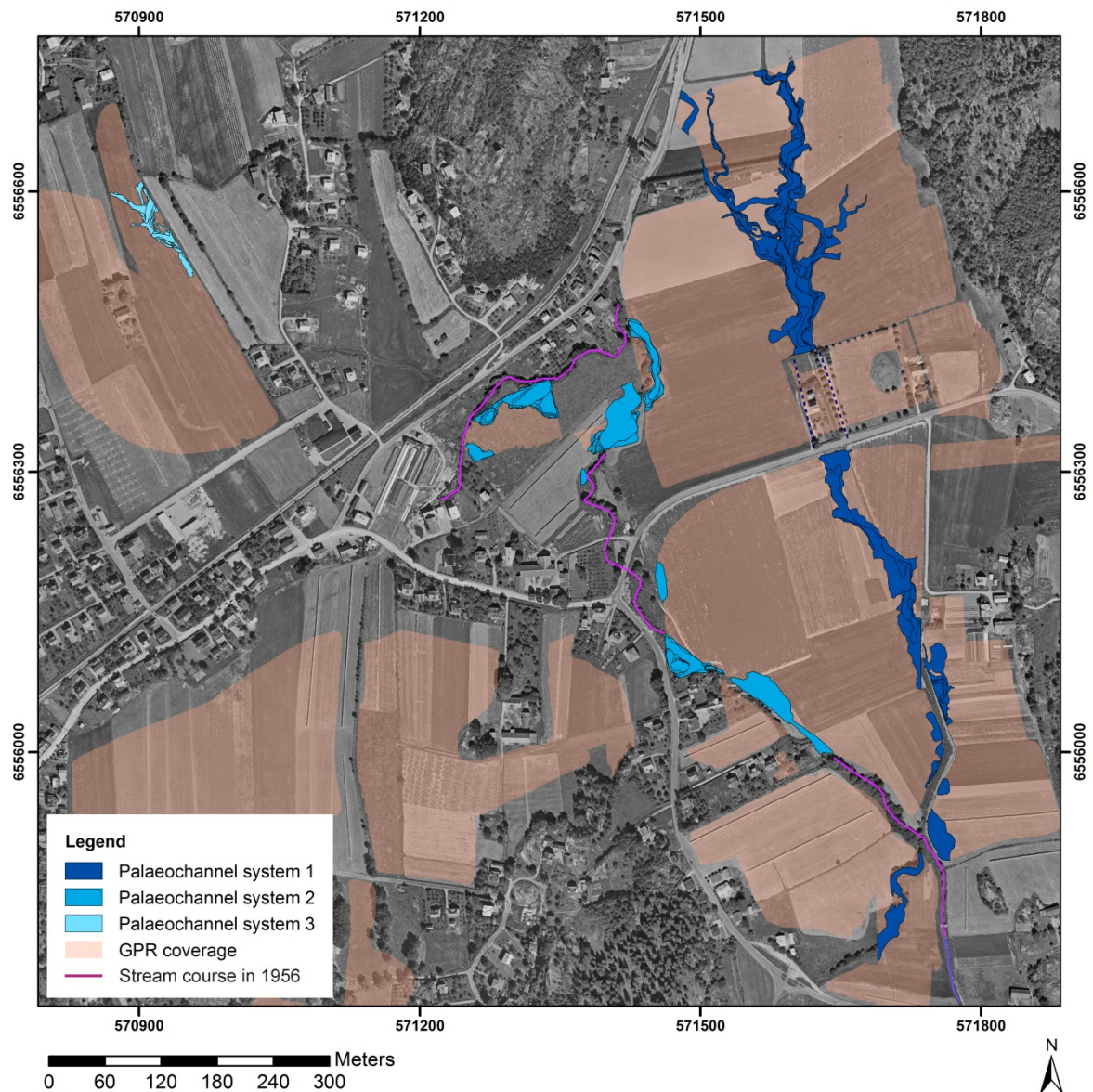


Fig. 3.13 Palaeochannel systems 1, 2 and 3 superimposed onto an aerial orthophoto taken in 1956 (basis: Norge I Bilder, Norwegian map authorities, Geovekst and Municipality, resolution 20 cm), before the stream courses were regulated. Note the slight differences between locations of the palaeochannels based on the geophysical prospection data sets and stream courses in 1956 (pink line) caused by lateral channel migration

3.5.3. Hydrological information

Palaeochannel systems (1, 2 and 3) feature prominently in the GPR data sets at Gokstad (Fig. 3.13), whereas the geomagnetic data sets not-surprisingly contribute little hydrological information. Palaeochannels are for the most part only faintly visible in the magnetometer data sets as negative anomalies when superimposed on the GPR data.

The largest dendritic drainage pattern with at least two tributary channels (palaeochannel system 1) runs through much of the valley and southwards (Fig. 3.14) to *Heimdaljordet*. This feature is partially still visible as shallow depression in today's topography. Close to the Gokstad mound, the channels are disturbed by a modern pipe observable in both GPR and magnetic data sets, which must have been buried before 1956 for regulation purposes (www.norgeibilder.no) (Fig. 3.14d).

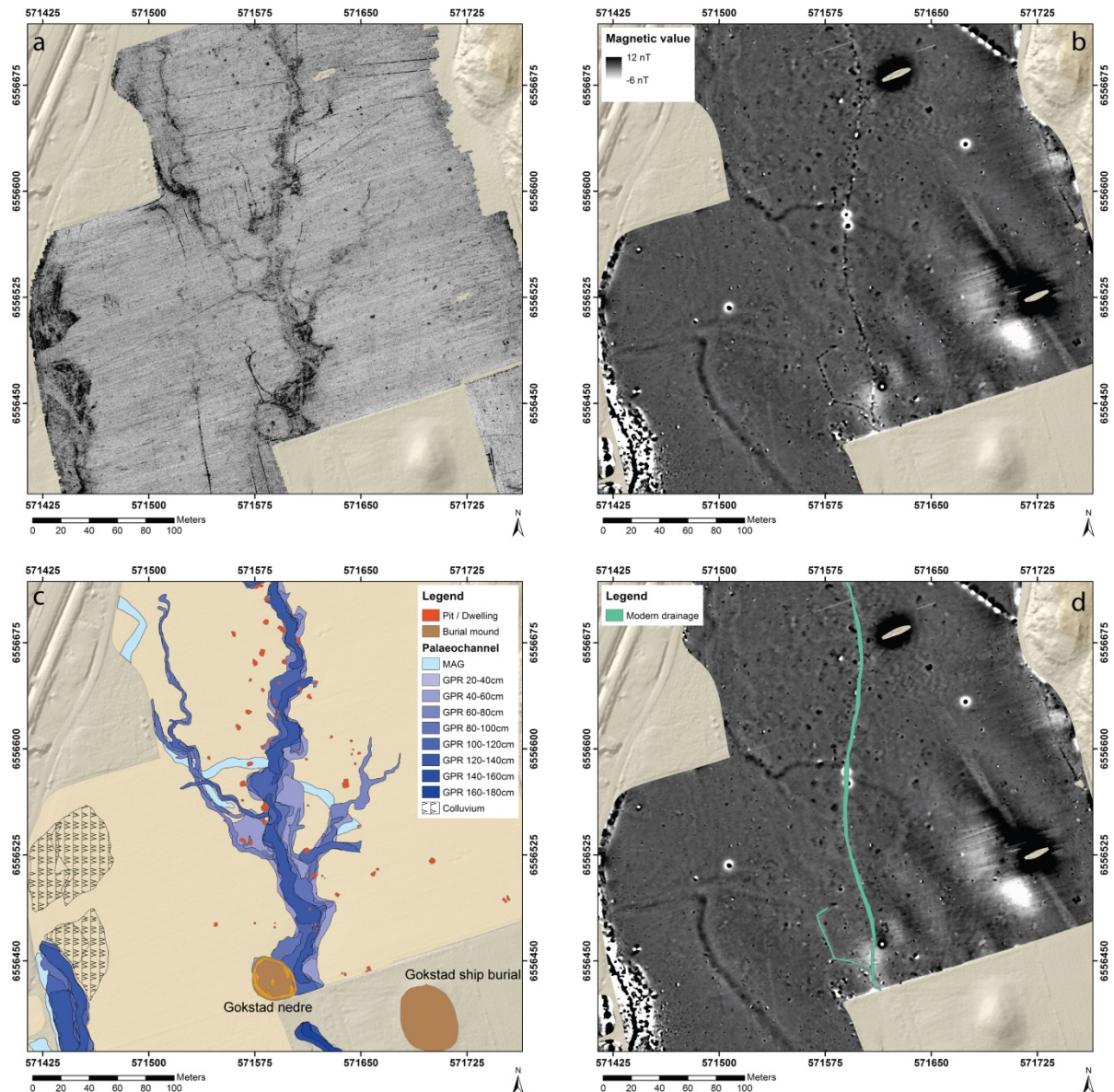


Fig. 3.14a Palaeochannel system 1 featuring two tributary channels is easily identifiable in the GPR depth-slice (60-80 cm BGS), where it overlaps with remains of *Gokstad nedre* burial mound. 3.14b The meandering channel system is only faintly visible in the magnetometry data set of the same area. 3.14c Integration of archaeological and palaeoenvironmental information based on GPR and magnetometry surveys. 3.14d Interpretation of the modern drainage pipe installed after 1956, which is clearly visible in the magnetic data as linear anomaly with alternating polarization (most likely ceramic pipe)

Between 40 and 60 cm BGS, channels first become noticeable in the GPR data sets as absorbing areas. At its widest part, the area affected spans 24 m and encompass several channels, with individual channels as narrow as 1 m. The visibility of the channels increases as properties shift to reflective appearance between 60 and 80 cm depth; the width

decreases to 18 m. At ca. 120 cm depth, tributary channels disappear with the stream bed narrowed (max. ca. 6m) to a few channels.

North of the Gokstad mound, the palaeochannel system 1 overlaps with the remains of *Gokstad nedre* burial mound (Askeladden ID 12256, <https://askeladden.ra.no/askeladden/>), which is surrounded by a ring ditch and not to be confused with the nearby main Gokstad mound. The ditch starts to become visible between 40 – 60 cm depth BS and ceases between 100 – 120 cm depth BS, whereas the palaeochannel appears between 60 – 80 cm depth BS and disappears at around 140 cm depth BS. The *Gokstad nedre* burial mound was known from aerial pictures; however, its superposition with the palaeochannel went unnoticed prior to the geophysical survey, and then immediately raised questions whether the channel existed before the construction of both burial mounds. Establishing the relative-chronological relationship between the archaeological and the palaeoenvironmental feature became significant for the understanding of the archaeological landscape at Gokstad (see discussion). The analysis of the 2D GPR depth-slices did not bring a definite answer to this (Fig. 3.15a). Data were therefore rendered as colour-coded volumes and this visualisation strongly indicates that the palaeochannel is very likely to have been older than *Gokstad nedre* burial mound (Fig. 3.15b). In order to test these findings, a sample core (4019) was taken at the intersection between the palaeochannel and the surrounding ditch of *Gokstad nedre* burial mound, as derived from the detailed GPR data set (Fig. 3.16).

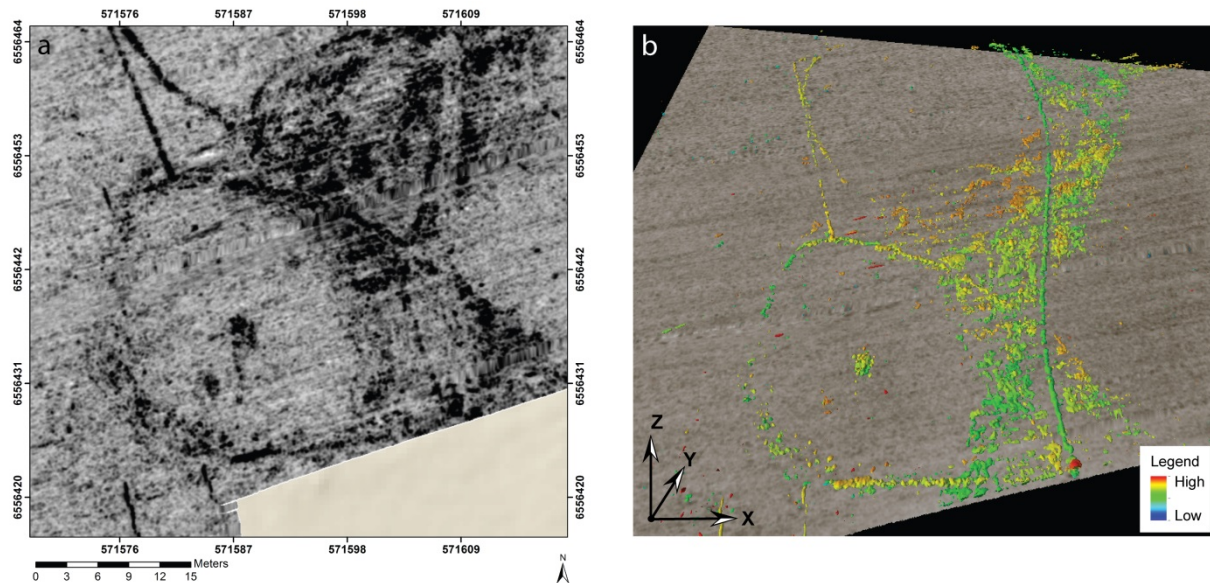


Fig. 3.15a GPR depth slice displaying the intersection of palaeochannel system 1 with the burial mound *Gokstad nedre* at 65 – 70 cm BGS. 3.15b 3D volume rendering of the corresponding GPR data color-coded according to depth, which supports the superposition of the ditch surrounding the burial mound compared to the palaeochannel

Seven different layers were identified during the stratigraphic analysis of the core (Table 3.3). At ca. 67 cm depth BS a poorly sorted, relatively loose unit consisting of silty sand and very small, subangular stones is interpreted as the infill of the ring ditch, reaching down to ca. 95 cm depth BS. This unit is followed by a poorly sorted, ca. 50 cm thick unit of silty sand, associated with the channel infill. Units 5 and 6 are associated with marine sediments due to their reduced nature and well sorted, fine texture. Superimposing the core stratigraphy onto the radargram (Fig. 3.16) shows a clear congruence and supports the results of the volumetric analyses of the channel system existing before the construction of the mound – an observation with far-reaching consequences for the Viking Age landscape. Along palaeochannel 1, magnetic anomalies with an approximate square base of 4x4 m were detected close to the Gokstad mound and interpreted as either large pits or, less likely, dwelling houses, whose function might be connected to the stream (Fig. 3.14c). Anthropogenic interference is also evidenced by a series of un-interpreted constructions visible in the GPR data sets between 40 – 120 cm depth BS overlapping with the palaeochannel system 1. A disturbance in the southern part of the same area shows

absorbing properties (60 – 80 cm depth BS), and is further supported by a strong dipole anomaly clearly visible in the geomagnetic data.

Table 3.3 Sediment descriptions of evaluation cores and observed layers

Core	Unit	Thickness (cm)	Texture	Upper Boundary	Sorting	Stoniness	Moist colour	Comments
4019	1	0-29/36	clayey silt	sharp, tilted	/		dull yellowish brown (10 YR 4/3 grayish yellow (10YR 4/2) dark greyish	topsoil
	2	29/36-53	silty sand	sharp, tilted	well sorted			
	3	53-65/69	silty sand	sharp, tilted	well sorted		brown (2.5 Y 4/2) dark yellowish	gleyed with large, distinct mottles
	4	65/69-95	silty sand	/	poorly sorted	2%, very small stones, subangular	brown (10 YR light yellow	ditch, gleyed with large, distinct mottles, moist
	5	95-147	silty sand	clear, straight	poorly sorted	<1% small stones, subangular	orange (10 YR	palaeochannel, gleyed with mottles, clay lenses
	6	147-170	silty clay	clear, straight	sorted very well	<1% small stones, subangular	gray (5 Y 4/1)	intertidal/marine?, gleyed, moist
	7	170-200	silty clay	/	sorted	<1% very small stones, subangular	gray (5 Y 4/1)	intertidal/marine?

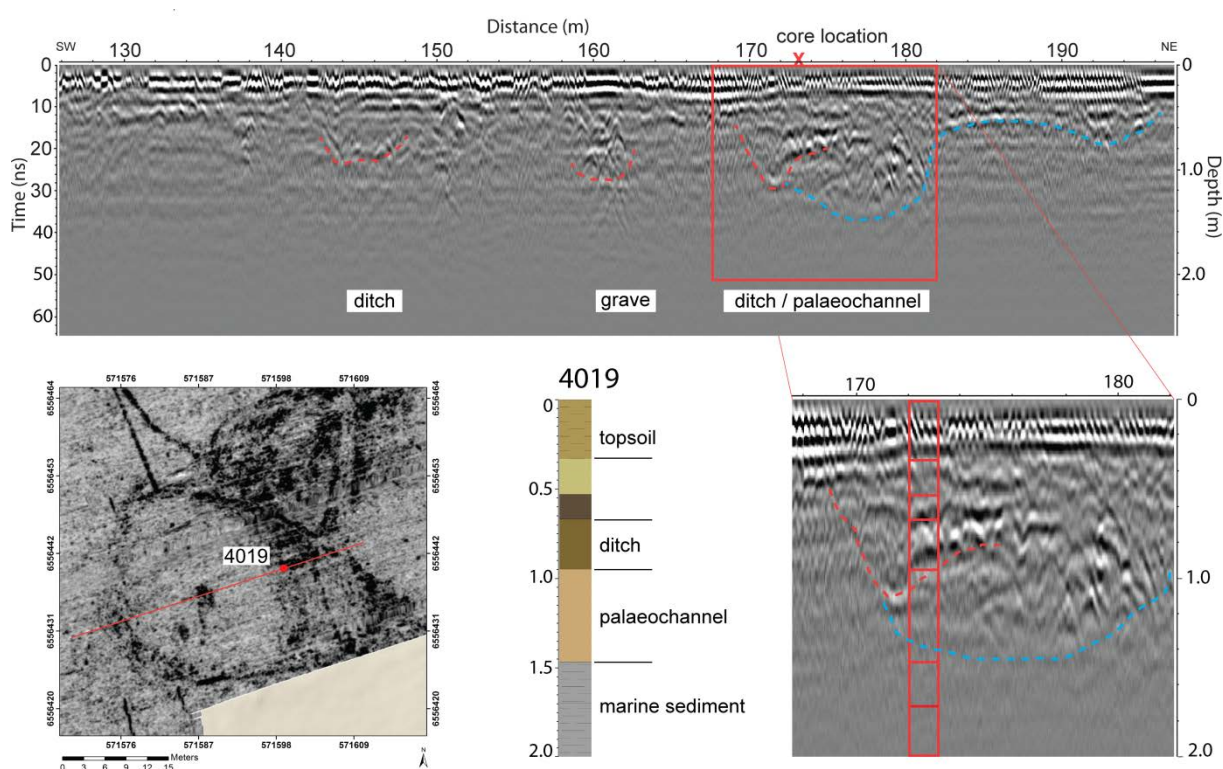


Fig. 3.16 The radargram shows both the ring ditch and the grave of *Gokstad nedre* burial mound. Note the intersection of the eastern ditch section with the palaeochannel. The magnification shows congruence of core stratification (4019) and reflectors at the boundaries of ditch and palaeochannel, before the electromagnetic energy attenuates in the finer, moist marine sediment

Faint traces of a narrow palaeochannel (max. ca. 3.5 m wide) were detected in *Heimdaljordet* (Fig. 3.9), and are attributed to palaeochannel system 1. This part of the channel is intersecting the coastal deposits and therefore stratigraphically younger. An aerial picture from 1956 shows a meandering stream with a belt of trees along its banks, which provides a *terminus post-quem* for its regulation and explains why the stream bed is still well visible in today's topography.

Palaeochannel system 2 crossed areas to the west of Gokstad mound and probably joined palaeochannel system 1 close to *Heimdaljordet* (Fig. 3.13). This system was regulated and the areas subsequently converted into a dirt road at some point in time after 1956, which explains why its traces are inconclusive and only partially visible in the GPR data. Reflective layers can be seen from around 20 cm depth BS and cease at ca. 160 cm depth BS.

Palaeochannel system 2 deviates from the unregulated stream visible on the aerial picture from 1956, probably due to lateral migration of the channel. The complementary use of magnetometry proved significant here, with the magnetogram showing many small dipole anomalies in the area of the stream, which is largely coherent with reflective areas in the GPR data. Such anomalies were observed as well at other sites in Norway (McGraw and Bill, 2014) and established to have been caused by accumulations of magnetic cobble stones and boulders, cleared by farmers and re-deposited on non-arable land, such as forested areas or (former) channel incisions (personal communication Christer Tønning 2014).

Palaeochannel system 3 was detected on sloping terrain in the western part of the survey area. The remains of the meandering stream are only partially visible at the eastern edge of the survey area on the sloping areas (Fig. 3.13) between 40 and 180 cm depth BS with a maximum channel width of ca. 4.7 m.

3.5.4. Palaeo-topographic information

Complex patterns found in both magnetometry and GPR (Fig. 3.17) data sets are frequently observed at Norwegian survey sites. These patterns mainly occur on steeper terrain and in sloping areas as evidenced in geophysical data sets obtained from Slagendalen and Tjølling in

the framework of the Vestfold Project (<http://lbi-archpro.org/cs/vestfold>). Although their source has not been known for certain, it apparently is rather of geological and not archaeological nature.

In the western part of the Gokstad area, the collected GPR data featured oval, absorbing areas (each around 3,000 m² in size at 40 – 120 cm depth BS) reminiscent of the gently rolling topography, embedded in a less absorbing matrix (Fig. 3.17b). This pattern becomes even more pronounced by a thin, reflective band (around max. 10 m wide) sloping towards the valley bottom between 20 – 180 cm depth BS. When comparing the GPR data with the magnetic data, large dipole anomalies representing magnetic bedrock buried at shallow depth are roughly congruent with the absorbing areas identified in the GPR data (Fig. 3.17a and b). The positive match between patterns/anomalies and today's topography is further underlined by a slope model, resulting in a picture similar to the one derived from the geophysical data (Fig. 3.17c). The source for the absorbing ovals in the GPR data, however, is not directly the bedrock itself. First, because the characteristic glassy appearance of the corresponding anomalies is absent (see above) and second, because modern buried drainage pipes/systems (visible between 20 – 120 cm depth BS) are embedded within these zones. The pattern is thus understood as rather an indicator for bedrock (Fig. 3.17b), that illustrates a former land surface buried in the course of erosion and accumulation processes. These processes eventually resulted in the rolling lowlands visible today (Fig. 3.17d).

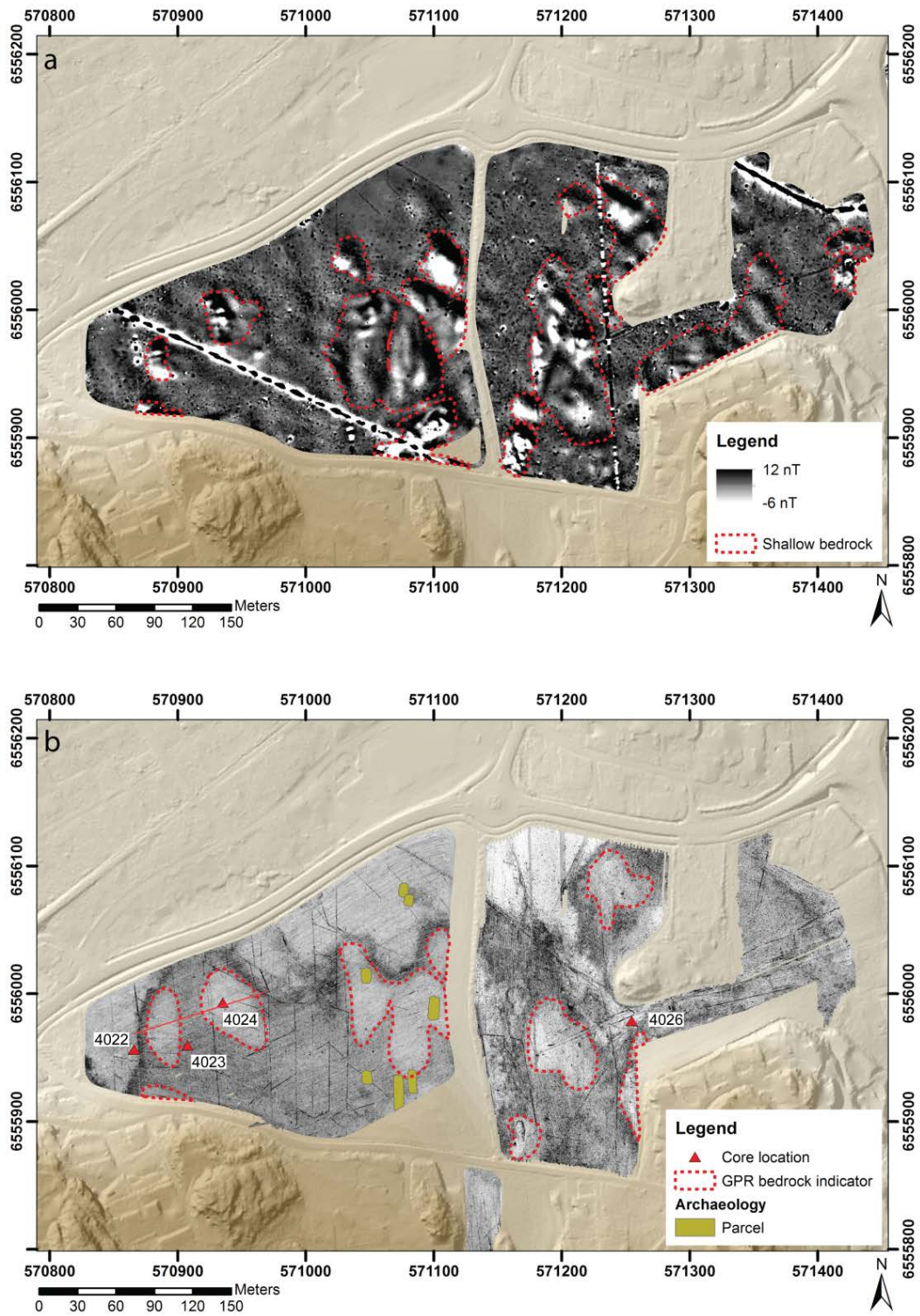
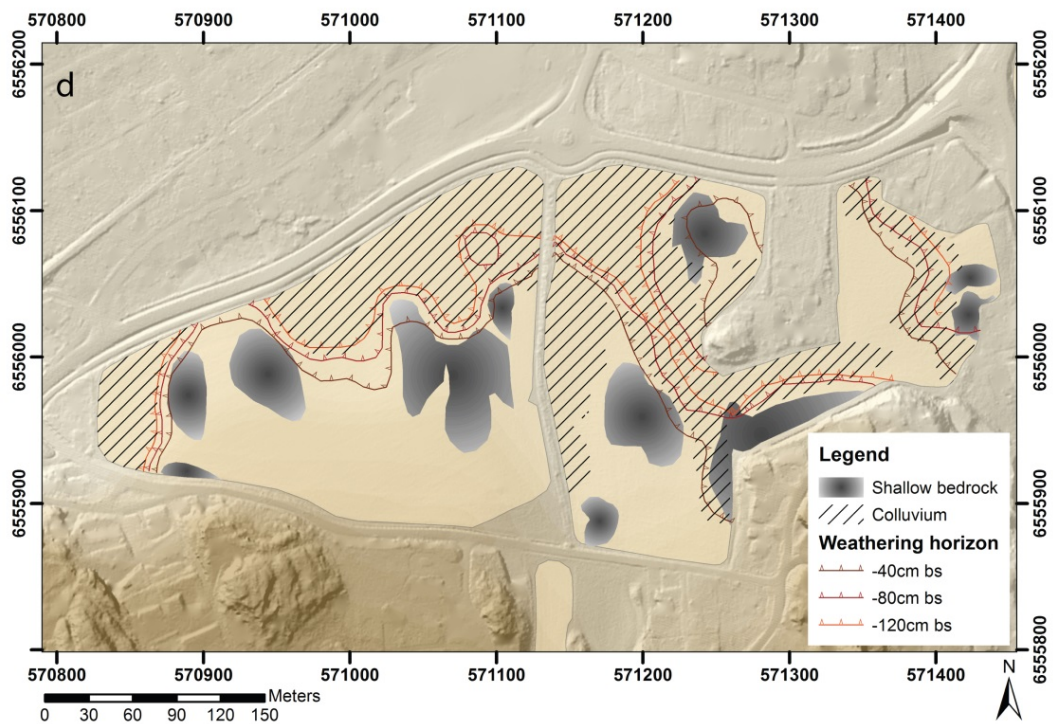
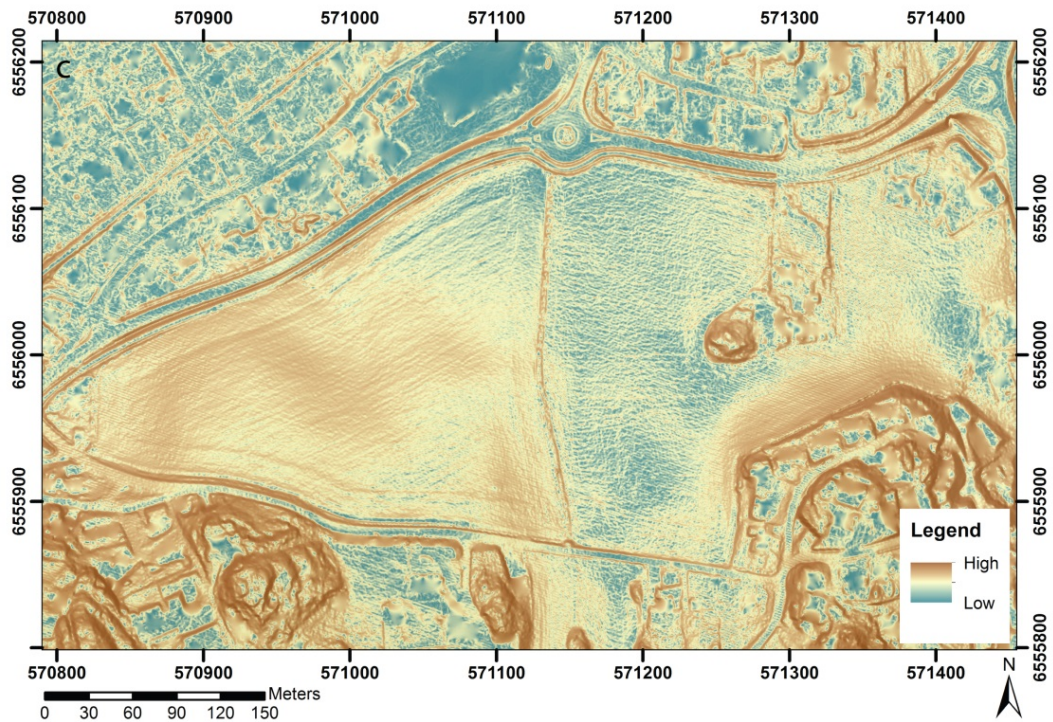


Fig. 3.17a Magnetic data image on the sloping areas in the western part of the Gokstad survey area shows large dipole anomalies caused by magnetic bedrock (outlined in red). 3.17b The same bedrock is displayed in the GPR data as absorbing areas (outlined in red). A strongly reflective band indicates erosion and accumulation processes. Several core locations (4022-4024, 4026) for evaluation purposes were defined based on the GPR data. Note also the archaeological structures detected in the GPR data sets, which are tentatively interpreted as settlement structures



3.17c The slope model highlights the topographic relation of the pattern observed in the geophysical data. 3.17d Palaeoenvironmental interpretation of the features observed in the geophysical data as buried shallow bedrock, colluvium and weathering horizons

In order to probe this interpretation, two cores (4023 and 4024) were taken. Core 4023 was retrieved from a relatively sterile area located in-between cores 4022 and 4024, in order to capture a sedimentological background signal. It comprised four stratigraphical units (0-1.00 m depth BS) mainly consisting of a sandy, poorly sorted soil matrix. It is only in unit 4 (77-100 cm depth BS) that the amount of fine material (silt ca. 40 %, clay ca. 30 %) is higher. Core 4024 targeted the absorbing areas visible in the GPR data and showed four stratigraphic units. Units 2-4 (0.23 – 1.00 m depth BS) contain a high amount of silt (ca. 50 %) and clay (ca. 30 %) (Fig. 3.18 and Table 3.4). Fine material retains more soil moisture and consequently has a higher relative dielectric permittivity. This leads to signal attenuation, which eventually causes the absorbing areas. Unit 4 was interpreted as very homogenous, moist, marine sediment containing the highest amount of silt (57 %) and clay (31 %), covering the bedrock where it reinforced the stagnant effect of the solid geological body. The correlation of the stratification of core samples 4022-4024 illustrates the undulating palaeo-topography, which is also evident in the corresponding radargram, showing magnetic bedrock covered by clay-rich marine sediments. Areas in-between the bedrock were in-filled with colluvial material.

Table 3.4 Sediment descriptions of evaluation cores and observed layers

Core	Unit	Thickness (cm)	Texture	Upper Boundary	Sorting	Stoniness	Moist colour	Comments
4022	1	0-30	clayey sand	sharp, straight	/	<1% small stones, subangular	brownish black (2.5 Y 3/1) dark olive brown (7.5 Y 4/3)	topsoil, moist
	2	30-55	silty sand	sharp, straight	/	2% very small stones, 5% small stones, both	yellowish brown (2.5 Y 5/4)	strong mottling some sample material lost,
	3	55-90	medium sand	/	poorly sorted	5% small stones, both	yellowish brown (2.5 Y 5/4)	indicating large clast sizes and poor weathering product; most sample
	4	90-100	medium sand	/	poorly sorted	subangular	(2.5 Y 5/4)	material lost, indicating large clast
4023	1	0-30	silty sand	abrupt, straight		<1% very small stones, 1% small stones, 2% small stones, olive brown	brownish black (2.5 Y 3/1) (2.5 Y 4/3)	topsoil
	2	30-45	medium sand	/	poorly sorted	subangular	4/3)	
	3	45-77	medium sand	clear, straight	poorly sorted	2% small stones, subangular	yellowish brown (2.5 Y 5/3)	
	4	77-100	medium sand	/	poorly sorted	2% small stones, subangular	yellowish brown (2.5 Y 5/3)	some mottling
4024	1	0-20/25	silty sand	abrupt, tilted		2% small stones, subangular	brownish black (10 YR 3/2)	topsoil
	2	20/25-40	silty sand	clear, straight		1% small stones, subangular	dull yellowish brown (10 YR	
	3	40-55/65	sandy silt	clear, tilted		<1% very small stones, subangular	dull yellowish brown (10 YR	
	4	55/65-100	clayey silt	/			brownish black (10 YR 3/2)	intertidal-marine deposit
4026	1	0-20/30	clayey sand	gradual, tilted		5% small stones, subangular	brownish black (10 YR 3/2)	topsoil
	2	20/30-43	silty sand	abrupt, straight		2% very small stones, subangular	dark brown (10 YR 3/3)	
	3	43-87	silty sand	abrupt, straight		<1% very small stones, subangular	yellowish brown (2.5 Y 5/4)	mottling
	4	87-100	silty sand	/		2% small stones, subangular	olive brown (2.5 Y 4/3)	mottling, moist

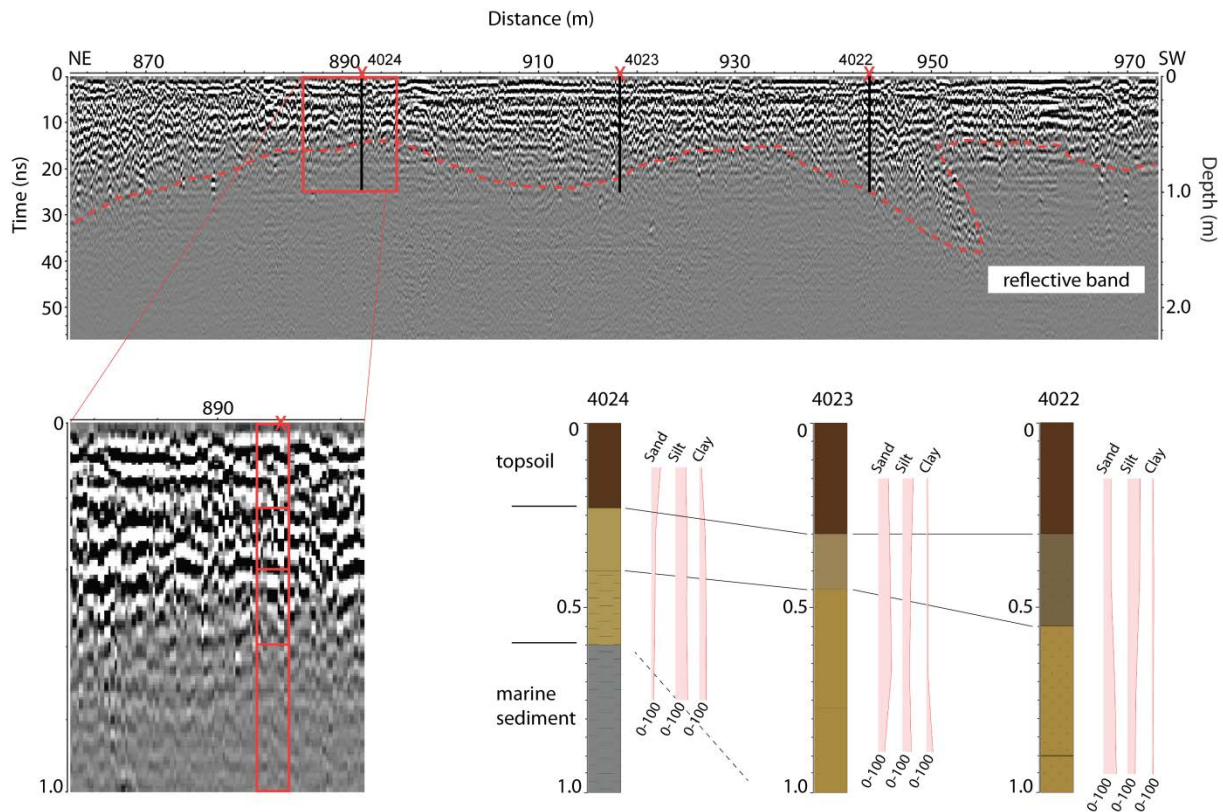


Fig. 3.18 The radargram illustrates the undulating buried palaeo-topography consisting of shallow buried bedrock that is covered by colluvium. The stratification of cores 4022-4024 supports this finding. The position of cores 4022 and 4023 on the radargram is schematic

The reflective band (Fig. 3.17b) is interpreted as grus weathering product. Sørensen (1988) investigated weathering processes of monzonite in the Vestfold area. He described this type of weathering as a surficial phenomenon, which manifests as thin veneers of grus observable mainly on coarse-grained plutonic rock, and is found in Vestfold at different altitudes from hilltops to sloping areas and down to current sea-level, where land was exposed after sea-level retreat ca. 1000 years ago (Sørensen, 1988). At Gokstad, grus seems to accumulate at the foot of the gently rolling topography where it mixes with finer sediment. This might speak for colluvial processes involved, but needs further geological examination. Reflective bands are frequently observed in Norwegian GPR data sets and often occur in conjunction with buried bedrock and steeper terrain (compare data sets from Tjølling and Slagendalen, Province Vestfold). The source of these reflections, though, was unknown until recently. These observations are further supported by the core stratigraphy of 4022, displaying a layer

of medium, poorly sorted sand including 5 % subangular, small pieces of rock at ca. 90 cm depth BS, which matches the reflective pattern of the GPR data at this location.

A similar pattern interpreted as palaeo-topography was observed in a field further towards the east (Fig. 3.17a and b). Particularly noticeable were strongly absorbing areas in the GPR data, interpreted as depressions in-between the bedrock being in-filled by eroded fine, moist material after the land was exposed through sea-level retreat not later than 4.000 BC. This interpretation is supported by the formation of young cambisol roughly matching the in-filled areas (Soil WRB, 2006). Core sample 4026, however, showed four stratigraphic units consisting of a much coarser grain size, mainly silty sand (Table 3.2), than expected, with a clay content of only <12 %. The strong absorption of the radar signals thus may have been caused by elevated soil moisture due to precipitation accumulated in the bowl-shaped depression.

3.6. Discussion and Conclusions

The reconstruction of palaeo-environments is a complex task that requires a combination of different methods from different fields in order to derive a comprehensive picture (Courty et al. 1990; Brown 1997; Dincauze 2000; French 2002; Rapp and Hill 2006), in particular when reconstructing the landscape ascribed to a certain period such as the Viking Age.

The most significant issue regarding palaeoenvironmental information extracted from geophysical prospection data is the lack of a chronological framework. This problem is due to the non-invasive nature of the method, which prevents the extraction of scientifically datable samples, and it also affects the interpretation of prospected and mapped archaeological features. Yet, archaeological features as spatially distinct results of anthropogenic activities can be based on their shape, orientation and distribution often be associated with a particular archaeological period. In contrast, palaeoenvironmental structures formed by natural geological processes as part of dynamic systems spanning different time scales – from days or years to centuries or millennia – present an entirely different type of information. The situation is further complicated by the often continuous

nature of palaeoenvironmental information: structures and patterns detected in geophysical data sets can indicate rather geomorphological processes than represent a temporally well-defined structure – as exemplified in the Gokstad data sets by the palaeo-topographic traces and the beach deposits. These differences complicate the integration of palaeoenvironmental and archaeological data, particularly when using a chronological concept designed solely for the archaeological record. Another important observation is that palaeoenvironmental structures can exert a strong influence, rendering them relevant to the interpretation of archaeological landscapes long after the initial geomorphological process that created them has become inactive. Examples are soil formation processes, drainage or erosion and accumulation patterns.

In order to overcome this limitation, invasive dating techniques of palaeoenvironmental structures and patterns, including optical, radiometric or in certain cases dendrochronological dating techniques (Rapp and Hill, 2006), certainly would present an option in order to establish a robust chronological framework for data integration. However, this approach in some cases may offer only a limited temporal resolution, which might prove problematic when applied to a relatively narrow time period such as the Viking Age (793 – 1066 AD).

Even though geophysical data sets do not provide absolute dates, they can hold relative chronological information, which can aid in establishing a sequence of events even without a robust scientific dating strategy in place. At Gokstad, a number of basic spatio-temporal observations could be made based on sea-level retreat and subsequent shoreline displacement, which provided a *terminus post-quem* for archaeological and palaeoenvironmental features. These observations helped in providing a coarse chronological framework of absolute dates and shed light on certain stages in the development of the landscape.

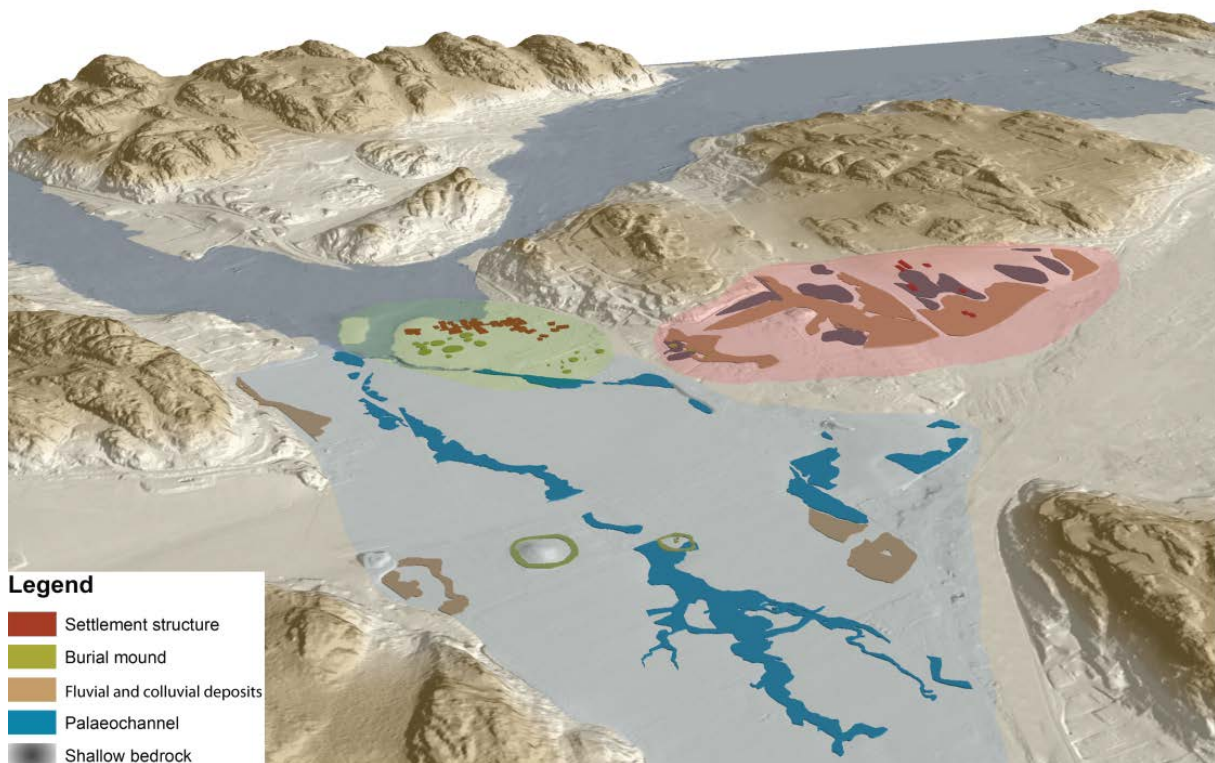


Fig. 3.19 3D reconstruction of the Gokstad area with sea-level reconstruction (at 3.6-4.0 m asl) and integrated archaeological and palaeoenvironmental features (view towards southwest). This study resulted in different zones emerging with a concentration of archaeological remains at the Viking Age shoreline (green), while structures in the dried up fjärd (blue) so far seem to have been limited to few burial mounds. The slope areas (red) provide a more complex picture with settlement traces possibly dating to the Viking Age, that have yet to be subjected to more detailed archaeological investigations. A use for activities that only left elusive physical traces in this zone, such as pasturing or agriculture, might present an additional option

Landscape development

Between 5000-4000 BC the post glacial rebound of the Scandinavian shield first exposed the upper parts of the slope areas in the Gokstad area from the sea. It took another two millennia (until 2.000 BC) before the shoreline first reached the lower areas. At the time of exposure, some parts of the bedrock must have still been covered by marine sediment, as indicated by the analysis of the GPR data and proven by the coring results. However, over time, wave action and currents along the shoreline partially uncovered the bedrock surfaces and exposed them to weathering processes (Sørensen et al., 2007). The weathered material – small, angular stones as observed in core 4022 (unit 4) – accumulated at the base of the

bedrock outcrops, where it was mixed with finer soil/sediment material and formed the strongly reflective bands that are so characteristic for the GPR data collected in the fjärd landscapes.

During the following millennia until the beginning of the Viking Age (793 AD), the newly exposed land surface was subjected to erosion and accumulation processes, fuelled by its more pronounced topography when compared to the relatively flat valley bottoms. In the course of these processes, fissures and depressions between the bedrock outcrops were in-filled, eventually softening the formerly rugged topography. Over time, soils became more oxidised even though still displaying stagnic properties, which reflects the subjacent marine sediment.

Around 1000 BC, the northern parts of the valley bottoms started to become exposed due to the land uplift, and it might well have been at that time that palaeochannel system 1 formed. Even today, the stream course as detected and mapped by GPR runs along the thalweg – a line marking the lowest points along a river valley or streambed – and thus represents the most probable flow line. The process of shoreline displacement continued to affect the valley bottom for the next 1.800 years, while the sea slowly retreated over a distance of ca. 500 m towards the south and *Heimdaljordet*, most probably including a small river estuarine. This scenario is also supported by the volumetric GPR data extraction and coring results, which confirmed the presence of the stream before the construction of the Iron Age mound *Gokstad nedre* at some point in time between ca. 500 and 1.000 AD. When exactly the pits or dwellings detected alongside palaeochannel 1 were built, must be subject to further archaeological investigations. However, their spatial distribution alongside the stream strongly suggests a contemporaneity of both features.

The beach deposits detected at the archaeologically significant area *Heimdaljordet* formed when the shoreline displacement reached this part of the valley bottom at some point in time after 1 AD. The development of this formation continued during the Viking Age and extended further south following the shoreline displacement. Beaches are dynamic systems and develop their specific morphodynamic character due to a variety of interrelated factors, including topography, sea-level trend, waves, tides, sediment characteristics and geologic settings (Bascom, 1953; Komar, 1998; Short, 2004). The identification of the exact beach type and formation processes of the sandy beach sediments at *Heimdaljordet* are therefore

beyond the scope of this study, but some basic observations can be made based on the integrated data sets. Glacial rebound and related local fall of the sea-level led to a significant alteration of the coastline in this area since the end of the last glaciation. As the shoreline moved further southwards, it transitioned from forming a relatively narrow, elongate fjärd to a small, protected harbour bay – accessible by two straits, the Mefjorden and the Sandefjordsfjorden. This modification might have entailed changes in beach forming factors and subsequently led to the formation of a sandy beach.

The GPR data acquired at *Heimdaljordet* indicate a relative chronological sequence of events starting with the formation of the beach deposits. Around the second half of the 8th century AD (Bill and Rødsrud, 2013), the settlement was built on top of a part of the beach deposits. During the lifetime of the settlement the Gokstad mound was erected in around 900 AD (Nicolaysen, 1882) some 500 m to the north of *Heimdaljordet* in close proximity to palaeochannel system 1. The GPR data clearly illustrate that this channel system cut into the beach deposits after the sea-level had retreated further southwards after 800 AD, exposing the beach deposits to fluvial erosion. Based on these observations and considering the natural flow direction along the valley bottom, it seems probable that this channel system formed an estuary while draining into the sea at or in close vicinity to *Heimdaljordet*. The channel was regulated after 1956.

Archaeological implications

As this study has demonstrated, large-scale, high-resolution geophysical data sets by itself cannot provide all necessary information required for a palaeoenvironmental reconstruction. However, they contribute a spatially connected base-map for selected, targeted investigations and the formulation of new questions. Such a base-map presents a starting point for integrated analyses, where archaeological and palaeoenvironmental aspects are considered as equally important parts, and thereby aids in investigating their spatial connection and distribution.

The described approach becomes particularly evident in case of the palaeochannel systems recorded in the Gokstad area. Palaeochannels, river valleys and floodplains were frequently addressed in the archaeological interpretation of geophysical data sets (Darwin et al. 1990;

Weston 2001; Eugene et al. 2004; Mansfield 2007; Conyers et al. 2008 ; Bayer et al. 2011). A number of geoarchaeological studies have also focused on the investigation of these palaeoenvironmental archives (McHugh et al. 1988; Carey and Brown 2006; Howard et al. 2008). The detailed mapping of palaeochannel systems can be challenging, and has until recently often required extensive coring surveys (Berendsen and Stouthamer 2000; Bishop et al. 2012), which are both time-consuming and cost-intensive. The use of remote sensing techniques in this field is increasing with increasing availability of topographic and optical data, such as SRTM, JERS-1 and Landsat (de Fátima Rossetti et al. 2009; Bishop et al. 2012; Luo et al. 2012). However, the corresponding resolution is in general much lower (meters), than the high resolution (centimetres) of the GPR data collected at Gokstad. The detailed visualisation of palaeochannel system 1 demonstrated the great potential of the precise mapping of entire floodplains for comprehensive interpretation and targeted sample extraction. Further intrusive investigations of the fluvial and alluvial deposits at Gokstad could offer detailed information on the landscape development and palaeoenvironmental changes, provided that a robust chronology can be established (Brown, 1997). Common issues, such as GPR signal attenuation in water bearing and/or clayey material, as well as a lack of textural information, could be overcome in the future through a combined use of high-resolution large-scale GPR surveys with multi-coil Electro-Magnetic Induction (EMI) measurements (Schrott and Sass 2008; De Smedt et al. 2011).

The in-filled fissures and depressions between the once exposed, and now buried, bedrock in the slope areas, as detected in both GPR and magnetic data, might present another type of palaeoenvironmental archive, potentially reaching back to a time when the land was first exposed in around 5.000–4.000 BC. Originating from colluvial processes, these archives could be used in a similar way for a more encompassing palaeoenvironmental reconstruction of the Gokstad area, exploiting proxies such as Mollusca and erosion/accumulation patterns (Wilkinson, 2003).

Sandy beaches are present in the fjård landscape around Gokstad, but they do not occur overly frequently. In the geophysical data sets, beach deposits were identified solely at *Heimdaljordet* close to the Viking Age settlement that has been interpreted as a trading post. The question arises whether the fact that the trading station was built along a sandy shoreline is of archaeological significance? The choice of location for a Viking Age trading

post will have been influenced by many factors. A suitable landing site or even a natural harbour (Fig. 19) at a location linked with the land-based infrastructure might have been the most important requirement (Ilves 2009; Bill et al. 2013; Macphail et al. 2013). Ships during the Viking Age (until the 11th Century) existed in various sizes, but generally were light, low-boarded vessels requiring only shallow draught, while being greatly manoeuvrable. Draughts of Viking Age ships varied from only 0.5 m for shallow-going, small warships, to 1.5 m for the largest known Scandinavian cargo ship from this period, the Hedeby 3 vessel from ca. AD 1.020. Draughts of the Oseberg and Gokstad ships have been calculated to 0.8 m and 1.2 m respectively (Jensen 1999, Appendix B, p.2). Therefore, landing sites for these vessels did not necessarily require constructions of jetties or quays, and such implements were not identified in the geophysical data sets. A sandy beach as found at *Heimdaljordet* would have facilitated the beaching and launching of Viking ships, to load them or haul them up during winter time without supplementary infrastructure (Ilves, 2012, 2009). This possibility subsequently leads to the question, whether potential trading sites could be linked to similar palaeoenvironmental settings, which together with archaeological factors might act as an indicator for the discovery of other trading posts.

Beach deposits themselves can act as local sea-level indicators, but require a robust dating strategy in order to securely correlate palaeoenvironmental features with chronology (Tamura, 2012; Tamura et al., 2012; Taylor et al., 1996). During the Viking Age (800–1.000 AD), mean sea-levels have been calculated to around 3.6 - 4.0 m asl (Sørensen et al. 2007). At *Heimdaljordet*, data integration demonstrated that some of the settlement traces would have been located within this reconstructed shoreline range (Fig. 11). It is rather unlikely that dwellings were erected in such close proximity to the waterline, as short term sea-level variations, such as spring tides and winter storms, can cause sea-levels to rise temporarily for several meters (Sørensen et al. 2007; Ekman 2009) and would have to be taken into account. Connected to this analysis two points need to be stressed: First, the sea-level visualisation used in this study is based on raster classification of present day topography, which proved highly suitable when applied on a large scale in order to establish a coarse chronology for the landscape development. Used on a much smaller scale, such as the settlement traces at *Heimdaljordet*, the topography probably altered over the last 1.100 years, which might lead to erroneous assumptions regarding distribution and functional aspects of the mapped settlement structures. Secondly, local sea-level reconstructions are

complex and depend on many factors (Pirazzoli and Pluett 1991; Church et al. 2008; Lambeck et al. 2010; Draganits et al. in Press). This is also why local shore line reconstructions are rare. Most data relate to sea-levels averaged from small neighbouring regions – in the case of the Gokstad study mean sea-levels originate from the Kaupang region located ca. 15 km to the southwest (Sørensen et al., 2007). It would therefore be of great importance to establish a local sea-level model for the Gokstad area, which also considers the possibility of marine transgression (Cannell, forthcoming; Macphail et al. 2013).

Methodological assessment

On a methodological level, the pilot study Gokstad has yielded valuable information regarding the overall approach as well as concerning specific requirements and limitations for analyses and visualisation of palaeoenvironmental features.

First, palaeoenvironmental analysis of archaeological geophysical prospection data requires detailed knowledge about soils and sediments, geology, topography and geomorphological processes in the study area, in order to permit the identification of the often complex sources of unprecedented anomalies or reflectors. Magnetometry has played a minor but complementary role in the Gokstad survey area, comparable to the ALS data or soil maps. This, however, is site specific and very much based on the wet, iron-depleted soils and sediments in the southern fjärds. The crucial point is the integration of this information in a GIS in order to understand the interaction of the different palaeoenvironmental factors and their response to the near-surface geophysical methods used.

Second, since palaeoenvironmental features have not been investigated intensively earlier at this area, experience and data sets comparative in scale and resolution are sparse or non-existent, which complicates the identification process. Here, neighbouring disciplines such as sedimentology and geology can aid to some extent. This is specifically exemplified through the case of the beach deposits mapped at *Heimdaljordet*. Coastal morphology and in particular beach ridges and dune systems are investigated regularly using geophysical methods, such as GPR to image the internal structure and stratigraphy of geomorphological features (Harari 1996; Neal et al. 2002; Bristow and Pucillo 2006; Clemmensen and Nielsen 2010; Roskin et al. 2014). Most of these studies merely use linear GPR profiles for the

generation of cross sections, while acquisition of geophysical data for archaeological purposes benefits from high-resolution plane view data visualisations. This study has shown that the additional use of cross sections or radargrams aids in the identification process of palaeoenvironmental features through comparison with geoscientific research, as well as presenting a suitable foundation for the correlation with coring results.

Third, because of the points stated above, the geoarchaeological evaluation of the interpreted structures and patterns is absolutely necessary in order to initiate an iterative process with the goal to deepen the understanding on how palaeoenvironmental information can be included in and derived from archaeological geophysical prospection data sets. For this purpose, a combination of large-scale, high-resolution surveys and targeted borehole information has proven most promising and efficient. The investigation of basic physical properties of soils and sediments, such as grain size distribution, colour, stoniness and inclusions as well as the stratigraphic sequence aid in evaluating the interpretation of palaeoenvironmental information detected in the geophysical data sets, and simultaneously provides insight into the nature of their geophysical response. In order to further improve these field evaluations, future research should include the use of parameters diagnostic for magnetometry and GPR, including MS, dielectric permittivity and electric conductivity in combination with techniques such as micromorphology.

Finally, some of the structures and patterns identified can easily be linked to the archaeological interpretation, such as palaeochannels and former shorelines. In other cases, including palaeo-topography and geology, the relevance for the observed archaeology of the area is more difficult to recognise and requires expertise in geophysical prospection, environmental settings of the study area as well as the local archaeology. To simply disregard non-archaeological information, however, would be misleading and eventually result in a selective and biased form of data reduction. It is unquestionable, that palaeoenvironmental reconstruction requires a range of different methods. The analysis of large-scale, high-resolution archaeological geophysical prospection data sets cannot be used in isolation for palaeoenvironmental information – it must always be regarded as part of a comprehensive complementary approach. But, and this seems crucial, data are often readily available, even though initially intended to discover and map archaeology. Therefore it would be short-sighted not to make use of them. In this respect, geophysical archaeological

prospection data provides the basis for field-specific questions and further targeted research.

Chapter IV

3D visualisation and integration of palaeoenvironmental information extracted from large-scale, high-resolution archaeological GPR data – Examples from Norway

4.1. Introduction

New technical developments in the field of ground-based geophysical prospection including motorised data acquisition and enhanced data processing has led to the investigation of ever larger areas with ever increasing transect spacing. Consequently, large scale, high resolution data sets are now available for research and thus offer the possibility to investigate archaeological sites at unprecedented scale (Gabler et al., 2013; Leckebusch, 2003a; Linford, 2006; Trinks et al., 2014, 2010b). Archaeological sites, however, do not only consist of archaeological elements such as settlement traces or burials.

As demonstrated in chapter III, traces of palaeoenvironmental information can be frequently identified in geophysical prospection data, if data sets are of sufficient scale and resolution. Palaeoenvironmental information in form of e.g. old river systems or beach ridges constitute important parts of the complex and dynamic systems that are called archaeological landscapes (Lawrence B. Conyers, 2015; Doneus, 2013; Schneidhofer et al., 2016). This type of information is provided particularly with three-dimensional survey methods such as GPR as well as electromagnetic induction (EMI) and electrical resistivity (De Smedt et al., 2011; Neal and Roberts, 2000; T. Saey et al., 2013; Trinks et al., 2014; Van Dam, 2012).

As mentioned before, the potential of palaeoenvironmental information for large scale, high resolution data sets was not fully appreciated let alone exploited until recently. With the increasing availability of large-scale, high-resolution data sets, however, a growing number of studies recognise the impact palaeoenvironmental information detected in geophysical data sets can have on the investigation of archaeological landscapes. This includes potential base maps for palaeoenvironmental reconstruction (Fitch et al., 2005; Gaffney, 2008; Leopold et al., 2010; Wegmann et al., 2012) and the opportunity of assessing the influence of environmental settings on the geophysical methods itself (Conyers and Cameron 1998)

Palaeoenvironmental information, however, differs substantially from archaeological structures found in geophysical data sets and this was also discussed in chapter III. Archaeological features such as houses or burials generally are spatio-temporally distinct, more or less well-defined structures. Consequently, shape and extent of these structures are relatively easily detected and mapped based on 2D data. Palaeoenvironmental structures and patterns originating from geomorphological processes such as erosion and accumulation, in contrast, often exhibit a more continuous nature that becomes evident by occupying a larger area as well as a wider temporal range.

While archaeological features are the result of ceased anthropogenic activities, palaeoenvironmental information is the product of geomorphological processes spanning time scales from minutes up to millennia. This spatio-temporal complexity of palaeoenvironmental features complicates their accurate identification and interpretation based solely on 2D. In order to handle this inherent complexity and fully exploit this data type, palaeoenvironmental information must be visualised and interpreted in 3D.

Considering the specific nature of palaeoenvironmental information mentioned above, however, an encompassing analysis could not be a simple, linear process. It must include several analysis stages including 3D visualisation based on data subsets identified in an initial 2D analysis, which ideally leads to a visualisation of results in a 4D GIS where dynamic environments can be adequately illustrated. Naturally, not all geophysical data sets can be subject to such an approach. Magnetometry for example yields only two-dimensional data, although inverse modelling can produce volumetric information about the source of the anomaly (Argote et al., 2009; Neubauer and Eder-Hinterleitner, 1998). GPR on the other hand provides three-dimensional data sets well suited for 3D visualisation and analysis of palaeoenvironmental information.

To date, archaeological GPR data is mainly visualised using 2D amplitude maps based on either time or depth and subsequently imported into a GIS environment for further analysis, mapping and interpretation (Lawrence B. Conyers, 2015; Neubauer, 2004). For interpretative classification, data bases are established and eventually, two-dimensional thematic maps are created (Neubauer, 2004, 2001b). In certain cases, such maps are transferred into 2.5 D environments in order to provide a more realistic impression of the subsurface structures (Poscetti, 2016).

While 2D visualisation including amplitude maps as well as 2.5D approaches such as sections and animations of 3D data blocks are well established in the analytical routine of GPR data interpretation, the use of 3D visualisation for GPR data is less widespread (Leckebusch, 2003b; Leckebusch and Peikert, 2001; Verdonck, 2012; Watters, 2007). 3D visualisation of palaeoenvironmental information derived from GPR data and a subsequent integration with archaeological features and environmental settings such as topographical data and soil or geological maps has not yet been published.

This chapter aims to discuss differences in visualising palaeoenvironmental and archaeological information detected in high-resolution GPR data and to present new techniques of 3D visualisation and integration exemplified by several data sets from Norwegian Viking Age sites including Gokstad, Kaupang and Oseberg/Slagendalen.

4.2. 3D Visualisation of GPR Data in Archaeology

Since the first application of GPR for archaeological purposes in the 1970ies, visualisation has evolved from individual numbers, to single traces, to sections and amplitude maps (Conyers, 2013; Conyers and Cameron, 1998; Neubauer, 2001b). Visualisations in 3D, however, only started in the 1990ies, when the necessary computing power became available to researchers. Early examples of earth-scientific studies can be found in (Annan et al., 1992; Daniels et al., 1997, 2003) and Watters (2007) provides a detailed general overview about GPR visualisation techniques and their development.

In archaeology, the application of three-dimensional data visualisation in GPR started around 2000 (Barceló, 2000) with studies using isosurfaces, rendered as polygonal surfaces (Jürg Leckebusch 1998; Jürg Leckebusch 2001; Jürg Leckebusch and Peikert 2001; Nuzzo et al. 2002; Jörg Leckebusch 2003). The study by Nuzzo et al (2002) is of particular importance as it additionally demonstrates one of the first approaches of volume rendering in GPR data visualisation. Nevertheless, isosurfaces presented the method of choice regarding 3D visualisation during the last 15 years - most probably, because it was readily available in some wide-spread GPR processing software packages such as GPR slice (www.gpr-

survey.com), GPR software (www.gpr-archaeology.com/software) and Reflexw (<http://www.sandmeier-geo.de/reflexw.html>). Examples include studies by Leucci & Negri (2006), Leucci et al (2010), Verdonck (2012), Saey et al (2014), Sonnemann & Chhay (2014) and Urban et al (2014), although even isosurfaces were not overly frequently applied in archaeological studies.

One reason for this limited use includes the issue of complexly stratified features with a range of different amplitude values covered also experienced in “conventional” 2D data visualisation. The main obstacle, however, stems from insufficient contrast between the archaeological targets and the surrounding material resulting in undesired reflections often called “noise”(Leucci and Negri, 2006). The latter problem naturally intensifies with increasing resolution, which leads to a reduced benefit when using isosurfaces. In recent years, these problems have been addressed by data processing using target-specific attributes such as energy, coherency and similarity (Böniger and Tronicke, 2010) in order to get cleaner data sets and subsequently be able to visualise more meaningful structures. Loosely connected to the topic of 3D visualisation in geophysical prospection using isosurfaces and therefore mentioned at this point are MS down-hole studies (Dalan and Goodman, 2007).

As mentioned above, volume rendering evolved around the same time as visualisation with isosurfaces. Nuzzo et al (2002) first used 3D rendering, followed by a study by Conroy & Radzevicius (2003) featuring a good discussion of both. Compared to isosurfaces, however, volume rendering was rarely applied in archaeological studies. The amount of memory required, graphic cards standards and compatibility issues between GPR data formats and external visualisation software might have played a role in this development. The most significant study regarding the use of volume rendering in archaeology presents the work of Watters (2009, 2007) and in particular her approach of directly interpreting GPR data in 3D using segmentation - a vast field in medical research concerned with non-invasively mapping and analysing anatomical data (Lakare, 2000).

A rather recent development in the field of GPR 3D data visualisation is the development of point-based data visualisation. Conversion of GPR data to point clouds and handling of these data sets by using the numerous 3D software packages including elaborate LAS filtering tools present an interesting strategy (Kamp et al., 2013; Markussen et al., 2016).

The use of 3D visualisation for palaeoenvironmental information contained in large scale, high-resolution archaeological geophysical prospection, however, is rather unprecedented due to the issues already mentioned in the introduction. Earth science and exploratory research f using this data type to investigate e.g. geomorphological processes or the search for hydrocarbons work with much coarser resolution and mostly depend on sections and thus acquire single GPR profiles (Lawrence B Conyers, 2015; Van Dam, 2012) in stark contrast to the large scale surveys now available in archaeology.

The focus of this study, therefore, is the presentation of a workflow for 3D visualisation of palaeoenvironmental information found in GPR data and its subsequent integration into a GIS environment for comprehensive analysis and interpretation. Factors considered include the memory required for 3D rendering of large data sets as well as compatibility between different software packages. This approach is exemplified by selected data sets from Norway. The 3D GPR data will also be used for a basic 3D reconstruction of a part of the Gokstad archaeological landscape.

4.3. Methodology

GPR is an active three-dimensional prospection method, where depth information is acquired through transmission of an electromagnetic pulse and the recording of its reflections by a receiver unit (Annan, 2008; Conyers, 2013). The two-way travel time can be converted into depth information based on the propagation velocity. Data are acquired along profiles of pre-defined grids. Together with vehicle speed and antenna frequency, these parameters determine the spatial resolution of the GPR data. As with 2D visualisation, post-processing procedures and filters used directly influence the quality of 3D visualisation (Fig. 4.1).

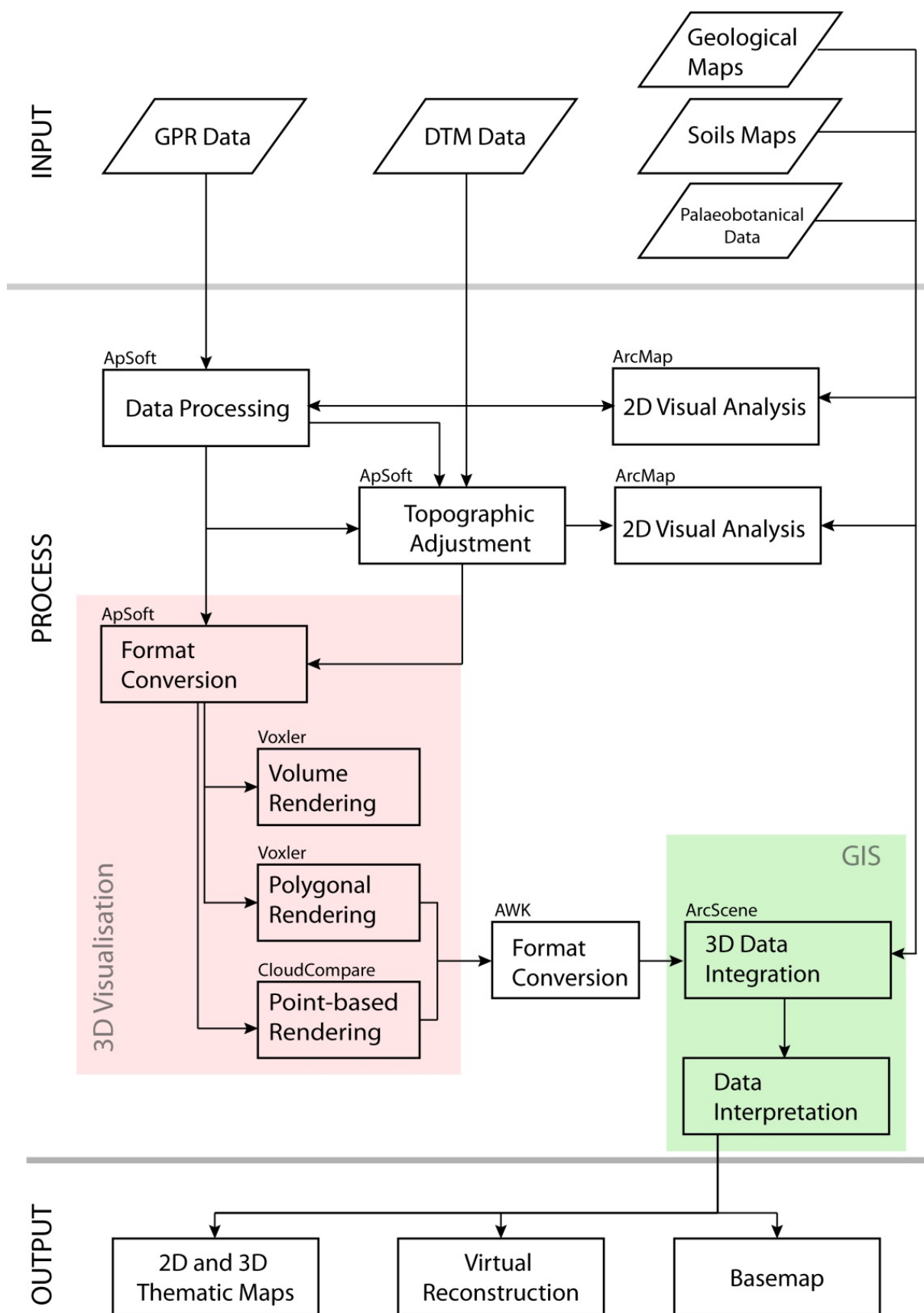


Fig. 4.1 Input-Output diagram for 3D visualisation of GPR data

A processing step particularly important for 3D visualisation of palaeoenvironmental information is topographical adjustment. Here, individual traces are adjusted to a digital terrain model optimally based on airborne laser scanning (ALS) data before being converted into a 3D data cube. While applied in 2D visualisation only when generating amplitude maps of structures exhibiting steep topography such as burial mounds (Conyers, 2013; Trinks et al., 2014), inclusion of topographical data provides a more realistic and thus comprehensible 3D visualisation of the subsurface. Topographical adjustment, however, is not to be confused with topography-tilt correction where the tilt of individual traces in steeper terrain is accounted for in order to achieve a more accurate positioning of the actual subsurface features (Leckebusch and Rychener, 2007; Lehmann and Green, 2000). Most of the available 3D software packages both in geoscientific (including Voxler 4) as well as in medical fields provide two options for data import: via a stack of consecutive 2D images as well as by their individual 3D data formats. While stacks prove problematic when it comes to subsequent data integration due to issues of scaling and georeferencing, the use of individual 3D formats often necessitate advanced skills in data conversion. Thus, 3D visualisation in GPR data analysis is not as easily put into practice, which might constitute an obstacle in the widespread application of this method. To overcome this issue, a customized conversion tool was implemented into ApRadar in order to generate a file format directly importable into Voxler 4.

In this study, three different modes for 3D visualisation of GPR data were tested: Point-based visualisation, isosurfaces and volume rendering. Point-based visualisation originates from converting the initially gridded 3D data block to XYZ points with associated scalar values. These values correspond to the grey-scale range (0-255) calculated from the original trace amplitudes. The resulting point clouds are easily imported into CloudCompare, where data can be filtered and further manipulated. The final 3D visualisation resembles volume rendered GPR data, but with less memory required (Fig.4.2 and 4.3). As a result, point-based visualisations are very time-efficient.

a

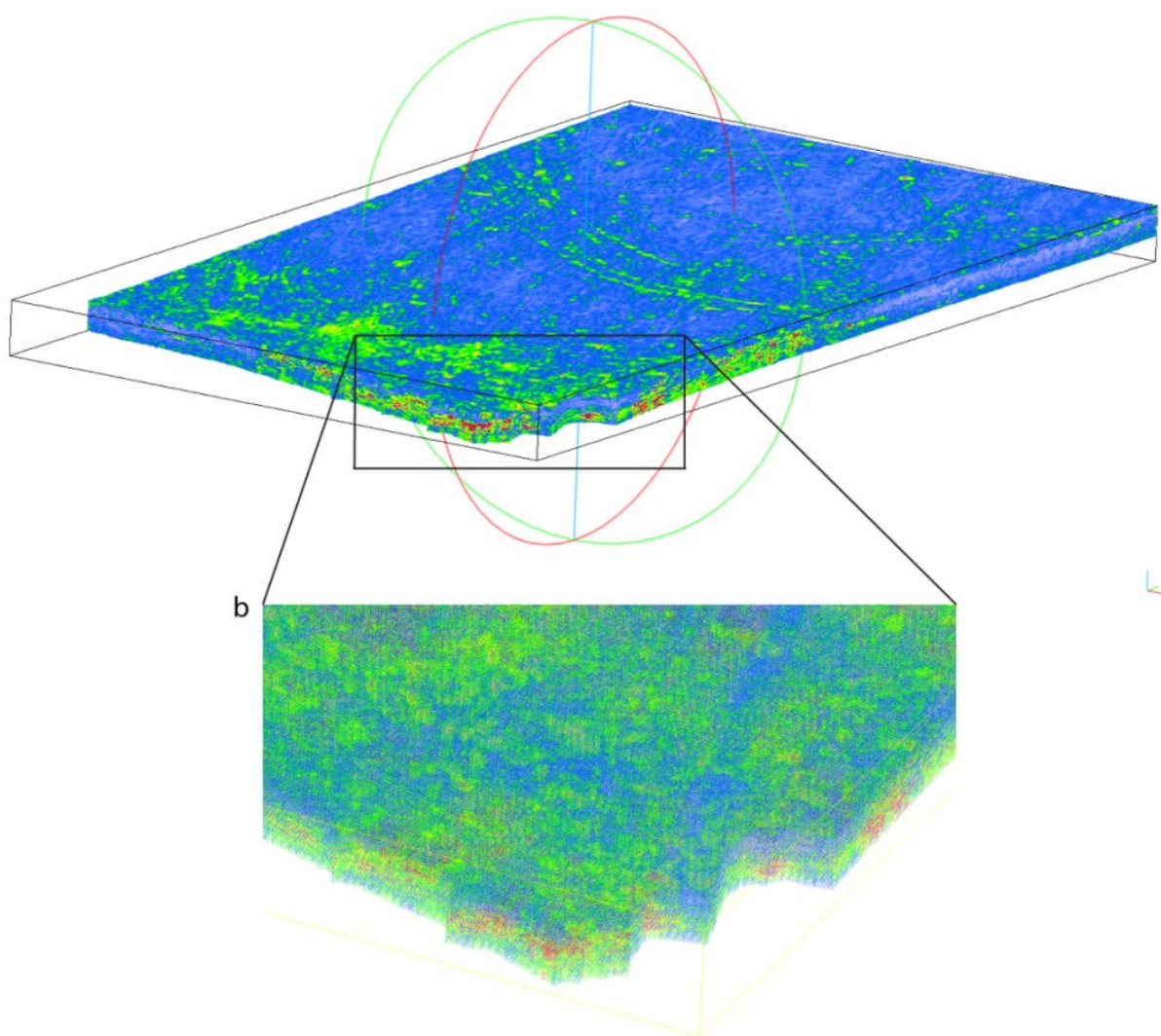


Fig. 4.2a Point-based data visualisation of subset A of the beach deposits in Gokstad in CloudCompare.
4.2b The data set consists of points with coordinates derived from the source data grid and a color representing the data value

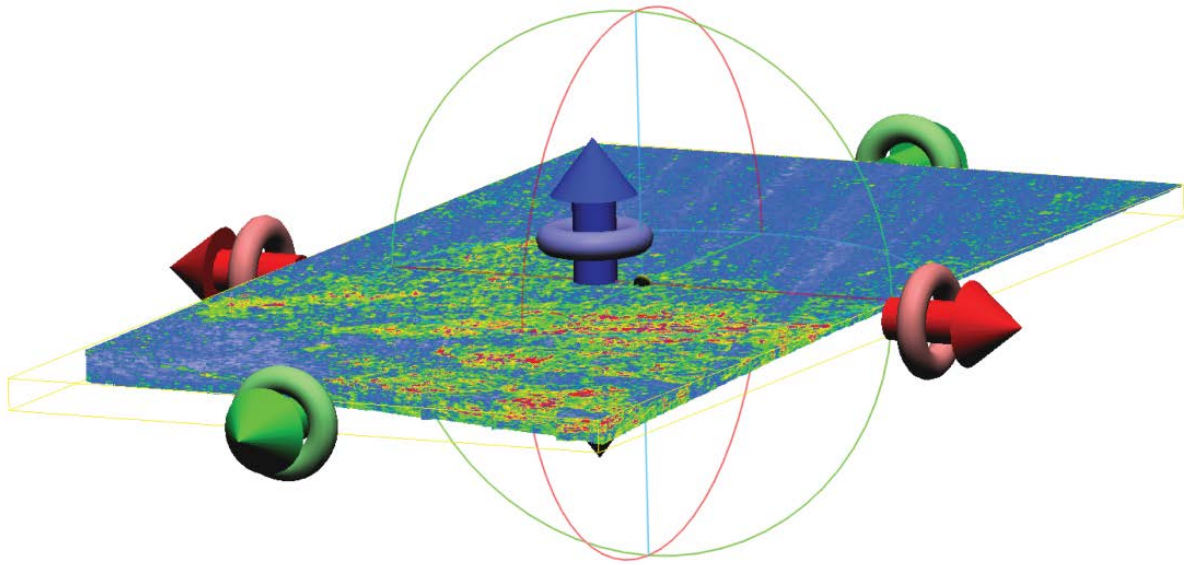


Fig. 4.3 Arbitrary slicing and colour adjustment in CloudCompare. This 3D visualisation required 3.95 GB of memory in CloudCompare compared to 6.43 GB visualised as Volrender in Voxler 4 for the same data set

However, upon import to ArcScene, point colour is lost and thus the current level of data integration for this visualisation mode is limited. Due to this limitation, this study concentrated on 3D GPR data visualisation using isosurfaces and volume rendering, which will be discussed in detail below. Since data integration is integral to palaeoenvironmental analysis of geophysical data, compatibility between 3D visualisation software and GIS environments was of key importance in the workflow presented here (see Fig. 4.10). This task was accomplished relatively easily with point-based data, since the resulting point-clouds are stored in a text-based format and as such are importable into most 3D software packages including free and commercial software such as CloudCompare, Meshlab (<http://meshlab.sourceforge.net/>) or Geomagic and ArcGIS. Isosurfaces, in contrast, require a more complex import process including a sequence of conversion tools as well as additional software for cleaning, filtering and data reduction prior to data integration in a 2.5D or 3D GIS environment.

The situation is different with volumetric data, which depend on a proper 3D renderer for display – a feature often not provided by conventional GIS environments such as ArcGIS. Although volume rendering offers important clues for visual analysis, it is currently not

suited for data integration. However, a limited form of data integration for volumetric, vector and surface data is offered by Voxler 4.

4.4. Software for 3D visualisation of GPR data

The most important factor regarding the choice of software packages suitable for 3D visualisation of high-resolution GPR data was the capacity to address a sufficient amount of memory. This requirement quickly ruled out 32-bit applications in favour of 64-bit applications. Compatibility regarding the available import/export data formats and functions between 3D visualisation software and GIS presented another important consideration. Finally, freeware or affordable educational licenses were preferred.

For point-based 3D visualisation, a range of free and commercial software is available. In this study, we settled for the open-source CloudCompare V 2.2.6.1. (64-bit version) (<http://www.danielgm.net/cc/>) due to its intuitive GUI. The picture is different with 3D volume renderer. Here, most software is developed for either the geoscientific or medical market. While medical software often provides a high amount of detail as well as options for 3D mapping, geoscientific packages are designed towards integration of geo-located data. Based on these considerations, we opted for Golden Software's commercial well and volumetric 64-bit data solution Voxler (versions 3 and 4) as a widely used application that offers affordable licenses (Golden Software, 2012).

GPR data were processed and filtered using the LBI's in-house software ApRadar (ZAMG ArcheoProspections®/LBI ArchPro). Applied processing steps included standard procedures for archaeological purposes such as remove constant shift (dewow filter), band-pass frequency filtering, average-trace-removal and time-zero determination for each single trace and Kirchhoff migration. Depth slices are calculated by adding up the absolute amplitudes of according time ranges. As there is no amplitude-gain corrections applied to single traces, the depth slices are then adjusted to the same mean value by multiplication. ApRadar was also used for topographic adjustment of traces as well as conversion of GPR data to either ASCII data for point-based visualisation or a customary format compatible with Voxler 4 for

isosurfaces and volumetric visualisation – an implementation specifically developed for the workflow presented in this study.

Data integration in ESRI ArcScene 10.2 was enabled by a sequence of conversion scripts written in AWK that allowed data exchange between 3D renderer and GIS environment. This procedure will be discussed in detail below under “data integration”. 3D reconstruction was carried out using 3ds Max.

All visualisations (apart from 3ds Max) were carried out on a standard laptop with the following specifications: Intel® Core™ i7-4702MQ CPU (2.20 GHz, 4 Cores, 8 Logical Processors), 16 GB physical memory (RAM), as well as two graphic cards (Intel® HD Graphics 4600 and NVIDIA GeForce GT 750M).

4.5. Case study sites

In order to test the proposed approach, three different case study sites from the Vestfold project as well as the Gokstad revitalised project were selected: Gokstad (Bill and Rødstrud, 2013; Macphail et al., 2013; Nicolaysen, 1854; Schneidhofer et al., 2016), Kaupang (Skre, 2007b) and Oseberg/Slagendalen (Gansum, 1995) (Fig. 4.4). Despite being known for their exceptional archaeological heritage mostly dating to the Viking Age, the landscapes surrounding the monuments include rich and diverse palaeoenvironmental data well suited to demonstrate the potential of 3D GPR data visualisation for this type of information (Table 4.1).

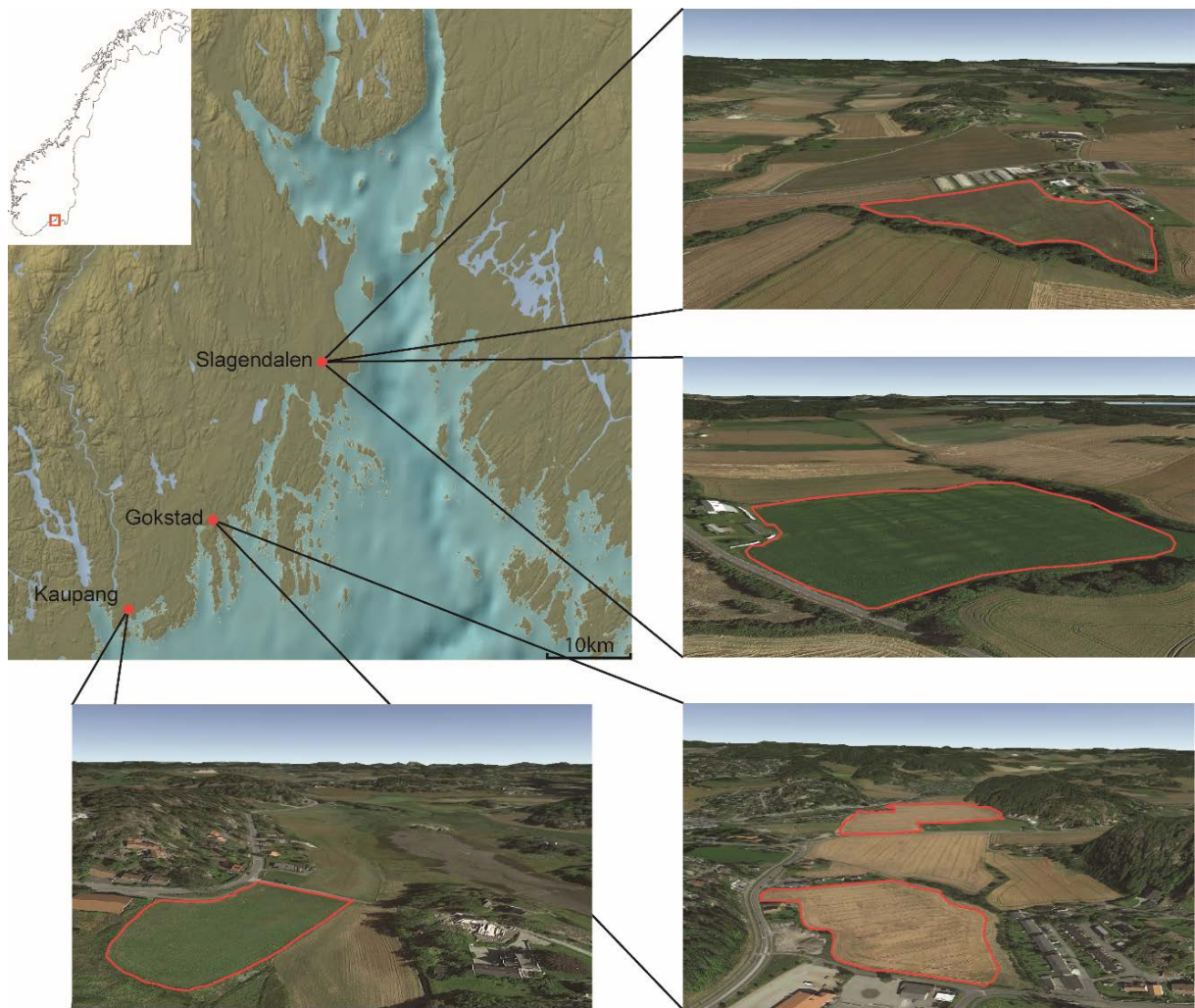


Fig. 4.4a Location of all three case studies in the county Vestfold, Norway with 3D views (Google earth) of the respective test data sets at each site. 4.4b Basberg. 4.4c Rom. 4.4d Gokstad features two test data sets. Viking Age settlement *Heimdaljordet* with the beach deposits are in the front, while the data set including the palaeochannel lies in the back

Table 4.1 Description of test sites and overview about selected 3D visualisation modes, data integration and 3D reconstruction

Site	Gokstad	Kaupang	Båsberg/ Slagendalen
<i>Archaeology</i>	<i>Gokstad</i> ship burial mound, Trading post <i>Heimdaljordet</i> , both dated to Viking Age	Settlement, extensive cemetery (both dated to Viking Age)	<i>Oseberg</i> ship burial mound (Viking Age), burial mounds (Iron Age), settlement (Iron Age)
<i>Palaeoenvironmental settings</i>	shallow Fjärd, sediments and soils characterised by sea-level retreat, shallow buried bedrock, extensive palaeochannel systems, beach deposits	Coast, sediments and soils characterised by sea-level retreat, shallow buried bedrock, beach ridges	River valley, soils and sediments characterised by sea-level retreat and fluvial deposits, shallow buried bedrock, topography outlined by rolling hillcrests along the valley
<i>Survey settings</i>	16 channel 400 Mhz antenna MIRA Malå Geoscience, 8cm x 6-8 cm spatial resolution, resampled 8 x 8 cm.	16 channel 400 Mhz antenna MIRA Malå Geoscience, 8cm x 6-8 cm spatial resolution, resampled 8 x 8 cm.	6 channel 500 Mhz SPIDAR network GPR (Sensors & Software), 25 x 10 cm spatial resolution, resampled 10 x 10 cm.
<i>Subset Dimensions</i>	Beach deposits B: 81 x 46 Beach deposits A: 131 x 42 Palaeochannel: 81 x 64	104 x 71	Basberg: 74 x 68 Rom: 48 x 43
<i>File size</i>	Beach deposits B: 141 MB, Beach deposits A: 101 MB Palaeochannel: 117 MB	93 MB (not topographically adjusted)	Basberg: 31 MB Rom: 202 MB
<i>Data Processing</i>	Hilbert transformation, gain, background removal, 2D migration	Hilbert transformation, gain, background removal, 2D migration	Hilbert transformation, gain, background removal, 2D migration
<i>Point-based</i>	X		
<i>Polygonal surfaces (Isosurfaces)</i>			X
<i>Volumetric rendering</i>	X	X	
<i>Data integration</i>		X	X
<i>3D reconstruction</i>	X		

4.5. 3D data visualisation

Successful 3D visualisation of GPR data depends on different elements for both isosurfaces as well as volume rendering. The main limiting factor concerns the amount of data, which largely is based on extent and spatial resolution of the respective data set in combination with available memory (main RAM and dedicated memory on the graphics card). Today's dedicated high-end graphics cards are equipped with several gigabytes of memory, and the general switch to 64bit processing has largely removed previous memory issues. However, data sets today are of unprecedented scale and resolution, making the selection of subsets for targeted 3D visualisation therefore in most cases inevitable. This can be problematic, since large-scale, high-resolution surveys are often a precondition for the correct identification of a complex subsurface stratification. Thus, subsets need to be selected carefully based on amplitude maps and 2D animations for their informative value regarding the pending research questions prior to 3D visualisation. Visual analysis of target features including amplitude value ranges and contrast presents a necessary first step in every 3D visualisation. However, extent and spatial resolution can be further decreased directly in the 3D visualisation software if necessary. Another element that increases file size is topographic adjustment. Depending on the steepness of the terrain, the data cube expands vertically, including vast amounts of no-data cells.

For volume rendering, the Volrender module provided in Voxler 4 was used. Volrender is a direct, image-based 3D renderer built on the principles of volume ray casting, yielding high-quality renderings. GPR data are converted into a uniform lattice with the Hilbert-transformed amplitude values imported and stretched between 0-255. A simulated ray of light cast through the lattice is emitted and absorbed depending on the scalar value of each voxel and accordingly coloured. By adjusting colour maps and opacity, a targeted visualisation of structures inside the 3D volume becomes possible (Golden Software, 2012).

From an analytical point of view, volrender presents the most efficient 3D visualisation of GPR data simply based on the volumetric nature of this data type (Annan, 2001). Recognising formation processes and understanding their relevance and possible connection to the archaeological record is much facilitated by being able to visualise the investigated subsurface in proper 3D. A range of different graphic as well as computational tools enable

further manipulation of the data and thus allow a more targeted study of individual structures and patterns. Particularly arbitrary slicing should be stressed as it plays a decisive role in visually analysing the data from a geoarchaeological perspective by providing dynamic profiles as opposed to static profiles.

These advantages are well exemplified by a high-resolution GPR data set from the Viking Age Gokstad (Nau et al., 2015). Here, traces of a settlement and burials were discovered alongside a large, unidentified pattern that, based on the 3D visualisation, emerged as beach deposits (Schneidhofer et al., 2016). After the initial 2D data interpretation, a comprehensive understanding of the palaeoenvironmental situation at *Heimdaljordet* could not be achieved due to the complexly stratified subsurface. Thus, two subsets (a and b) were extracted from the initial data, topographically adjusted and visually analysed using volrender in Voxler 4 (Fig. 4.5).

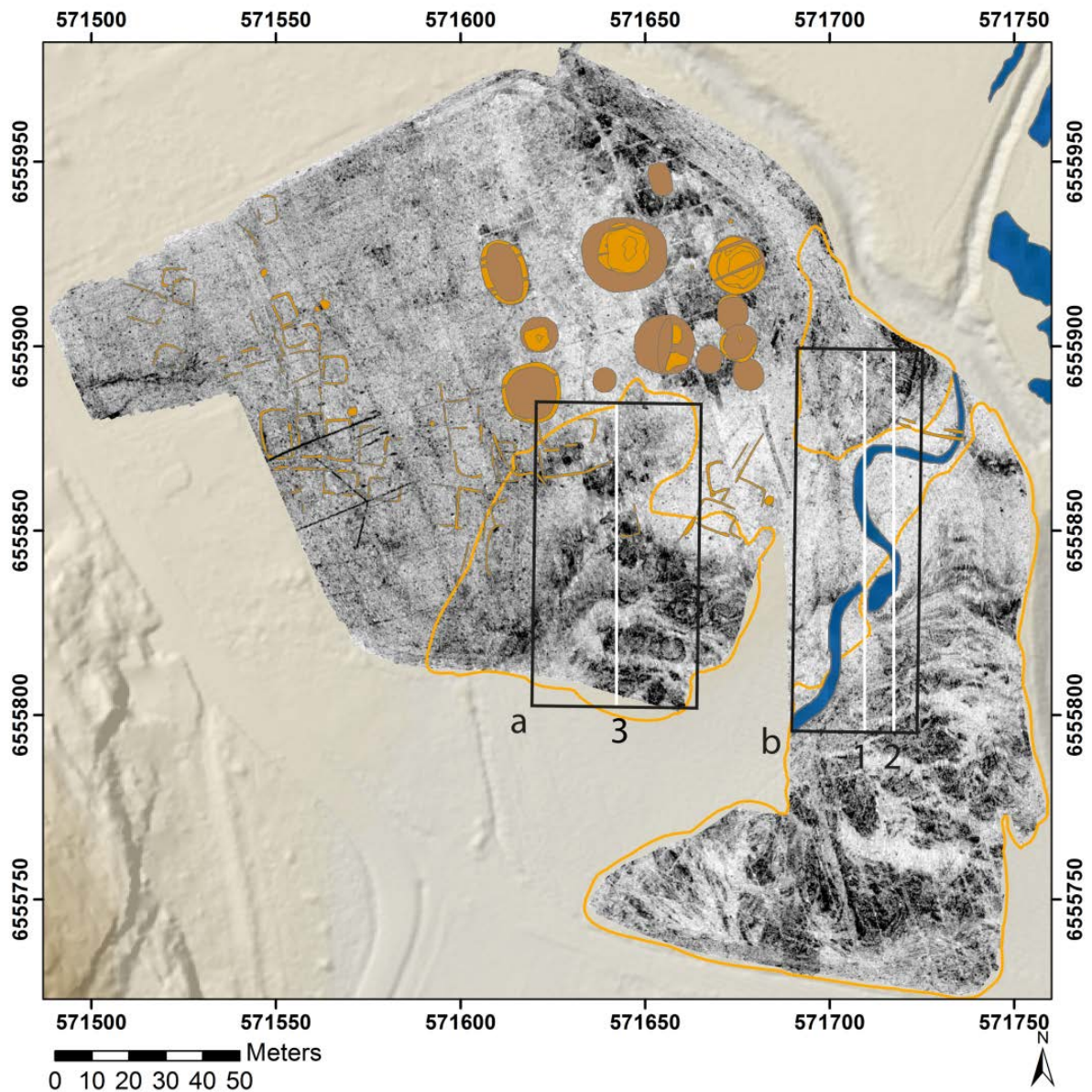


Fig. 4.5 GPR amplitude map 75-80cm Below Ground Surface (BGS) overlain by the interpretation of burial mounds and settlement traces. The beach deposits in the south are outlined in yellow. Subsets a and b are marked by black rectangles, individual profiles are highlighted in white and numbered 1, 2 and 3 (see also Fig. 6)

Subset a (Fig. 4.6) targets a coastal area close to both the building plots and the burial mounds and displays the typical laminated layers of a beach deposit composed of varying grain size fractions (Komar, 1998). Their gentle dipping that slightly deviates from today's surface makes these layers visible also on 2D depth slice animations.

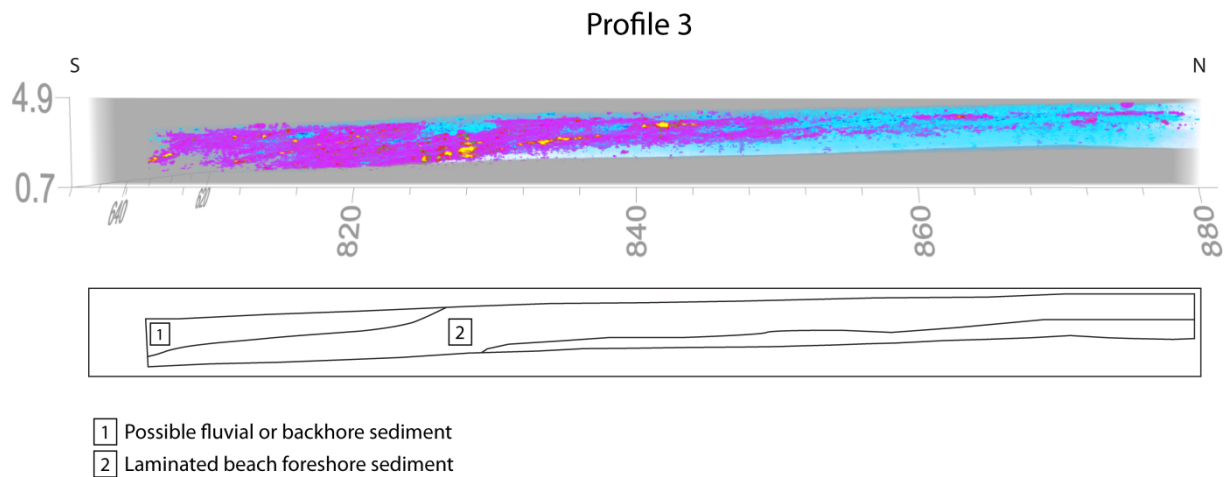


Fig. 4.6 Profile 3 shows a sequence similar to profile 1. The laminated beach foreshore sediment, however, seems to directly overly marine sediment. Vertical exaggeration 2

Subset b (Fig. 4.7) aims at a more complex part of *Heimdaljordet* towards the east of subset a. Here, different depositional phases including the fine lamination of beach foreshore sediment and the patchier, discontinuous appearance originating from a different formation process - possibly fluvial or backshore sediment - can be traced by managing colours and opacity accordingly. These sediments in turn are cut by a stratigraphically younger small meandering palaeochannel.

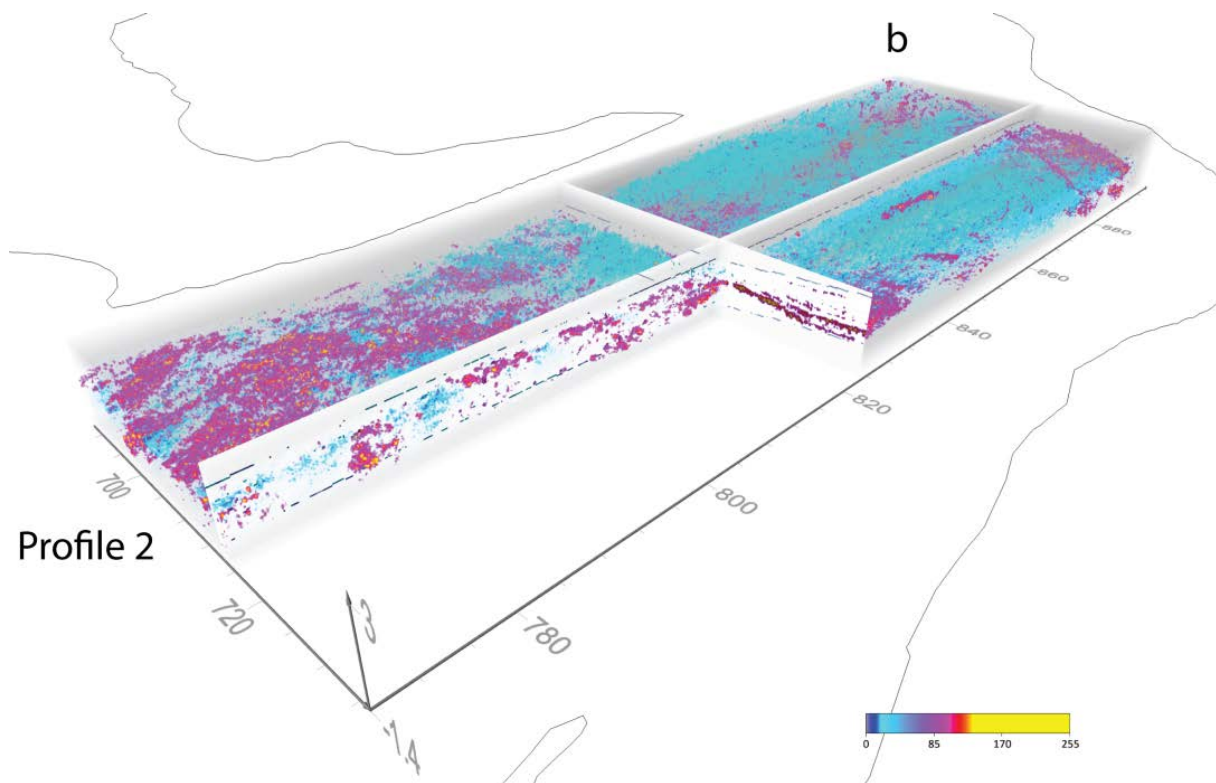


Fig. 4.7 Profile 2 of subset b demonstrates how multiple sections through the beach deposits and the palaeochannel can be used to understand the complex subsurface stratification at *Heimdaljordet*. Vertical exaggeration 1.5

The stratigraphic sequence and spatial connection of these palaeoenvironmental elements were difficult to entangle based solely on the 2D depth slices, in particular with regard to their stratigraphic relation to archaeological features (Fig. 4.8).

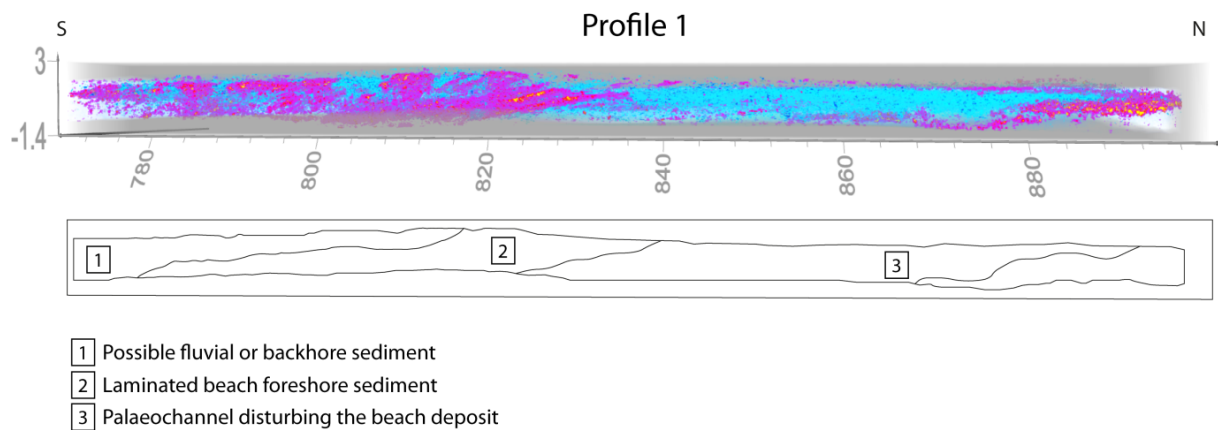


Fig. 4.8 Profile 1 illustrates a sequence of laminated beach foreshore sediment, overlain by possible fluvial or backshore sediment and cut by a stratigraphically younger palaeochannel. Vertical exaggeration 2

Another example from Gokstad exhibits 3D visualisation of a part of the extensive palaeochannel system located in this area (Fig. 4.9). Palaeochannels usually are spatially distinct palaeoenvironmental features and as such can be detected and mapped using 2D amplitude maps. The benefits of volume rendering become evident when looking more closely at the channel infill, which mainly displays highly reflective material resulting in good contrast of the channel when compared to its more absorbing surroundings.

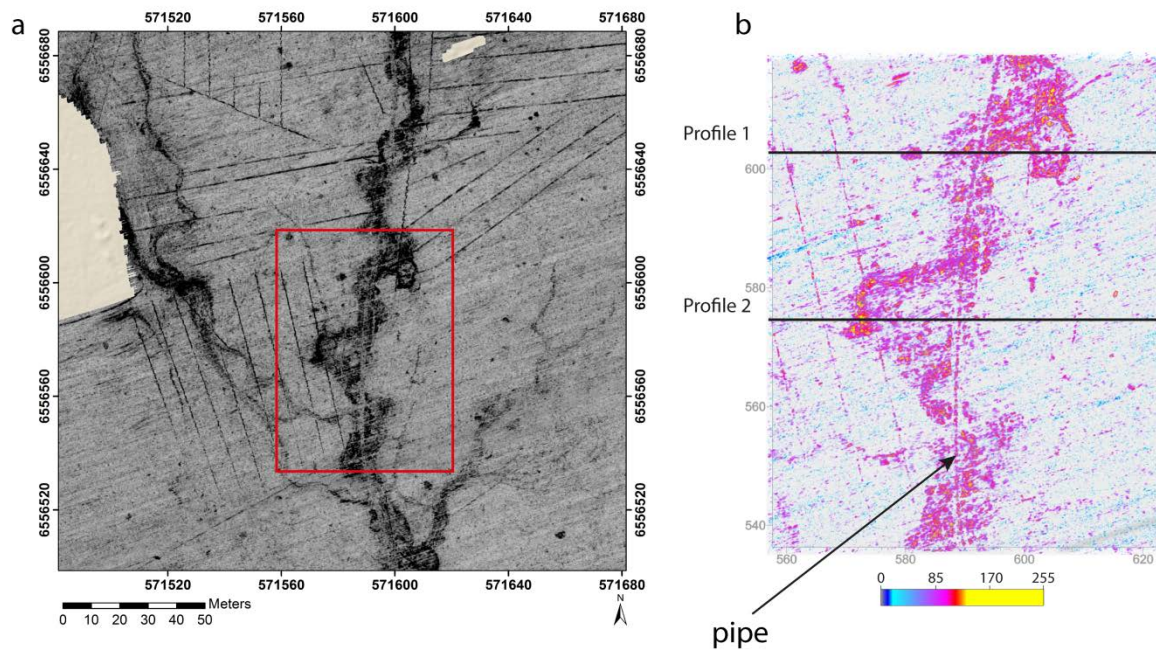


Fig. 4.9a GPR amplitude map (70-75 cm BGS) with the subset outlined in red. 4.9b Top view of the same extent using volume rendering and locations of profiles 1 and 2. Note the modern pipe, which regulates the stream since 1956, as well as the amount of detail in the course of the river. The legend refers to the arbitrary scalar values of the initial grey-scale images

The use of arbitrary slicing shows the shallow profile typical for the drainage systems of the fjärds in this part of Norway, which is based on low gradient topography, wide valley bottoms and consequently slow flow velocity (Brown, 1997; Embleton and King, 1970; Fairbridge, 1985)(Fig. 4.10 and 4.11). By adjusting the colour editor to highlight specific amplitude values within the channel infill, successive depositional phases characterised by material of varying physical properties, most probably associated with different flood regimes (Brown, 1997), can be visualised. In contrast to 2D amplitude maps and animations, where grey-scale images allow for the human visual system to perceive a maximum of contrast, 3D volume rendering requires the use of complementary colours. Colour maps, however, need to be individually adjusted to each data set depending on the amplitude range of the target features.

Profile 1

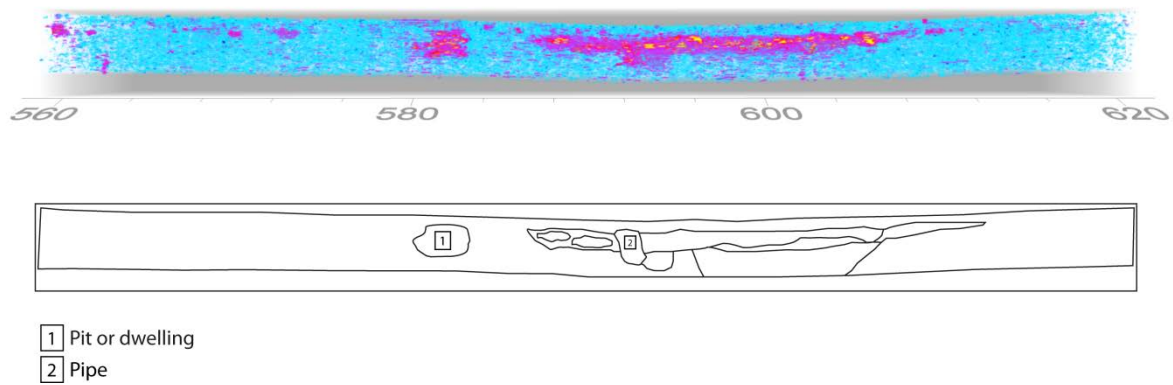


Fig. 4.10 Profile 1 shows details of the palaeochannel infill and the modern pipe. It also displays an archaeological feature interpreted as pit or dwelling that was erected at the stream margins and shows a distinctively rectangular shape. Vertical exaggeration 1.5

Profile 2

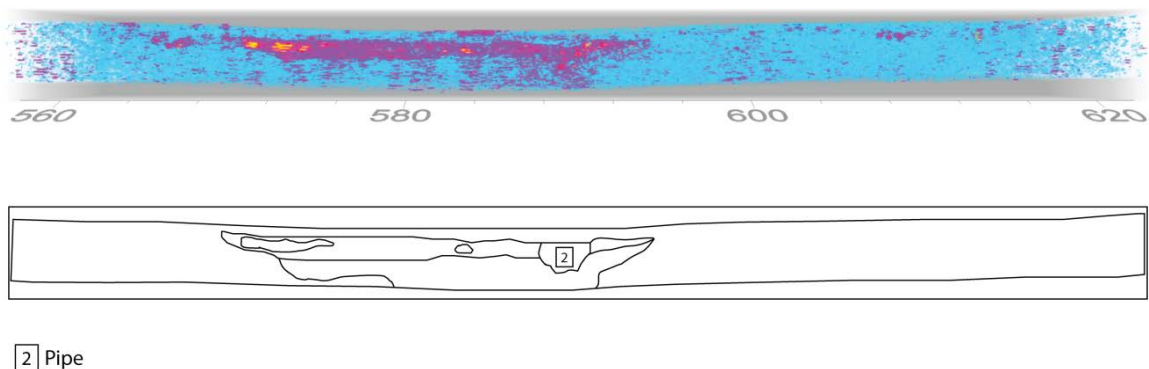


Fig. 4.11 Profile 2 shows details of the palaeochannel infill and the modern pipe. Vertical exaggeration 1.5

As mentioned above, volume rendering offers different options to manipulate 3D GPR data. The subset from Kaupang targeted a part of the former shoreline close to the settlement area and accommodated several burial mounds built on top of a complex stratification including a sequence of beach ridges (Fig 4.12). Additionally, the entire area was heavily disturbed by a dense network of modern drainage pipes buried in 80 – 100 cm depth BGS that made data interpretation based solely on 2D depth slices and animations difficult. In

such cases, volume rendering allows excluding certain amplitude values by setting them transparent (Fig. 4.13).

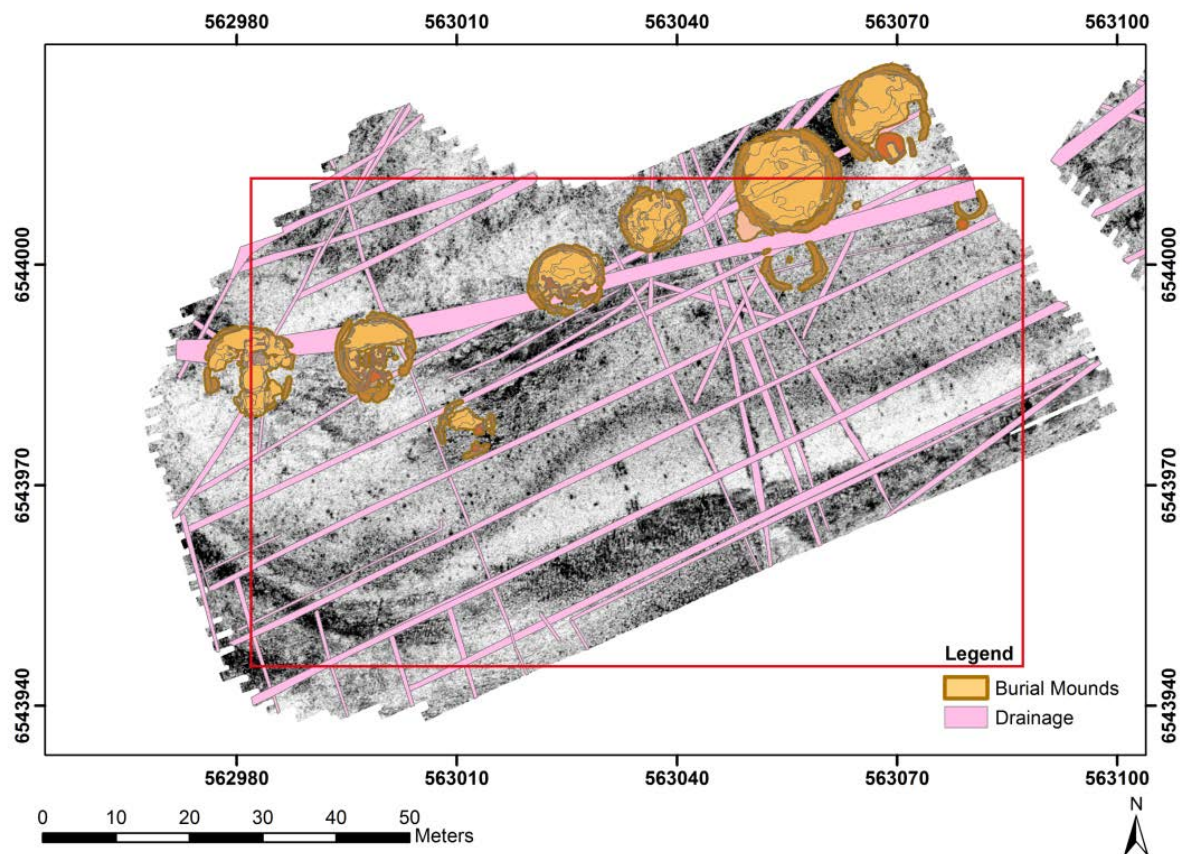


Fig. 4.12 GPR amplitude map (45-50 cm BGS) displaying beach ridges, overlain by the 2D interpretation of the burial mounds and a dense patterns of drainage ditches. The red rectangle marks the subset subject to 3D visualisation

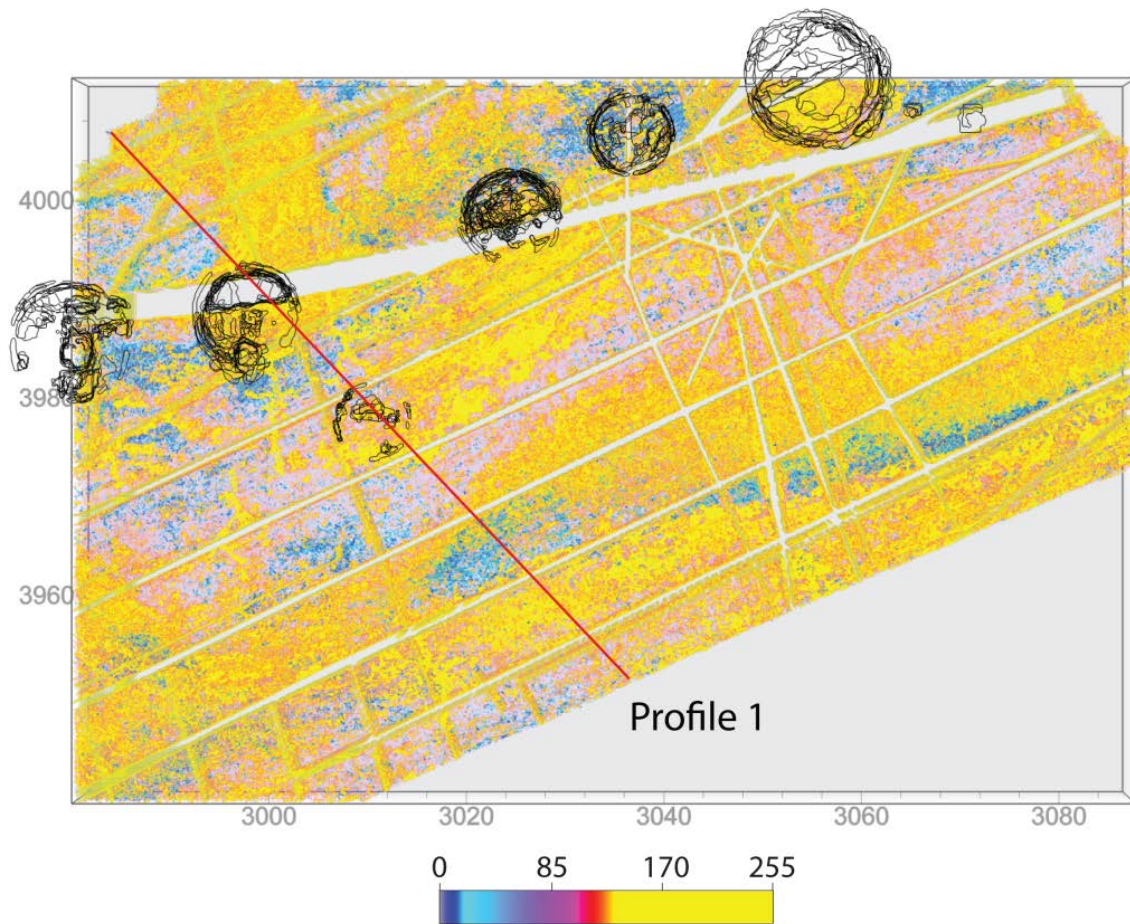


Fig. 4.13 Volume rendering of subset with integrated polylines (shapefiles) from 2D interpretation. The dense drainage network was rendered transparent and thus no longer disturbs the interpretation process. Vertical exaggeration 1.5. Red line marking the location of Profile 1 in Fig. 4.15.

Due to the complexity of the subset, it was important to integrate archaeological and palaeoenvironmental features. Voxler offers limited options for handling raster and vector data that can be used for a general overview of the investigated subsurface. In the case of Kaupang, surface data aided in embedding the area into its topographical context, while the shape files originating from the 2D mapping of the burial mounds in ArcMap provided the exact location and shape of the archaeological features (Fig. 4.13 and 4.14).

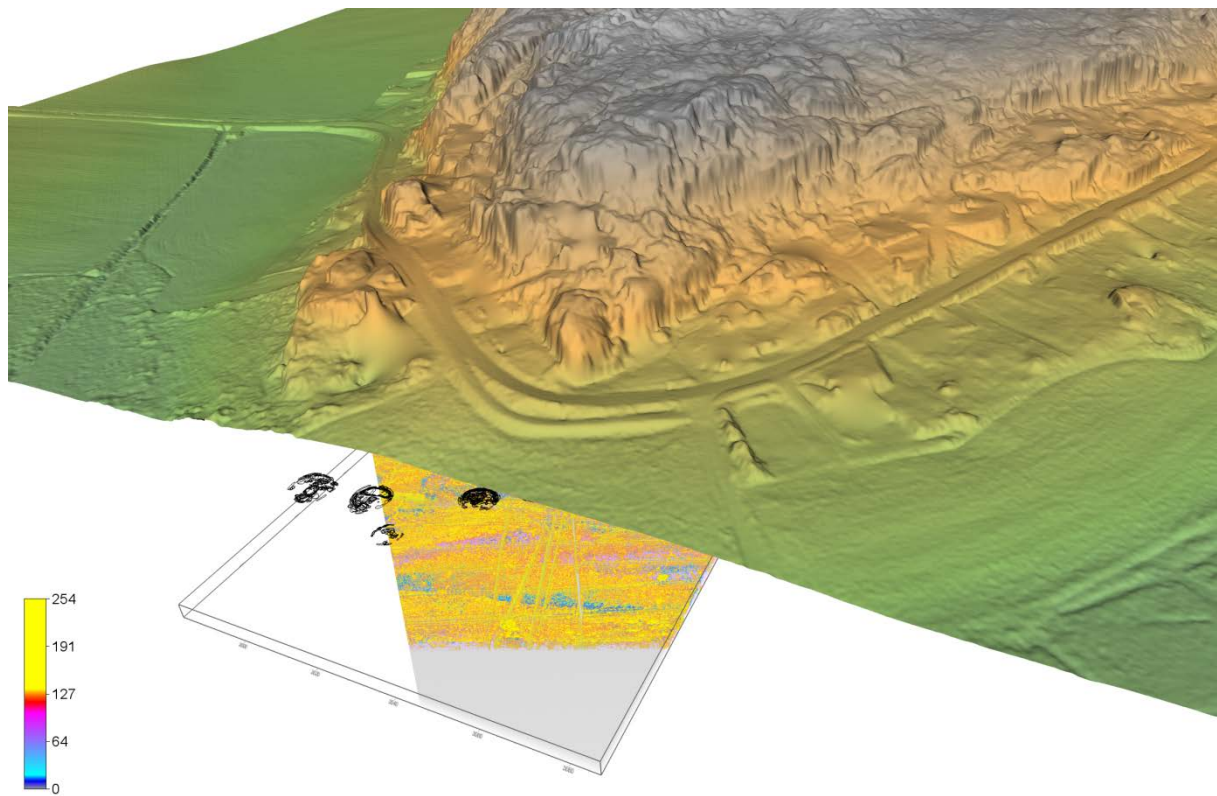


Fig. 4.14 Limited integration of ALS data with archaeological interpretation and volume rendered GPR data from Kaupang in Voxler 4. Vertical exaggeration 1.5

The use of arbitrary slicing yields a very detailed picture of the internal structure of the beach ridges, which were created when the sea level was higher than today (Fig. 4.15). By adjusting the colour map editor, alternating layers of absorbing and reflective material could be equally highlighted and so evidenced different formation processes possibly caused by seasonal variation and/or storm events (Taylor et al., 1996) – relevant information for local sea-level reconstructions, the understanding of coastal formation processes and further targeted geoarchaeological sampling.

The 3D visualisation evidences that the palaeotopography differed substantially from today's topography. A fact that becomes important when using sea-level reconstructions based on raster classification of current ALS data. In the case of Kaupang, some of the burial mounds detected in the GPR data and dated to the Viking Age would have been beneath the local sea level (+ 3.6 m above current sea-level) calculated for this epoch. This is further proof that local sea-level reconstructions are necessary when it comes to small-scale palaeoenvironmental reconstructions, and for this, a thorough understanding of landscape

development is required. The volume rendering also indicated shallowly buried bedrock, on top of which at least one of the burial mounds was erected. The data set of Kaupang was not topographically adjusted due to its large file size.

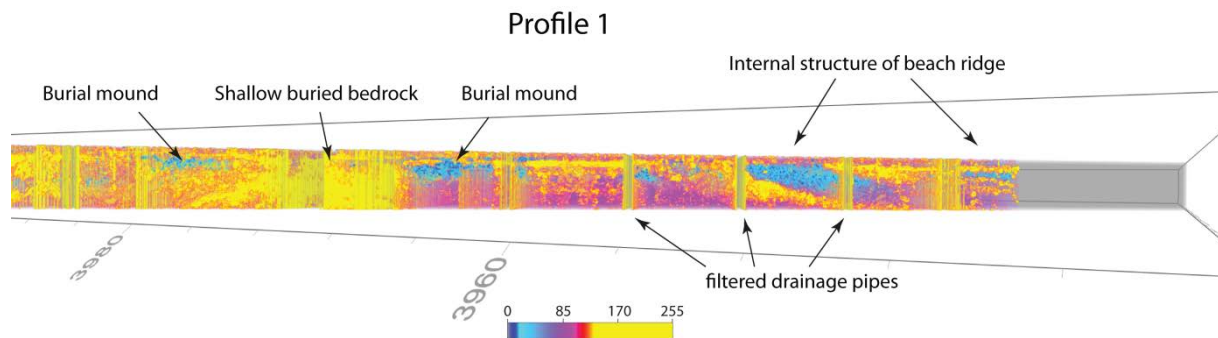


Fig. 4.15 Profile 1 highlights different depositional events in the internal structure of the beach ridges, shallow buried bedrock and burial mounds. The disturbing modern drainage ditches have been digitally removed. Vertical exaggeration 1.5

4.6. GIS Data integration

Isosurfaces, which represent rendered polygonal surfaces of reflection values, offer certain advantages over volume rendering, among them in most cases a substantial data reduction and consequently a decrease in memory requirements. However, this method only works on data sets that display strong contrast between target features and surrounding subsurface material. Additionally, choosing a certain iso value has to be considered already as a first interpretation step (Leckebusch, 2003b). In the approach presented here, isosurfaces are primarily used for data integration in ArcScene and other programs, which do not provide a volume render.

As mentioned above, isosurfaces were used in a number of archaeological studies and their application in Archaeology does not present a new development. Yet, the import into a GIS

environment such as ArcScene and thus an encompassing data integration of archaeological and palaeoenvironmental features with additional data sets from the fields of geology, soil science, sedimentology, hydrology or geomorphology has to our knowledge not been undertaken yet, even though examples from mineral and hydrocarbon exploration are of some relevance. While such integration is standard when using 2D data visualisations and can be easily achieved through georeferencing of different data sets, integration of 3D GPR data is more complicated. Reasons for this include limited compatibility of 3D data exchange formats between different software packages, a lack of 3D renderer capabilities in GIS and certain memory requirements in particular when dealing with high-resolution palaeoenvironmental data. Some 3D rendering software packages such as Voxler offer limited options for data integration as demonstrated with the Kaupang example. This, however, cannot substitute a geographic information system.

4.6.1. Investigating archaeological landscapes

Thus, in order to be able to comprehensively investigate archaeological landscapes and their development through time, this study aimed to design a workflow for integrating colour-coded isosurfaces into ArcScene (Fig. 4.16). Challenges for this task included primarily the lack of direct compatibility between Voxler and ArcScene, but also large file sizes and translation between local and georeferenced coordinate systems due to a limited number of digits available for coordinates in most 3D renderers (see below). Conversion of file formats, therefore, presented a key task in the proposed workflow. A conversion sequence was established in order to meet different stages and demands in data integration and interpretation, and at the same time allowed for further methodological development work. Conversion tools were written in the AWK interpreted programming language used for automated rule-based text processing. We found that AWK provides sufficient functionality and is relatively simple to use. The conversion sequence was based on the Wavefront OBJ 3D file format, a simple text-based standard format readable by most 3D applications and as such presenting a suitable foundation for conversions into different 3D exchange formats. Once converted from Voxler's own Open Inventor format (.IV) to OBJ, data were cleaned and

reduced to less than about 650000 faces using Meshlab. After reduction, data were optionally colour-coded (texture-mapped) according to depth by using another AWK script. Colour coding aids in investigating the stratification, particularly when data are complex. In a last step, the OBJ file is converted to VRML format, which is importable into ArcScene using the *Import 3D* tool. As briefly mentioned above, most 3D renderers cannot cope with large coordinate values often found in geodata. Georeferencing is preserved by extracting the largest numbers from all vertex coordinates, working with small coordinates in the OBJ and re-applying the stored offsets into the final VRML files before import.

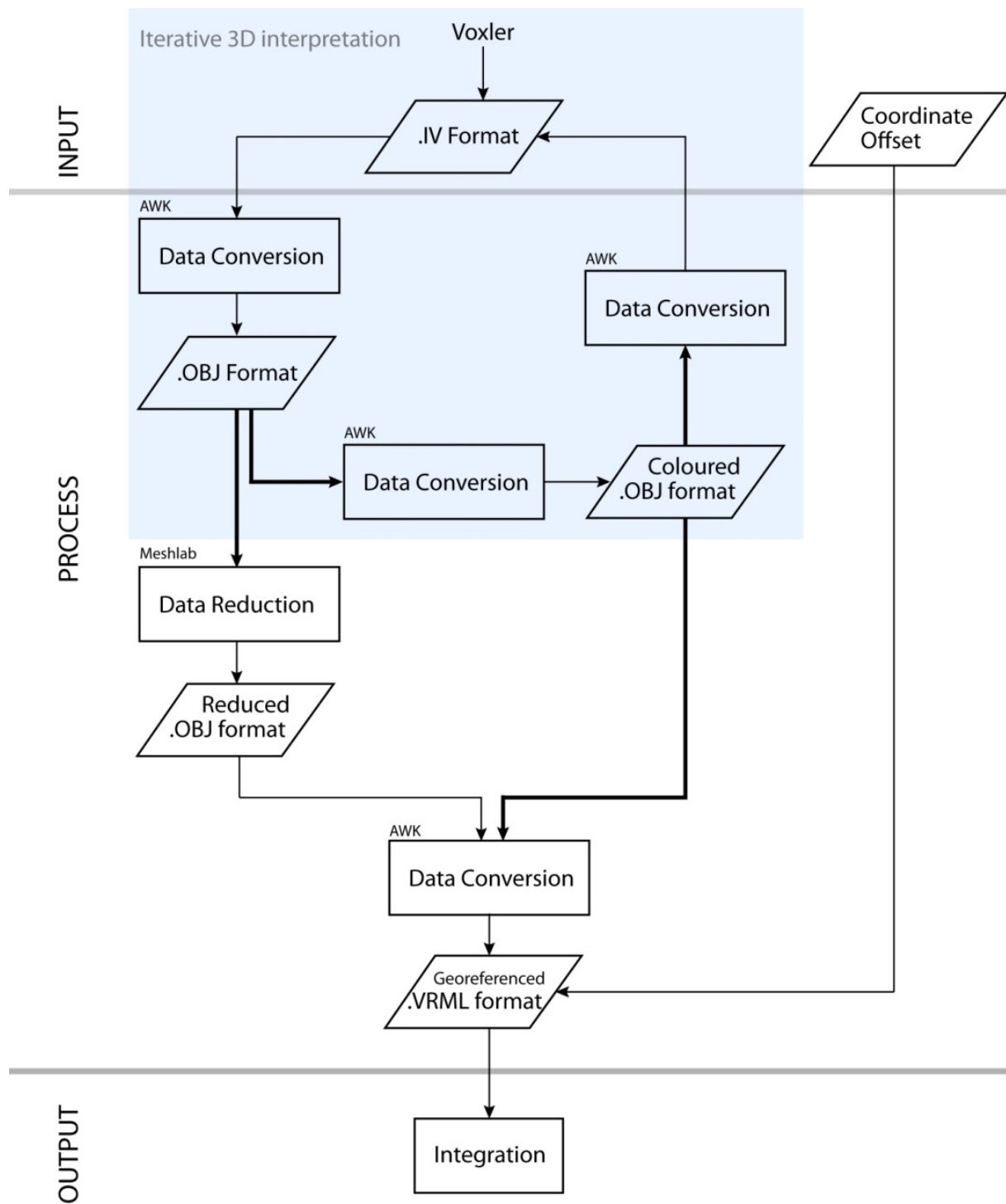


Fig. 4.16 Input-Output diagram for the integration of isosurfaces into ArcScene. Note the iterative approach of 3D interpretation before data are further converted for import into the GIS.

4.6.2 The burials in Slagendalen

A data set from Basberg in Slagendalen well demonstrates the benefits of such an integrated 3D approach. The high-resolution GPR data displayed an interesting distribution of roughly rectangular shaped archaeological features interpreted as burials, which were closely associated to a reflective band, first described in Schneidhofer et al. (2016). Reflective bands occur frequently in Norwegian GPR data and are interpreted as the remains of weathering processes connected to (former) bedrock outcrops (Schneidhofer et al 2016). The location of these burials always lined up along such a palaeoenvironmental structure aroused interest, particularly since similar situations were detected across the entire Slagen valley, which also accommodates the famous Oseberg ship burial dated to the Viking Age.

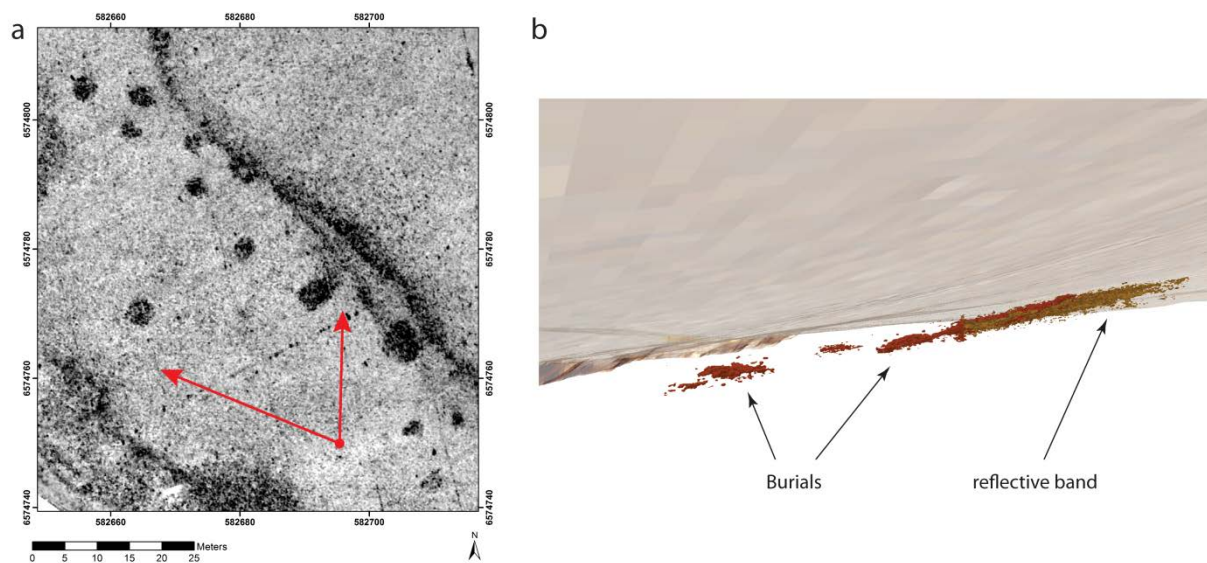


Fig. 4.17a GPR amplitude map (50-55cm BGS) from a subset of Basberg showing most likely burials along a reflective band. Red arrows mark the view direction for image b. 4.17b View towards north-west. Integration of burials and band visualised as cleaned isosurfaces in ArcScene together with a DTM of the Basberg area. The 3D view shows features detected with GPR below the current surface

A subset was thus visualised as topographically adjusted isosurfaces in Voxler 4 and subsequently imported into ArcScene for further data integration (Fig. 4.17). Here,

sedimentological and soil maps as well as topographic and reconstructed sea level data showed that the assumed burials were erected on top of the reflective band along a barely noticeable ridge on the slopes and roughly parallel to the main course of the river at the valley bottom (Fig 4.18). Magnetic data indicated that the burials were purposefully erected beyond the floodplain. Basic sea level reconstructions based on raster classification provided a *terminus post-quem* for the construction of the burial mounds between 2000 – 1000 BC.

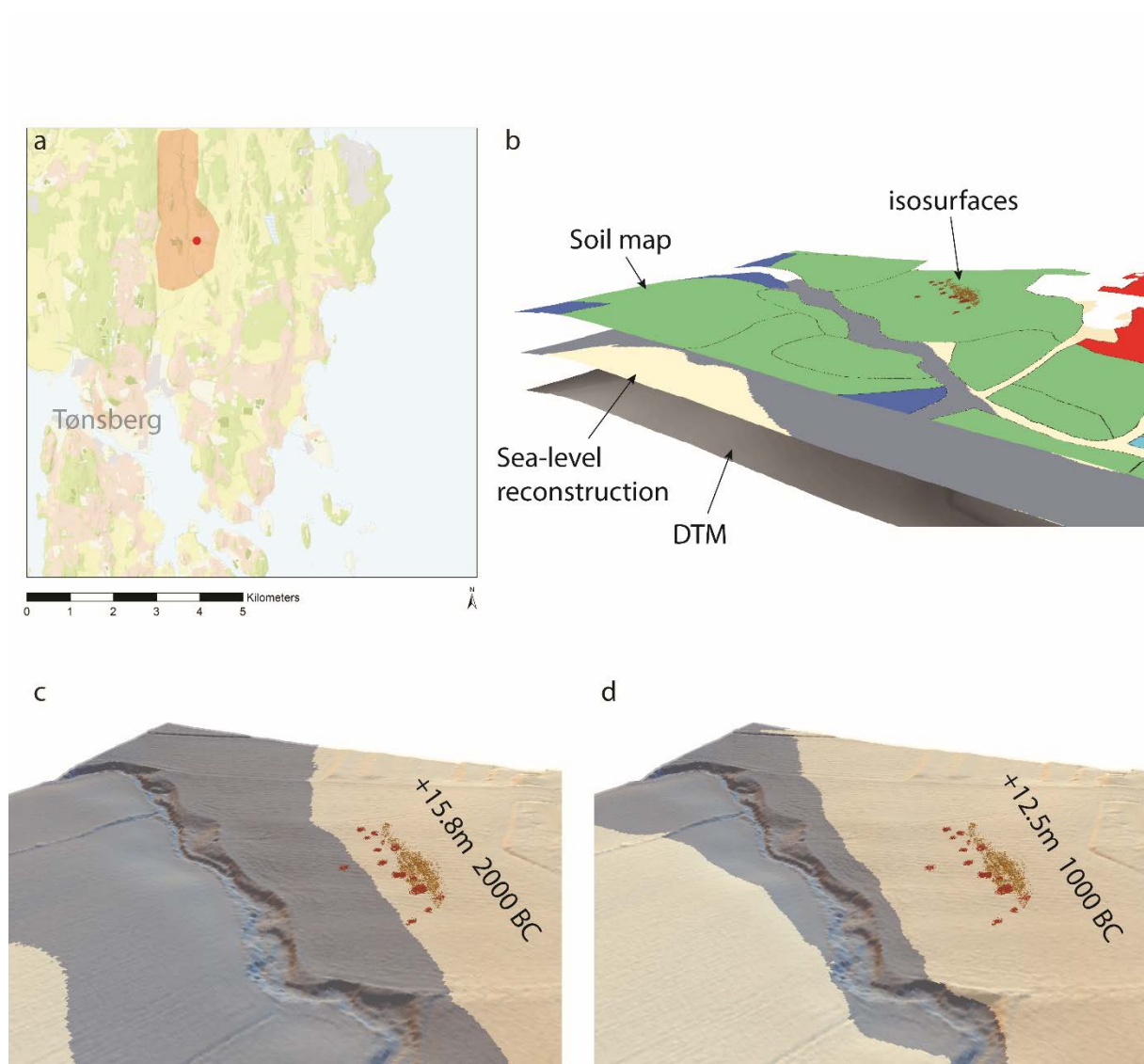


Fig.4.18a Location of Basberg in the Slagen Valley close to Tønsberg and ca. 4 km northwest of the current sea border 4.18b Isosurfaces of burials and band integrated with topographic, reconstructed sea-level and soil data. 4.18c Isosurfaces with reconstructed relative sea-level at 15.8 m above current sea-level based on calculations for 2000 BC. 4.18d Isosurfaces with reconstructed sea-level at 12.5 m above current sea-level based on calculations for 1000 BC. Based on these additional data sets, data integration yields a *terminus post-quem* for the graves between 2000 and 1000 BC. Sea-level data are based on Sørensen et al. (2007)

4.6.3 Rom mound

Integrated and coloured 3D data from Rom burial mound just ca. 700 m north of Basberg illustrate the benefits of colorization according to depth when dealing with more complex data sets (Fig. 4.19 and 4.20). The burial mound with a modern disturbance in the centre is well visible. In the southern area, the surrounding ring ditch is disturbed by a palaeochannel running close-by (Schneidhofer et al. submitted).

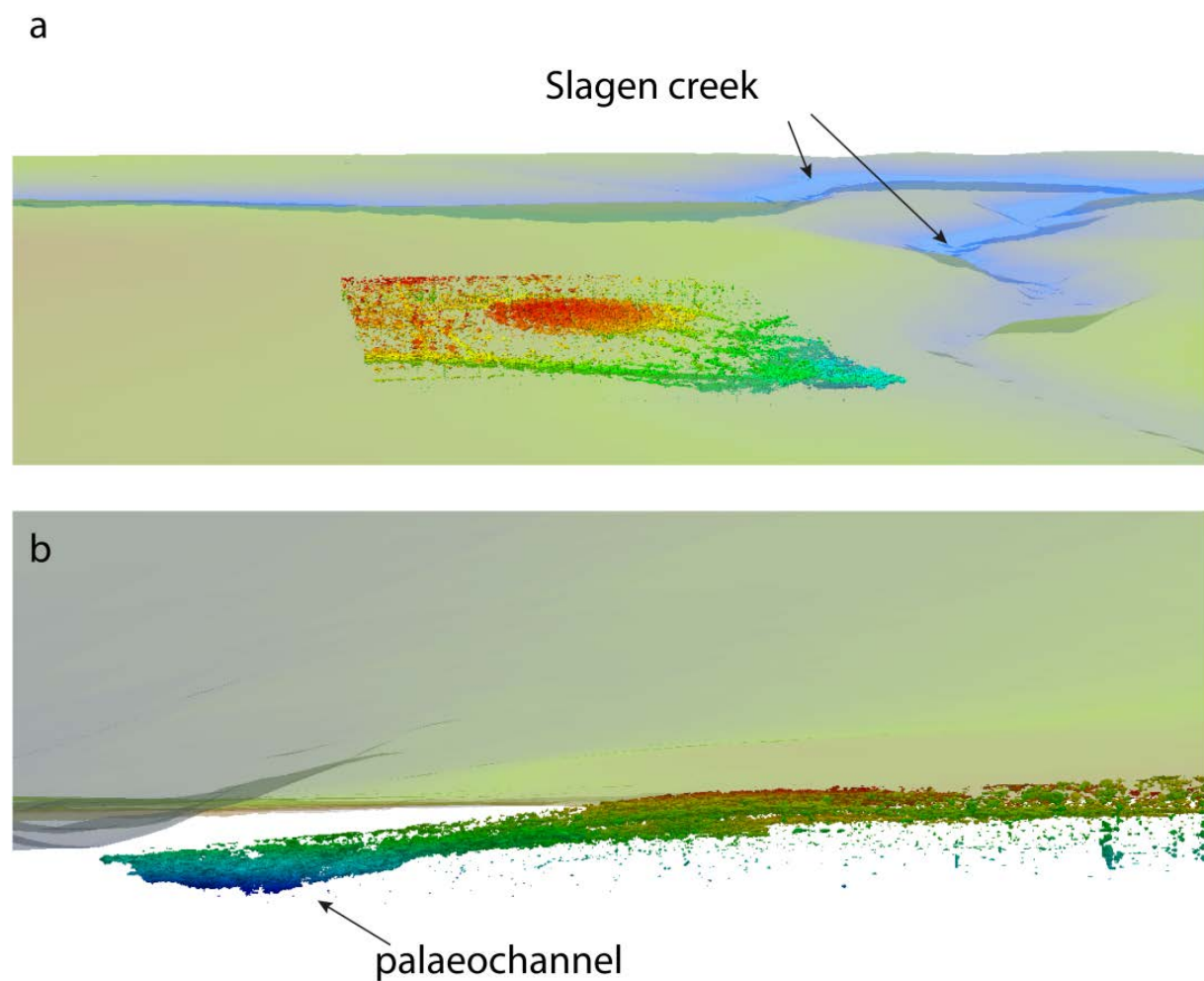


Fig. 4.19a Colour-coded isosurfaces displaying Rom burial mound and a close-by palaeochannel from the Slagen creek integrated with topographic data (DTM, 0.5 m). 4.19b View from underneath today's surface (rendered semi-transparent). Note the proximity of the palaeochannel and today's course of the river

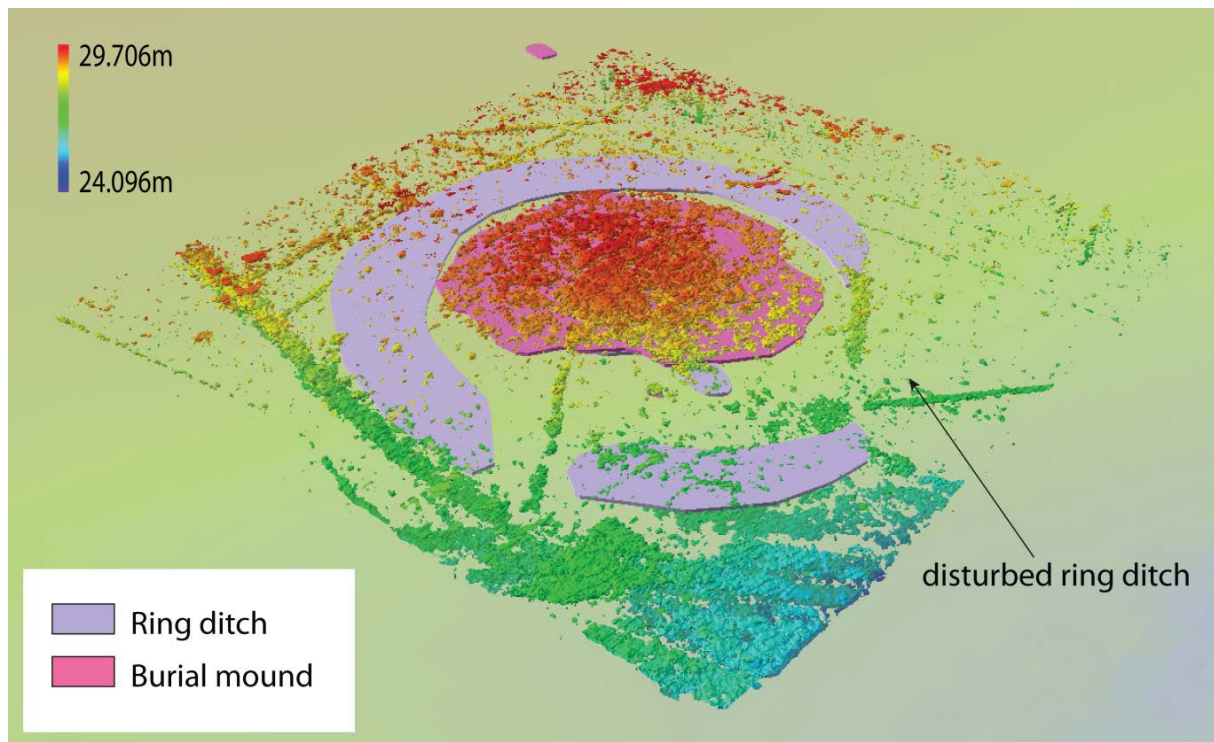


Fig. 4.20 Isosurfaces integrated with manual interpretation of Rom burial mound and topographic data. View towards northeast.

4.6.4 3D reconstruction

An additional benefit of clean isosurfaces is the possibility to directly use them for 3D reconstruction of the archaeological landscape under investigation. Such an integrated 3D visualisation as the synthesis of different elements including ALS, three-dimensionally visualised GPR and palaeoenvironmental data aids in the iterative process of the archaeological interpretation. It acts as a backdrop for the archaeological content and is useful for both research as well as public outreach purposes. The following example illustrates the Gokstad archaeological landscape at the time of the Viking Age. The isosurfaces of a part of the palaeochannel (see also Fig. 9-11) exported from Voxler 4 were imported into 3ds Max and formed the geometrical basis for the 3D modelling of the former riverbed (Fig. 4.21). It should be noted that the DTM used in this reconstruction is based on ALS data of the current topography, which is likely to deviate from that of the past. For the

surface, a procedural texturing model as commonly used in computer graphics was applied. Vegetation was added based on results of palaeobotanical studies from the Gokstad area (Skjelsvik et al., 1958) (Fig. 4.22).

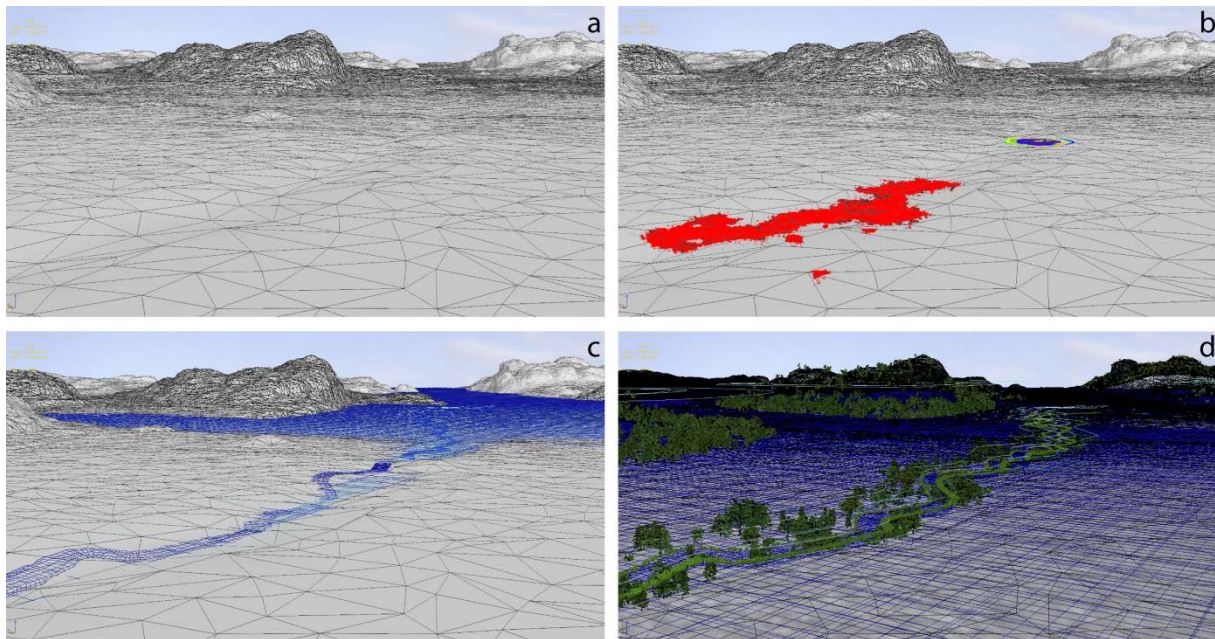


Fig. 4.21a Surface model in 3ds Max based on ALS data (0.5m resolution) 4.21b Addition of isosurfaces for the river model and shapefiles from the 2D interpretation of Gokstad nedre burial mound in ArcMap 10.2. 4.21c Modelling of river and sea-level 4.21d Adding vegetation. The generated virtual model follows the guidelines established in the London Charter (Denard, 2009) and the principles of Seville (Archaeology, 2011). Special attention is provided to scientific transparency and traceability



Fig. 4.22 3D reconstruction of the Gokstad landscape during the Viking Age. The river is bordered by vegetation and runs in close vicinity of Gokstad mound and Gokstad nedre mound towards the shoreline in the south, where a trading post is located. Bedrock outcrops are sparsely wooded, the area to the east (left) shows indications of marshy conditions. The valley bottom is used for sheep pasture, as these animals are known to be relatively salt-tolerant (Britton et al., 2008; Macphail et al., 2013)

4.7 Discussion and Outlook

This study has demonstrated that 3D visualisation of GPR data is a powerful tool for analysing palaeoenvironmental information. It aids in visualise a three-dimensional subsurface that otherwise would have to be translated mentally from 2D data such as sections or amplitude maps into 3D. This ability is of particular importance with the often unprecedented and complex palaeoenvironmental structures and patterns contained in large scale, high-resolution archaeological geophysical prospection data. Yet, a thorough understanding is the basis for an accurate 2D mapping of these features and for recognising their significance for the archaeological landscape under investigation.

Volume rendering in particular has proven beneficial for the visualisation as basis for the understanding of complex data, since it allows adjusting colour and opacity for specific

amplitude values. This is particularly helpful when focusing on absorbing areas, which sometimes are difficult to differentiate from the surrounding matrix and thus tend to be overlooked (Lawrence B. Conyers, 2015). Additionally, 3D visualisations are the result of transfer functions and algorithms and as such present a quantitative projection of the 2D GPR data. Although the selection of a certain iso threshold as well as colour and opacity settings can be considered as first step of the interpretation, the output is still reproducible and can be used for comparative purposes.

However, some observations need to be discussed here. First, the quality of 3D visualisations depends on the quality of the initial data sets. Key factors are high resolution and contrast. Data that do not comply with these requirements often tend to result in unidentifiable amorphous structures – a likely reason why the method has not been regularly used for archaeological features. Another necessary element for the recognition of palaeoenvironmental structures and patterns is a sufficiently large survey area.

Second, 3D visualisation of GPR data is currently not an instant procedure. Available memory and graphic cards determine the amount of data that can be visualised. Consequently, data suitable for 3D visualisation need to be pre-selected based on pending questions from the interpretation. In certain cases, larger areas necessitate divisions into several parts, which requires more time, jeopardises the identification process and altogether is impractical. The high resolution needed for a meaningful 3D visualisation, in turn, presents a challenge particularly for the use of isosurfaces, where it leads to an increased processing time (Verdonck, 2012) as well as to fragmentation that is difficult to interpret and requires time-consuming cleaning and editing before data integration. Topographical adjustment proved essential for data analysis, yet can substantially increase the memory requirements, as was the case with the Kaupang data set.

Third, limited compatibility between different 3D renderers on the one hand and between 3D renderer and GIS software on the other presents one of the biggest challenges when it comes to 3D visualisation of GPR data. This limited compatibility is a problem in both directions. While 3D renderers such as Voxler 4 at least do support the import of georeferenced raster and vector data, manipulating these data in terms of colour or even extrusion is not possible. In addition, preserving the coordinate values in the single-precision floating-point renderers available requires some insight in, and tricks with, 3D file formats.

Going the other direction by trying to integrate volume rendered GPR data in a GIS, where most of the 2D interpretation is done, often is not feasible due to the lack of a volume renderer in most GIS. Isosurfaces, of which limited sets can be imported into 3D environments as featured by ArcScene, need to be first converted, cleaned, reduced and georeferenced in a relatively time-consuming process using custom-made conversion tools.

Despite these challenges, however, the benefit of 3D visualisation and integration of GPR data for understanding archaeological landscape development is unquestioned. Even though this study primarily focused on palaeoenvironmental information, the workflow presented is equally applicable to the interpretation of archaeological features. It is probable that with the increasing capabilities of hard- and software, many of the challenges discussed above will be overcome and that the analysis of GPR data will continue heading towards full 3D interpretation as has been long called for (Leckebusch, 2003b). Next steps in this direction will include a simplified and more automated implementation of interactive 3D visualisation in the interpretation of GPR data as well as specific data processing for the demands of 3D visualisation such as increased contrast, data fusion and reduced noise. One of the most required tools is 3D editing and the option of segmentation as elements of a true 3D interpretation. It is to be expected that GIS will soon feature better 3D renderers, as well as more georeferenced-preserving import/export options in 3D rendering software in order to facilitate the necessary data integration.

From a methodological point of view, it should be stressed that data integration does not present simply a final stage in data interpretation, but is essential already throughout the analysis and must form part of an iterative refinement process.

Chapter V

In-situ and laboratory-based magnetic susceptibility measurements at the archaeological site of *Heimdaljordet*, Gokstad

5.1 Introduction

As mentioned in chapter II, the area surrounding the Gokstad mound (Fig. 5.1 and 5.2) in Vestfold County, Norway, became subject to geophysical archaeological prospection surveys in the framework of the Gokstad revitalised project.

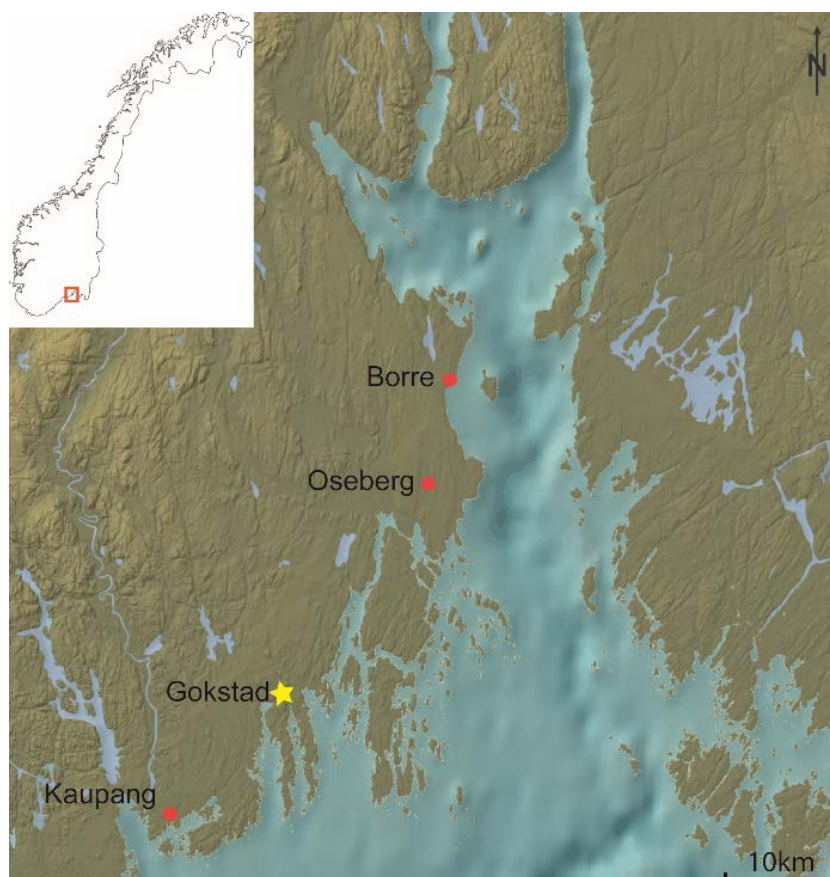


Fig. 5.1 Location of the study site *Heimdaljordet* in Gokstad at the western side of the Oslo Fjord, Vestfold County, Norway amid other important Viking Age sites

The used prospection approach was based on complementary large-scale, high-resolution magnetometry and GPR measurements. In terms of archaeology, the most significant findings were discovered at *Heimdaljordet*, where GPR surveys revealed aligned, rectangular features in the south-western part that were interpreted as the remains of a Viking Age settlement. The north-eastern part of *Heimdaljordet* displayed a cluster of levelled burial mounds (Fig. 5.3a).

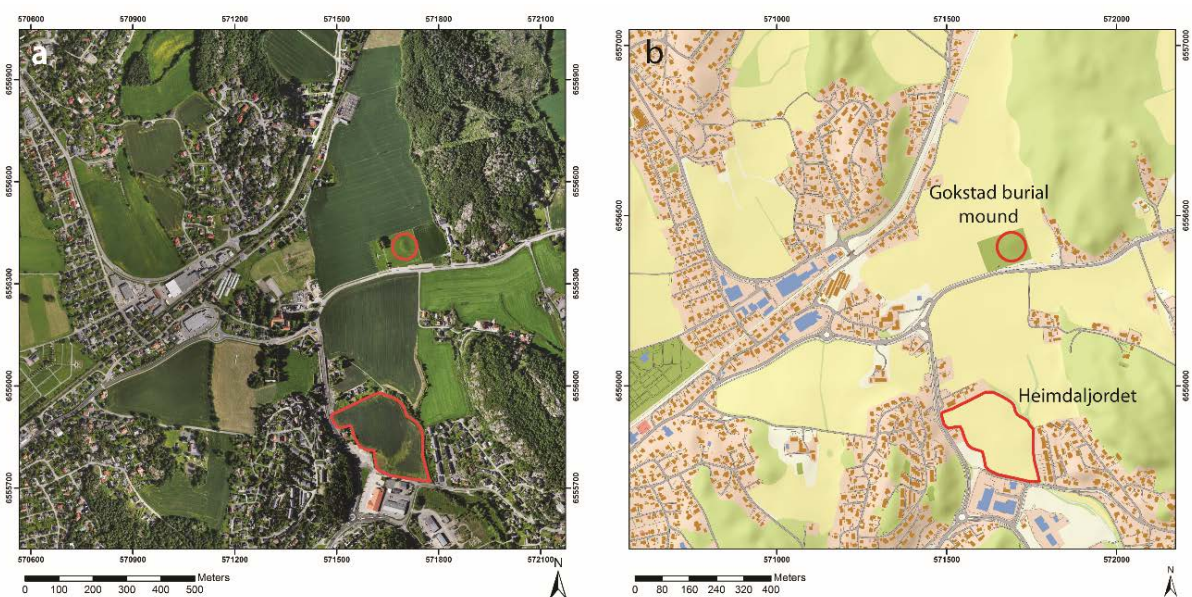


Fig. 5.2a Aerial photograph of the Gokstad area with the site *Heimdaljordet* situated ca. 500 m south of the Gokstad mound (both marked in red). 5.2b Map of the same area

A second geophysical prospection survey conducted in April 2012 conducted by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology using a high-definition 16 channel 400 MHz MIRA with a particularly high resolution of 8×8 cm enabled the generation of clearer and more detailed pictures of the structures buried in the subsurface (Fig. 5.3). In sharp contrast to the rich GPR data, fluxgate magnetometry conducted in September 2011 using a motorized Foerster system consisting of 10 FEREX CON 650 gradiometer probes with a 25×10 cm resolution, did not detect any of the structures mentioned above (Fig. 5.4). This was even more surprising as settlement traces

often contain materials displaying enhanced magnetization such as fire places, ceramic and metal objects susceptible to magnetometry (Neubauer, 2001a).

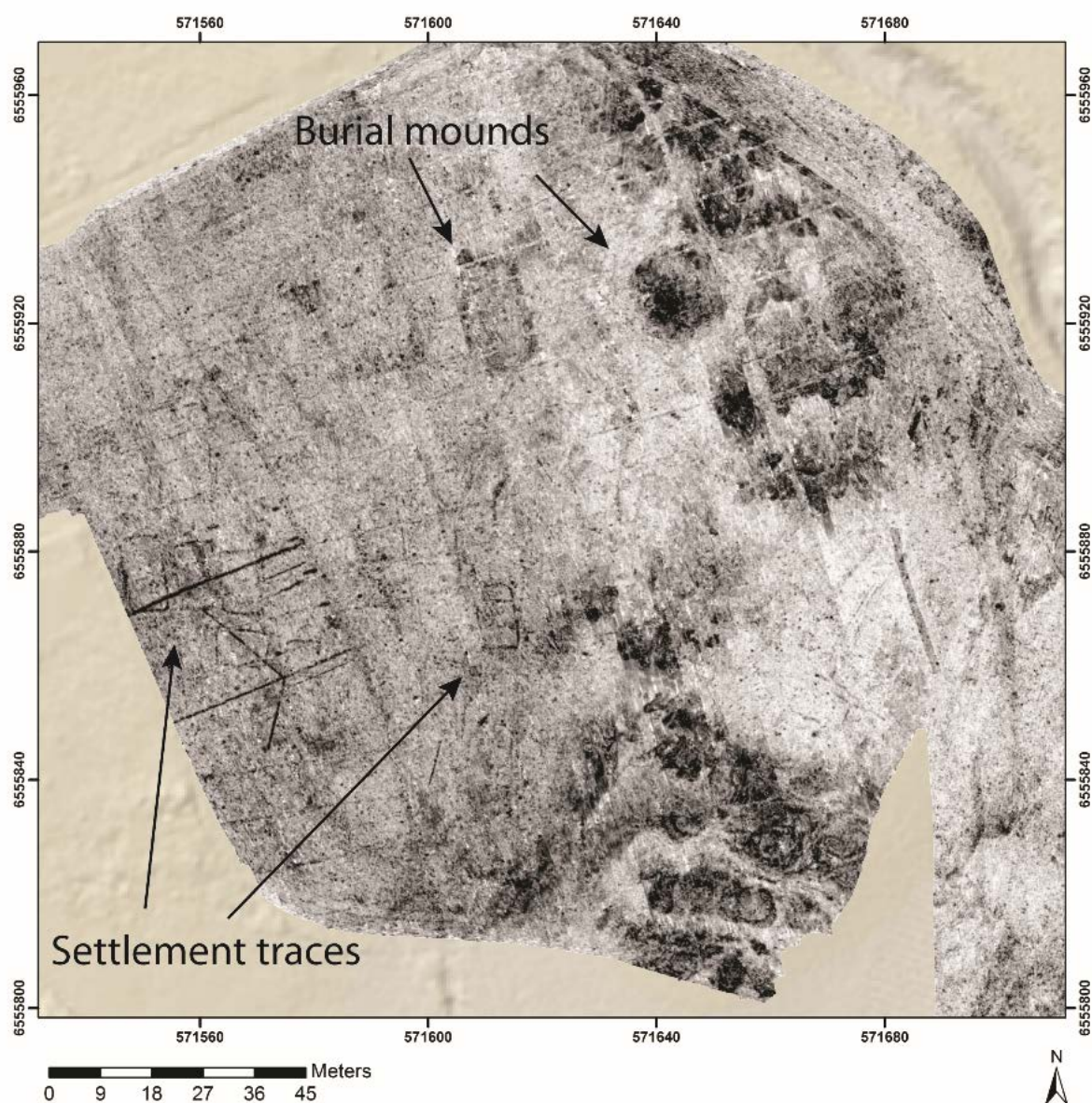


Fig. 5.3 GPR depth-slice (70-75 cm BGS) displaying the *Heimdaljordet* study site with its settlement traces in the western part and burial mounds in the north-eastern part.

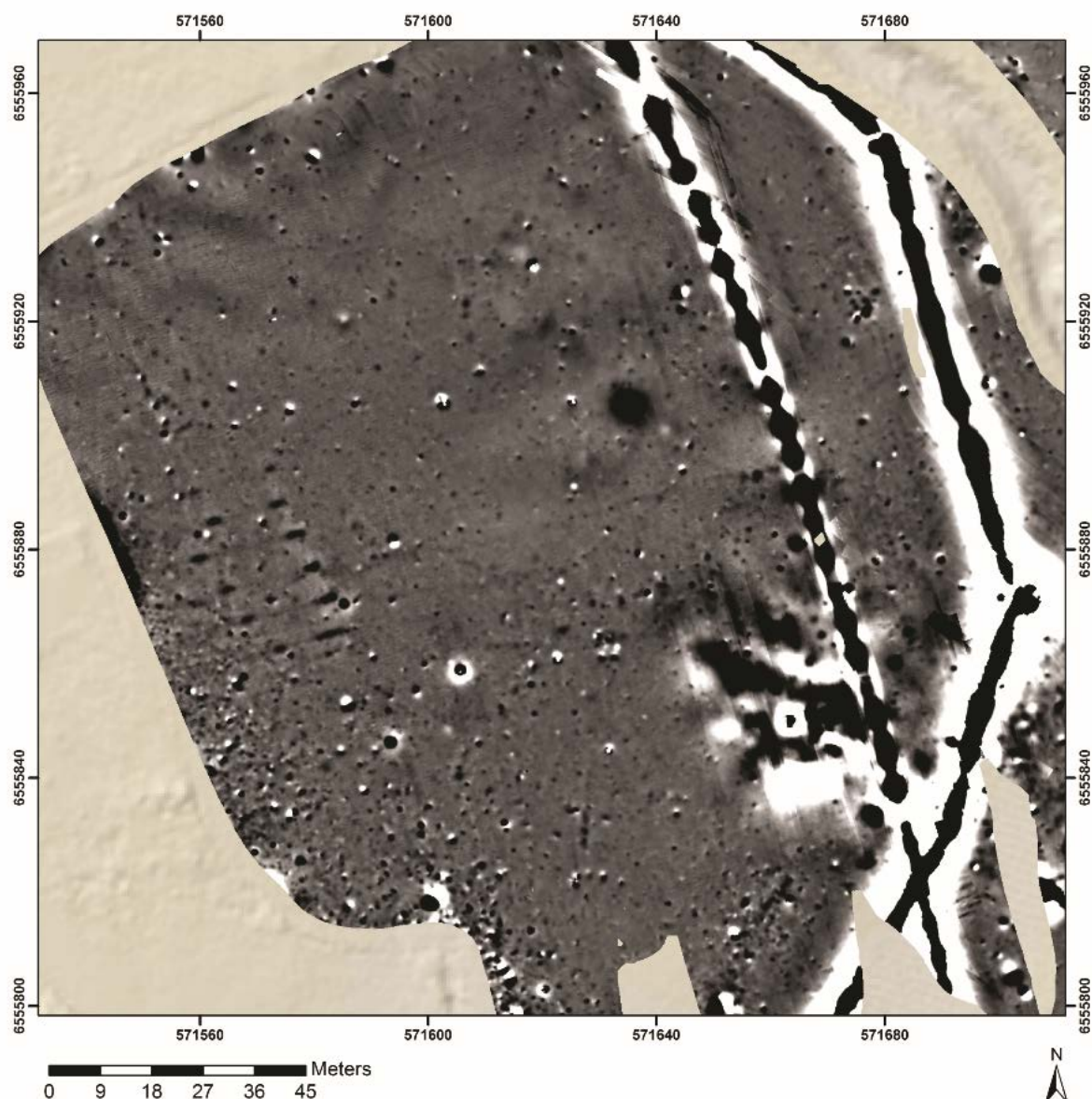


Fig. 5.4 Magnetogram of the *Heimdaljordet* study site. Note the lack of settlement traces and burial mounds as detected in the GPR data.

In July and August 2012, *Heimdaljordet* was subjected to extensive archaeological fieldwork, including metal detector surveys, sieving analysis, borehole surveys and eventually excavation work based on the findings from the GPR surveys. These activities allowed access to soils and sediments and enabled a geoarchaeological field evaluation in order to generally compare the results of archaeological geophysical prospection data interpretation and excavation results, to preliminary investigate possible reasons for the low visibility in the magnetic data of both settlement traces and graves and to further add to the knowledge

base of (palaeo)-environmental settings and their implication for the archaeological interpretation of archaeological geophysical prospection data.

5.2 Background

5.2.1 Complementary archaeological geophysical prospection techniques

At *Heimdaljordet*, the use of complementary archaeological geophysical prospection techniques including magnetometry and GPR presented the key to successful survey results. Magnetometry is a passive technique, which measures local variations in the Earth's magnetic field (Neubauer 2001). GPR on the other hand actively transmits electromagnetic energy into the ground and records returning reflections caused by contrasting physical properties at the interface of different subsurface materials. By converting the GPR signal's two-way travel time into depth using a known or estimated signal velocity it is possible to generate a three-dimensional data block from densely sampled 2D GPR profiles (Goodman et al., 1995; Leckebusch, 2003a).

As discussed in detail in chapter II, both techniques are dependent on sufficient physical contrast between natural or man-made structures or deposits and the surrounding soils and sediments, yet they respond to different physical properties. It is thus possible that e.g. structures are well visible in GPR data, but not detectable in magnetic data (Watters, 2009). Complementary survey approaches therefore are inevitable in order to maximise results and ensure comprehensive information on buried structures of archaeological or historical interest. While insufficient contrast of physical properties can lead to archaeological information being overlooked in geophysical data sets, a phenomenon known as “ghost feature” presents another, related issue: Under certain circumstances, geophysical sensors can detect and visualise buried structures that otherwise remain invisible to the human eye when excavated traditionally (Simon et al., 2012). Both cases can cause problems for the archaeological interpretation, either in the understanding of a specific site or landscape, as well as for the further development and use of archaeological geophysical prospection

amongst archaeologists. As mentioned above, reasons for these issues are directly linked to physical properties and contrast of subsurface materials. Detailed knowledge about soils and sediments in certain environmental settings and their response to different archaeological geophysical prospection techniques are therefore crucial in order to scientifically assess and subsequently enhance the quality of the geophysical and archaeological data interpretations (Lawrence B Conyers, 2015; Schneidhofer et al., 2016).

The geoarchaeological field evaluation at *Heimdaljordet* was therefore particularly focused on the magnetic properties of top- and upper subsoil, which accommodated most of the shallowly buried archaeological features detected in the GPR data. MS was chosen as basic diagnostic parameter for preliminary insights about magnetic properties and magnetic contrast. Investigations focused on two excavation trenches and a number of core samples at selected locations.

5.2.2 Magnetic susceptibility measurements

MS is a physical property indicating the degree to which a material can be magnetized when exposed to an external magnetic field. MS is defined as the ratio of magnetisation induced in a sample relative to the intensity of the inducing magnetic field; it depends on a range of different factors, including mineral composition as well as the frequency of the inducing magnetic field. MS can be expressed as volume susceptibility (κ) or mass susceptibility (χ), where both quantities are normalised by either a calibrated volume or a calibrated mass (Dalan & Banerjee 1998, Tite & Mullins 1971). MS *in-situ* measurements are conducted with field sensors and result in volume MS values. Local differences in soil density, porosity, water content and the possible presence of inclusions such as stones, metal or pottery fragments, can considerably influence κ and therefore need to be considered when using volume MS for comparative purposes. Laboratory based analyses allowed to better control these parameters (Dalan 2006) by using a standardised approach.

Previous studies have repeatedly used laboratory-based MS measurements in order to test the applicability of magnetic surveys on specific sites, as well as to aid in the interpretation

of magnetometry results (Dalan & Banerjee 1998, Challands 1992, Gaffney & Gater 1993, English Heritage 1995).

5.3 The study site *Heimdaljordet*

The study site *Heimdaljordet* is situated 500 m south of the Gokstad ship burial mound, about 1.5 km to the north-east of Sandefjord, Norway (Fig. 1, 3 and 4). *Heimdaljordet* comprises approximately 3.5 ha of arable land, which until very recently was subject to agricultural use and ploughing. The site lies around 4 m above sea level. Its sedimentary cover roughly consists of clayey silts and sands overlying undisturbed marine sediments² (Fig. 5.5).

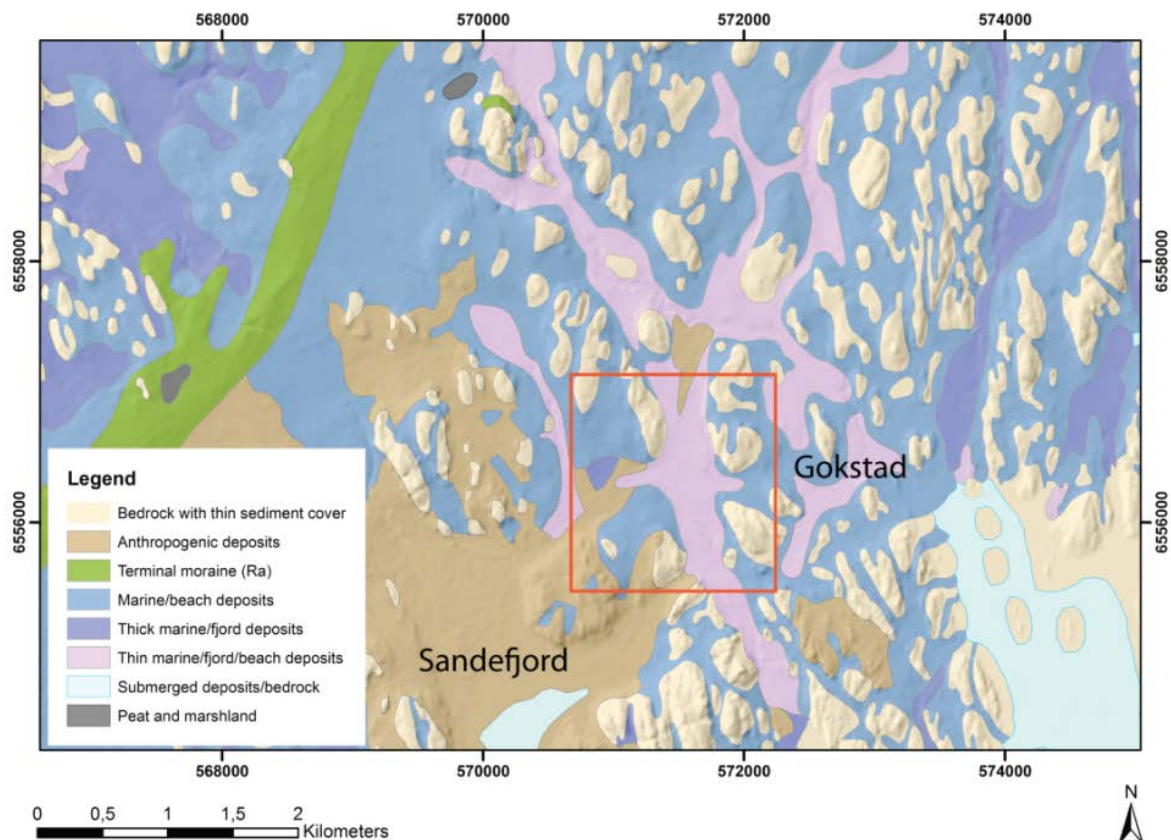


Fig. 5.5 The entire region around Gokstad is covered mainly by marine sediments as a result of post-glacial rebound and subsequent sea-level retreat. The red rectangle marks the image section of Fig. 5.2

² As observed during the borehole survey

Almost the entire study area is covered by stagnosol typically showing a profile sequence of 25-30 cm ploughed topsoil (Ag), followed by often gleyed subsoil (Bg) which overlies the parent material: marine sediments consisting of mainly silts and clay silts (Cg). (Cannell, n.d.) (Fig. 5.6). Stagnosols are characterised by a stagnant zone that impedes surface water from draining and often show redoximorphic properties caused by repeated cycles of water saturation and subsequent drying, resulting in the small-scale redistribution of Fe and Mn based on reductive mobilisation, dissolution and oxidative re-precipitation. Due to the periodic saturation, stagnosols are difficult to cultivate. In addition to widespread drainage systems, deep ploughing is often needed in order to improve the hydraulic conductivity of the soil (Soil WRB, 2006). A relatively small part in the centre of the study area accommodates arenosol, which is self-draining and consists of sorted sands. A slight depression towards the southeast marks the presence of a palaeochannel and is classified as endostagnic cambisol – a young soil with weakly developed soil structure. The southern part of the survey area is described as anthropic regosol – a water saturated area characterised through anthropogenically re-deposited material (<http://wms.skogoglandskap.no/cgi-bin/jordsmonn>).

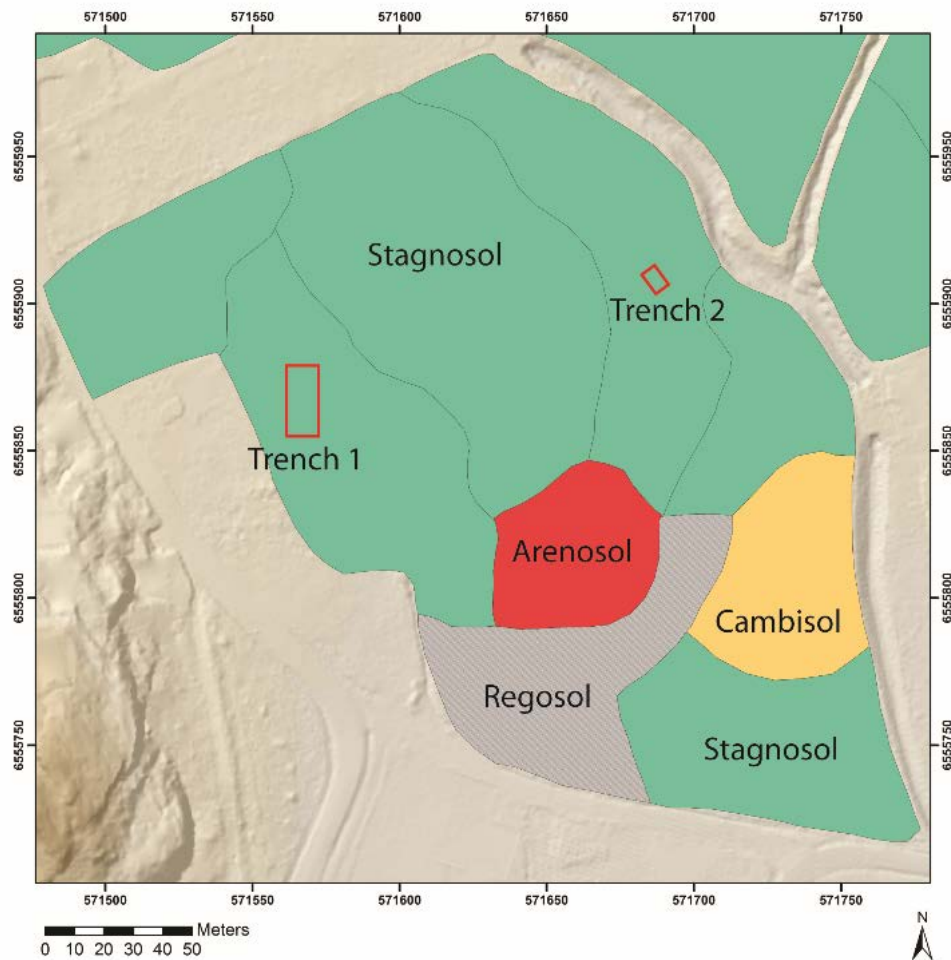


Fig. 5.6 Soil map of the study site *Heimdaljordet*. Most of the area is covered by periodically water saturated stagnosol. Red rectangles are marking the location of trench 1 and trench 2

At *Heimdaljordet*, intense traces of human activities presumably dated to the Viking Age were discovered based almost exclusively on the GPR data (Fig. 5.7). The central and western part of the survey area showed a range of reflective, linear features visible between 0.35 and 0.75 m BGS resulting in a preserved depth of ca. 40 cm. These features are between 0.4 m and 0.7 m wide and form rectangular structures with subrounded corners with dimensions between 6 -7.5 m x 10 -13.5 m. The structures are interpreted as small back-filled ditches marking the building plots of a Viking Age settlement. The lack of postholes is attributed to poor preservation due to deep ploughing required by the stagnic soils at *Heimdaljordet*. Part of the features is distributed seemingly aligned along a path or street running from north-west to south-east, while some features are rather randomly placed. The mound cemetery is located in the east and north-east of the settlement area. 13

individual graves are clearly identifiable as alternating reflective and absorbing features. The ring ditches surrounding the monuments are between 0.7-1.8 m wide and enclose circles of 6 - 8 m in diameter.

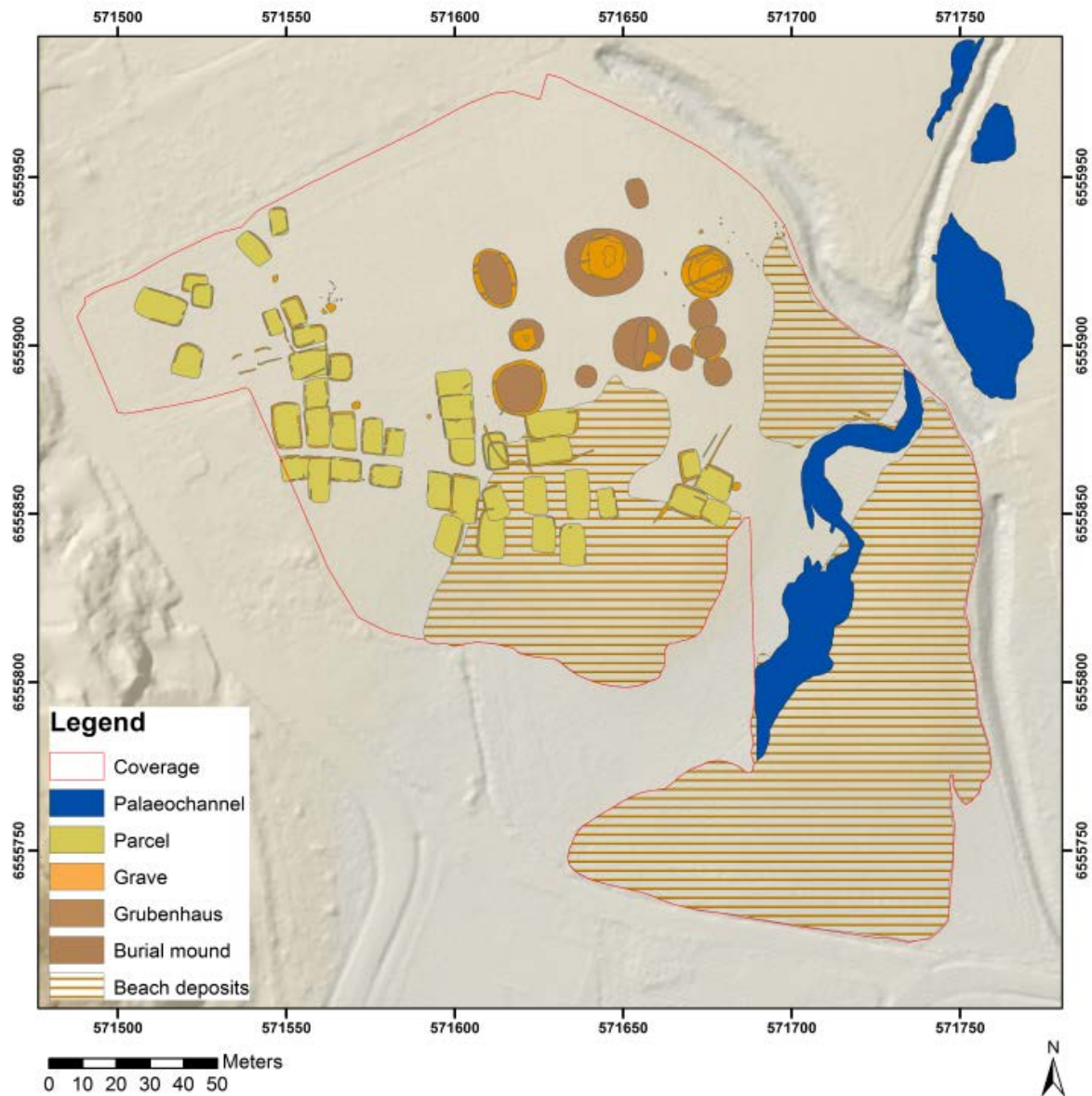


Fig.5.7 Archaeological and palaeoenvironmental interpretation based on the high-resolution GPR data with settlement traces in the west, burial mounds in the north-east and beach deposits cut by a palaeochannel in the south-east

Based on these results, as well as on the results of a metal detector survey in May 2012, two trenches were dug targeting one of the building plots and parts of the street, as well as the location of a 9th century sword hilt that was unearthed during the metal detector survey and originated from just below the topsoil (Fig. 5.8). These openings allowed access to the subsurface materials in order to conduct a geoarchaeological evaluation.

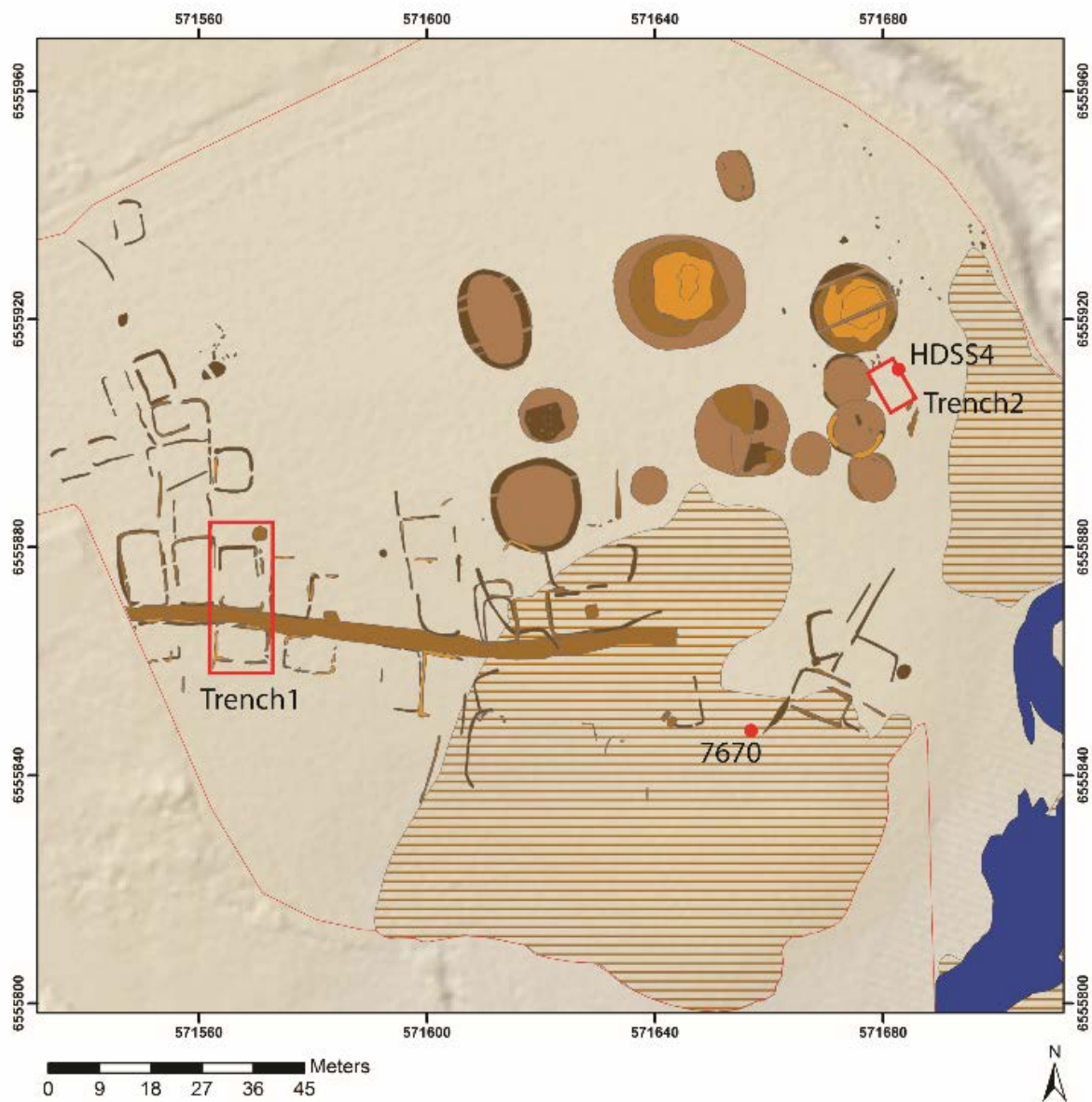


Fig. 5.8 Based on the interpretation map the location of excavation trench 1 was chosen. trench 2 investigated the location of a sword hilt discovered in the course of metal detector surveys. Note the location of core 7670 in an area undisturbed by archaeological structures and the location of profile HDSS4 in trench 2

5.4 Fieldwork

Fieldwork was conducted during the archaeological excavation and took place from August 6th to 10th 2012. Due to the relatively short time available on site for *in-situ* measurements and sampling, the evaluation strategy had to be adjusted to the then stage of the excavation, which at that point featured two open trenches: trench 1 targeted a building plot in the settlement area (Fig. 5.8) situated along a proposed path. The topsoil had been removed, but archaeological features were still intact. Trench 2 focused on the area where the sword hilt had been found during the metal detector survey (Fig. 5.8 and 5.12). In this case, the removal of topsoil revealed the decayed remains of a small vessel embedded in the subsoil with iron nails outlining the boat's structure. The situation thus quickly identified as a boat grave, where the sword had been laid down as grave good.

As illustrated in the GPR data, most archaeological features only reached down to ca. 0.75 m below surface, which emphasized the endangerment of features and their exposure to partial destruction by ploughing activities. Yet, at the same time, such a shallow overburden pointed at the topsoil as significant factor in the detectability of the archaeological features. It therefore was important to get more information on magnetic properties and variability of topsoil as well as subsoil in comparison to that of the archaeological features. Investigations included *in-situ* measurements of volume MS as well as sampling for laboratory-based mass-specific MS measurements.

During three of the four days intended for fieldwork, heavy rainfall prevented any sampling or *in-situ* measurements in the excavation trench. The stagnosol described above prevented the water from draining resulting in the temporal flooding of *Heimdaljordet*. The Bartington meter is sensitive to changing temperatures and wet conditions (Bartington manual OM0408) and its response showed a drift that exceeded the tolerable threshold. Due to these time issues, only about two thirds of trench 1 (12 x 15 m) – where some building plots were still intact after top soil removal – could be measured with a 50 x 50 cm sample resolution in order to determine the actual contrast between archaeological features and the surrounding soil (Fig. 5.9). Measurements were conducted using a Bartington MS2 meter equipped with the loop sensor MS2D. The lower resolution was not a particular limitation to the study, since the focus was set on the investigation of the contrast in values between

archaeological features and the surrounding sediments, rather than an actual mapping of the buried features. Standing water also prohibited *in-situ* measurements of profile HDSS4 in trench 2.



Fig. 5.9 *In-situ* volume susceptibility measurements in trench 1 after removal of top soil using a Bartington susceptibility meter and a MS2D probe

Systematic high-resolution *in-situ* sampling (every 2 cm) for MS was performed vertically across three profiles from topsoil and transition to subsoil (HDSS1-HDSS3) in trench 1 (Fig. 5.9 and 5.10). Profile depth was limited based on the progress of the still on-going excavation work. Material for lab-based MS measurements was collected from profiles HDSS1-3 by systematic subsampling of roughly every 10 cm (Fig. 5.10). Core 7670 collected from a location free of archaeological remains outside the trench was sampled every 2 cm for mass-specific MS measurements (Fig. 5.8).

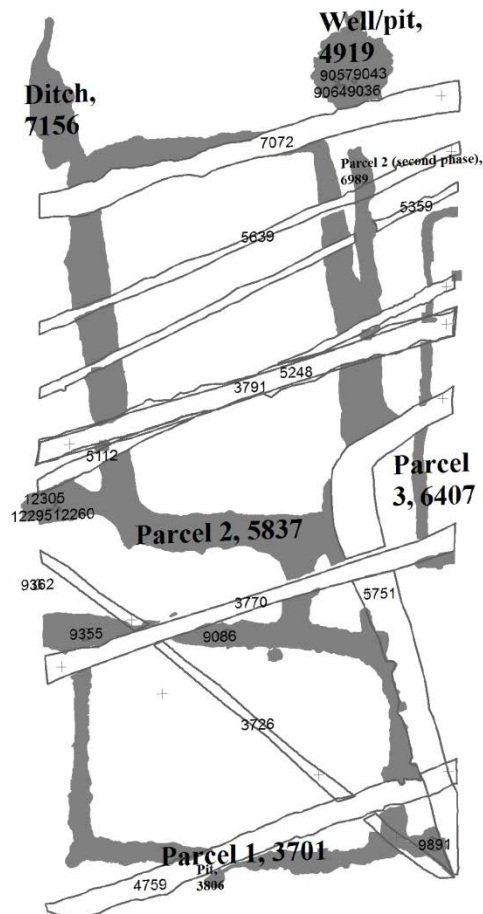


Fig. 5.10 Preliminary map of the archaeological structures identified in trench 1 at *Heimdaljordet*. The ditches interpreted as building plots are marked with grey fill. Most of the linear structures running from south-west to north-east are plough marks. Compare also to Fig. 5.11a. (from Gokstad revitalised project/ Christian Løchsen Rødsrud)

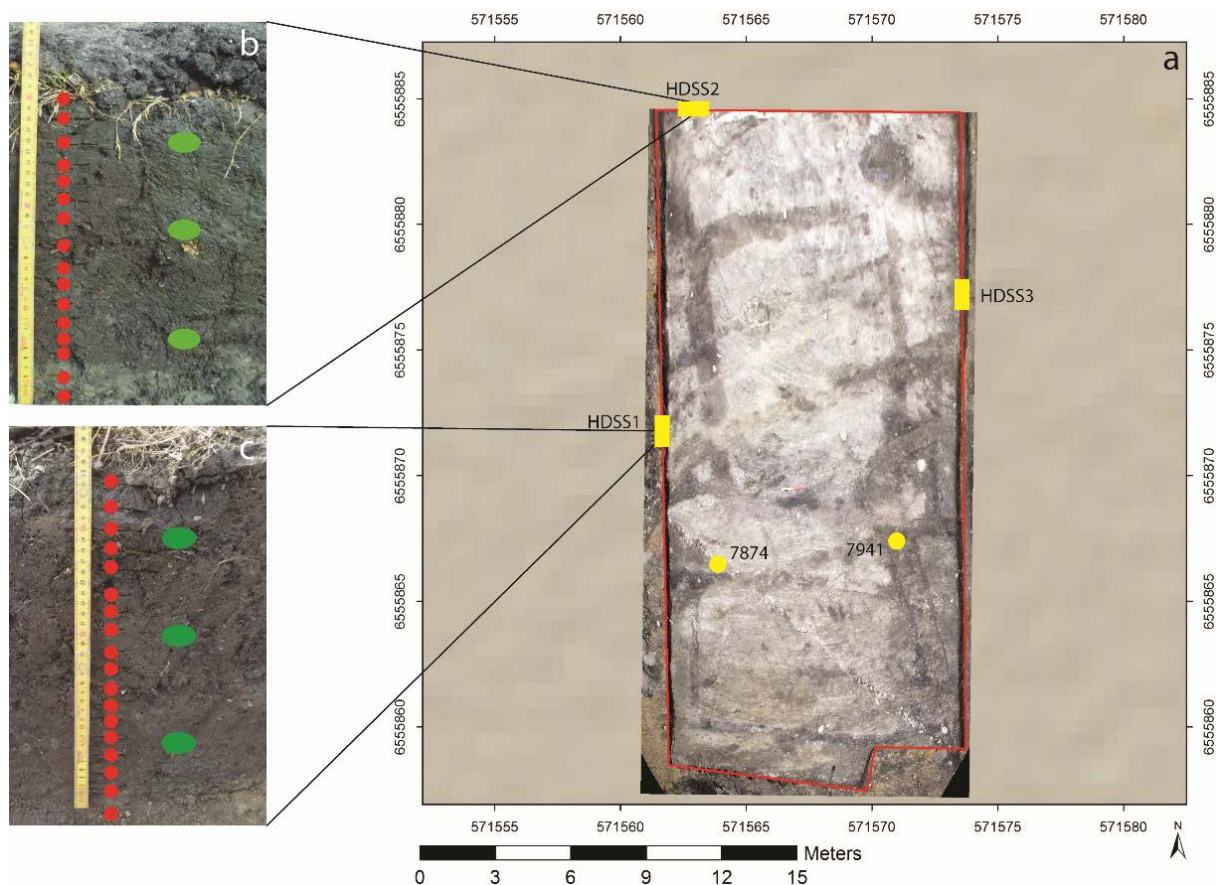


Fig. 5.11a Ortho-photo of excavation trench 1 which focused on a rectangular arrangement of ditches, presumably Viking Age property plot boundaries, detected by high resolution GPR measurements. The photo displays archaeological features embedded into the subsoil as seen after topsoil removal. Note also the disturbance by modern drainage ditches visible in the trench. Locations for MS measurement from profile (yellow bars) and core (yellow points) samples are marked. 5.11b, c Sample locations HDSS1 and HDSS2 taken from profiles of trench 1. Volume susceptibility was measured *in-situ* at a 2 cm interval (red points) and included the transition to subsoil. Material for mass specific susceptibility measurements was sampled at an approximately 10 cm interval from top to bottom (HDSS1-1, HDSS1-2 etc.: green ovals) and was taken to the laboratory for further analysis. HDSS3 with four subsamples followed the same principle, yet any photographic documentation was unintentionally destroyed

Several archaeological features were individually targeted in trench 1. Core samples from unexcavated archaeological features located within this trench (core 7874 from parcel ditch 9355; core 7941 from parcel ditch 5751 overlying the “path” 9362) (Fig. 5.10, 5.11a) were taken back to the laboratory in order to measure mass-specific susceptibility values of stratigraphic sequence, and to gain more information about the contrast towards the subsoil in which the features were embedded in.

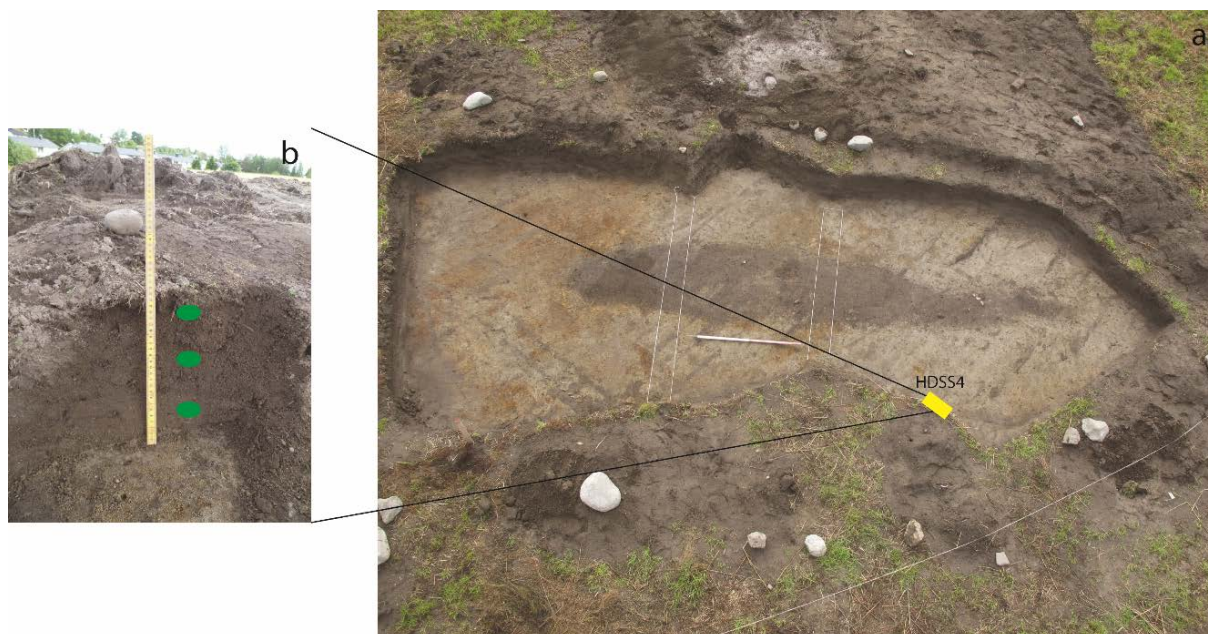


Fig. 5.12a. Oblique photo of the boat grave in excavation trench 2. The picture clearly shows the remains of a small, decayed vessel together with indications of iron panning at the transition between top- and subsoil (Macphail et al., 2013). 5.12b Sample location HDSS4 taken from the profile of trench 2. The measurement of volume susceptibility *in-situ* was prohibited by the unfavourable weather conditions. Material for mass specific susceptibility measurements was sampled at an approximately 10 cm interval from top to bottom (HDSS4-1, HDSS4-2 etc.: green ovals) and was taken to the laboratory for further analysis

5.5 Methods

Soil and sediment samples were described following selected criteria (texture, stoniness) from Hodgson (1976). Stratigraphic relations were established in the field. Colour was determined using the Munsell Soil Colour Chart (Munsell 2000).

In-situ MS measurements were performed using a Bartington MS2 meter equipped with a MS2D surface scanning probe (penetration depth ca. 10-15 cm) and a F surface point probe (penetration depth ca. 2 cm).

Laboratory-based MS samples were dried in an oven at 40°C for 24 hours in order to reduce the mass contribution of water. Samples were then ground in a porcelain mortar and subsequently sieved down to <2mm. The resulting sample material was filled in 10 cm³

plastic containers and the actual sample mass was weighed on a KERN 440 precision balance. Volume MS was measured at room temperature with a Bartington MS 2 susceptibility meter (Bartington manual OM0408) using a sensor type MS2B at low (0.465 kHz) frequency with a precision of <1% (Dearing, 1994). Volume susceptibility measurements were converted to mass specific susceptibility values, taking into account corrections for the actual sample mass.

Results of the MS analyses were processed and visualised using RockWorks 15.0 software. All columns were vertically exaggerated by a factor 20 for improved data display. The ortho-photo displaying trench 1 has been calculated and rectified using Agisoft Photoscan Professional Edition Version 0.9.0, and georeferenced in ArcGIS 10.0. Pictures used for this procedure have been kindly provided by Christian Løchsen Rødrud.

5.6 Results

Results of the planar 12 x 15 m volume-specific *in-situ* MS measurements in trench 1 generally show low susceptibility values ($6 - 55 \times 10^{-5}$ SI) for both archaeological features and the surrounding subsoil with a few outlier around 100×10^{-5} SI. Although poor, the contrast is sufficient for archaeological features to be detected by MS measurements after removal of topsoil (Fig. 5.13).

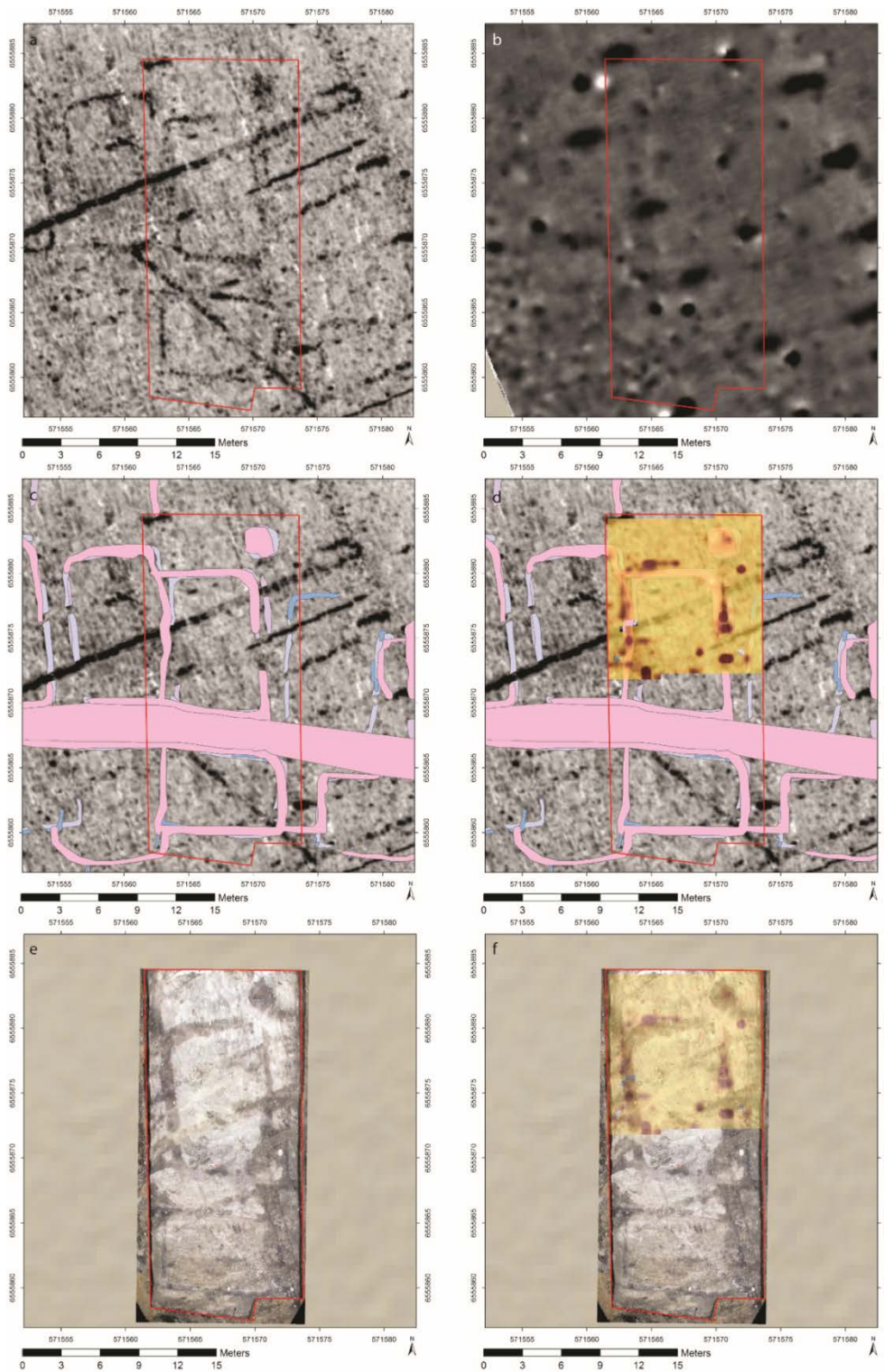


Fig. 5.13 Sequence of integrated data including at (a) 70-75 cm BGS with the outline of trench 1, 5.13b magnetic data with the outline of trench 1, 5.13c GPR data interpretation of features targeted in trench 1, 5.13d GPR data interpretation superimposed with results from the planar *in-situ* volume MS measurements, 5.13e ortho-photo of trench 1 after removal of topsoil with building plots clearly visible, 5.13f ortho-photo superimposed with the planar *in-situ* volume MS measurements

5.6.1 Profiles

Profiles HDSS 1-HDSS 3 (Fig. 5.14) investigated at trench 1 comprise silt to clayey silt, with 15% very small (2-6mm) subangular stones. Small (6-20mm) subangular stones occur only in low quantities (<1%). Colour (very dark greenish grey/Munsell code 5GY 3/1) remains consistent in almost all samples, which points at the generally reduced conditions typical for stagnic soils (<http://wms.skogoglandskap.no/cgi-bin/jordsmonn>). Subsample HDSS3-4 encompasses subsoil material, which accommodates the archaeological features yet shows similarities to the properties found in the topsoil. Mass-specific MS values of HDSS1-HDSS3 do not show a continuing decrease in MS values from top to bottom, as clearly as it would be expected according to the LeBorgne effect (Graham & Scollar 1976). Although generally decreasing with depth, the topsoil in profiles HDSS1-HDSS3 is characterised by rather heterogeneous MS values. *In-situ* volume-specific MS measurements along the profile show a similar, yet more pronounced picture. HDSS2 yielded a volume-specific peak value of $\kappa 102 \times 10^{-5}$ SI at around 8cm, while HDSS3 displayed 85×10^{-5} SI at 12 cm below surface, in contrast to surrounding values of ca. 15×10^{-5} SI. Closer investigation of the soil material at profile HDSS3 located a piece of rock (6 × 4cm) as potential source of the increased values. The rock was macroscopically identified as amphibolite created from magmatic rock such as basalt (Fettes and Desmons, 2007).

Profile HDSS4, taken from trench 2, comprehends medium sand with 15% very small subangular stones and <1% small subangular stones. The upper part of the topsoil contains ca. 1% organic inclusions in the form of thin roots. Colour descriptions (very dark greyish brown/ Munsell 10YR 3/2) indicate enhanced drainage properties as can be expected from this sandy soil, resulting in more oxidised material compared to the finer material of trench 1. This difference in texture is also reflected in the mass-specific MS values, which show a clear increase with depth. This could tentatively indicate iron mobilisation and re-precipitation at the transition to the subsoil as clearly indicated in trench 2 (Fig. 5.12a).

Core 7670 (Fig. 5.15) taken from soil outside of the excavation trenches shows physical properties similar to samples collected at profile HDSS4. Texture of the topsoil is described as medium sand with 15% very small subangular stones, less than 1% small subangular

stones, 5% organics (mainly crop remains) and 1% charcoal. The transition to the subsoil is sharp (transition zone less than 0.5cm), with texture changing to fine sand and less than 1 % very small, subangular stones. For high-resolution mass-specific MS measurements of topsoil and transition to subsoil from a location undisturbed by recent or archaeological features, core 7670 was systematically subsampled in the laboratory at 2 cm intervals. Results show MS values decreasing with depth. The transition from top- to subsoil is clearly marked by a drop of 60% from χ_{LF} 25 to $10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The highest value χ_{LF} $40 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ at 12 cm BGS indicates certain heterogeneity also in this soil profile (Fig. 5.15).

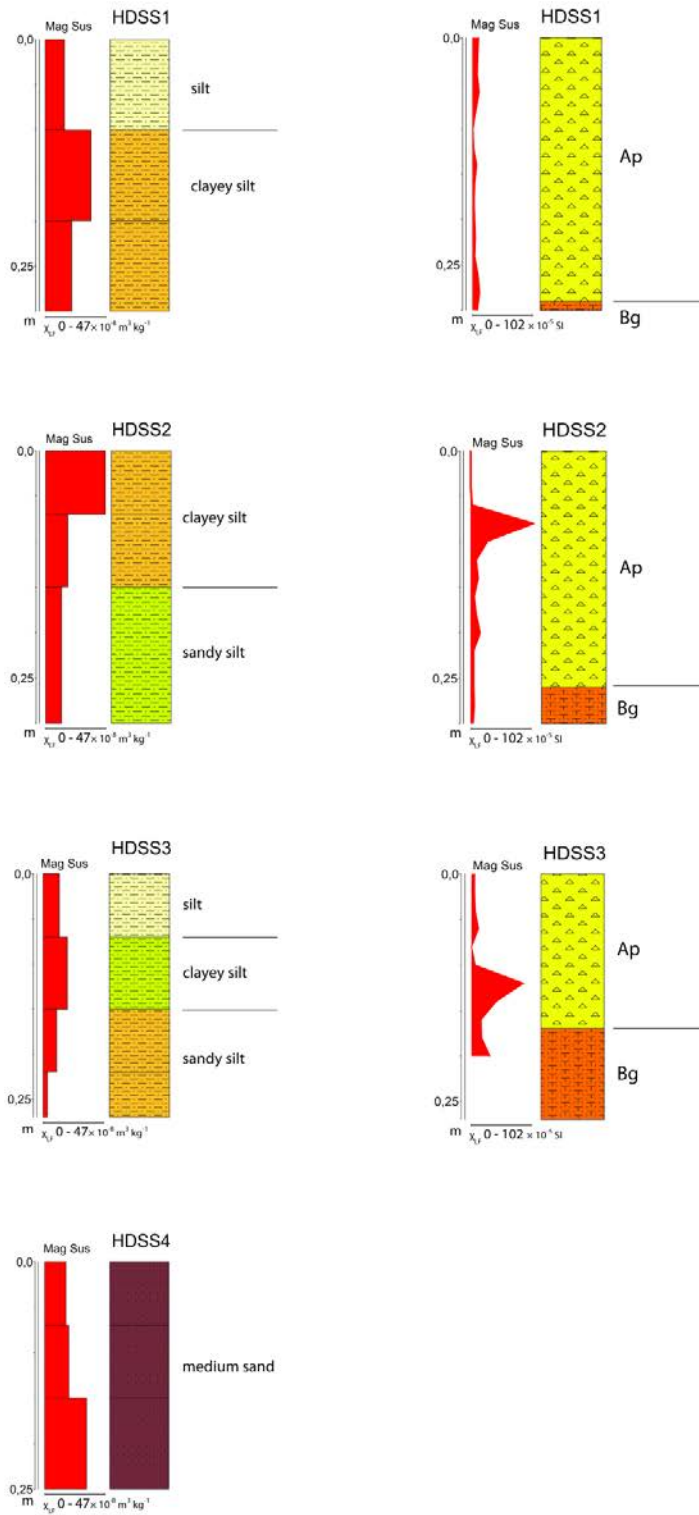


Fig. 5.14 Profile samples HDSS1-HDSS4 of topsoil and transition to subsoil with mass specific susceptibility values in $10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (left) and volume specific susceptibility values in 10^{-5} SI (right)

5.6.2 Archaeological features

Since the excavation progressed slower than anticipated, most archaeological features were still unexcavated and could not be accessed for evaluation purposes as planned during the time appointed for fieldwork. In order to investigate MS values of archaeological features and establish the contrast between them and the surrounding soil material, two core samples were taken in trench 1.

Core 7874 (Fig. 5.15) was collected from parcel ditch 9335 at parcel 3701 located in trench 1 (Fig. 5.10, 5.11a) and showed four stratigraphic units, with unit 1 and 2 possibly representing the parcel ditch fill: unit 1 is described as rather loose, coarse sand, with 15% very small, 1% small subangular stones and 2% charcoal inclusions. Unit 2 consists of clayey sand and shows < 1% very small subrounded stones and 1% charcoal inclusions. The abrupt boundary between unit 1 and 2 indicates a sudden change in depositional processes indicating at least two phases of ditch back-fill. The subrounded stones form a certain contrast to the more subangular stones found in the surrounding sediments. Unit 3 displays mottles, which indicate changing hydrology matching the stagnic properties of the surrounding soil. Unit 4 is described as silty clay and shows a very dark greenish grey (Munsell code 5GY 3/1) colour typical for gleyed subsoil observed at *Heimdalsjordet*. Laboratory measurements (Fig. 5.15) show a stepped decrease with generally low mass specific susceptibility values. Unit 1 which is interpreted as stratigraphically younger parcel ditch fill of ditch 9335 (Fig. 5.10, 5.11a) shows the highest MS value with $\chi_{LF} 14 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The potential stratigraphically older parcel ditch fill, unit 2, still yields $\chi_{LF} 10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. MS values of subjacent units 3 and 4, which already belong to the subsoil, do not show a marked difference in MS values and remain relatively constant between $\chi_{LF} 9$ and $\chi_{LF} 10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, while indicating reduced conditions.

Core 7941 (Fig. 5.15) was taken from ditch 5751 located above the path 9362 between parcels 3701 and 5837 (Fig. 5.10, 5.11). This archaeological feature was neither detected in the magnetic nor in the GPR data and comprised six stratigraphic units. Apart from unit 4 (sandy silt), all units are described as clayey silt. Units 1 and 2 show brownish colours, which could indicate more oxidised conditions and might be related to archaeological remains. Unit 1 possibly represents ditch 5751, while unit 2 could be interpreted as the “road” 9362 based

on the higher compaction most likely causing the GPR signal reflections and subsequently its visibility in the GPR data. This, however, needs to be further clarified and correlated with the excavation reports. Stones are only abundant in very low quantities (<1%) in units 1 and 2. Units 4, 5 and 6 show greenish/greyish colours and mottling (unit 5) indicating gleyed conditions in the subsoil. Mass-specific MS values generally are low and decrease with depth. Unit 1 and 2, potentially related to archaeological features both display the highest values with $\chi_{LF} 11 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$, followed by a drop of 45 % in unit 3, which contains the lowest values ($\chi_{LF} 6 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$).

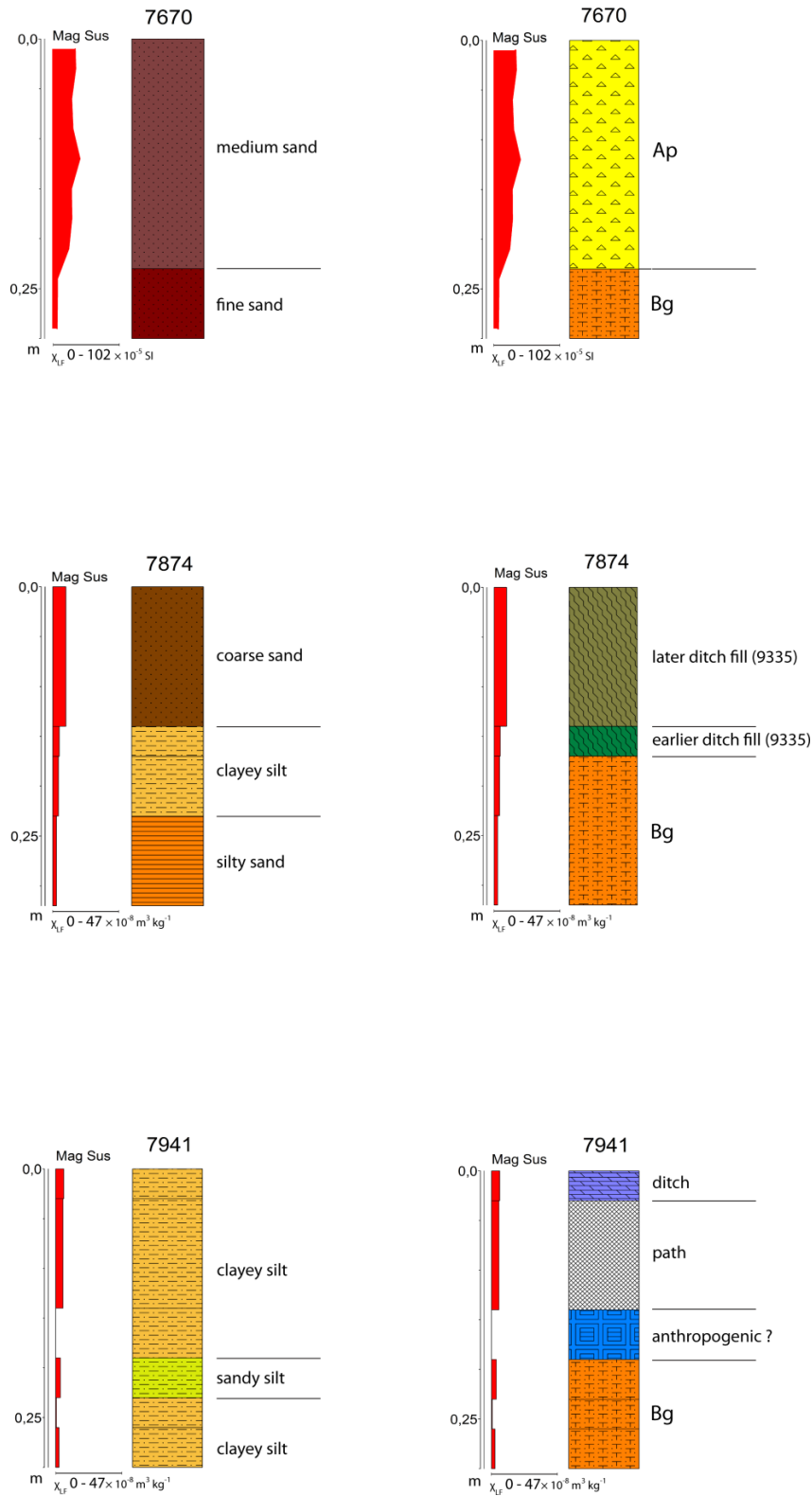


Fig. 5.15 Core samples showing topsoil and transition to subsoil with volume specific susceptibility values in 10^{-5} SI (core 7670) and archaeological features with mass specific susceptibility values in $10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (cores 7874, 7941)

5.7 Discussion

The study was designed to investigate the physical and magnetic properties of sediments and soils in order to evaluate the geophysical survey results at the area of *Heimdaljordet* and to aid in the archaeological interpretation of the geophysical data. The most important question concerned the limited visibility of the archaeological features in the magnetic data compared to the much clearer GPR results (Fig. 5.3). Additional points of interest included a general characterisation of soils and sediments with special regard to their response to magnetic surveys, and the subsequent implications for the interpretation of the prospection data.

MS measurements generally yielded low values across both profile and archaeological samples with a range of χ_{LF} 6 to $47 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ in mass-specific MS, and κ 3 to $102 \times 10^{-5} \text{ SI}$ in *in-situ* volume-specific MS. This does not come as a surprise considering the stagnic properties of the soil covering most of *Heimdaljordet* resulting in periodical water saturation, which generally provide unfavourable for the formation and preservation of ferrimagnetic minerals (Kattenberg, 2008). More oxidised soils such as brown earth, in comparison, usually show higher mean values around χ_{LF} $150 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (J. a. Dearing et al., 1996).

Magnetic enhancement and depletion processes

The mechanisms leading to either magnetic enhancement or magnetic depletion in soils and sediments are complex. It is agreed, that enhancement of magnetic contrast is dependent on the conversion of weakly magnetised iron compounds to ferrimagnetic minerals, such as maghemite, magnetite or greigite (Fassbinder 2014). How exactly these processes are taking place, is still subject to debate (Fassbinder 2015). Le Borgne discovered first magnetic enhancement in topsoils and explained this so-called Le Borgne effect mainly by different conversion processes that he at that time believed to mainly begin with hematite (Fassbinder, 2015). In the course of the fermentation process, poorly crystalline iron oxides are converted first to magnetite based on decomposition of organic material in anaerobic soils and subsequently upon re-oxidation due to drier, more aerobic conditions form maghemite (Le Borgne 1955, Maher 1998, Fassbinder 2015). Natural or human-induced

fires, Le Borgne found, start another enhancement process depending on iron content, organic matter, burning temperature and soil porosity, where hematite and goethite are reduced to magnetite, followed by oxidation to maghemite (Le Borgne 1955, Tite & Mullins 1971, Maher 1998).

However, subsequent research indicated more complex processes involved in magnetic enhancement. For example, the formation of magnetite is still subject to debate with potential processes including inorganic process, where ferrous iron is oxidised and converted to magnetite, and biologically controlled processes involving magneto-tactic and iron-reducing bacteria. Particularly the formation of maghemite is not fully explained yet. Fassbinder (2015) summarised recent research and states the oxidation of magnetite originating from rock or sedimentary parent material, the de-hydration of lepidocrocite between 260-300 °C and the conversion of goethite by natural fires in the presence of organic material (Fassbinder 2015). According to recent research, Le Borgne's suggestion of hematite as initial source for the formation of maghemite is to be doubted due to lack of evidence under natural conditions (Fassbinder 2015). Anorganic as well as biological (magnetotactic bacteria) processes might be responsible for the formation of greigite, which often is found in limnic and marine sediments. Apart from processes causing the formation of ferrimagnetic minerals, the persistence of these ferrimagnetic minerals and/or concentrations of detrital ferrimagnets resistant to weathering processes plays another significant role for magnetic enhancement in soils and sediments (Maher 1998).

Magnetic depletion, in contrast, occurs in soils that are either permanently waterlogged, such as gleysols, or periodically water-saturated with changing oxidation/reduction cycles, such as stagnosols. These soils typically show low values in MS, as high water content in soils does not favour for iron oxides to accumulate or convert to ferrimagnetic minerals. The reason for this lies in the mobilisation of iron, or even its loss through weathering and subsequent reduction processes. The oxidation of Fe^{2+} bearing primary minerals releases Fe^{3+} ions, which in turn can either become incorporated into other iron compounds *in-situ*, or – if subject to further reduction processes – get mobilised within the soil solution. If exposed to re-oxidation, Fe^{3+} re-precipitates as Fe^{2+} in a paramagnetic form (Maher 1998, Mullins 1974, Fassbinder 2015). Recent studies have shown that permanent or periodically waterlogged conditions even can lead to the dissolution of ferrimagnetic minerals.

An alternative reason for the low susceptibility values of some soils is the presence of considerable amounts of weakly magnetic components such as clay or diamagnetic components including organic matter or quartz, leading to a dilution of magnetic properties (Maher 1998).

Limited visibility

The three factors significant for the detectability of archaeological features in magnetic surveys are contrast, volume of target and distance to sensor (Neubauer, 2001a).

Considering the facts mentioned above, the environmental settings at *Heimdaljordet* surely did not provide favourable conditions for a magnetometry survey in terms of contrast. Previous studies have repeatedly shown that soils influenced by water, such as gleysols and stagnosols as well as podzols usually display low MS values (Mullins 1974, Maher 1998). As described above, complex pedogenic and weathering processes are responsible for magnetic depletion. In contrast to permanently waterlogged soils with constant anaerobic conditions, the stagnosol at *Heimdaljordet* is characterised by periodical water saturation, which results in repeated cycles of oxidation and reduction. How exactly these changing conditions affect and even prevent the conversion of iron compounds to ferrimagnetic minerals requires further investigation (Maher 1998).

Table 5.1 Mass specific MS measurements from cores 7874 and 7941. Note the low contrast between samples taken from archaeological features and the subsoil, in which they are embedded

Core	Sample	Type	$\chi_{LF} 10^{-8} \text{ m}^3 \text{ kg}^{-1}$	Core	Sample	Type	$\chi_{LF} 10^{-8} \text{ m}^3 \text{ kg}^{-1}$
7874	1	Ditch	14.38	7941	1	Ditch	11.68
	2	Ditch	10.64		2	Path	11.19
	3	Subsoil	10.22		3	Anthropogenic ?	06.98
	4	Subsoil	09.09		4	Subsoil	09.72
					5	Subsoil	07.41
					6	Subsoil	08.92

Any magnetic dilution/depletion process caused by periodical water saturation naturally also affected the back-fill material of the archaeological features.

This is supported by the low mass-specific MS values of layers ascribed to archaeological features in cores 7874 and 7941 in comparison to the surrounding subsoil (Table 5.1) as well as by the low contrast between building plots and surrounding subsoil material as shown in the *in-situ* volume-specific MS measurements of trench 1 after topsoil removal.

This very limited yet existing contrast draws the attention towards the magnetic properties of the topsoil and its role in the limited visibility of the archaeological features in the magnetic data. As mentioned above, both mass specific (χ_{LF} $16 - 47 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) as well as volume specific ($3 - 102 \times 10^{-5} \text{ SI}$) susceptibility values measured at *Heimdaljordet* generally are low. The topsoil, however, shows a greater variety in MS, illustrated by occasionally peaking values of volume specific MS (compare HDSS2 – $102 \times 10^{-5} \text{ SI}$ and HDSS3 – $85 \times 10^{-5} \text{ SI}$) interpreted as inclusions of magnetic bedrock (see also HDSS3). This observation is further supported by the mass-specific values, which are lacking these peaks - most likely due to the fact that rock material $> 2\text{mm}$ was systematically excluded from the sample as part of the standardised laboratory processing. The bedrock geology around Gokstad commonly consists of strongly magnetic igneous rocks including monzonite, quartz monzonite and granite. Such shallowly buried igneous bedrock is a very common issue in Norway and can obscure large areas through the strong dipole anomalies it is causing. At *Heimdaljordet*, this is well illustrated at an area in the south-east of the survey field (Fig. 5.2). Small, eroded pieces of this bedrock as well as from erratic blocks transported and deposited by glacial processes, however, present another issue. Such inclusions of varying sizes may display weaker magnetisation than shallowly buried igneous bedrock, yet they nonetheless contribute towards the magnetic variety of the topsoil. These individual anomalies are often too small in size and strength to be differentiated in the magnetogram as is, in contrast, the case with distinct strong dipole anomalies caused by ferromagnetic material.

To conclude, the composition of generally weak, mainly paramagnetic soil material intermixed with non-archaeological ferrimagnetic inclusions results in a very heterogeneous and noisy background that might contribute to masking the weak magnetisation of the archaeological features embedded in the subsoil. Some variation in the topsoil occurs naturally due to pedogenic and weathering processes. This usually presents no significant

issue where the contrast between the archaeological features and the surrounding subsurface material is more pronounced.

Another factor influencing the detectability of buried features is the distance to the sensor. The intensity of magnetic fields decreases inversely proportional to the square of the distance. Subsequently, the sensitivity of the measurement devices used in a survey plays a significant role in the detection of archaeological and palaeoenvironmental features. At *Heimdaljordet*, archaeological features were relatively shallowly buried (ca. 30 cm BGS). However, the low magnetic contrast between these features and the surrounding subsoil as illustrated above can pose a problem even at this depth. Magnetic data at *Heimdaljordet* were acquired with Foerster fluxgate sensors providing a sensitivity of 0.1 nT and an accuracy of 0.3 nT. The use of Caesium vapour magnetometers offering an increased sensitivity of up to one picotesla together with accuracy ranging from 0.005 nT (handdriven) and 0.01 (motorised) (Neubauer, 2001a) could aid in detecting such low a contrast between archaeological features and the surrounding subsoil as observed at *Heimdaljordet*. Greater sensitivity, though, might also amplify the magnetic variation in the topsoil mentioned above.

Specific data processing and filtering might present another option in refining magnetometry data in such challenging environmental settings. Conventional data processing using e.g. Wallis-filters usually aims to limit the influence of non-archaeological patterns in the background in order to enhance the detectability of archaeological features. At *Heimdaljordet*, however, this procedure might have rather led to a further reduction of the already poor visibility of the archaeological features.

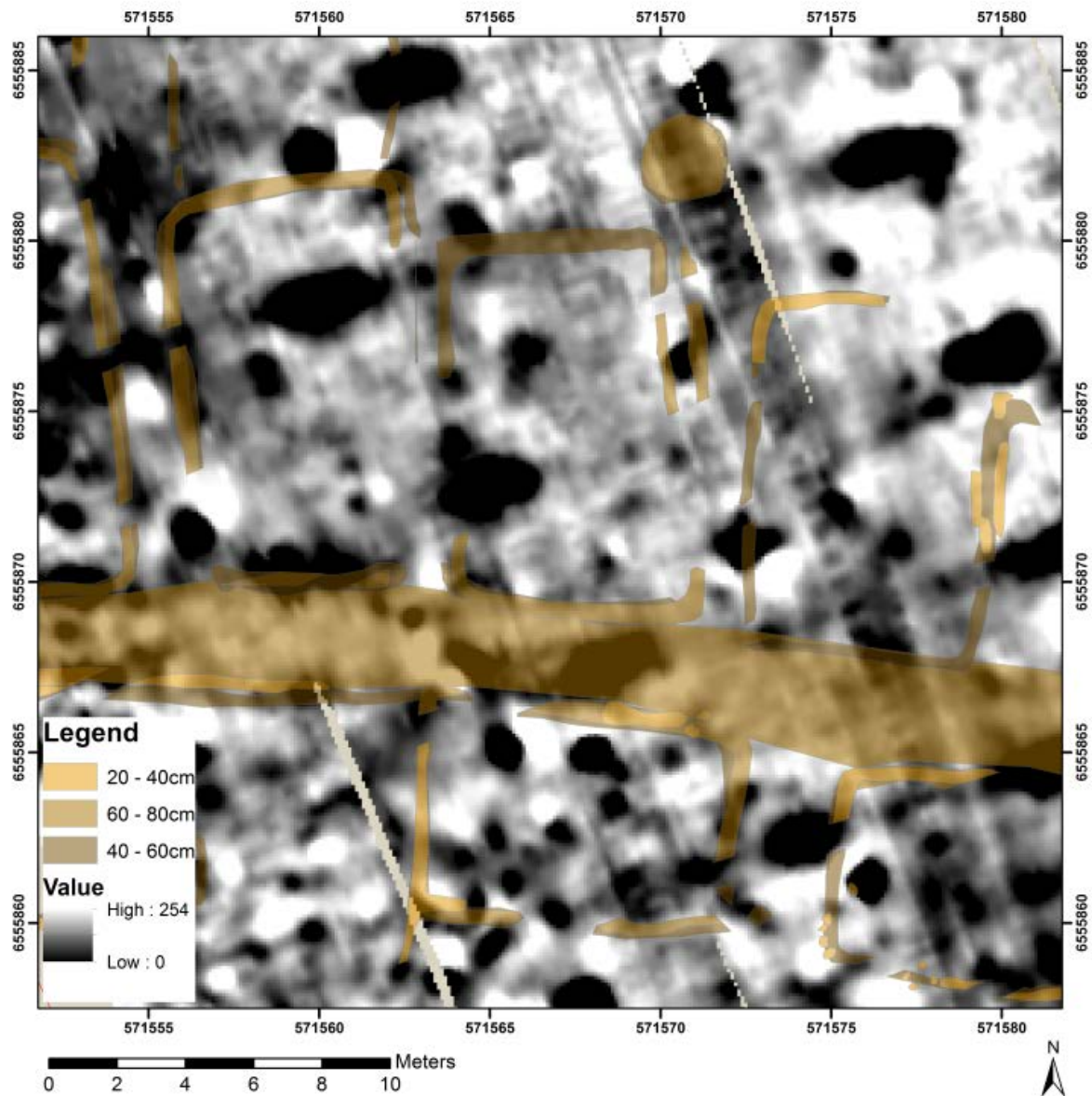


Fig. 5.16 Magnetogram processed with settings to enhance the visibility of the archaeological features. The superimposed ditches as interpreted based on the GPR data reveal a number of strong magnetic anomalies that might indicate thermoremanently magnetised material

Preliminary testing of different processing settings for the visualisation of magnetic data indeed aided in tracking some of the building plots (Fig. 5.16). However, this method mainly emphasised the presence of thermo-remantly magnetised materials interpreted as settlement debris such as ceramics, slag and metal objects or hearth residues. Considering the distribution of such anomalies as indicators for human activities, this approach might prove useful in future, similar environmental settings.

Chapter VI

Testing an approach for geoarchaeological field evaluations of magnetic and GPR data interpretation

6.1 Introduction

Due to its potential of covering large areas with high resolution in a relatively small amount of time, motorised archaeological geophysical prospection techniques are increasingly gaining importance as a heritage management tool (Bunting et al., 2014; Chapman et al., 2009; Cowley, 2011; Nau et al., 2015; Neubauer et al., 2012). To further promote this trend, however, archaeological geophysical prospection must provide reliable and accurate data interpretations. A reliable data interpretation depends on the experience of the prospector, expertise in local archaeology and an encompassing understanding of the environmental settings of the study area. While the importance of the first two factors is widely accepted, the significance of environmental settings often is set aside in ordinary archaeological geophysical prospection surveys. Issues are mostly only recognised, when excavation results deviate from archaeological geophysical prospection interpretations (Simon et al., 2012). Not addressing these issues can substantially damage the confidence in geophysical prospection methods as heritage management tools and subsequently prevent the method to develop its full potential. The implementation of regular geoarchaeological field evaluations, where geophysical prospection data are evaluated and calibrated based on relevant physical properties of the actual subsurface materials can aid in counteracting this development (Fassbinder, 2015; Kattenberg and Aalbersberg, 2004; Linck and Fassbinder, 2014; Simon et al., 2012). Such evaluations can thereby be used to enhance the understanding of the geophysical background signal created by soils, sediments and archaeological deposits, while simultaneously investigate specific questions and issues observed during data interpretation. A precondition for a geoarchaeological field evaluation, however, is access to the subsurface. This fact can prove problematic due to the non-invasive nature of geophysical prospection techniques and its use on sites under heritage protection (Gaffney et al., 2012; Neubauer et al., 2011; Trinks et al., 2014) as well as due to a

growing number of large scale investigations (Gabler et al., 2013) far too extensive to investigate intrusively. Here, archaeological and geotechnical excavations present valuable opportunities, yet are not always possible and surely not suitable for large scale archaeological geophysical prospection surveys. In the latter case, targeted borehole surveys have been used as exemplified at Gokstad (compare chapter III), but naturally are limited regarding their representativeness. Apart from accessibility, a suitable approach for geoarchaeological field evaluations has to consider sufficient measurement accuracy, performance in the field as well as time and cost-efficiency in order to be successfully applied.

The aim of this study was therefore to establish an approach for geoarchaeological field evaluations that is appropriate for both excavations and borehole surveys as well as to find and test *in-situ* measurement devices for geoarchaeological field evaluations and assess them for their field application, accuracy and time-efficiency. For this purpose, a profile located in the area of the Viking Age site Gokstad (Fig. 6.1), on the grounds of the *Sverstad* farmstead (Fig. 6.2), was mechanically excavated and used as case study in order to test an efficient approach for the evaluation of magnetometry and GPR data.



Fig. 6.1 Location of the study site Gokstad among other prominent Viking Age landscapes in the Province Vestfold, Norway



Fig. 6.2 The study area of Gokstad with the well-known Gokstad burial (Macphail et al., 2013; Nicolaysen, 1882) to the east, the newly mapped Viking Age settlement and cemetery *Heimdaljordet* to the south-east (Bill and Rødstrud, 2013; Nau et al., 2015). In the west, on the field of the *Sverstad* farmstead, the test trench with the profile was dug during a geoarchaeological field evaluation of geophysical prospection data. Source: ©Kartverket, www.kartverket.no

6.2 Background and approach

Geoarchaeological field evaluation aims at correlating geophysical signal responses with the actual subsurface materials via relevant proxies in order to gain a better understanding of the signal's sources. Investigations can thereby focus on the natural background signal for a general calibration of the geophysical data or target specific questions emerging during the interpretation process. In both cases, the common aim is to enhance the interpretation of the geophysical data. The more evaluations are carried out, the more information can be gathered for different study areas. Eventually, this should lead to the build-up of a knowledge base for future geophysical surveys conducted in similar environmental settings.

As mentioned in the introduction, accessibility of soils and sediments is of key concern when establishing an approach for geoarchaeological field evaluations. Areas subjected to geophysical prospection become larger (Keay et al., 2009; Trinks et al., 2012) and slowly begin to substitute intrusive investigation methods such as topsoil stripping and test trenching in heritage management (Gustavsen and Stamnes, 2014; McGraw and Bill, 2014; Stamnes, 2016). This means, however, that compared to the total prospected area, the area available for geoarchaeological field evaluations is becoming proportionally smaller. Suitable approaches for geoarchaeological field evaluations need to respond to these changes. For this reason, *in-situ* methods are generally preferable to laboratory-based methods simply for their time-efficiency and often low costs, which allows for a sampling strategy that can cover large areas. An additional advantage when using *in-situ* methods presents the application on undisturbed sample material. However, most *in-situ* measurement techniques calculate values based on a pre-defined measurement volume and, compared with standardised laboratory procedures, deal with an unknown sample composition (Fassbinder, 2015), which can affect the representativeness of the sample taken. This particularly applies to materials displaying a very heterogeneous composition on a small scale. Volume-specific techniques are also prone to limited measurement accuracy due to operating errors (Walker et al., 2004).

The use of MS as relevant correlating factor and rapid assessment property for magnetometry is widely accepted (Dalan and Banerjee, 1998; Fassbinder, 2014; Kattenberg and Aalbersberg, 2004; Tite and Mullins, 1971). MS indicates to what degree a sample can

become magnetised by an external field and together with the remanent magnetisation governs the magnetic properties recorded during a magnetic survey (Rinita A. Dalan, 2006; Fassbinder, 2015; Neubauer, 2001a; Scollar et al., 1990). As demonstrated in chapter V, measurements can be conducted relatively time- and cost efficient either *in-situ* or lab-based, even though it has to be noted that MS can only provide limited information on e.g. magnetic mineral composition (Fassbinder, 2015). For a more encompassing understanding of the magnetic properties of a sample, the analysis of the remanent part of the magnetisation including natural remanent magnetisation (NRM), anhysteretic remanent magnetisation (ARM) and saturation isothermal remanence magnetisation (SIRM) would be advisable (Dalan and Banerjee, 1998; J. A. Dearing et al., 1996; Maher, 1986), yet are time-consuming and require a certain budget. The use of MS as a proxy for magnetic surveys thus was beyond question. Rather the sampling and especially the sample preparation procedure established in magnetic studies and its suitability when applied to geoarchaeological field evaluations stood in the focus of this study.

In contrast to magnetometry, GPR surveys have not been widely evaluated and approaches and techniques for archaeological field evaluations only began to emerge in recent years (Linck & Fassbinder, 2014). The response of electromagnetic signals to the subsurface materials they encounter is extremely complex with a range of contributing elements (Annan, 2008; Conyers, 2013). It is unquestioned, though, that the most significant factor for the electromagnetic wave propagation in low-loss materials is the water content, based on a high relative dielectric permittivity ($\sim 80 \epsilon_r$) compared to the other constituents in soils and sediments ($\sim 1 \epsilon_r$, mineral constituents $\sim 3-8 \epsilon_r$) (Annan, 2008; Cassidy, 2008a; Scollar et al., 1990; Visconti et al., 2014). Water content can be measured using lab-based as well as a range of different *in-situ* techniques (see below). Another aspect closely related to water content and thus to dielectric permittivity is the grain size distribution of soils and sediments (Arya and Paris, 1981). As already described in detail in chapter II, the grain size distribution of a material— together with its compaction, cementation and structure - determines the available pore space in soils and sediments and is indicative of permeability and ultimately of water content (Blume et al., 2010). The measurement of this parameter requires a laboratory environment and can be conducted using different methods including the relatively time and labour-intensive sedimentation technique as well as automated, more rapid approaches such as x-ray attenuation and laser diffractometry (Beuselinck et al., 1998; McCave and Syvitski,

1991). Finally, electrical conductivity, which is directly related to different aspects of the soil water and to salinity and amount of clay particles, presents another property significant for the electromagnetic wave propagation in soils and sediments (Doolittle and Butnor, 2009) and can likewise be measured *in-situ* as well as lab-based (Corwin and Lesch, 2005; Friedman, 2005).

Investigations at *Sverstad* aimed for a broad approach that enabled the testing and comparison of different techniques and different sampling strategies, the assessment of their applicability in the field, the time needed to conduct the investigations as well as the accuracy of the results. Measurements included *in-situ* and lab-based MS, water content using direct and indirect methods, electrical conductivity and temperature as well as grain size distribution analysis. Basic sedimentological descriptions and stratigraphic observations aided in characterising soil and sedimentary properties and their formation processes. At the same time, this investigation allowed to gather more detailed data about the natural background signal for the entire Gokstad area, which previously was subject to large scale, high resolution archaeological geophysical prospection surveys in 2012 and 2013 (Bill et al., 2013; Nau et al., 2015).

6.3 Methodology

MS was measured both *in-situ* as well as laboratory-based for comparative purposes. Additionally, the sample material intended for laboratory-based MS measurements was split into two different subsets: Processed material which was prepared using the standardised laboratory treatment for MS measurements. This included drying samples at room temperature in order to reduce the mass contribution of water, subsequent grinding in a porcelain mortar and finally sieving down to 2mm (Dearing, 1994). The second subset contained unprocessed sample material that did not undergo the above mentioned standard laboratory procedures. Instead, it was tried to preserve as much as possible of the original *in-situ* composition of the sampled material including free (and bound) water, organic and small clast inclusions; only clasts too large for the sample container were excluded. The aim of this approach was to investigate the potential difference between processed and

unprocessed samples sets with respect to their suitability for correlation with geophysical signals.

The resulting sample material was filled in 10 cm³ 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 $\times 10^{-8} \text{ kg}^{-1}$), taking into account corrections for the actual sample mass (Dearing, 1994). Results were plotted in line plots using MS Excel for comparison.

In-situ measurements of MS were conducted 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^{-7} SI units) (Fig. 6.3). Due to its small size, the SM-30 is well equipped for geoarchaeological field evaluations. However, the resulting relatively small measurement volume with the first 2 cm contributing 90% of the measurement value (<http://www.zhinstruments.com/sm-30.html>) can lead to over- or underrepresentation of the actual values (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 cm³ 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 $\times 10^{-8}/\text{kg}$), taking into account corrections for the actual sample mass (Dearing, 1994).



Fig. 6.3 The hand-held kappa meter SM-30 used to measure volume MS in the field

Water content can be measured using direct and indirect methods. The thermo-gravimetric method directly infers the water content from the difference in mass before and after the sample was placed in an oven at 105° C for 24h and calculates it on a mass basis (ISO 11465). This procedure is very accurate ($\pm 1\%$), but invasive and requires a minimum of two days of work in a laboratory (Muñoz-Carpena et al., 2006). Indirect measurements of water content have evolved due to an increasing need for large scale monitoring of soil moisture particularly for irrigation systems in agriculture and today presents an extensive research field (Jacobsen and Schjønning, 1993; Roth et al., 1992; Topp et al., 1980; Tran et al., 2012; Visconti et al., 2014; Wang and Schmutge, 1980). Indirect methods infer soil moisture by using a physical soil property as proxy. A good overview about different volumetric and tensiometric field methods can be found at Muñoz-carpena, Shukla, & Morgan, (2006). Dielectric permittivity has proven to be one of the most suitable proxies and this relation has sparked a range of different so-called dielectric methods, which use different electromagnetic signal properties including time, frequency, impedance and phase in order to estimate the volumetric water content (Muñoz-Carpena et al., 2006).

Among the most widely used dielectric methods are time domain reflectometry and frequency domain reflectometry. Time domain reflectometry determines the dielectric permittivity based on the time an electromagnetic pulse needs to travel along a transmission line plunged into soil (Noborio, 2001). This method was initially considered first because of its similarities to the principles of GPR and because specific soil calibrations generally are not deemed necessary (Jones et al., 2002). However, the length of the sensor prongs (often > 10 cm in order to assure a certain accuracy (Walker et al., 2004)) prevented the use of TDR sensors as well as that of phase transmission, which feature a circular sensor geometry, for regular geoarchaeological field evaluations (Muñoz-Carpena et al., 2006). Many soil moisture sensors are built for monitoring where sensors are buried and permanently installed. For evaluation purposes though, the sensor has to be planted repeatedly into soils and sediments at exposures. In very dry, hard or stony soils and sediments, this can impede the plantation of the sensor or even damage it. Apart from being a hazard to the sensor itself, such unfavourable conditions can also affect the measurement accuracy. Dielectric methods estimate the soil moisture based on a certain measurement volume, which depends on sensor length and geometry. If the sensor is not completely planted into the soil, or cracks have formed around the sensor prongs originating from dry, hard soil or clast inclusions, readings will become erroneous and/or unrepresentative. Relatively high asset costs emerging from the complex sensor technology of TDR presented an additional obstacle. Based on these insights, frequency domain reflectometry was chosen, which is characterised by relatively short sensor prongs (5 cm), thereby facilitating a controlled planting into the sample material, as well as relatively low asset costs and little maintenance.

At *Sverstad*, *in-situ* volumetric water content (m^3/m^3) or apparent dielectric permittivity, respectively, was measured using a 5TE standard capacitance sensor from Decagon Ltd and logged with a Decagon ProCheck (Fig. 6.4). 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 – the time needed for this process yields the capacitance of the dielectric medium. Capacitance is directly related to dielectric permittivity taking also into account parasitic capacitance inherent to the system and 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 $\pm 0.03 \text{ m}^3/\text{m}^3$ VWC or $\pm 3 \%$ VWC for soils with $< 10 \text{ dS/m}$ (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 agriculture (Jacobsen and Schjønning, 1993; Roth et al., 1992; Topp et al., 1980; Tran et al., 2012; Visconti et al., 2014; Wang and Schumugge, 1980). Temperature, salinity, bulk density and clay content as well as sensor technology used influence the estimation of the water content. Particularly measurements with a frequency $> 100 \text{ Mhz}$ require a soil specific calibration (Muñoz-Carpena et al., 2006). For the study at *Sverstad*, specific soil calibrations were not conducted; instead, the Decagon in-house calibration for mineral soils was used.

In order to prevent permanent damage to the sensor through hard soil and sediments or clast inclusions and to ensure that the measurement accuracy is not reduced by cracks, a piercer made of stainless steel was constructed, that exactly matches the sensor dimensions. With this tool, sample locations can be screened and prepared before the sensor is carefully planted into the soil/sediment. Although air pockets cannot be entirely ruled out, this procedure greatly extends the sensor life and enhances the measurement accuracy.

Soil apparent electrical conductivity was measured likewise using the 5te sensor via two electrodes sitting on two of the prongs. σ values were expressed at 25°C and accuracy ranges within $\pm 10\%$ from $0\text{-}7 \text{ dS/m}$. Temperature was measured in $^\circ\text{C}$ using a thermistor mounted underneath the sensor overmold (DecagonDevices, 2015).



Fig. 6.4 Moisture sensor with custom-made steel piercer

Selected criteria including stoniness and inclusions following Hodsgon and Avery (1976) were used to describe soils and sediments. Stratigraphic observations followed the principles of archaeological stratigraphy (Harris, 1989) and focused on stratigraphic relations of individual units, depositional and post-depositional processes. For colour description, the Munsell code was used (Munsell, 2000).

Grain size distribution analysis was conducted using a *mastersizer 3000* based on laser diffraction measurements at the University of Reading. Grain size classes of a selected sequence were defined based on the International Scale ISO 14688-1 and subsequently attributed to the particle size distribution classification (PSDC) using the newly proposed triangle by Blott and Pye (2012) for sand, silt, clay (SSC). PSDC was calculated using the in-house MS Excel software GRADISTAT of Kenneth Pye Associates Ltd, which can be downloaded at their webpage (<http://www.kpal.co.uk/gradistat.html>).

6.4 Results

In order to test different geoarchaeological field evaluation approaches, the author and archaeologists of the Vestfold fylkeskommune opened a small test trench of ca. 1 x 2 m in a field at *Sverstad*, located in the area of the Viking Age site Gokstad, Province Vestfold. Prior to that, the field was prospected by a 6-channel SPIDAR GPR system and a multi-sensor magnetic measurement device, both using a 25 x 10 cm spatial resolution. The study site is covered by endostagnic cambisol (<http://wms.skogoglandskap.no/cgi-bin/jordsmonn>) showing an A-B-C profile (Soil WRB, 2006) overlying incoherent marine deposits (2011 NGU, Løsmasser), which have been deposited above igneous intrusive bedrock, in this area mainly monzonite and quartz monzonite (<http://geo.ngu.no/kart/berggrunn>). The location lies at an altitude of ca. 29 m above the current sea-level and became dry land between 3000-4000 BC based on sea-level reconstructions in the area of Larvik (Sørensen et al., 2007). The test trenching was carried out within the scope of regular topsoil-stripping activities undertaken by the Vestfold fylkeskommune following GPR and magnetometry surveys in 2013 and 2014 and aimed at verifying some of the archaeological features discovered in the archaeological geophysical data and interpreted as clearance cairns (Fig. 6.5 and 6.6). Clearance cairns, also known as *rydningsrøyser* in Norwegian archaeology, are features frequently found in Scandinavia, but also occur in the United Kingdom. As the name suggests, these features originate from farmers clearing their fields of stones and boulders for better plant growth and to avoid damages to the plough blades and date from the Bronze Age to recent times (Pedersen, 1990; Sageidet, 2005). In order to avoid modern disturbances caused by drainage ditches, the exact location of the test trench was selected based on the GPR data. The trench was opened mechanically using an excavator and extended down to a depth of 1.60 m, where intruding groundwater prevented further action (Fig. 6.7).

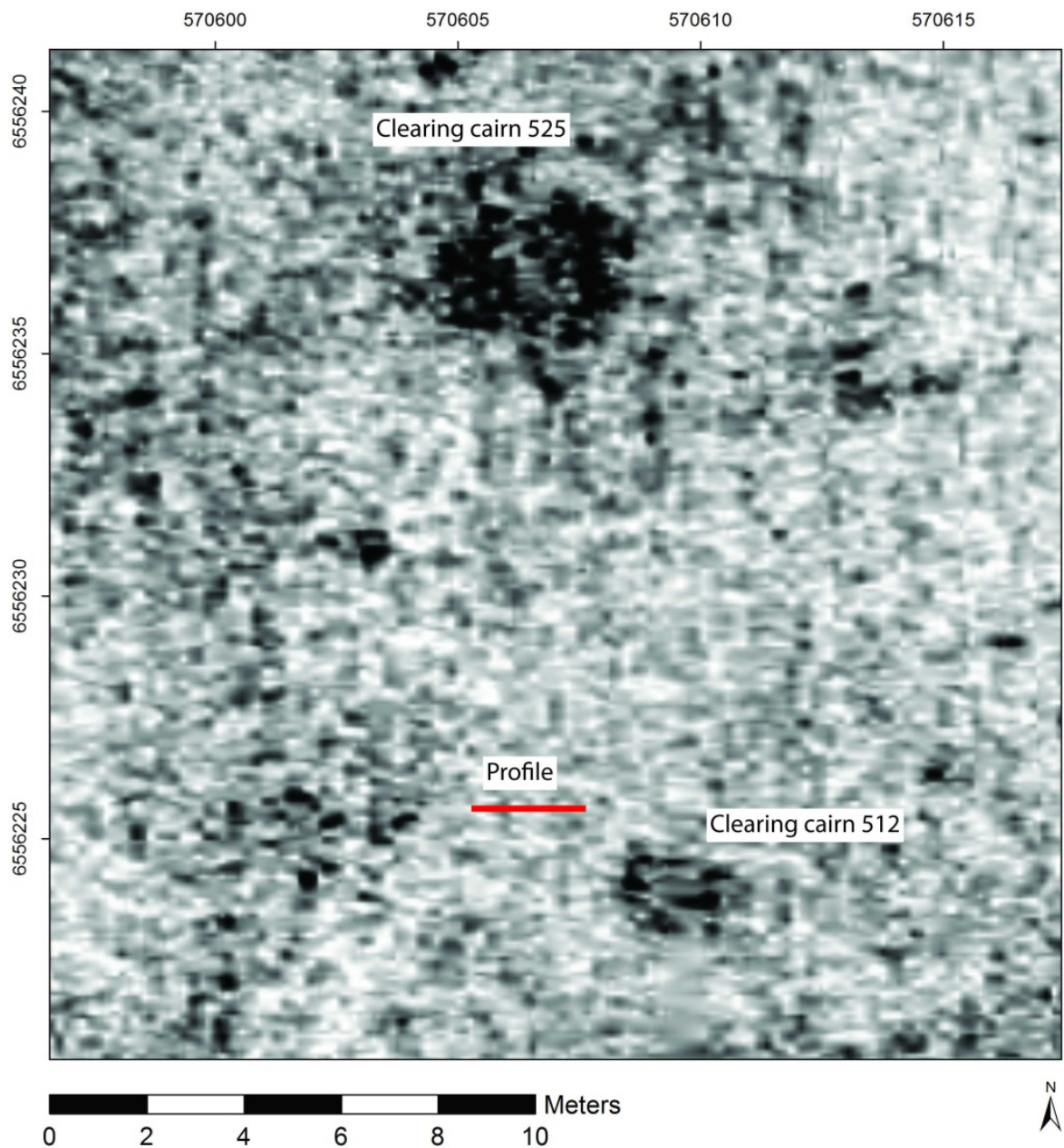


Fig. 6.5 GPR depth slice 65-70 cm BGS displaying the two clearance cairns as strongly reflective features targeted during the geoarchaeological field evaluation. The profile location was selected based on an area free of disturbance from drainage ditches and archaeological features

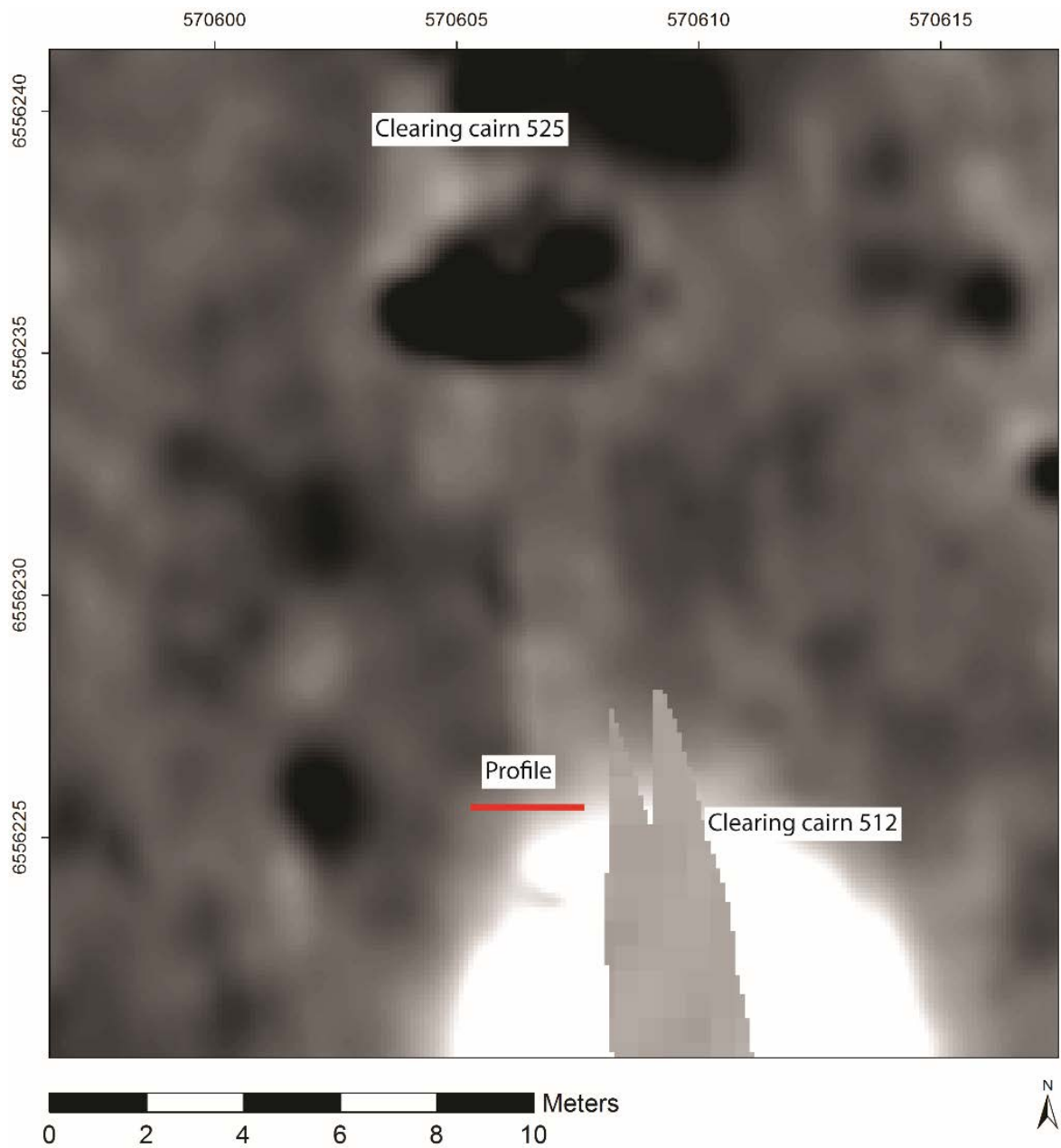


Fig. 6.6 Magnetometry data with the locations of the two clearance cairns. Clearance cairn 512 was completely obscured due to shallowly buried magnetic bedrock – a problem frequently occurring in Norway. In the middle of the dipole anomaly, data could not be acquired due to obstacle blocking the survey path

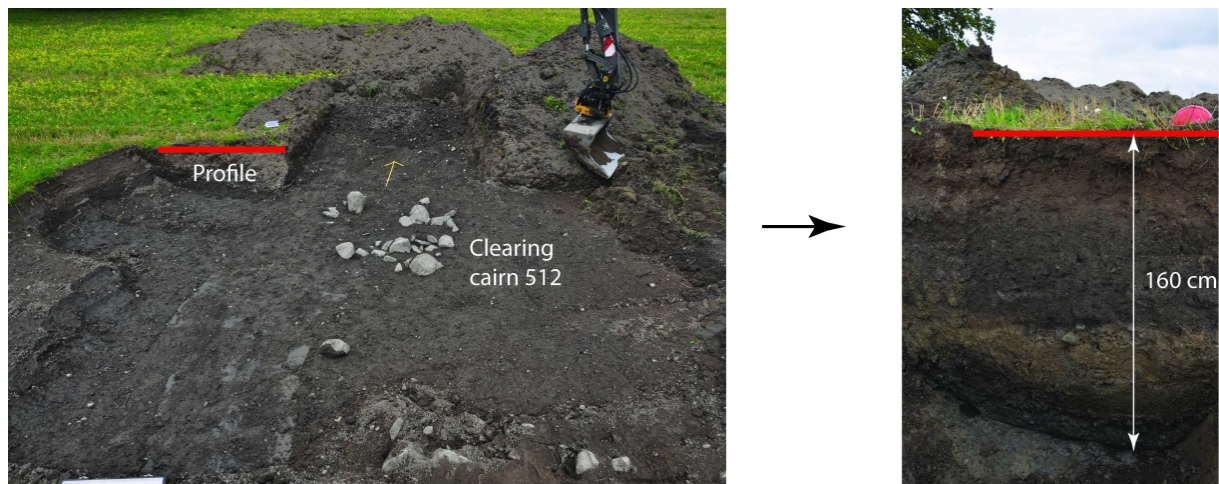


Fig. 6.7 Clearance cairn 512 with the exact position of the profile. The profile was dug mechanically in an undisturbed location down to ca. 1.60 m below surface, where ground water started to intrude

The profile was cleaned and soils, sediments and stratigraphical observations were described in the field (Table 6.1). Six different stratigraphic layers could be identified with topsoil (Ap) and sandy subsoil (B) overlying fine-grained marine sediment (C). This less permeable zone displayed redoximorphic properties as a result of repeated drying and wetting cycles. A charcoal lens was observed at the transition between subsoil and marine sediment. Clast inclusions were most abundant in layers [2] and [3], while diminishing in the lower parts of the profile. These results showed a sedimentological situation frequently observed in Norway with marine sediment being less permeable and subsequently acting as a stagnant zone, overlain by stagnic – endostagnic soils mixed with clasts of varying sizes (<http://wms.skogoglandskap.no/cgi-bin/jordsmonn>). The transition from subsoil to marine sediment at ca. 1 m below surface marks a clear difference in physical properties and is especially relevant for the GPR signals. Water content and particularly electrical conductivity notably increase in the lower part of the profile, leading to signal attenuation as illustrated by the radar trace (see below).

The small charcoal lens tentatively interpreted as part of an archaeological feature at ca. 1m below surface was only discovered upon excavation and well illustrates some of the issues magnetometry faces in Norway. First, the entire area at this point was masked by a strong dipole anomaly originating from shallowly buried magnetic bedrock. Second, the charcoal lens is buried relatively deeply in relation to its rather weak magnetisation – a combination

that exceeds the sensitivity of the sensors used and results limited detectability. These issues are intensified by the magnetically variable overburden, caused by magnetic clast inclusions well illustrated by the *in-situ* volume MS values. One focus of data processing is to neutralise background noise as much as possible with the aim to enhance the visibility of the magnetic anomalies present in the data set. In case of magnetically weak features, however, this approach can lead unintentionally to the opposite effect. The high MS values of the marine sediment underlying the charcoal lens contribute to this problem.

Table 6.1 Sedimentological description and stratigraphic observations of the layers discovered at Sverstad

Unit	Stoniness	Colour description (Munsell Code)	Layer description
1	5% very small, subangular stones; 10% small, subrounded stones, 5% medium, subangular stones	very dark brown (10YR 2/2)	topsoil; small pieces of straw, thin roots, large amounts of organic material
2	10% very small, subangular stones; 10% small, subangular stones, 15% medium subangular stones	very dark greyish brown (10YR 3/2)	relatively homogenous material with few larger stones (> 5cm), very compact
3	5%, small, subrounded stones; 10 % small, subangular stones	very dark greyish brown (10YR 3/2)	similar to unit 2 with main differences in colour
4	5% small, subangular stones	very dark brown (10YR 2/2)	transition between unit 3 and 4 marks the beginning of a stagnant zone with small amounts of water leaking from the upper layers ; large, roughly oval-shaped dark charcoal lense (ca. 30 cm x 15 cm); few large (>8cm) subrounded pebbles; redoximorphic features (orange/beige mottles); very compact
5	2% small, subangular stones	dark greyish brown (2.5Y 4/2)	very wet material, clear redoximorphic features (mottles); almost free of stones;
6	2% small, subangular stones	dark greyish brown (2.5Y 4/2)	very wet material, redoximorphic features (few mottles); almost free of stones; below 1.5 m: water table); possible intertidal material with dark colour indicating the presence of organic material

6.4.1 Magnetometry related evaluation techniques

Samples for MS were collected at a 10 cm interval for both *in-situ* as well as for lab-based measurements, which were taken back to the laboratory. *In-situ* measurements could have been collected at a smaller interval, but were matched with the lab-based samples for

comparative purposes. 10 cm distance between *in-situ* sampling points also ensured to avoid an inadvertent averaging of measurement results.

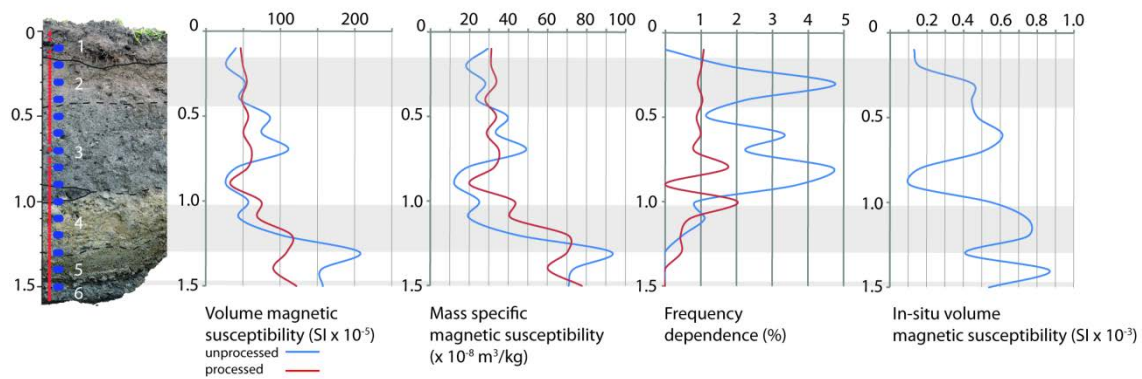


Fig. 6.8 Comparison of lab-based processed and unprocessed sample material with *in-situ* measurements collected every 10 cm. Note the difference in scale of each measurement technique

Comparisons of lab-based MS measurements show roughly similar curves for processed and unprocessed sample sets (Fig. 6.8). Both sample sets are mainly controlled by ferrimagnetic components, while the amount of diamagnetic elements, such as water or organic inclusions, which are excluded in the processed sample set, does not seem to substantially distort the MS values for the purposes intended in this study. Trends in mass specific MS values are more pronounced compared to volume MS measurements due to factoring in their different bulk densities.

Looking at the results of the mass specific MS measurements in more detail, it was noted that some of the unprocessed samples display higher values than their processed equivalents (compare units 3, and especially 5 and 6). This behaviour rules diamagnetic water as important diminishing constituent out and confirms ferrimagnetic components as the dominating factor for MS in these samples. The higher MS values of the unprocessed sample set could, on the one hand, potentially origin from small fragments of igneous rock still contained in the unsieved sample material. This is plausible as, geologically, the area around Gokstad is characterised by monzonite and quartz-monzonite, which can contain up to 1% of magnetite (Sørensen, 1988) and is known to create large magnetic anomalies (see

chapter III). An additional source for igneous boulders is the Ra moraine, which runs just ca. 4 km to the north-west of *Sverstad* (Fig. 2.21). Ferrimagnetic minerals control the MS of a sample due to their strong positive values – even if present only in relatively small amounts (Dearing, 1994). Exactly this might be the case at 130 cm, where values of processed and unprocessed samples deviate by ca. $40 \times 10^{-8} \text{ m}^3/\text{kg}$ - a magnitude indicating ferrimagnetic minerals such as e.g. magnetite as source for the high values in the unprocessed sample (Dearing, 1994).

Following a different perspective, the low MS values of the processed sample set could be the result of the ferrimagnetic iron-sulphide greigite, which – upon drying of the samples – oxidised to the magnetically weaker antiferromagnetic minerals lepidocrocite or goethite. Greigite usually occurs in lacustrine and marine sediments, but also is produced secondary by magnetotactic or sulphate-reducing bacteria in gleyed soils (Anthony et al., 1990; Fassbinder, 1994; Fassbinder and Stanjek, 1994).

Results of frequency-dependent MS indicate the presence of super-paramagnetic grains in the upper part (0-100 cm, units 1, 2 and 3) – yet only in the unprocessed sample set. While the processed sample set generally reports low % values with a maximum of 2% for the area close to the charcoal lens, the unprocessed sample set shows maximum values of up to 5% frequency dependence for units 1-3, indicating the presence of at least a certain amount of superparamagnetic grains. The deviation in results of processed and unprocessed sample sets again might hint at greigite as the source of the superparamagnetic grains (Dearing, 1994; J. A. Dearing et al., 1996), though if the stagneric properties of the cambisol present at the site are sufficient for such a formation admittedly remains questionable. A more detailed investigation of the magnetic mineral composition including the thermoremanent, isothermal remanent and anhysteretic remanent magnetisation, thus, would be highly advisable.

With the transition to unit 4 – a moist, fine-grained marine sediment – frequency-dependent MS values decrease (Maher, 1986). The lack of superparamagnetic grains in both the processed and the unprocessed sample sets in the lower part of the profile (units 3-5: 100-160 cm) could be caused by marine sediment, as gleyed soils seem to specifically favour the reduction of ultrafine (superparamagnetic) and fine (single domain) grain sizes (Maher 1986). This would, however, not correspond with the high MS values measured in the lower

zone. A better explanation might be the presence of ferrimagnetic iron sulphides such as pyrite, pyrrhotite or greigite in multi-or single domains. The absence of superparamagnetic grain sizes also indicates that the high MS values found in the marine sediments must be authigenic/lithogen (Dearing, 1994; Fassbinder, 1994).

Comparing processed/unprocessed lab-based measurements with the *in-situ* volume MS measurements shows a rough congruence of both data sets with a general trend of increasing values towards the lower part of the profile. Closer inspection, however, reveals certain differences. The *in-situ* measurements are characterised by alternating values particularly in the lower part of the profile (units 4-6). Peaks at 120 cm and 140 cm potentially are probably caused by the presence of igneous rock buried in the profile, which would substantially influence the readings. The small pick-up coil of the SM-30 of only 5 cm diameter could further add to this issue due to its small sampling volume, which can lead to distorted results if applied to magnetically heterogeneous materials (Mazurkevich et al., 2009).

6.4.2 GPR related evaluation techniques

In-situ measurements of water content/dielectric permittivity, electrical conductivity and temperature were collected *in-situ* using the 5te FDR sensor from Decagon. The sampling interval was intended for every 2 cm, but in some cases had to be adjusted due to difficulties of completely planting the sensor into the soil. Water content was also measured using the direct, gravimetric method – on the one hand to assess the accuracy of the indirect, dielectric method, on the other hand to test the suitability of lab-based water content measurements for geoarchaeological field evaluation. Samples for gravimetric water content and grain size distribution were both collected every 10 cm with the sample material for water content being placed in three subsets of plastic bags in order to prevent evaporation during transport prior to processing.

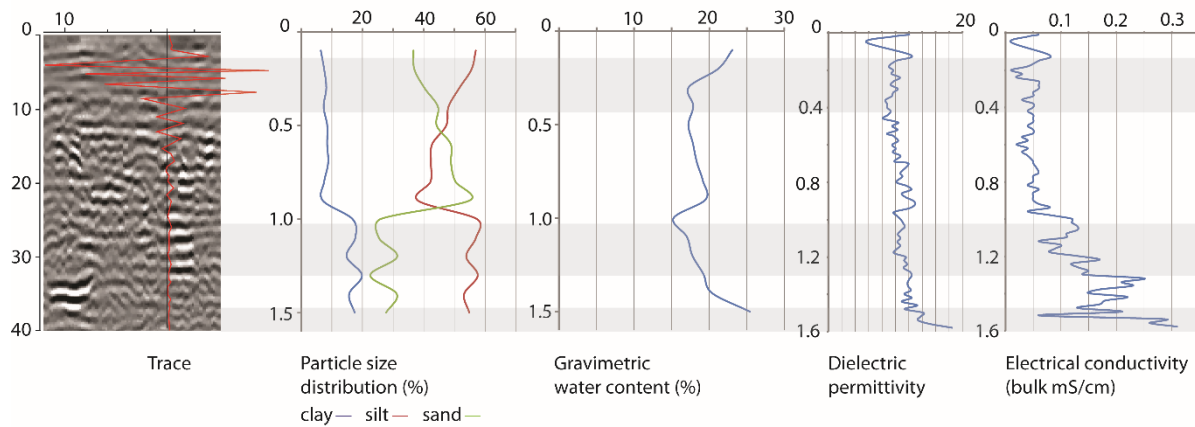


Fig. 6.9 Comparison of grain size distribution, gravimetric water content, volumetric water content and electrical conductivity collected along the profile

A single trace was extracted from the GPR data for a more distinct comparison, although it has to be noted that a single trace can be unrepresentative (Fig. 6.9). In this case, the trace shows high amplitudes in the upper part of the profile, most probably representing air-wave and ground-wave (Annan, 2001). Subsequently the trace travels downwards crossing top and subsoil, which triggers moderate reflections. At the transition between soil and the moist, fine-grained and more homogenous marine sediment, amplitudes diminish indicating that the electromagnetic energy gets attenuated.

Grain size distributions well reflect GPR data and observed stratigraphy at *Sverstad*. Unit 1 and units 4, 5, and 6 are all dominated by sandy silts, while units 2 and 3 have a slightly coarser texture with slightly clayey silty sand. The lower part of the profile (units 4, 5 and 6), however, displays a notable increase in the smaller grain size fractions clay (up to 58%) and silt (up to 20%). This transition from coarser to finer material is also displayed by the gravimetric water content (GWC). Generally, GWC shows values from 15-25%. High values of >20% for the topsoil is probably connected to good infiltration and water holding capacity mainly based on the typical high organic matter content of this soil horizon (Haase, 2011). Values decrease within unit 2 (ca. 15%) but remain relatively stable throughout most of unit 3 (17-20%). Water content notably decreases in the area of the charcoal lens to 15%, before increasing again at a constant rate throughout the fine-grained units 4-6.

Water content estimated from measuring the dielectric permittivity only partly matched the results of the GWC³ – generally, it responds in a similar, yet much less pronounced way. Values throughout the profile show few variance and cluster around $0.2 \text{ m}^3/\text{m}^3$ with a minimum in unit 1 ($0.09 \text{ m}^3/\text{m}^3$) and a maximum at the profile bottom in unit 6 ($0.33 \text{ m}^3/\text{m}^3$). Water content likewise increases towards the profile bottom within units 4-6; however, this trend starts off slowly and only really becomes more pronounced at unit 6 with values between 0.2 and $0.3 \text{ m}^3/\text{m}^3$. Electrical conductivity values, on the other hand, do greatly increase with depth and show values between bulk mS/cm 0.01 at the topsoil and bulk mS/cm 0.31 at the lowest point of the profile. This is most probably connected with an increase in clay size fraction and in salinity of the marine sediment (Doolittle and Butnor, 2009). The temperature range measured by the 5te sensor clusters closely around $18, 76$ (mean) with a standard deviation of 0.8 and therefore is not considered to greatly affect the apparent dielectric permittivity values or the water content respectively (Thring et al., 2014).

6.5 Discussion

Testing an approach for geoarchaeological field evaluation of archaeological geophysical prospection data sets has shed light on several issues regarding the accessibility of the subsurface, different sampling strategies, processing of MS sample material and the accuracy of indirect *in-situ* water measurement sensors.

For comprehensive geoarchaeological field evaluations, full exposure of soils and sediments – during for example an excavation – is preferable compared to borehole surveys, which only enable a very limited insight into stratification and formation processes. Description and sampling based on core material mostly impedes *in-situ* measurements due to an insufficient amount of sample material available (moisture sensors with 5 cm prongs would require at least a core diameter of $> 7 \text{ cm}$, which would necessitate the use of a power corer). Lab-based measurements for MS as well as GWC and electrical conductivity therefore

³ In hindsight, water content measurements should have been calculated by volume instead of mass for a better comparison with the volumetric moisture sensor results.

present an alternative option more suitable for borehole-based geoarchaeological field evaluations. In recent years, core scanning technology has been rapidly developing, which allows collecting continuous high resolution readings of different physical properties including MS and elemental composition. This technology is likely to develop further and certainly should be followed (Croudace and Guy Rothwell, 2015).

To conclude, if undisturbed samples are not possible or mass specific results are required for inter-site comparison, then lab-based measurements have to be conducted. It has to be kept in mind, however, that sampling always means interfering with the original structure and composition of soils and sediments under investigation and potentially can change physical parameters that are significant for a particular geophysical prospection technique. The investigations at *Sverstad* have shown that this particularly applies to the *in-situ* measurements of MS. The processing of samples excludes the mass contribution of water (even though this is only a minor contribution if the material is magnetically controlled by ferrimagnetic components, but it can become significant if the material contains mainly paramagnetic components) and all parts > 2mm, which concerns mainly stones and organic material. In this part of Norway, where igneous bedrock prevails, the exclusion of stones > 2mm can seriously distort the evaluation results. The comparison between processed and unprocessed sample sets stressed that the presence of even small fragments of magnetic rock substantially influenced the readings. Subsequently, their inclusion in the analysed material resulted in a better reflection of the actual magnetic properties of the subsurface than the sample material undergone standardised laboratory procedures.

Generally, therefore, undisturbed *in-situ* sampling strategies are in most cases preferable when it comes to geoarchaeological field evaluations. Care should be taken, however, when using a small measurement volume on very heterogeneous material, as this can lead to unrepresentative and misleading results. Multiple readings can aid in reducing this effect by providing averaged results. Another possibility presents the use of a larger sampling volume as is provided e.g. by the Bartington SM 2D with a diameter of 18 cm. In some cases, however, this would lead to either a very low resolution or to an unintended averaging of measurement values.

In-situ water content measurements using the indirect, dielectric FDR technique have not entirely met the expectations for a correlation with the GPR profile data and traces. The

resulting curve reflected the trend of increasing water content towards the profile bottom only very general. The distinct increase in water content at the transition between subsoil and marine sediment as evidenced by results of the GWC and macroscopic sedimentological is missing in the indirect values for water content. The reason for this remains unclear, but is possibly connected to higher clay content and increased salinity of the marine sediment and their influence on the FDR measurements (Visconti et al., 2014). An additional and rather unexpected issue presented the close clustering of results derived from the moisture sensor. The manufacturer *Decagon Devices* states an accuracy range of ± 1 unit of dielectric permittivity in ranges from 1-40 (soil range) and subsequently $\pm 0.03 \text{ m}^3/\text{m}^3$ VWC or $\pm 3 \%$ VWC for soils with $< 10 \text{ dS/m}$ (DecagonDevices, 2015; Visconti et al., 2014), which seemed sufficient for detecting trends throughout the sediment sequences and for correlation purposes intended in this study where contrast is the most essential factor. Soil-specific calibrations were therefore not conducted for the investigations at *Sverstad*; instead, the Decagon in-house calibration for mineral soils was used. The close range in values, however, exceeded the stated accuracy range and this might have contributed to the only weakly defined increase in water content in the lower part of the profile. The accuracy could be improved to 1% by conducting soil-specific calibrations in order to account for the different types of soils and sediments and their varying composition and subsequent physical parameters. Yet calibrations are time and cost-intensive and therefore not applicable on a regular basis in geoarchaeological field evaluations.

The use of indirect dielectric methods for geoarchaeological field evaluations is, however, unquestioned and the ability of these sensors to rapidly measure apparent relative dielectric permittivity as well as electrical conductivity at the same time – two important parameters for electromagnetic signal propagation – is significant for evaluating GPR surveys. Future research avenues in this area must therefore focus on dielectric sensors that do not require soil-specific calibration while being sufficiently accurate, easy to handle and maintain and cost-efficient. It is to be expected that the development in the field of *in-situ* soil moisture measurement will lead in this direction.

The study has thus demonstrated that dielectric sensors (capacitance/FDR sensors) can be used for *in-situ* water content measurements, yet that results have to be tentatively regarded as general trends and in combination with other proxies such as grain size

distributions and electrical conductivity. Meanwhile, measuring water content using the thermo-gravimetric method presents a feasible alternative, not just as a substitute for *in-situ* measurements at exposures or excavations, but for use in borehole surveys where moisture sensors are not applicable.

Chapter VII

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

7.1 Introduction

As mentioned in the previous chapters, the interpretation of archaeological geophysical prospection data must provide information as accurate and detailed as possible in order to further promote the use of this non-invasive method in heritage management and research projects alike. Accuracy and level of detail depend on a range of factors, including technical parameters of the measurement systems used, experience in interpreting geophysical data sets as well as expertise in local archaeology (Cowley, 2011; Neubauer, 2001a). 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 (Bonsall et al., 2014; Cassidy, 2008b; Scollar et al., 1990; van Dam, 2001). Local and regional palaeoenvironmental settings including soil types, geology, topography as well as erosion and accumulation processes all influence the quality of prospection data and their interpretation (Becker, 2009; Fassbinder, 2015; Kattenberg and Aalbersberg, 2004; Linck and Fassbinder, 2014), 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. The excavation followed motorised magnetometry and GPR surveys carried out in 2012 by the LBI ArchPro, the Vfk

and NIKU as part of the Vestfold project (see also chapter II). 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 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 MS, electrical conductivity and water content measurements as diagnostic elements for correlation purposes as well as for the pursuit of specific questions raised during the interpretation process. These included GPR signal attenuation, the masking of magnetic dipole anomalies, and insufficient contrast observed during the archaeological interpretation of the geophysical prospection data. The study presented here thus 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.

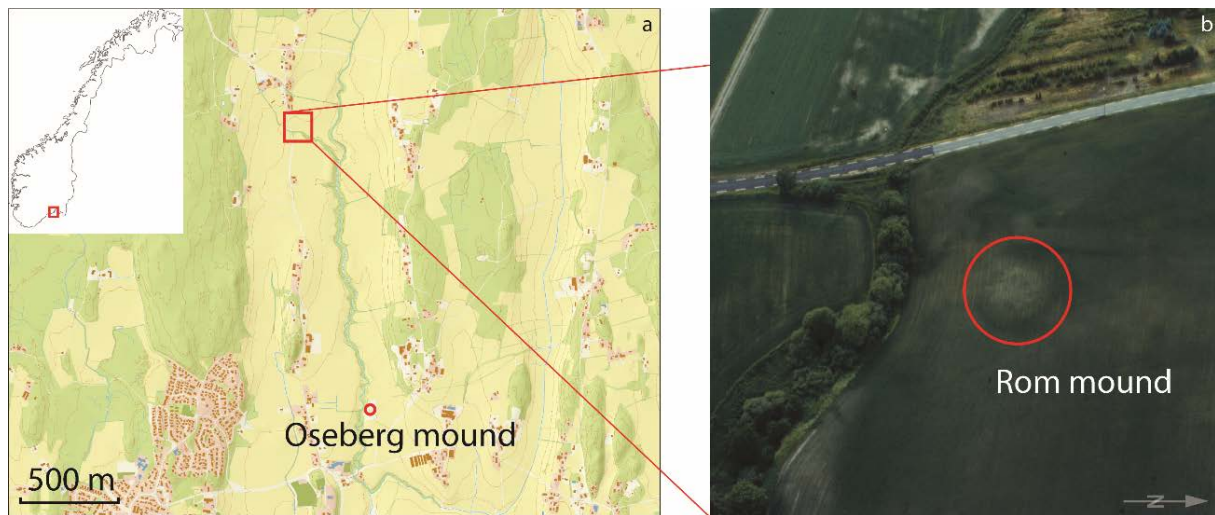


Fig. 7.1a The Rom mound located in Slagendalen near the western shore of the Oslo Fjord, ca. 200 km SSW of Oslo. 7.1b: Oblique aerial photo with the Rom mound showing as a negative crop mark

7.3 Site description

7.3.1 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 (see chapter II) (Brøgger et al., 1917; Gansum, 1995) (Fig. 7.1). 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 “fjærd” landscape (Embleton and King 1970; Bird and Schwartz 1985; Fairbridge 1985; Bird 2010, fig. 8.1.1) 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 7.2b). 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. 7.2a), 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.

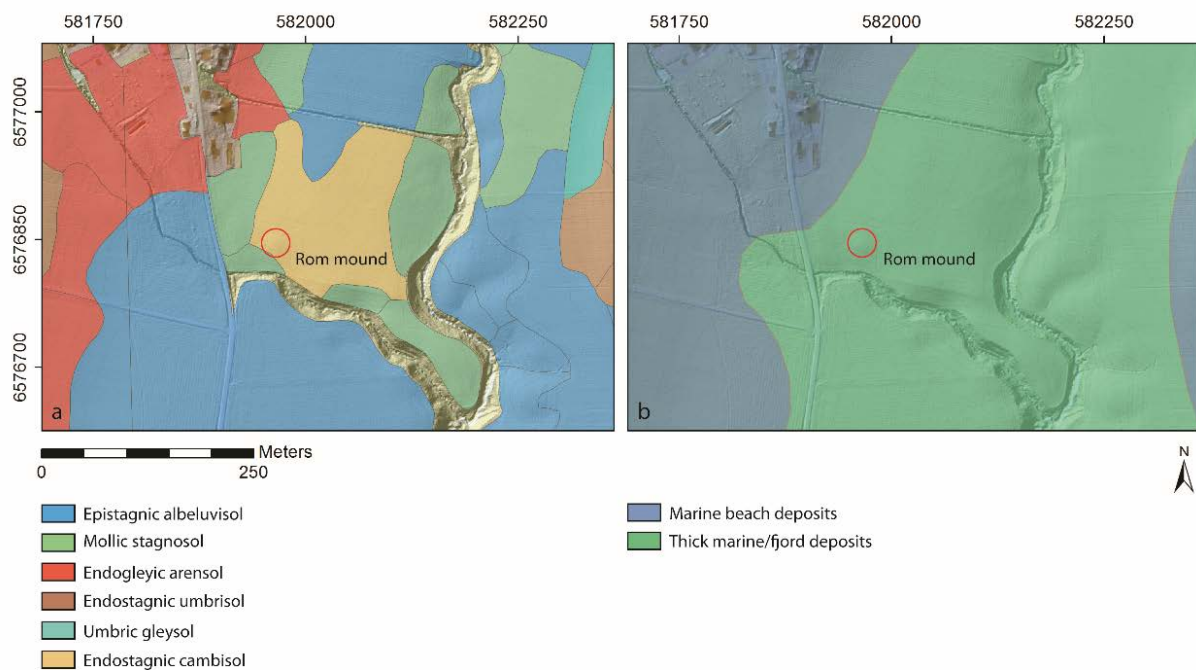


Fig. 7.2a Soil and 7.2b sediment map of the area surrounding the Rom mound. The monument is situated on endostagnic cambisol developed on thick marine/fjord deposits. Basis: NGU (Norges Geologiske Undersøkelse)

7.3.2 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/m²) 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. 7.3a and 7.3b).

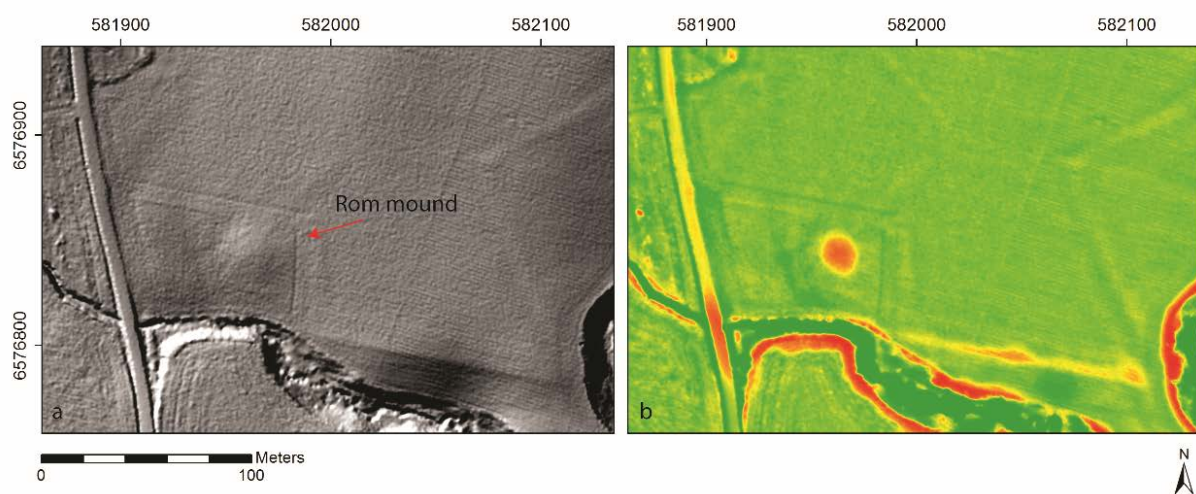


Fig. 7.3a Hillshade visualisation of the ALS data. 7.3b Local-relief model displaying the remaining state of preservation of the Rom mound relative to the current topography

7.3.3 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 Vestfold Project (see chapter II), conducted as joint research cooperation between the LBI ArchPro, Vfk, NIKU and the *Gokstad Revitalised* Project. 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*). In 2014, a second ultra-high definition GPR survey was conducted using a 16 channel 400 MHz antenna MIRA system with a ca. 8 × 8 cm horizontal sampling resolution, a vertical resolution of 5 cm and trace sampling rate of a record every 0.16ns. This survey aimed for the most detailed non-invasively generated subsurface image of the remaining part of the mound and also served as comparative data set regarding the evaluation of level of detail in this study.

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. 7.4a and 7.4b). 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).

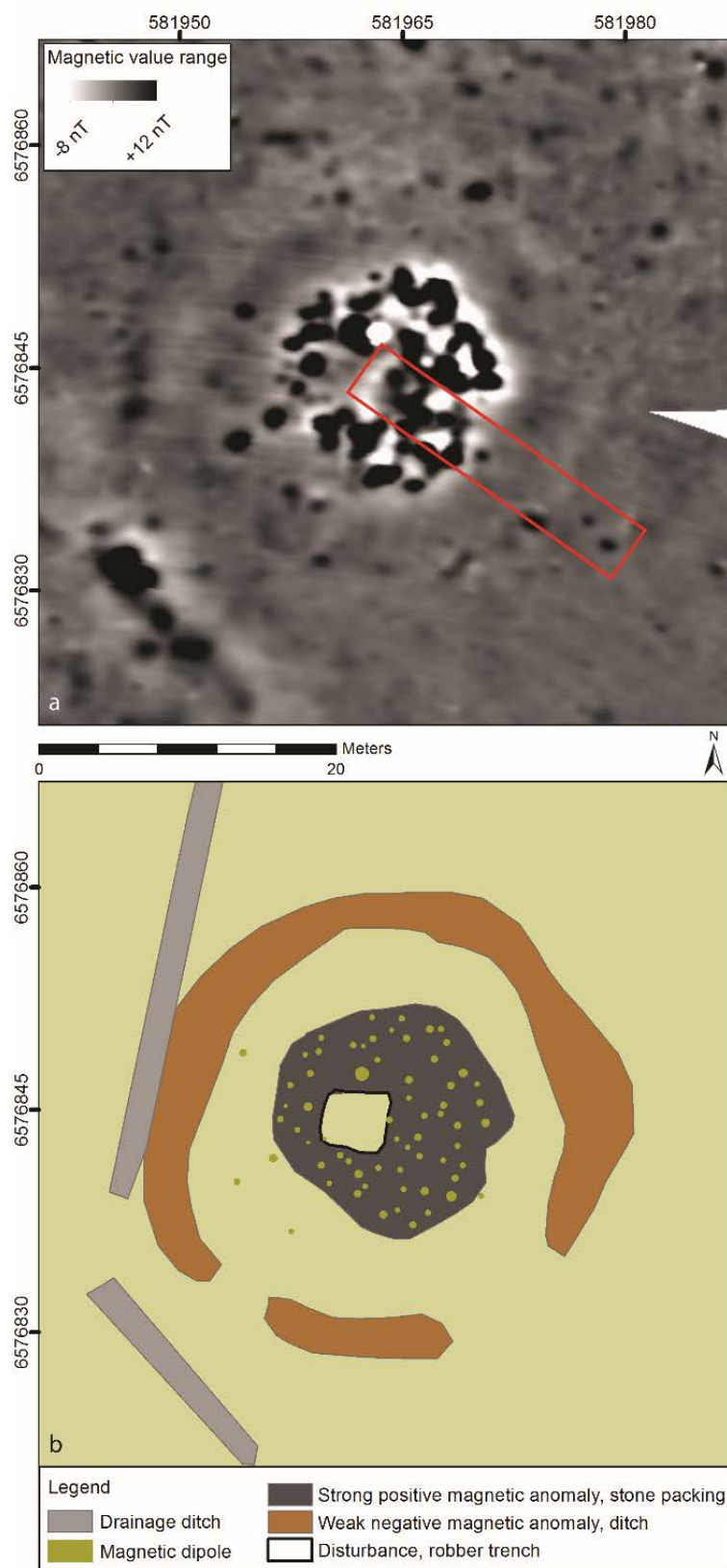


Fig. 7.4a Magnetogram (10 × 10 cm resampled pixel resolution) of Rom mound with red rectangle marking the 2013 excavation trench; 7.4b Archaeological interpretation of the magnetic prospection data

A GPR survey using the SPIDAR system, which was chosen as primary investigation method, enabled a clear three-dimensional picture of the subsurface (Fig. 7.5a and 7.5b). 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.

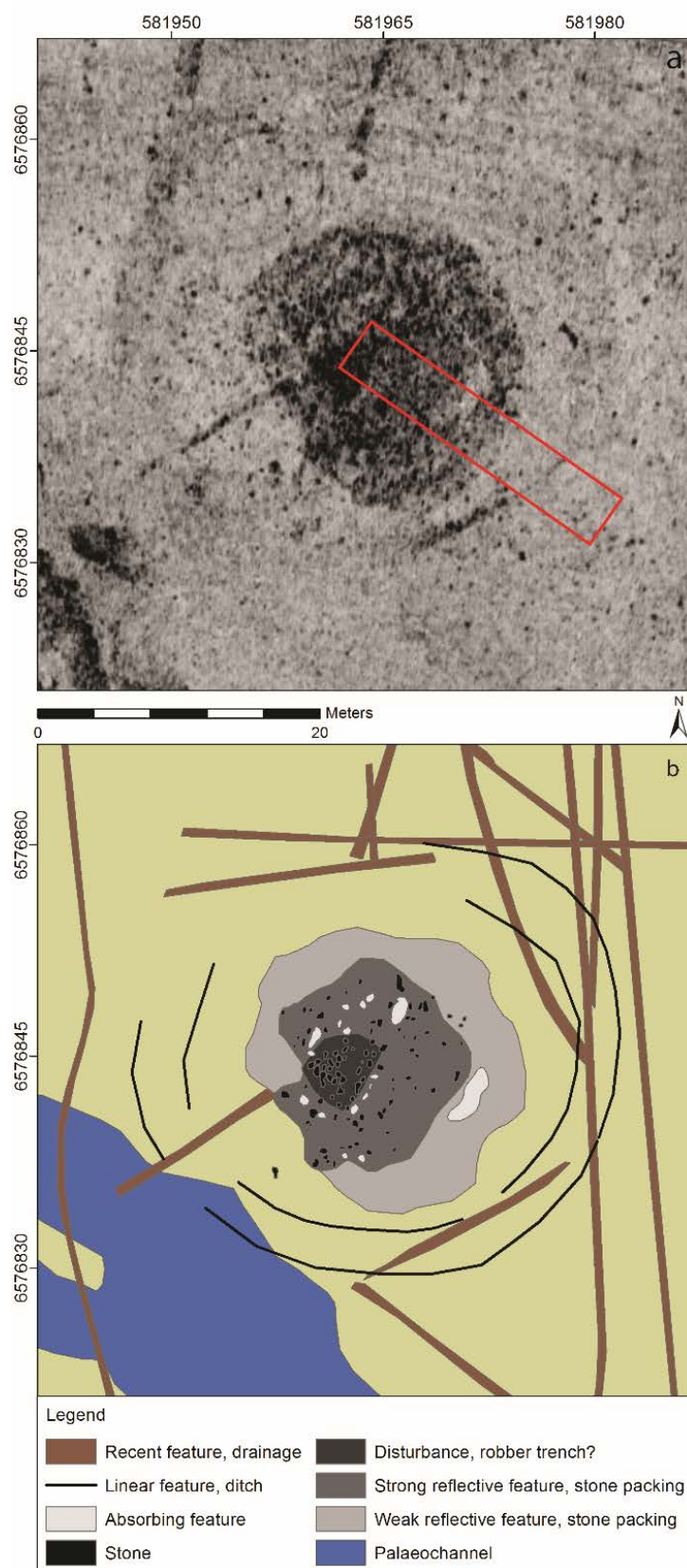


Fig. 7.5a GPR depth-slice 40-60 cm BGS (10 × 10 cm resampled resolution) of the Rom mound with red rectangle marking the 2013 excavation trench. 7.5b GPR data interpretation of depth-slice 40-60 cm BGS

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.

7.4 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>).

In-situ and laboratory-based MS, dielectric permittivity/volumetric water content, electrical conductivity and temperature measurements followed the same approach as used at the *Sverstad* study and is described in detail in the previous chapter VI.

For the study at Rom, 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 $\pm 0.03 \text{ m}^3/\text{m}^3$ VWC or $\pm 3 \%$ VWC for soils with $<10 \text{ dS/m}$ (DecagonDevices, 2015; Visconti et al., 2014) 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.

7.5 Results and Discussion

7.5.1 Comparison of prospection data interpretation and 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 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. 7.4a and 7.5a). During the excavation process, the trench was extended twice as a response to new questions. In total, 32 stratigraphic units (SU) could be identified and associated with different construction phases (McGraw and Bill, 2014)(Fig. 7.6).

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 Tønning pers. comm.). 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 to shield the potato cellar from the moist, marine sediment underneath. 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. 7.6).

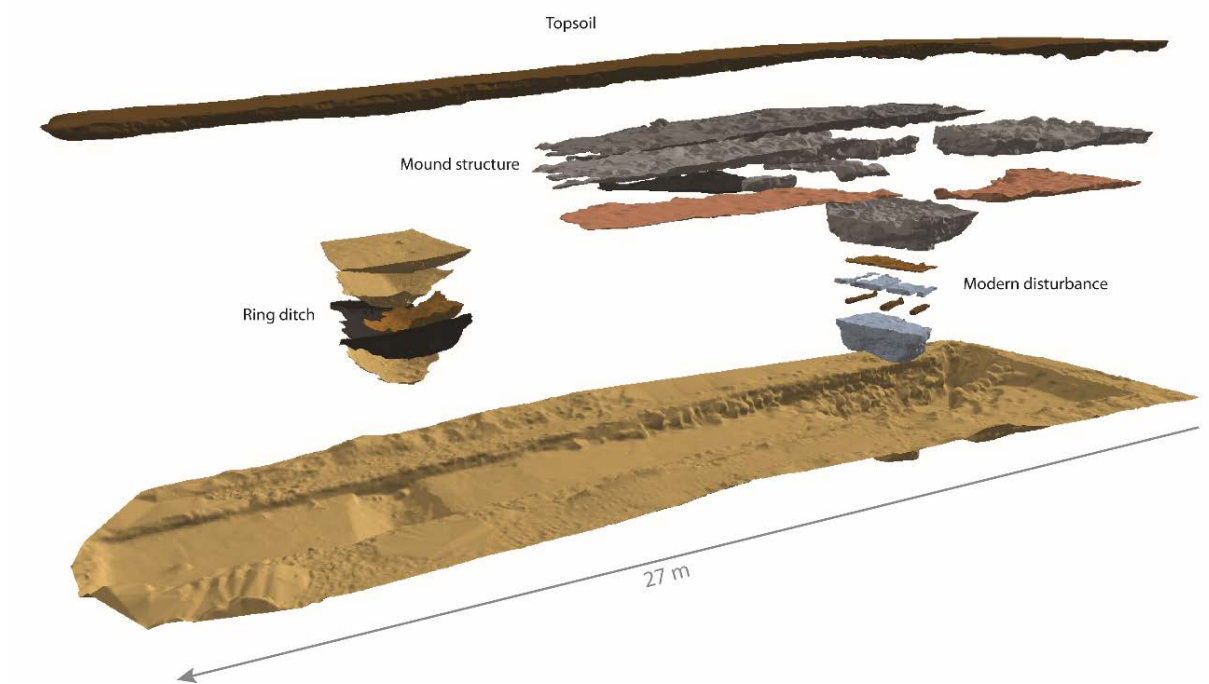


Fig. 7.6 3D explosion model of the excavated stratification at Rom mound. Three main structures could be identified: the mound structure itself, the surrounding ring ditch and the modern disturbance

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 illustrated when comparing the virtually reconstructed excavation against the interpretation of the prospection data in a 3D environment (Fig. 7.7a, 7.7b and 7.7c). The modern disturbance caused by digging a potato cellar into a former grave monument indeed presents a stratigraphically later interference and was thus correctly identified. The interpretation of the GPR data correctly recognised 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 vessels.

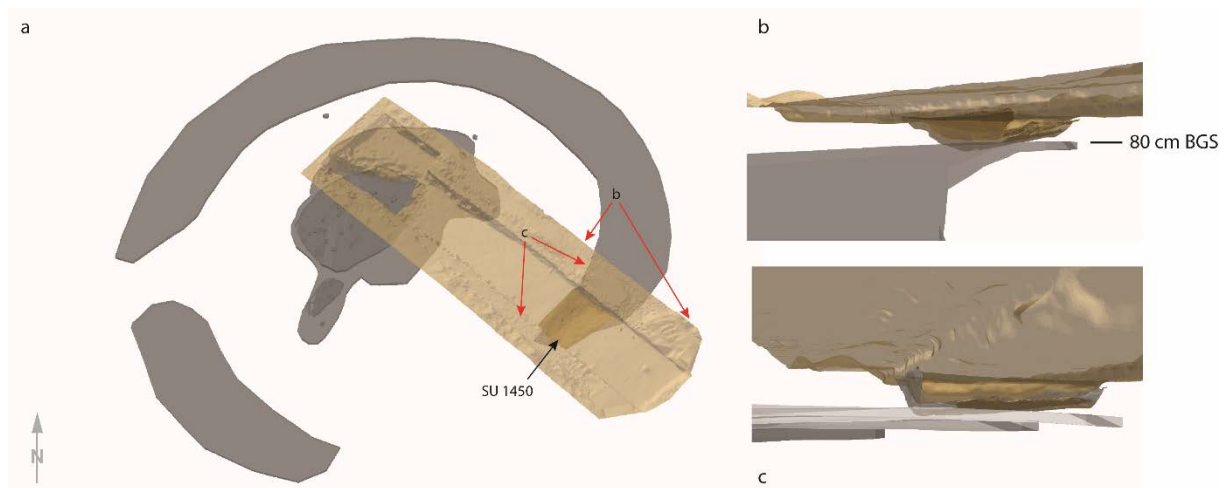


Fig. 7.7a Comparison of the virtually reconstructed archaeological stratification of Rom mound with 2.5 D GPR data interpretation (80-200 cm BGS) in ArcScene 10.2. Red arrows illustrate view directions for 7.7b and 7.7c. Figure 7.7b and 7.7c demonstrate the interpretation accuracy of the ring ditch as observed in the GPR data. Note the congruence between SU[1450] and GPR interpretation at ca. 80 cm BGS, where the ditch first becomes visible in the GPR data

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 initial 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 below ground surface, which might have benefitted the overall accurate time-depth conversion. (Fig. 7.8), Time-depth conversion can be problematic due to the laterally and vertically varying physical properties of different subsurface materials and usually ranges within an error margin of less than ± 10 % when based on hyperbolic velocity analysis (Cassidy, 2008a). 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 survey area (Annan, 2008).

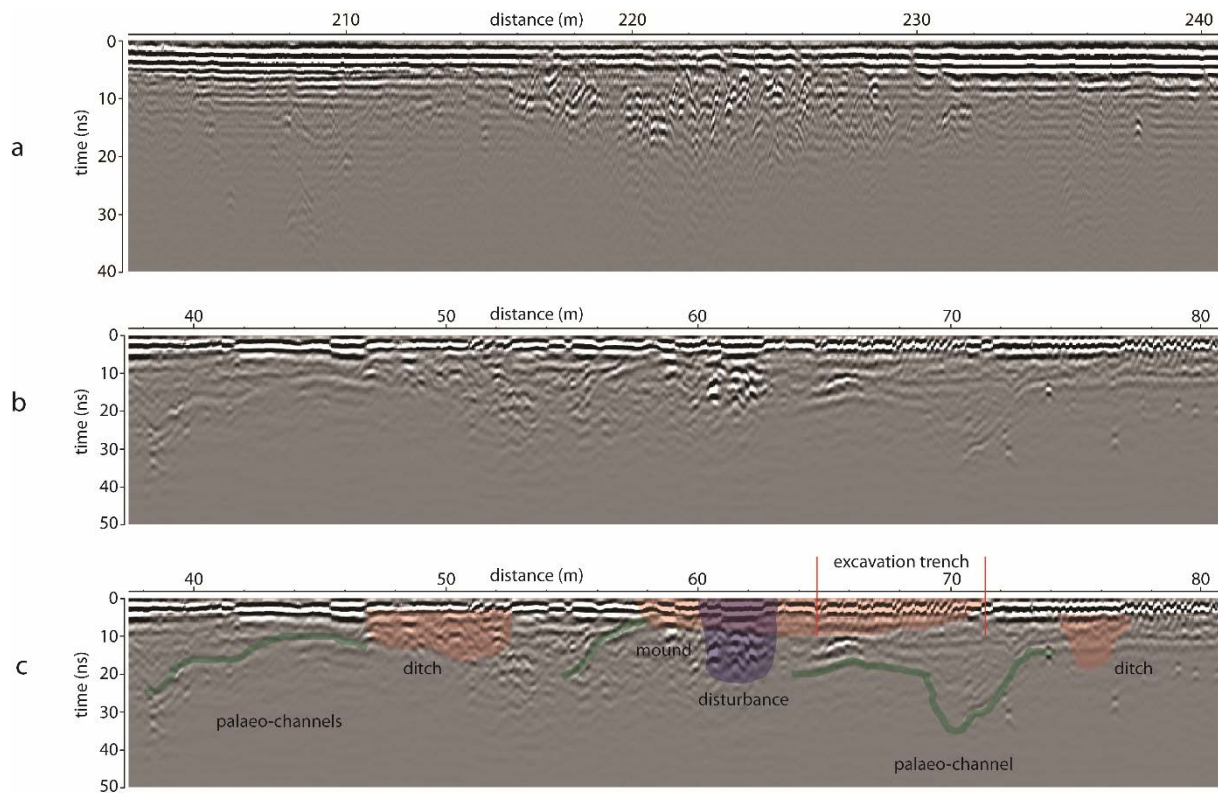


Fig. 7.8 Radargrams displaying sections through the entire mound structure from NW – SE. 8a This radargram was obtained using a SPIDAR GPR system in 2012. The lower 25×10 cm measurement grid resolution and GPR trace sampling rate of 0.2 ns resulted in a coarser, less detailed picture of the subsurface. Figures 7.8b and 7.8c, in contrast, show a radargram obtained from the second survey in 2014 using a high-definition 400 MHz MIRA. The image also displays the trench previously excavated in 2013. This data enables a much clearer imaging of the subsurface structure and highlights the presence of several palaeochannels based on the higher measurement resolution of $2\text{-}6 \times 12$ cm, resulting in a resampled image of 8×8 cm together with a high GPR trace sampling interval of 0.16 ns. Note the slightly different scales of figures 7.8a and 7.8b, 7.8c

The second survey using a 400 MHz high-definition GPR array (5×8 cm) one year after the excavation had been finished, clearly illustrates the additional benefit of a higher spatial sampling. A comparison of radargrams and depth-slices underline this claim and additionally reveal that the monument seems to have been placed onto a palaeochannel (Fig. 7.9).

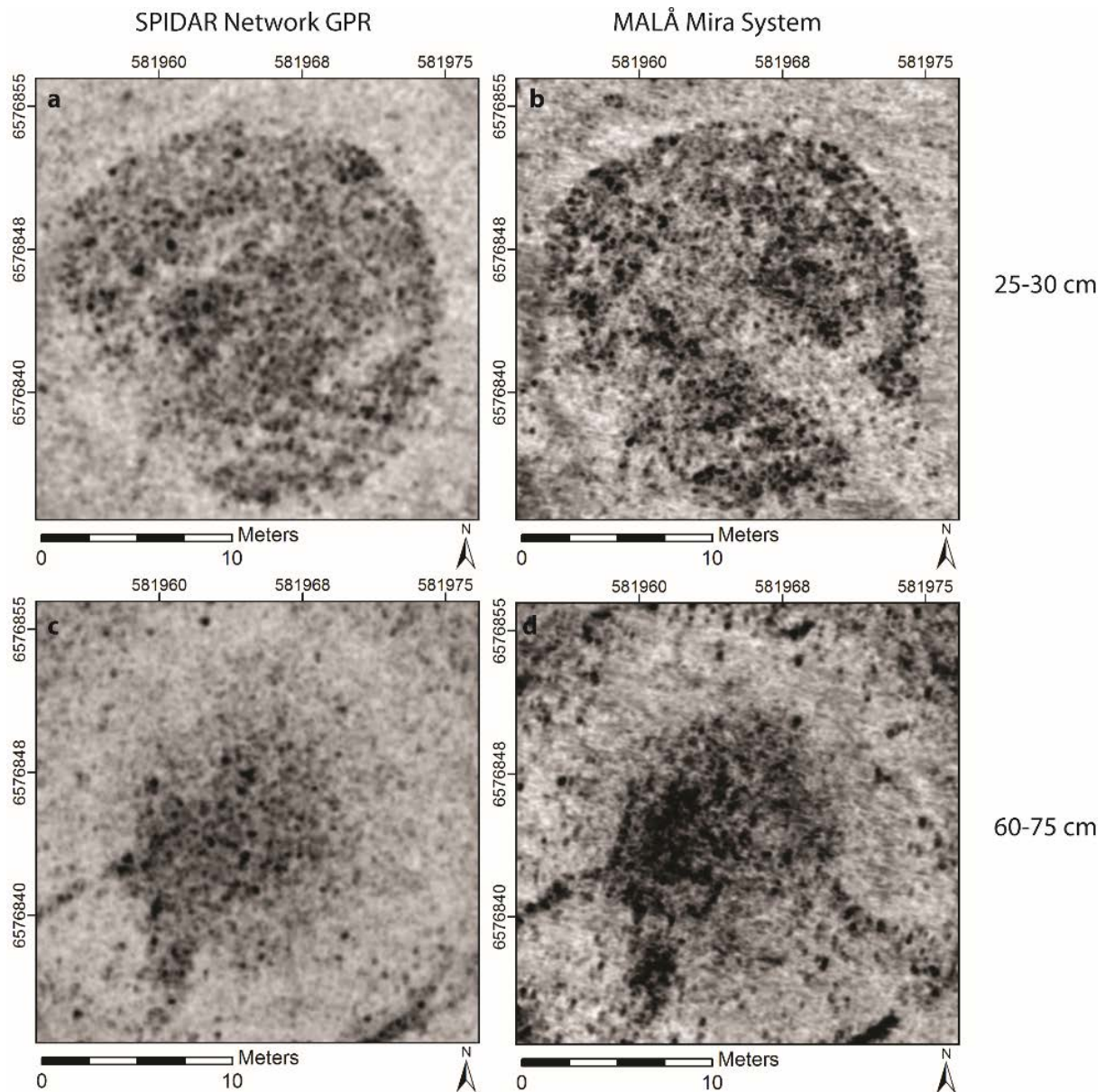


Fig. 7.9 Comparison of high and ultra-high definition GPR surveys. 7.9a shows depth-slices 25-30 cm BGS conducted with a SPIDAR GPR system. 7.9b: The same depth-slices acquired with the MIRA system displays a far more detailed and clearer image of the subsurface, including a kind of rim at the outskirts of the stone packing. 7.9c Depth-slice at 60-75 cm BGS collected with the SPIDAR GPR. 7.9d The corresponding depth-slice acquired with the MIRA system features a lining interpreted as part of the potato cellar, which is barely visible in the corresponding SPIDAR image 7.9c

The amount of detail potentially identifiable within prospection data sets presents a decisive factor, whether near-surface geophysical prospection is used for simply detecting archaeological and palaeoenvironmental information or otherwise can provide a more detailed base map for further, more targeted research, monitoring and protection strategies.

7.5.2 Specific questions addressed

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 (Gustafsson and Viberg, 2012; Trinks et al., 2010a). 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. To investigate this in more detail, every boulder of SU[692] was subjected to MS measurements using a handheld Kappameter SM-30. In total, 249 specimens were measured and MS values ranged between 0 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. The descriptive statistics (Table 7.1) 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 already suggest that the large dipole anomalies are caused by few, highly magnetic boulders (Table 7.1, Fig. 7.10) that mask their magnetically weaker surroundings.

Table 7.1 Descriptive statistics of MS values acquired from the stone packing

Descriptive Statistics	
Mean	4.429
Median	0.31
Standard deviation	11.675
Kurtosis	41.437
Skewness	5.345
Range	119.986
Minimum	0.014
Maximum	120
Count	249

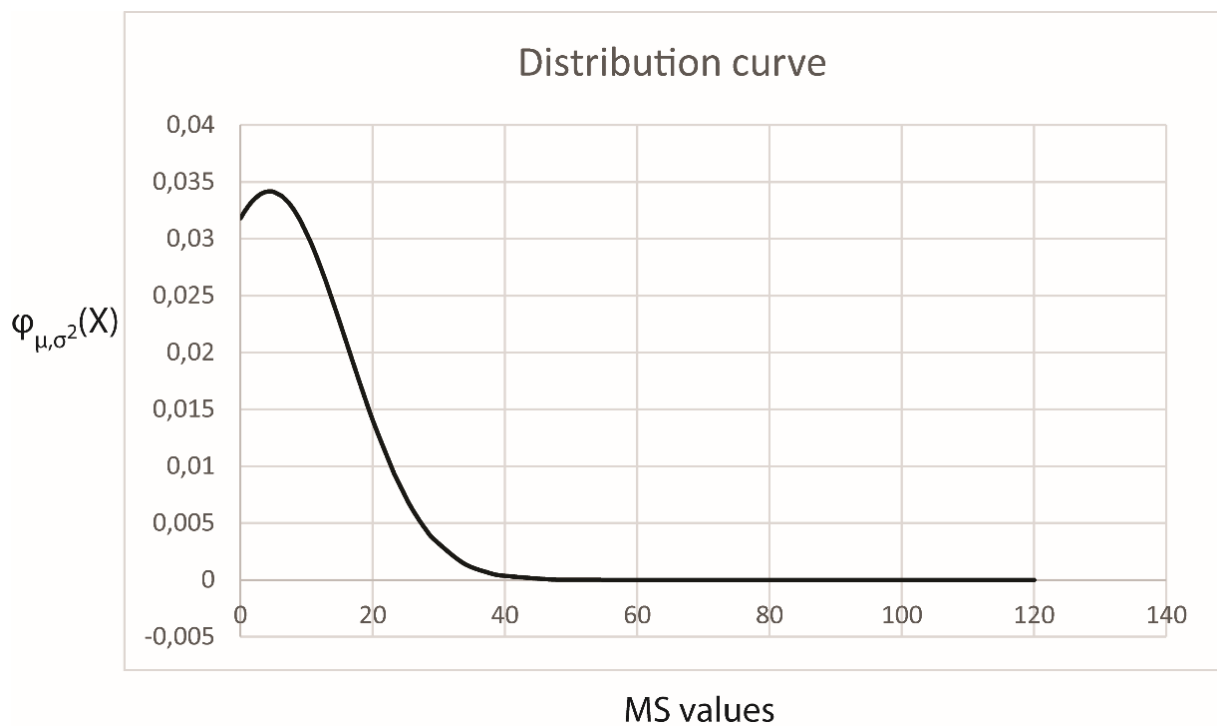


Fig. 7.10 Distribution curve of the 249 specimens tested for MS illustrates that the data are not normally distributed and thus support the hypothesis that the large anomalies are caused by only few highly magnetic boulders

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. 7.11). 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 253 greyscale values in order to minimise the size of the dipole anomalies. Figure 11 clearly illustrates that the large dipoles observed in the magnetogram mostly are incongruent with the numerous small rocks and that these anomalies can be linked to individual specimens only in certain cases. The field intensity of magnetic anomalies depend 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.

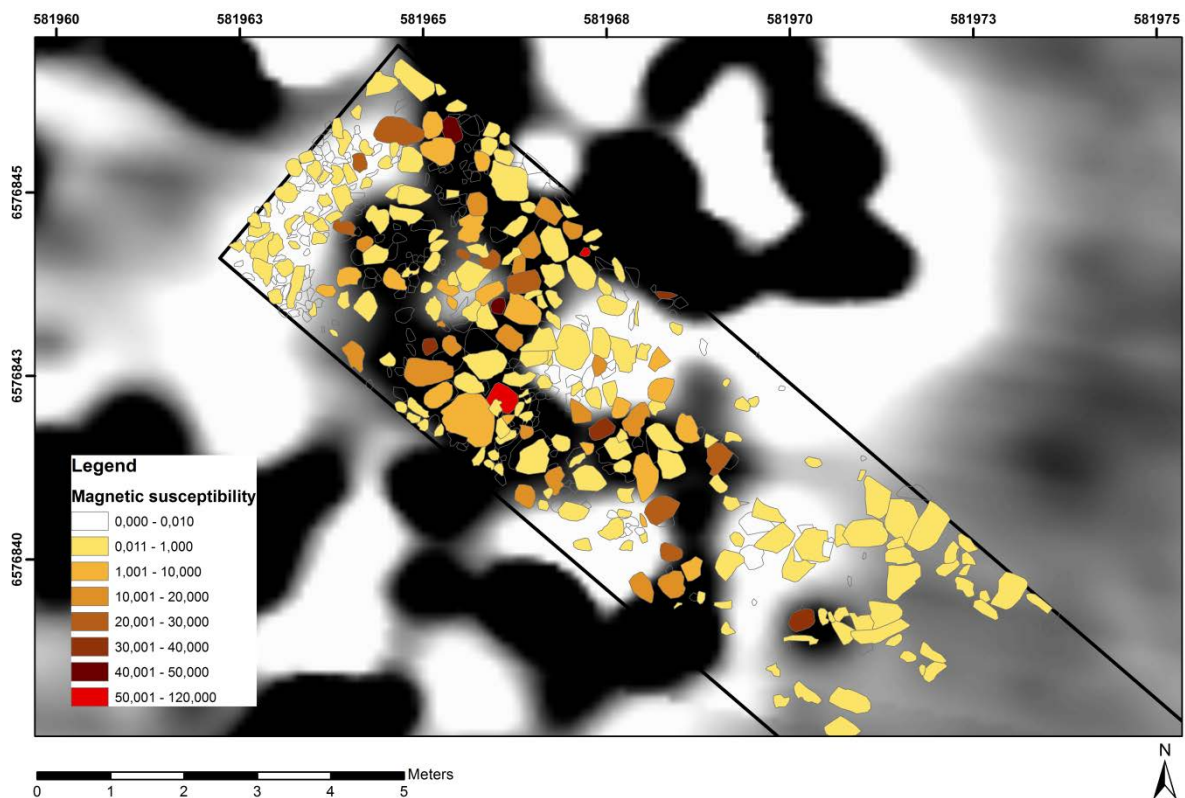


Fig. 7.11 MS of specimens measured at the top surface of SU[692], overlying large magnetic dipole anomalies

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 7.2). MS value classes between $0.014-10 \times 10^{-3}$, $10-20 \times 10^{-3}$ and $20-30 \times 10^{-3}$ SI units contained mainly granite, but also occasionally included metamorphic rock types namely quartzite, orthogneiss and diorite gneiss. MS values between $30-40 \times 10^{-3}$ SI units showed a more varied picture with granite, diorite/gabbro, orthogneiss and amphibolite. Only two samples revealed values between $40-50 \times 10^{-3}$ 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 (Olesen et al., 2007; Sørensen, 1988; Sørensen et al., 2007). Igneous rock originates from processes of melting and cooling, thereby undergoing thermo-remnant processes (Clark, 1990; David et al., 2008; Gaffney and Gater, 2003) and chemical (or crystallisation) remnant 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. Further investigations of the magnetic mineral composition of the boulders would be beneficial in order to obtain a more differentiated picture of the dipole anomaly sources. Such investigations would also be beneficial for GPR data interpretation, since – theoretically – ferrimagnetic minerals present >2 % could also affect the electromagnetic wave propagation (Cassidy, 2008b).

Concluding, visualisation and statistics demonstrate that the large dipole anomalies are created by individual fragments of igneous rock. These few strong anomalies mask the remaining more weakly magnetised stones. Without the possibility of a magnetic “migration”, these anomalies must be regarded as a schematic indicator for highly magnetic rocks, rather than an accurate visualisation of the buried stone packing.

Table 7.2 Macroscopical identification of magnetic rocks according to MS classes

Magnetic susceptibility classes ($\times 10^{-7}$ 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	Porphyry (1), Magmatic rock (1)	
>50	1	Mafic-ultramafic rock (1)	
	Total = 33		

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. 7.12a). However, during the excavation, these areas turned out to be zones simply void of stones (Fig. 7.12b). 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.

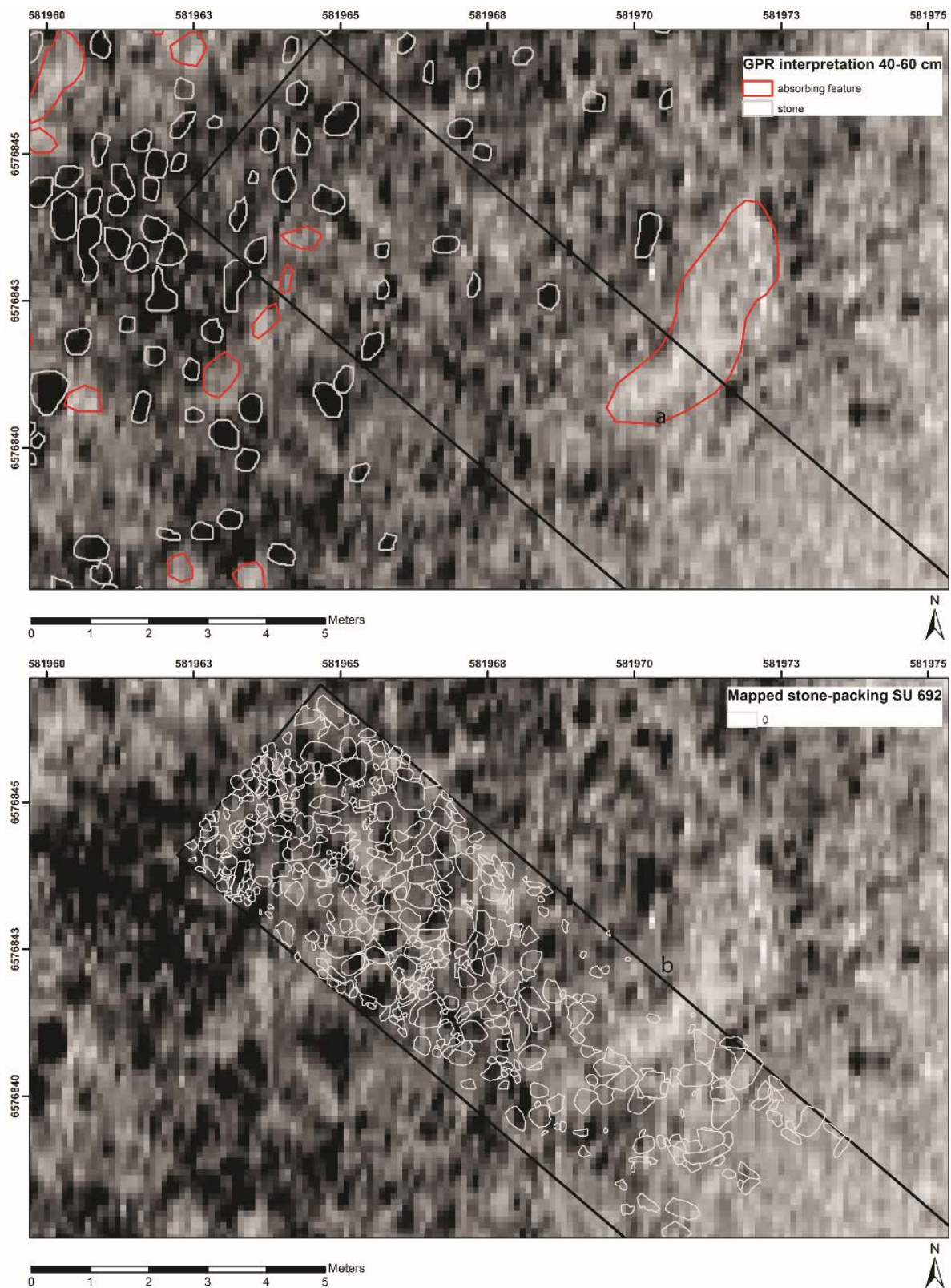


Fig. 7.12a GPR interpretation of depth slice 40-60 cm BGS with stones and absorbing features. 7.12b Mapped stone packing from SU[692] illustrates the limited congruence between actual stones and strong reflections. The “absorbing” features emerge as areas void of stones

7.5.3 Ditch

One of the most interesting finds from an evaluational perspective concerned the ring ditch surrounding the grave monument (Fig. 7.13a and 7.13b). Ditches typically possess enhanced magnetic values mainly due to backfill containing magnetically enriched topsoil, depending on the environmental settings (Dalan and Banerjee, 1998; Fassbinder, 1994; Le Borgne, 1960, 1955; Maher, 1986). 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. 7.14).

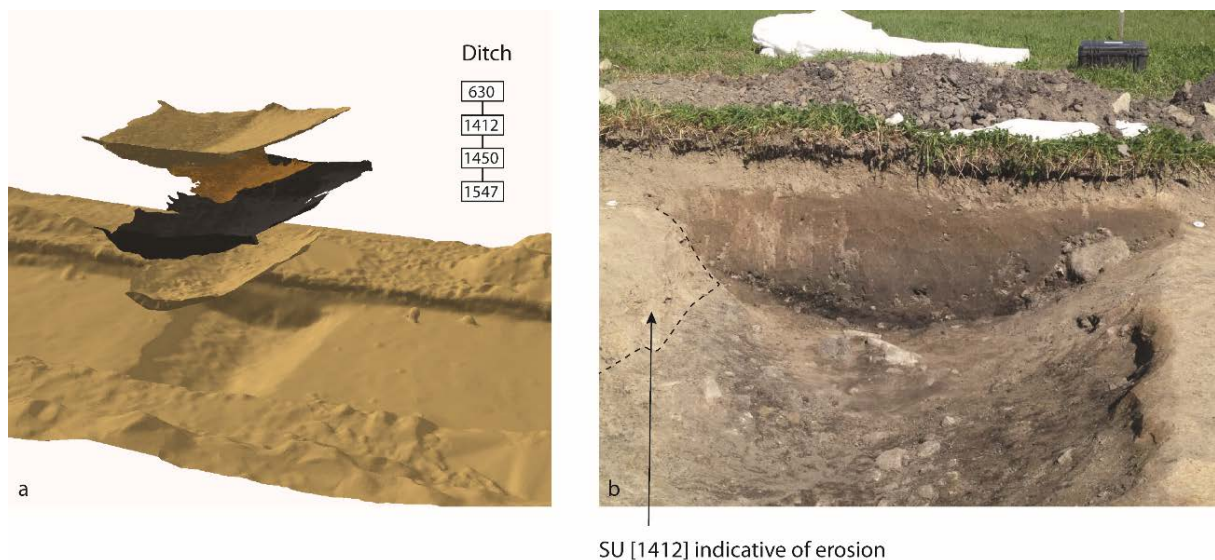


Fig. 7.13a 3D Explosion model of the ditch backfill surrounding the burial monument with associated stratigraphic sequence. 7.13b Top surface of SU[492] displaying the increase in clast inclusions and the presence of charcoal at its base. Northern ditch profile illustrates the stratification of the ditch fill

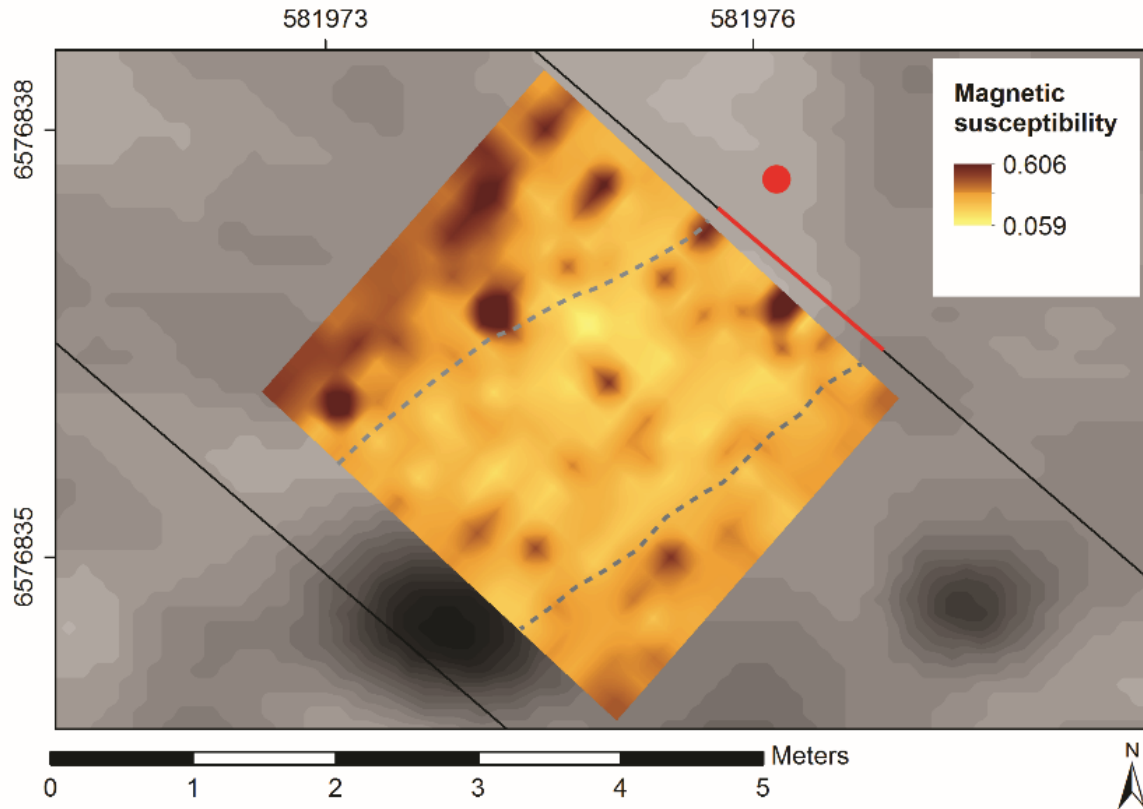


Fig. 7.14 Planar MS measurements on the top surface of SU[630] clearly illustrating low MS values compared to the north-western flank of the ditch. The south-eastern edge of the ditch appears more gradually expressed in the MS data

Our results support the findings from the magnetic data with very weak MS values around $0.1\text{--}0.2 \times 10^{-3}$ for the ditch backfill at the top surface of SU[630], and only slightly increased values between 0.2 and $0.4 \text{ SI} \times 10^{-3}$ for the surrounding material (Fig. 7.14). Maximum values cluster around $0.6 \text{ SI} \times 10^{-3}$, 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. 7.14). 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. 7.15) along this core.

Mass-specific low frequency MS values ranged between Xlf of ca. 10 and $70 \times 10^{-8} \text{ m}^3/\text{kg}$. The topsoil shows regular elevated values ($> 30 \times 10^{-8} \text{ m}^3/\text{kg}$), and decreases to around $10 \times 10^{-8} \text{ m}^3/\text{kg}$ between 30 and 70 cm BGS, which stratigraphically corresponds to layers 1 (SU[600]), 2 (SU[630]) and unit 3 (Table 3). 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. $40 \times 10^{-8} \text{ m}^3/\text{kg}$. 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 ($40\text{--}70 \times 10^{-8} \text{ m}^3/\text{kg}$) (Fig. 7.15). Layer 5 is believed to be of shallow marine origin and comprises sandy, clayey silt with orange mottling indicating exposure to varying moisture conditions.

Table 7.3 Sedimentological descriptions of the five layers observed in the core sample taken from the ditch (see also Fig 7.15)

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 heterogeneous
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

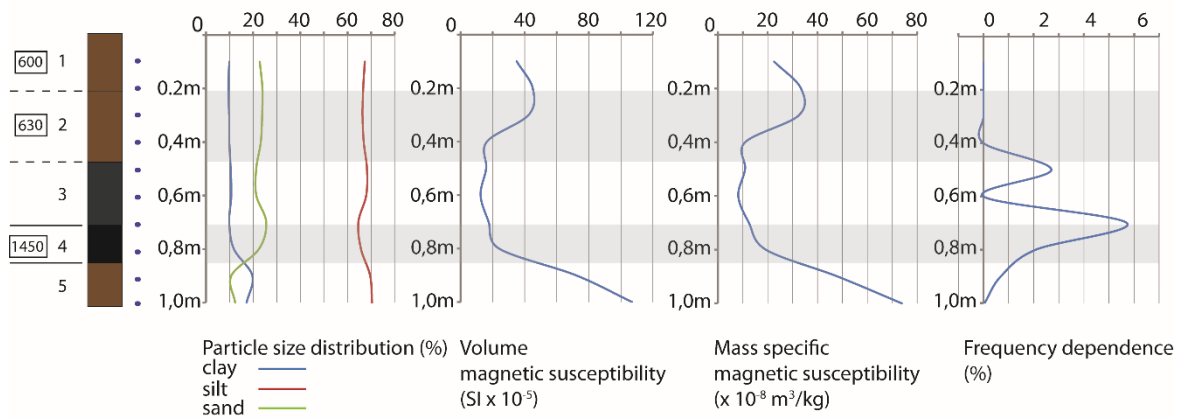


Fig. 7.15 Results from the laboratory-based analyses of undisturbed core sample material taken from ditch backfill

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. 7.16). This clear response is most probably attributable to the *in-situ* measurement of the actual composition of the layer, including 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 (Dearing, 1994; Maher, 1986). 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.

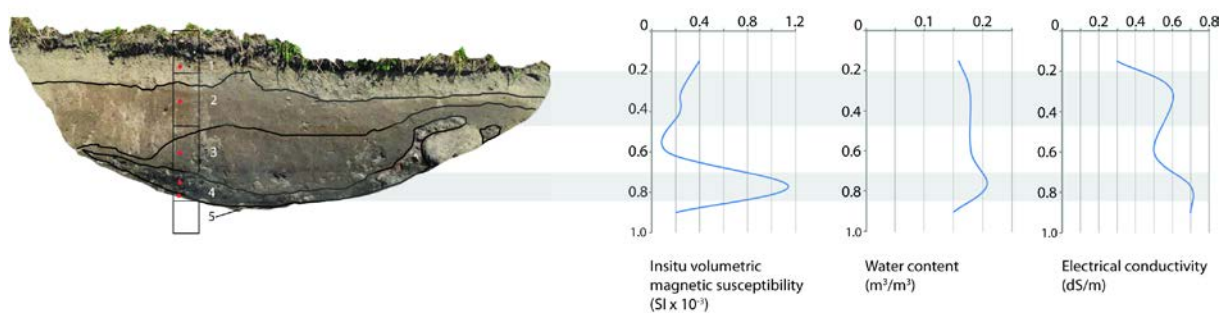


Fig. 7.16 Results from the *in-situ* measurements from the ditch backfill exposed during the excavation. Image shows the northern ditch profile

All results considered, the geoarchaeological evaluation could confirm the weakly developed magnetic properties of the ditch backfill in comparison to the surrounding soil material. 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 7.13b). 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 (Rinita A Dalan, 2006; Evans and Heller, 2003; Fassbinder, 2015; Maher, 1986). 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 mackinawite and greigite as well as ferrimagnetic pyrrhotite and pyrite (Kattenberg & 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 $0.02 \text{ m}^3/\text{m}^3$ in the area of SU[1450]. This increase is smaller than the precision range of the moisture sensor ($\pm 0.03 \text{ m}^3/\text{m}^3$) 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.

7.5.4 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. 7.17a and 7.17b).

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. 7.17a and 7.17b), 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.

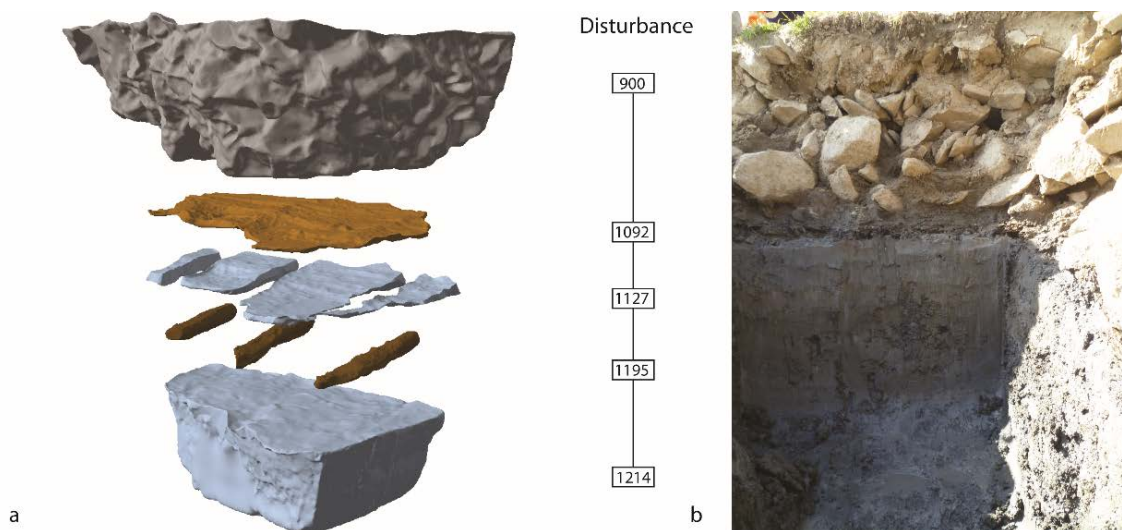


Fig. 7.17a 3D Explosion model of the modern disturbance cutting through the prehistoric burial monument with corresponding stratigraphic sequence. 7.17b Vertical section cutting through the disturbance caused by the modern potato cellar

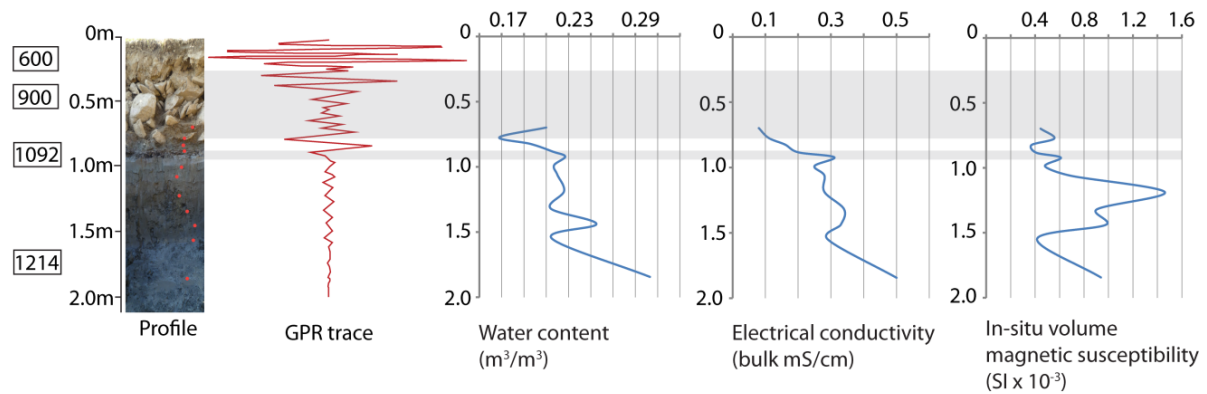


Fig. 7.18 Results from the *in-situ* measurements taken from the vertical section through the modern disturbance

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 (Lawrence B. 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. 7.18). 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. 7.18). 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 (Cassidy, 2008a; Doolittle and Butnor, 2009) (Fig 7.17). 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 both the 2012 and 2014 GPR surveys (see above) 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 7.15).

7.6 Conclusions and outlook

The geoarchaeological approach to evaluate GPR and magnetic data sets acquired at the Rom mound has permitted an assessment of the accuracy of the archaeological data interpretation. Quantitative data sets including volumetric water content/ dielectric permittivity, electrical conductivity and MS were collected during excavation on selected stratigraphic sequences and aided in correlating the geophysical signals with their stratification. This study demonstrated that the interpretation of archaeological geophysical prospection data is limited when it comes to the functional interpretation 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 further by the iterative implementation of geoarchaeological field evaluation. Geoarchaeological evaluation of archaeological geophysical prospection data give feedback on observations and assumptions made during interpretations on a regular basis, assumptions which

otherwise often cannot be verified and subsequently 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 implementing geoarchaeological evaluations also provides a step towards a more critical and testable use of archaeological geophysical prospection methods. Finally, 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 will enhance the quality of data interpretation in future surveys conducted in such challenging conditions as encountered in Norway and elsewhere.

Chapter VIII

Discussion and conclusions

8.1 Introduction

The final chapter VIII focuses on a critical assessment of the potential of palaeoenvironmental information for large scale, high resolution archaeological geophysical prospection data. It will start with conclusions drawn from the individual case studies, which were discussed at length in the respective chapters and sections. The second part highlights benefits and limitations of using palaeoenvironmental information contained in these data sets. The final section will provide an outlook to questions still unresolved and discuss future research avenues based on the conclusions of this thesis.

8.2 Conclusions drawn from the case studies

8.2.1 Targeted palaeoenvironmental analysis of geophysical prospection data

Chapter III comprised the first targeted analysis of palaeoenvironmental information contained in large scale, high resolution geophysical prospection data and thus was designed as a pilot study.

Results have demonstrated that abundant palaeoenvironmental information is contained in the archaeological geophysical prospection data sets and that it can be analysed and interpreted. Some of the structures and patterns identified can easily be linked to the archaeological interpretation, such as palaeochannels and former shorelines. In other cases, including palaeotopography and geology, the relevance for archaeology is more difficult to recognise and requires expertise in geophysical prospection, environmental settings of the study area as well as the local archaeology. To simply disregard non-archaeological information, however, would be misleading and eventually result in a selective and biased

form of data reduction. It is unquestioned, that palaeoenvironmental reconstruction requires a range of different methods and therefore the analysis of large-scale, high-resolution archaeological geophysical prospection data sets for palaeoenvironmental information cannot be used in isolation – it must always be regarded as part of a complementary approach. But, and this seems crucial, data are often readily available, even though initially intended to find and map archaeology. It therefore would be short-sighted not to use them. In this respect, archaeological geophysical prospection data provides the basis/primary data (Kvamme 2003) for field specific questions and further targeted research.

On a methodological level, the pilot study Gokstad has yielded valuable information regarding the overall approach as well as concerning specific requirements and limitations for analyses and visualisation of palaeoenvironmental features. First, palaeoenvironmental analysis of archaeological geophysical prospection data requires detailed knowledge about soils and sediment, geology, topography and geomorphological processes in the study area, in order to be able to identify the often complex source of previously unknown anomalies or reflectors. Secondly, since palaeoenvironmental features have not been investigated very intensively earlier, experience and data sets comparative in scale and resolution are sparse or non-existent, which complicates the identification process. Here, neighbouring disciplines such as sedimentology and geology can aid to some extent. Third, because of the above stated geoarchaeological evaluation of interpreted structures and patterns is absolutely necessary in order to initiate an iterative process that is aimed to deepen the understanding on how palaeoenvironmental information can be included in and derived from archaeological geophysical prospection data sets. For this purpose, a combination of large-scale, high-resolution surveys and targeted borehole information has proven most promising and efficient.

Magnetometry has played a minor, but complementary role in the Gokstad survey area, comparable to ALS data or soil maps. This might be site specific and based very much on the wet, iron-depleted soils and sediments in the fjärds of southern Norway (see below). However, magnetometry yields 2D data, which has to be considered when working with complex environmental systems. Finally, more work needs to be done on specific data processing suitable for palaeoenvironmental information, on an integrative three-

dimensional approach for data extraction and visualisation as well as the establishment of a data base for comparative purposes.

8.2.2 3D visualisation and integrative interpretation approach of GPR data

Based on the results of the pilot study at Gokstad (see also Chapter III), it became apparent that palaeoenvironmental information contained in large-scale, high-resolution geophysical data sets differs from archaeological information particularly in spatial and temporal scale. The complexity of these structures and patterns complicates any interpretation based solely on 2D data including amplitude maps and sections. This is why GPR plays a more vital role when it comes to identifying palaeoenvironmental information in archaeological geophysical prospection on an interpretative level – at the least in Norwegian settings.

Thus, chapter IV focused on the 3D visualisation of palaeoenvironmental structures and patterns contained in large scale, high resolution GPR data and here concentrated especially on volume rendering as well as on an integrative interpretation approach in a 3D GIS environment. The latter is important once more due to the complexity of this type of information, since data integration of palaeoenvironmental information in the form of isosurfaces with archaeological and additional palaeoenvironmental data sets is essential in comprehensively understanding and interpreting the archaeological landscape under investigation.

The first step encompassed the elaboration of a work flow for data extraction, 3D visualisation and subsequently data integration in a 3D GIS environment. The main challenges comprised conversion between different data formats and the search for a volume rendering software packages that could handle the large file sizes that arise from large scale, high resolution GPR data. Once this task was completed, data sets from Gokstad, Kaupang and Oseberg/Slagendalen were used to refine the workflow and test it using different parameters.

Results of these tests stressed the benefits of the approach, particularly regarding the role of visual analysis and data integration in the identification process of palaeoenvironmental information and how it relates to the archaeological structures potentially present in a data

set. It could also be shown that the best results for the interpretation of complex subsurfaces were achieved by using a combined 2D and 3D analysis approach.

However, tests also carved out some of the challenges and limitations this approach currently faces. Large file size and resolution as well as available memory respectively, issues with preserving georeference, missing compatibility between 3D visualisation software and GIS environments, and a lack of direct 3D editing options are the most restrictive factors. It is important to note, however, that all of these obstacles are of a technical nature and it is most likely that, as 3D visualisation and interpretation of GPR data will likely be increasingly used in the coming years, they will be overcome. Finally, future research avenues should focus on the implementation of this approach into regular analysis and interpretation routines of GPR data, in particular for palaeoenvironmental, but eventually also for archaeological information.

8.2.3 Geoarchaeological evaluation at *Heimdaljordet*

Large scale, high resolution GPR surveys conducted in the framework of the Gokstad revitalised project yielded traces of a Viking Age settlement as well as several burial mounds. Unexpectedly, these structures were barely visible in the magnetic data – a fact that aroused interest and prompted a closer investigation of the environmental settings at *Heimdaljordet*, conducted as geoarchaeological evaluation during an on-going excavation in the summer of 2012. Even though heavy rainfalls during three of the four days intended for fieldwork interfered with the planned investigation steps and also affected the overall research design of the evaluation, the investigation at *Heimdaljordet* yielded valuable insights into relevant physical and magnetic properties of soils and sediments.

Overall, *in-situ* and laboratory-based MS measurements yielded low MS values for both top- and subsoil as well as for archaeological features. These low values indicate the absence of large amounts of ferrimagnetic material most likely caused by chemical depletion and dissolution processes in the stagnic soil. As a result, magnetic contrast is low at *Heimdaljordet* as was evidenced by an *in-situ* MS survey across trench 1 after topsoil

removal, volume-specific *in-situ* MS measurements of top- and subsoil profiles as well as mass-specific MS analyses of core samples taken from archaeological features within trench 1. Naturally, this low contrast reduced detectability of the archaeological features in the magnetic prospection data.

Another factor adding to this trend is the magnetically variable topsoil covering the archaeological features. This is caused by the inclusion of magnetic fragments of bedrock as well as of errata transported by glacial processes, which creates a considerable amount of soil noise. The low visibility of the archaeological structures at *Heimdaljordet* was thus most likely caused by the combined effect of low magnetic contrast and considerable soil noise.

Even though evaluation techniques had to be cost-efficient and in addition had to be adjusted to the weather conditions and, results have contributed extensively to better understand the limited visibility in the magnetic data. However, in order to further pursue some of the questions emerged during this evaluation study, the analysis of additional physical parameters including elemental and mineral composition as well as more detailed laboratory analysis regarding different magnetic properties of soils and sediments would be desirable. This also includes future large-scale measurement of MS using susceptibility meters in combination with electromagnetic prospection devices which would form an important link in the data chain.

In conclusion, the geoarchaeological evaluation at *Heimdaljordet* has demonstrated the influence of environmental settings of a site to the analysis and interpretation of archaeological geophysical prospection data and once more supports the claim for complementary multi-method approaches in archaeological geophysical prospection. It has also highlighted the fact that for an encompassing qualitative assessment of a survey, basic knowledge of soil type and geology is often insufficient. Low visibility of archaeological features is caused by a range of interrelated palaeoenvironmental factors. In terms of magnetometry, this includes complex processes that contribute to either enhancement or depletion of ferrimagnetic materials in soils and sediments. As these processes are site-specific (Alekseev *et al.* 2002), the implementation of systematic geoarchaeological evaluation as necessary step in every survey approach would be required. This particularly applies in cases where geophysical surveys yield unusual results.

8.2.4 Testing an *in-situ* geoarchaeological evaluation approach

Geoarchaeological field evaluations will become increasingly important, as motorised, large scale archaeological geophysical prospection is more and more used for heritage management purposes. In order to further stimulate this development, geophysical data need to be reliable and testable. The study in *Sverstad* has demonstrated that geoarchaeological field evaluations can be conducted relatively time and cost-efficient, focusing on *in-situ* MS as an indicator primarily for the magnetic properties of soils and sediments, while water content/dielectric permittivity as well as electrical conductivity proved to be suitable parameters for correlation with and evaluation of GPR data.

This study, however, has revealed certain limitations to the respective techniques. MS measurements can be seriously distorted by standardised laboratory sample processing as this intervenes with the original composition of the subsurface as subjected to magnetic prospection. Under certain circumstance, *in-situ* MS measurements are therefore preferable to lab-based investigations. The measurement of water content as an important factor for the propagation of an electromagnetic signal has turned out to be more problematic. The accuracy of the FDR sensors without soil-specific calibration is limited and only very generally matched the thermo gravimetric water content measurements. The opportunity of measuring dielectric permittivity and electrical conductivity simultaneously with a single field sensor, however, presents a valuable ability. Future research avenues therefore should focus on further testing dielectric *in-situ* sensors with regard to their accuracy.

This study has also aided in defining the scope of geoarchaeological field evaluations. More sophisticated laboratory investigations particularly regarding the mineral magnetic composition and remanent magnetisation of a sample would be desirable as *in-situ* MS can only contribute basic information on this matter. The same applies to general and clay mineralogy as well as elemental composition of the subsurface materials. Yet, with respect to the ever larger prospection areas, geoarchaeological field evaluations require to be flexible and universally applicable in terms of conditions, time, effort and costs and therefore will have to deal with trade-offs in this direction.

Finally, geoarchaeological field evaluations should be systematically implemented in archaeological surveys. Although it is desirable to conduct an evaluation as close in time as

possible to the initial measurements, such investigations can also be conducted years after. Detailed knowledge about soils and sediments and their response to geophysical prospection techniques is essential in enhancing the quality of geophysical data interpretation.

8.2.5 Geoarchaeological evaluation at Rom

Based on the results of the case studies of *Heimdaljordet* and *Sverstad*, the excavation at Rom mound offered a further possibility to assess the accuracy of the archaeological data interpretation of GPR and magnetic data sets and to evaluate the geoarchaeological evaluation approach. A 3D single surface approach using a laser scanner for documentation yielded precise 3D models of the subsurface stratification and aided in the comparing the actual structure of the mound with the interpretation based on the geophysical data. Quantitative data sets including volumetric water content/ dielectric permittivity, electrical conductivity and MS were collected during excavation on selected stratigraphic sequences in order to correlate the geophysical signals with the subsurface stratification. Results demonstrated that the main elements of the site including stone packing of the mound as well as the disturbance were correctly identified in the interpretation of the geophysical data. When it comes to the functional interpretation of archaeological features such as recognise the disturbance as a storage facility, however, the case study evidenced certain limitations. Naturally, 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 – as shown here - further by the iterative implementation of geoarchaeological field evaluation.

Geoarchaeological evaluation of archaeological geophysical prospection data provides feedback on observations and assumptions made regularly during interpretations. Assumptions that otherwise cannot be verified and subsequently 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 its unusual magnetic behaviour. Conducting and implementing geoarchaeological evaluations also provides a step towards a more critical and repeatable use of archaeological geophysical

prospection methods. The study has also shown that geoarchaeological evaluations benefit from using data as vertical sections for correlation purposes but also for the detection of additional information as was the case with the palaeochannel beneath the burial mound. In geoarchaeology, sections are crucial for the investigation of formation processes and accessed mostly during excavations or coring surveys. The same applies to the use of geophysical techniques in the earth sciences and exploration, where sections enable the study of stratification and structure of for example dune systems.

Finally, 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 will enhance data interpretation both on a qualitative and interpretative level. This particularly applies to future surveys conducted in such challenging conditions as encountered in Norway and elsewhere.

8.3 Assessing characteristics and impact of palaeoenvironmental information on geophysical prospection surveys

The research project presented in this thesis has investigated the potential of palaeoenvironmental information for large scale, high resolution archaeological geophysical prospection. As the previous chapters have demonstrated, palaeoenvironmental information is present in various forms and types and it does influence geophysical data sets on different levels and in different ways. This includes distinct structures such as palaeochannel systems or ancient shorelines with direct relevance for the archaeological interpretation of a survey area (see chapter III), but it also encompasses more subtle relations such as physical and chemical processes in soils and sediments particularly referred to in chapters V-VII. It also has become evident, that the specific nature and complexities of palaeoenvironmental information must be thoroughly understood in order to be able fully exploit their potential. Such an endeavor requires expertise at the interface of geophysical prospection and geoarchaeology in order to assess the impact of palaeoenvironmental information on the outcome of a geophysical survey. Even though this research project has focused on large

scale, high resolution data sets, the observations made are to a large part also relevant for smaller-scaled surveys.

8.3.1 Environmental settings and geoarchaeological evaluation

As discussed in chapter II and supported by the case studies presented in this project, the influence of palaeoenvironmental information is noticeable in all areas of archaeological geophysical prospection. This impact, however, is nowhere more evident than on the qualitative level of a geophysical prospection – not least because ignoring this information can be of severe consequence for a survey outcome.

This has been demonstrated clearly by the case studies discussed in chapter V-VII, but was particularly highlighted by the limited visibility of archaeological features in the magnetic data of *Heimdaljordet*. Obviously, geophysical sensors cannot work miracles, but will only detect archaeological and palaeoenvironmental structures within the scope of their physical principles. If – based on the prevailing environmental settings, the chosen measurement device and the research questions asked – the investigated subsurface area does not show sufficient contrast for detection, resulting data sets will correctly display an area free of archaeology. In this respect, geophysical prospection is a precise method that will yield accurate results provided that techniques and devices were applied and operated correctly.

However, the question arises whether a geophysical study of high quality should be satisfied with this premise? Can archaeological prospection afford to settle for this correct and yet oversimplified result? Or do we as archaeologists and archaeological geophysicists have the responsibility to take a more detailed look at our data in order to raise the stakes for transparency and quality of geophysical survey results?

The limited visibility of archaeological structures at *Heimdaljordet* has demonstrated how environmental settings can interfere with – in this case – the use of magnetometry and how this influences the survey outcome. The geoarchaeological evaluation at *Heimdaljordet* highlighted how important a thorough understanding of these settings is for survey quality

and reliability of geophysical data as well as for interpretation accuracy. One could argue that the settlement and burial ground of *Heimdaljordet* was discovered by the use of complementary GPR surveys and thus would not have gone undetected by this approach. Yet too often, not all parts of a survey area can be prospected using more than one method due to time, access or budget issues. And too often, the resulting data sets are not critically scrutinized but erroneously understood as an accurate depiction of the archaeological remains present in the subsurface – regardless of the prevailing environmental settings.

Archaeological geophysical surveys must yield accurate data interpretations in order to maintain its reputation otherwise its acceptance as research tool will diminish. This certainly is true for the research community, but it applies even more to the use of geophysical prospection in heritage management where local to regional development planning depends on areas being cleared by heritage agencies before construction works can begin. Failing or even seemingly failing results are jeopardizing the entire field of geophysical prospection. Such a development and its far-reaching consequences could and still can be seen in Norway today (Gustavsen and Stamnes, 2014; Stamnes, 2016).

This is why a critical and encompassing interpretation of the acquired geophysical data sets is important. The term “critical” in this respect is used to contrast a “simple” mapping of visible archaeological structures in the data sets. It means to comprehensively investigate and understand a survey area, its environmental settings and their interrelations as well as any consequences for visibility/contrast (in particular a healthy interest in areas free of any archaeological structures and the reasons behind) and not least the consideration of how the archaeological landscape developed.

This includes desk-based assessments prior to surveys, as well as minimal-invasive coring surveys for more detailed investigations and identification of subsurface materials up to complete geoarchaeological field evaluations during and after the data interpretation (see also section 8.4 Future Research Avenues below).

The geoarchaeological evaluation at *Heimdaljordet* has demonstrated that with relatively simple time- and cost efficient measures, a first hypothesis for the reasons of the limited visibility in the magnetic data sets could be proposed – with significant impact on survey areas in the frame of the Vestfold Project showing similar environmental settings. Yet, it also

highlighted that for effectively correlating physical and electromagnetic properties of the subsurface materials with the geophysical records, a specific approach is required. This is mainly connected to the issue of evaluating non-invasive prospection methods with invasive evaluation techniques. Retrieving sample material will always interfere with the initial structure and composition of the investigated subsurface materials and consequently make an evaluation more difficult since the preconditions are not the same as during the survey. Certain geophysical techniques including the active, three-dimensional method of GPR are more prone to this issue, while the passive method of magnetometry, which is mainly dependent on the formation and preservation of ferrimagnetic minerals, is more robust in that respect.

Although this underlying problem cannot be evaded, its consequences can be limited by using *in-situ* measurement devices wherever possible. Such an approach has several advantages. First, the original composition and structure of the material under investigation can largely be preserved. Secondly, any standard processes in the laboratory (actually designed to generate comparable and reproducible results) that might further increase selectiveness in the material being measured (Dearing, 1994), are avoided. This is important, as a geoarchaeological evaluation tries to quantify actual contrast between subsurface and target materials rather than producing standardized comparable values of different materials. The importance of this differentiation was clearly demonstrated by the results of the geoarchaeological evaluation at *Sverstad*. Here, deviations between *in-situ* and laboratory-based results of MS measurements stressed the significance of the original sample composition for its correlation with the geophysical data. The selective sample processing in the laboratory, which excludes small fragments of magnetic bedrock by default, ultimately resulted in an unrepresentative sample composition for the evaluation.

Another issue regarding geoarchaeological evaluations is the trend towards ever larger survey areas covering tens of hectares up to square kilometers while displaying varying environmental settings. Therefore, any geoarchaeological evaluation needs to be time and cost-efficient; otherwise it simply won't be applicable to these large scale surveys.

While the evaluation of magnetic surveys has a longer tradition and with MS a diagnostic element that owns these required characteristics (Fassbinder, 2015), the evaluation of GPR surveys is more problematic in this respect. Water content as the most indicative property

for the propagation of electromagnetic waves in earth material is not as easily measured *in-situ*. The measurement principles are complex and without soil specific calibration accuracy is limited. As a consequence, no standardized geoarchaeological field evaluation approach for GPR is available yet. In this respect, the *Sverstad* study has brought significant, if preliminary suggestions for a geoarchaeological evaluation approach based on *in-situ* measurements of MS, dielectric permittivity/water content and electrical conductivity. Apart from these methodological findings, the evaluation at *Sverstad* yielded new insights into the natural background signal of the subsurface materials common in Vestfold County, and these observations are significant for the entire Vestfold Project.

Testing the accuracy of the interpretation of a geophysical prospection data set based on the individual environmental settings of a survey area presented a further step towards enhancing reliability and transparency of geophysical surveys data. The excavation of Rom mound in the Slagendalen provided an ideal testing ground for a geoarchaeological evaluation with precisely that aim. This study enabled further testing of the *in-situ* geoarchaeological evaluation approach, and allowed to investigate in detail phenomena observed during the interpretation such as a negatively magnetic ditch surrounding the mound. Results confirmed that the incorporation of palaeoenvironmental information into the interpretation of the geophysical data can enhanced its detailedness: the possible presence of magnetic bedrock allowed the identification of the burial mound structure as built of a dense stone packaging and also aided in recognizing the stratigraphically younger disturbance. The evaluation at Rom, however, also highlighted the limitations of *in-situ* approaches regarding detailed information about the magnetic mineral composition of soils and sediments; answering such questions would require more sophisticated laboratory-based methods (Dalan and Banerjee, 1998).

8.3.2 Palaeoenvironmental structures and patterns

Palaeoenvironmental structures and patterns are frequently present in large scale, high resolution geophysical prospection data sets, thereby representing a different, yet equally

important aspect of this information type. The pilot study Gokstad (chapter III) has successfully demonstrated that palaeoenvironmental information can be identified, interpreted, mapped and visualised in a targeted analysis. The combination of palaeoenvironmental structures and patterns with archaeological features within an integrated interpretation has enriched the picture of the Viking Age landscape around Gokstad, and even allowed insights into the landscape development since the land surfaced after the height of the last glaciation. This approach also provided a base map for palaeoenvironmental information that can be used in a similar way to traditional archaeological interpretation maps for intrusive investigation such as archaeological excavations and geoarchaeological studies. For example, the detailed mapping of the course of the palaeochannel systems I-III in the Gokstad landscape generated a centimeter-accurate map suitable for the planning of coring surveys in order to retrieve sample material for the study of micro and macro fossils. This capacity is not just relevant for archaeological studies, but might also be of interest for neighbouring disciplines such as physical geography, palaeoclimatology and palaeobotany (Chapman et al. 2009, Dalan & Bevan 2002). Here, planar and large scale geophysical data could provide a high resolution planning basis for further and more targeted investigation methods such as coring programs.

Another argument for the use of palaeoenvironmental information within the interpretation process is the new perspectives it offers on how archaeological landscapes can be perceived. Palaeotopography, palaeochannel systems, but also ancient shorelines all represented significant elements in the structural layout of past landscapes. They also most likely played a decisive role on how people have perceived their surroundings and how they exploited its resources (See chapter III). At Gokstad, several hypotheses emerged from the palaeoenvironmental analysis including the identification of areas potentially being used as burial grounds, as well as indications for the location of agricultural fields and pastures. The consideration of palaeoenvironmental information might even shed light on human-environment interactions by giving details on human-induced palaeoenvironmental change such as erosion caused by deforestation or industrial activities such as mining and quarrying.

A limitation that has to be highlighted, however, presents the lack of a chronological control. As already discussed in length in the discussion of chapter III, the chronological component is often difficult to achieve for palaeoenvironmental information – much more so than for

archaeological information. The pilot study Gokstad has demonstrated that if stratigraphic sequences of a landscape can be established, they can provide a relative chronological frame that enables a certain temporal control.

Finally, it is important to notice that for such an approach to come into effect, the availability of large scale, high resolution data sets are essential. The identification of palaeo-topographical information or the mapping of a palaeochannel system requires a certain survey scale. An additional matter is the appointment of experts trained in the fields of geophysical prospection and geoarchaeology. An encompassing palaeoenvironmental analysis implies more than quickly mapping the course of a palaeochannel.

In conclusion, the palaeoenvironmental analysis of large scale, high resolution geophysical data has demonstrated a profound impact on the interpretation of archaeological landscapes. Clearly, however, such an approach must be regarded as a first step towards a complete palaeoenvironmental reconstruction – something for which a more comprehensive approach is necessary.

8.3.3 The situation in Vestfold

The case studies presented in this research project are all geographically located in the south of Norway, in the County of Vestfold. As mentioned before, every survey site possesses a unique collection of environmental settings. These settings can differ substantially even from close-by neighboring areas and consequently, all sites have to be examined individually. There are, however, a number of general observations regarding palaeoenvironmental information that can be projected onto the entire area of Vestfold County and possibly even further.

The use of magnetometry in Vestfold County remains challenging and particularly at *Heimdalsjordet* has brought unsatisfying results. Reasons for this phenomenon are based on a combination of different palaeoenvironmental factors including stagnic soils, the presence of shallow buried magnetic bedrock and consequently soil noise, which leads in many cases to

poor visibility of archaeological and palaeoenvironmental structures. The presence of magnetic boulders, in contrast, was clearly identifiable in the magnetic data sets and allowed a more detailed interpretation of the materials involved in structures such as burial mounds. Due to the overall challenging conditions for magnetic surveys, GPR has been promoted to the geophysical method primarily used in Vestfold. GPR surveys yielded good results, although the presence of fine-grained, moist marine sediments in certain cases caused limit penetration depth. Fortunately, due to the geomorphological history of Norway, most of the archaeological features are buried within the first 1.50m BGS and thus penetration depth seems to be overall sufficient. For Vestfold, however, this means that the prevailing environmental settings demand for a complementary approach, which at the moment is provided by the use of large scale, high resolution GPR and magnetometry surveys.

As all of Norway, Vestfold displays a rich palaeoenvironmental history with traces of a diverse and dynamic landscape development. This is evident by the current geomorphology and certainly also reflected in the amount of palaeoenvironmental information available in the geophysical data sets acquired during the Vestfold project. Yet this abundance is also a clear signal towards the importance of implementing systematic analyses of palaeoenvironmental information in large scale, high resolution archaeological geophysical prospection.

As a direct result of the research project presented here, the Borre Monitoring Project was initiated in June 2016 by the Vestfold fylkeskommune and the LBI ArchPro. The project investigates the influence of environmental settings in combination with the effects of seasonality onto GPR surveys. The aim is to establish the best survey conditions for GPR surveys with regard to the prevailing environmental settings. Two test areas at the royal burial site of Borre in Vestfold County containing two hall buildings from the Viking Age will be surveyed regularly with a 500 MHz single channel GPR during a time span of 14 month. In order to tie the geophysical data to the ground settings, *in-situ* measurements of water content, electrical conductivity and soil temperature are recorded in real-time at three locations inside the test areas. Additionally, physical properties of soils and sediments including elemental and mineral composition as well as grain size distribution present will be analyzed in the laboratory. A local weather station measures precipitation rates and solar radiation. This monitoring approach was developed based on the results experience

gathered at the case studies *Sverstad* and Rom. The results will lead to a better understanding of the propagation and reflection patterns of the electromagnetic wave and subsequently contribute to enhancing the interpretation quality and accuracy of GPR surveys in similar conditions.

8.4 Future research avenues

Implementing the analysis of palaeoenvironmental information into the interpretation routines is not just beneficial for its outcome, it is a necessity. There is, however, further work required. The last section of this thesis therefore will discuss future research avenues and ways to implement palaeoenvironmental information into the geophysical prospection routines.

8.4.1 Palaeoenvironmental analysis of geophysical data

The pilot study Gokstad in chapter III has demonstrated the benefits of a targeted palaeoenvironmental analysis of large scale, high resolution geophysical data sets. It is unquestioned that such an approach needs to become a regular stage in any interpretation process. Yet, as mentioned before, the mapping and consideration of palaeoenvironmental structures and patterns has not been the focus of most archaeological geophysical prospection surveys. Consequently, comparative examples for palaeoenvironmental features are scarce, which complicates the identification process for interpreters not trained in geoarchaeology or relevant fields of the earth sciences. Additionally, the structures and patterns present in a specific data set depend on the environmental settings prevailing in the study area and thus will differ from site to site.

Therefore, it would be of importance to establish a comparative reference collection in order to facilitate the identification and interpretation of palaeoenvironmental structures and patterns. An online image data base including detailed explanations for the source of an

anomaly or feature could provide an easily accessible reference collection and eventually lead to an increased use of this type of information in the future.

Another focus should lie on the use of further complementary methods such as EMI and electric resistivity, which have repeatedly demonstrated their potential for palaeoenvironmental information in archaeological geophysical prospection (De Smedt et al., 2011).

8.4.2 Role of geoarchaeology in geophysical prospection

As mentioned above, understanding the environmental settings of a study area is essential in assessing the quality of geophysical survey data. The success of a geophysical prospection is dependent on the physical properties of soils and sediments, yet a systematic consideration of these properties within the survey routine is still missing. The question thus arises how various environmental aspects and their interactions can be factored into the planning process and execution of a geophysical survey as well as in the interpretation of the resulting data sets.

Based on the results of this thesis, geoarchaeological elements should systematically be implemented into the survey routines as follows:

A first step prior to the actual data acquisition encompasses a desk-based assessment of all available information on the prevailing environmental settings including geology, pedology, hydrology, climate, geomorphology, vegetation cover and topography (Fig. 8.1). This information leads to recommendations for the survey design but at the same time could already identify areas that require special attention during the interpretation process.

During data acquisition, survey conditions including current vegetation cover, ground conditions and weather conditions are closely monitored and recorded. Additionally, targeted, minimal invasive coring gathers data about the physical properties of the subsurface materials – ideally during a first screening of the results while still present at the survey area. Sampling locations are selected based on areas of interest identified at the

planning stage, preliminary survey results as well as on observations made on-site. Data processing is adjusted to archaeological, environmental as well as geological parameters in accordance to the pending research questions. Data visualisation and integration is carried out in 2D and 3D with a particular emphasis on integrating all available data in a GIS environment, which forms the basis of an iterative interpretation cycle. The interpretation stage requires archaeological, geophysical as well as environmental expertise and includes the combined interpretation of archaeological as well as palaeoenvironmental structures and patterns which eventually leads to the complete interpretation of the archaeological landscape under investigation. Optionally, a geoarchaeological evaluation of the interpretation as part of an excavation would play an essential part in enhancing the quality of the geophysical data interpretation.

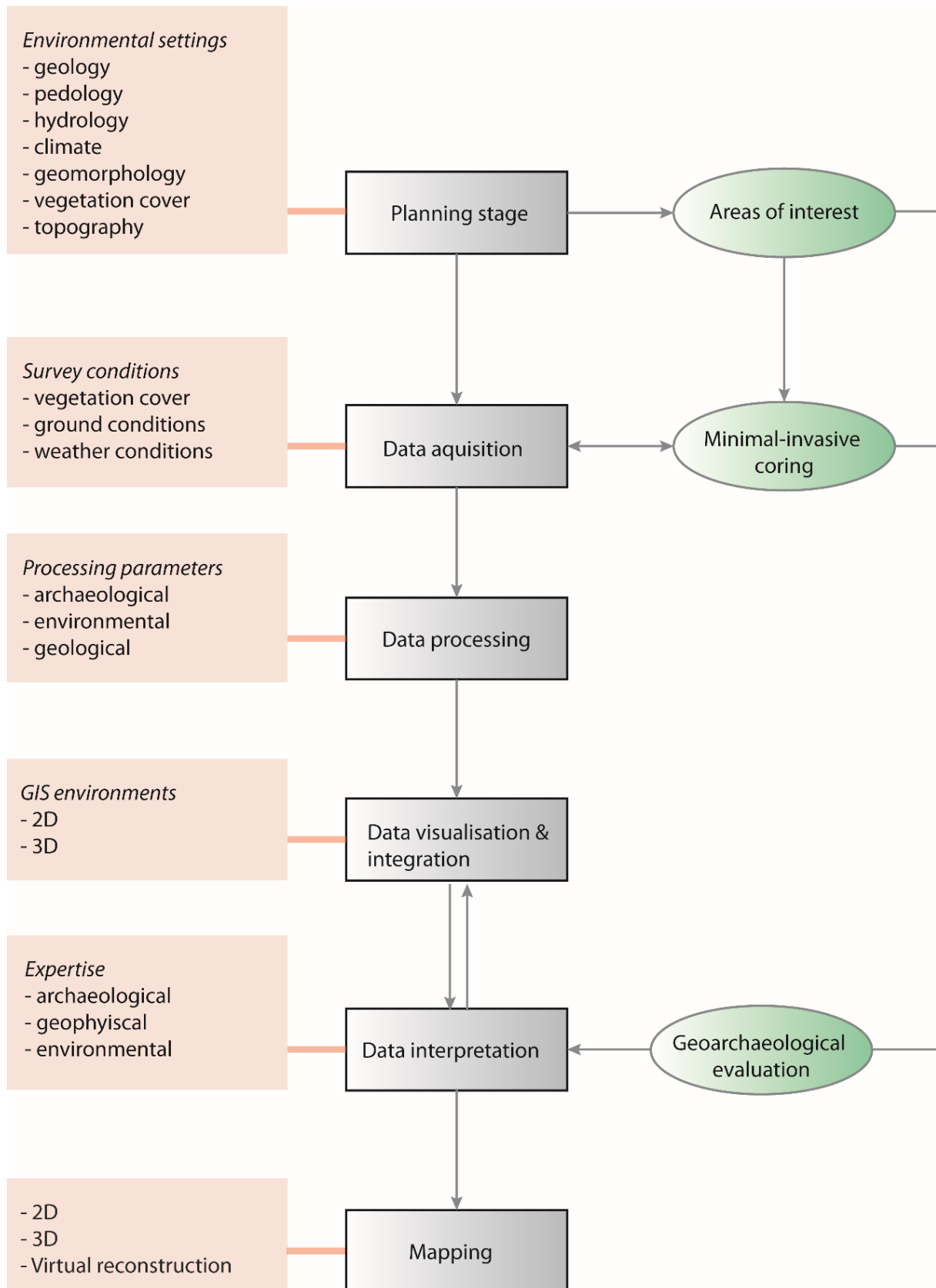


Fig. 8.1 Flow diagram of the systematic implementation of environmental aspects into the archaeological geophysical prospection routine

The systematic incorporation of environmental considerations into geophysical prospection routines is of particular importance when part of a long-term heritage management strategy. Here, geoarchaeological evaluations of frequently observed archaeological and palaeoenvironmental structures could greatly enhance the quality and required reliability of geophysical surveys. This approach also includes detailed investigations of physical and in particular electromagnetic properties of the natural background materials and their potential for contrasting archaeological deposits in different areas with similar environmental settings.

8.4.3 Methodological aspects

Methodologically, the approach of *in-situ* geoarchaeological field evaluations needs further tests particularly in terms of representativeness and significance, precision and accuracy. The latter concerns especially the *in-situ* measurement of water content, respectively dielectric permittivity as diagnostic element for the propagation of electromagnetic waves. The use of a cost-efficient tool that does not exceed maximum dimensions and provides the required precision and accuracy without requiring soil-specific calibration would be of key importance. Additionally, it has become evident that more detailed knowledge about elemental and mineral composition as well as magnetic mineral composition of the subsurface materials would enable a deductive approach in determining the necessary minimum of diagnostic elements for a significant geoarchaeological evaluation. This also applies to a rise of evaluations in purely quantitative terms that allows targeting different survey areas displaying different environmental settings.

Another point requiring revision is the question how meaningful an *in-situ* approach is compared to laboratory-based methods. In this respect, Vestfold may present specific conditions regarding the presence of magnetic bedrock that might or might not be as relevant in other environmental settings.

The extraction, visualisation and integration of palaeoenvironmental structure and patterns in 3D leave much room for improvement. Of particular importance is the integration of

volumetric GPR visualizations into a 3D GIS environment. Such a visualisation on a regular basis would greatly facilitate the interpretation of palaeoenvironmental information and enable an assessment of their connection with and relevance for any potential archaeological features. Presumably, as computational power progresses and the demand for virtual archaeology increases, geophysical prospection data will be analyzed and interpreted more and more in 3D GIS environments, eventually leading to a dynamic 4D output of archaeological landscape development. In order to achieve this, established and newly emerging 3D GIS environments have to be tested for compatibility with the requirements of 3D visualisation of geophysical data. This concerns file formats and file sizes, but in particular will have to target new ways of visualisation modes, algorithms as well as statistical approaches to highlight specific parts within geophysical data set.

Another research avenue that would certainly be beneficial for the use of palaeoenvironmental information is the focus on processing routines. For example, the interpretation of GPR data is usually based on the analysis of reflection strength and signal travel time. Changes in amplitude and frequency of the returning radar signal, however, could deliver more information about the composition of subsurface materials regarding soil humidity, porosity and clay content (Böniger and Tronicke, 2010; Zhao et al., 2015). Further, a more detailed investigation of the magnetic amplitude signatures might provide means to better differentiate between buried magnetic boulders and archaeological pits – a frequent issue in magnetic data sets from Vestfold.

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