The late Nordic Iron Age and Viking Age royal burial site of Borre in Norway: ALS- and GPR-based landscape reconstruction and harbour location at an uplifting coastal area

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ABSTRACT

The Nordic Iron Age and Viking Age royal burial site of Borre on the western coast of the Oslofjord in Norway is an exceptional archaeological site in Northern Europe. The burial mounds, associated archaeological structures as well as geomorphological features have been analysed by a 1 x 1 m digital terrain model derived from airborne laser scanning. The interpretation of this data used different derivatives of the digital elevation model including hillshade, slope map, local relief model and their combination. Additionally, ground penetrating radar profiles have been measured to investigate the internal structure of selected micro-topographic features. Based on the high-resolution topographic data, four smaller burial mounds were added to those previously known. Scandinavia is strongly affected by ongoing post-glacial isostatic recovery and, consequently, a sequence of elevated beach ridges were documented within the burial site down to the present shoreline. Local sea-level reconstructions in the Oslofjord indicate that the burial site of Borre was located close to the shoreline in the period of its use when the local sea-level was 3.5-5 m higher than today. Two prominent ridges between 4.5 and 0 m above present day sea-level are interpreted as Viking Age jetties facilitating safe landing on an otherwise unprotected coast.

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1. Introduction

Airborne laser scanning (ALS) has found widespread application in archaeological research (Crutchley and Crow, 2010), providing high-resolution digital terrain models (DTM) with a ground sampling distance of typically 0.5-0.1 m and a vertical accuracy which is usually better than 0.1 m. In open areas, these DTMs are of high value as they display the detailed topography (Challis, 2006). ALS-based DTMs are, therefore, of great importance in detecting and documenting archaeological and palaeoenvironmental features in vegetated areas (Doneus and Briese, 2011; Doneus et al., 2013).

Here, sophisticated visualisation techniques (Hesse, 2010; Kokalj et al., 2011; Doneus, 2013) of the microtopography provide a new understanding of the layout and function of archaeological remains, which are commonly better preserved there compared to areas with less vegetation, where archaeological remains are exposed to erosion and/or ploughing.

Any archaeological interpretation of prospection data has to include mapping in 3D, describing and explaining both the relevant archaeological structures and (palaeo-) environmental features. Reading and extracting archaeological information from prospection data, therefore, require an understanding of the dynamic interaction between humans and environment. This is especially important when working with ALS-derived data, as Earth's topography is a combination of manmade structures and geomorphological processes including erosion, sedimentation and tectonics (Crutchley and Crow, 2010). Consequently, the interpretation of
these high-resolution DTMs clearly demand an integration of archaeological and geoarchaeological interpretation.

This is especially true for Scandinavia where remains of the last glaciation, such as drumlins, moraines, periglacial processes, but also the isostatic rebound of the Scandinavian crust, shape the landscape. These features are also omnipresent in excavation and prospection data and therefore have a pronounced impact on the archaeological interpretation. This will be demonstrated using the prehistoric site of Borre as a case-study. The investigated site is situated on the western shore of the Oslofjord (Fig. 1) and is well-known for its outstanding Iron Age royal burial mounds (Brøgger, 1916; Roedth, 1991; Myhre, 1992a, 2003a, 2003b; Myhre and Levanger, 2013) (Fig. 2). Borre is mentioned in the Old Norse literature (Krag, 1991) and the myths connected to the place were already established before the archaeologist Nicolaysen excavated a Viking ship in one of the large burial mounds in 1852 (Nicolaysen, 1854). Despite huge interest for the monumental mounds, there have been relatively few archaeological investigations in the 20th century. Later, questions concerning possibly related settlement and harbour have been raised and after 2007 geophysical prospection and airborne laser scanning have produced data that might change the understanding of the Borre site. This article is the first step to address these questions and to show the applicability and benefit of integrated remote sensing, geophysical and geoarchaeological investigations for archaeological interpretations.

2. The late Nordic Iron Age to Viking Age royal burial site of Borre

Borre is an exceptional burial site in Scandinavia, located on the western shore of the outer Oslofjord, close to a narrow part between the towns of Horten and Moss, where the fjord is some 5 km wide. The site is situated close to rich agricultural lowlands, and the small island of Bastøy is 2 km distance from the shore of Borre (Fig. 1). At present some of the larger mounds measure more than 40 m in diameter and up to 7.5 m in height (Fig. 2). Archaeological findings and radiocarbon dating indicate that the site was in use between 600 and 1000 AD (Myhre, 1992a; Gansum, 2009; Myhre

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Fig. 1. Location of Borre National Park in the Oslofjord drawn on a 20 × 20 m digital terrain model of the Norwegian Mapping Authority (http://norgeskart.no) in the Universal Transverse Mercator (UTM) coordinate system. Bastøy Island is 2 km off the coast of Borre. Blue lines indicate isolines of the present day crustal uplift related to post-glacial rebound in mm yr⁻¹ after Dehls et al. (2000). Sites where shoreline displacement reconstructions have been carried out, shown in Fig. 4, are indicated. The Ra Moraine of the Younger Dryas (c. 12.8–11.5 kyr BP) which provided the boulders for archaeological constructions at Mølen and probably also at Borre is indicated in orange after the online geological map of the Geological Survey of Norway (http://geo.ngu.no/kart/losmasse). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Borre is mentioned already in Norse Sagas, especially in the skaldic poem Ynglingatal, as the burial place of one or two kings of the Ynglinga dynasty (Krag, 1991; Myhre, 1992b). The written sources and the myths connecting Borre to the Ynglinga lineage provide an important frame for the archaeological interpretation (Østigård and Gansum, 2009).

One of the large mounds (mound 1) was destroyed by the Norwegian Public Roads Administration in 1851–1852, and during a subsequent rescue excavation was carried out by Sverre Marstrander at the Spellemannshaugen (mound 9), leaving some photographs but no report. Between 1988 and 1992, Bjørn Myhre conducted a large archaeological research project at Borre (Myhre, 1992b, 1994, 2003a,b, 2006; Myhre and Levanger, 2013). He documented seven large burial mounds, two large cairns, three chamber graves and more than 30 smaller mounds at Borre, while at least two large mounds and one large cairn have been destroyed after 1852.

The main target for the Borre project (1988–1992) was to understand the landscape context of the mounds and to search for related settlements as well as a harbour (Myhre, 1992b; Jerpåsen, 1993, 1996). Building remains were found but these appeared to be small (Myhre, 1992a). The search for a harbour at Borre ended with negative results (Keller, 1993, 1994). Geophysical surveys carried out in 2007 revealed the presence of large hall buildings in the vicinity of the mounds (Trinks et al., 2007; Gansum, 2008, 2009), but the question of a possible harbour remained unanswered.

The present study is especially concerned with the documentation of archaeological features, landscape reconstruction and the location of the former harbour of Borre. Additionally to agriculture, Viking society was strongly bound to the sea, including fishing, maritime trade, military actions as well as piracy (Hedeager, 1988, 1990; Carver, 1995; Crumlin-Pedersen, 1995; Warmind, 1995; Gansum, 1997; Hedeager and Tvarno, 2001; Solberg, 2003; Skre, 2007; Bill, 2010; Hedeager, 2011). Consequently, for these activities the need for safe landing possibilities and the protection against wind as well as waves were an important concern (Rolfsen, 1974; Myhre, 1997; Ulriksen, 1998; Wamers, 2002; Westerdahl, 2002; Stylegar, 2006; Eliassen, 2009; Falck et al., 2013). It is anticipated that a royal burial site situated next to the shore, with large hall buildings and burial mounds that contained at least one ship burial should have had a harbour. So far, however, no traces have been found with traditional archaeological surveys, and therefore its existence and location is still a matter of debate.

Due to the position of Borre in the Oslofjord, the interpretation of this site is closely connected to an assessment of the local sea-level variation, which in this area is the result of two competing processes — global sea-level rise and post-glacial rebound of the Scandinavian crust (Dehls et al., 2000; Ekman, 2009; Lambeck et al., 2010a,b; Simpson et al., 2012; Doneus et al., 2013). All available data have been integrated in a GIS project, and it is argued that using the high-resolution topographical data from ALS, manmade structures as well as geomorphological processes can be visualised and therefore enhance the archaeological understanding of this important site. Based on the geoarchaeological integration of high-resolution ALS topography, ground penetrating radar (GPR) and regional ALS data, the interaction between the burial site, landscape and sea-level change as well as the potential location of the Viking Age harbour are investigated.
3. Post-glacial shoreline displacement in southern Scandinavia

Shoreline displacement in Scandinavia results from the combination of two processes: global sea-level change (ChapPELL and Shackleton, 1986; Church et al., 2008) and post-glacial rebound due to unloading from the former Scandinavian ice shield (e.g. Pässe, 2001; Lambeck et al., 2010a). Empirical models combine both processes into a shoreline displacement curve (Pässe, 2001; Persson, 2008, 2011, Fig. 40; Persson, 2012, Fig. 71).

3.1. Latest Pleistocene and Holocene global sea-level rise

Global (or eustatic) sea-level changes are worldwide variations caused by changes in the volume of ocean water — mainly related to the amount of ice on the continents, sea water temperature as well as salinity — and volume changes of ocean basins connected to plate tectonic processes (Pugh, 2004). The global sea-level is usually measured relative to a reference ellipsoid or the Earth’s centre of gravity (Ekman, 2009). This is not trivial, because the geoid, the equipotential surface of Earth’s gravity field, does not form a perfectly regular shape of the sea surface. Height variation between the geoid and a geodetic ellipsoid may amount to 100 m (Pugh, 2004). Additionally, the geoid is modified by modifications of the local gravity redistribution of mass, for example due to earthquakes or melting ice (Mitrovica et al., 2010).

Oxygen isotope data (Lisiecki and Raymo, 2005) combined with geological sea-level indicators in tectonic stable areas, indicate that since the end of the Last Glacial Maximum c. 19 ka, the global sea-level has risen about 125 m ± 5 m to its present level (Fleming et al., 1998; Church et al., 2008). The maximum rate of sea-level rise between 17 and 7 ka was around 10 mm yr\(^{-1}\). Most of the melting of the large ice sheets was completed by c. 7 ka BP, with sea-levels less than 3 m below present position (Fleming et al., 1998; Lambeck et al., 2010b). Subsequent decelerating sea-level rise resulted in a global sea-level at 2 ka BP, almost identical with the one at the end of the 19th century (Lambeck et al., 2010b).

Analysis of global tide-gauge records since 1880 indicates that the late 19th century onset of presently observed global sea-level rise is at average around 1.8 mm yr\(^{-1}\), which is about 10 times faster than in the previous 2000 years (Church et al., 2008). According to these data the global average sea-level rise between 1880 and 2009 is about 210 mm (Church and White, 2011). Since 1933, tide-gauge data from several hundred stations have been collected globally by the Permanent Service for Mean Sea-Level (PSMSL, 2012) and estimates of global sea-level rise derived from ~200 tide gauge records between 1993 and 2009 result in even higher rates of 2.8 ± 0.8 mm yr\(^{-1}\) (Church and White, 2011). Most of the presently observed sea-level rise derives from melting of ice sheets and mountain glaciers as well as warming of the oceans. The global sea-level rise, based on precise satellite altimetry from 1993 to 2012, is measured at 3.1 ± 0.4 mm yr\(^{-1}\) in this period (CuslerG, 2013). In summary, the global sea-level rise in the last 2000 yr is <0.5 m, and therefore any sea-level variations observed on a coast different from this amount are related to local and regional processes.

3.2. Post-glacial rebound of Scandinavia

In contrast to the global sea-level, relative sea-level is measured as the distance between the sea-level and a local datum. Superimposed on global sea-level variations, mean local sea-levels are additionally modified by processes including vertical tectonic movements (Pirazzoli and Pluet, 1991), hydro-, sediment- and glacio-isostatic adjustments (Lambeck et al., 2010a), erosion and deposition and even gravitational pull of ice sheets (Mitrovica et al., 2010). Short-term processes including waves, tides, currents, and winds (Pirazzoli and Pluet, 1991) are disregarded here. The Earth’s crust together with the lithosphere aim to a state of gravitational equilibrium called isostasy in geology (Watts, 2001). The formation of ice sheets represents an additional load in this system, resulting in crustal subsidence below and surrounding the ice sheets (glacio-isostasy). The subsidence causes viscous flow of mantel material radially from the centre of subsidence towards the periphery, resulting in the formation of a gentle bulge up to several thousand kilometres from the centres of the ice sheets. During deglaciation the originally subsided areas experience uplift, while the bulge areas subside (Lambeck and Johnston, 1995). Therefore, the actual local sea-level change depends very much on its location relative to former ice sheets (Pirazzoli and Pluet, 1991). In addition to the glacio-isostasy, sea-level changes cause variations of water depths in shelf areas, resulting in hydro-isostatic adjustments (Lambeck et al., 2010a).

During the Last Glacial Maximum, during Marine Isotope Stage 2 (26.5–19.0 ka BP, Clark et al., 2008), all of Scandinavia and the surrounding areas were covered by the Scandinavian Ice Sheet (Mangerud et al., 2011), which possibly reached up to 3000 m thickness in central parts in the area of the Gulf of Bothnia (Lambeck et al., 2010a,b). The weight of the ice sheet caused subsidence of the crust in the order of several hundreds of meters, with maximum subsidence in the area of the Gulf of Bothnia (Lambeck et al., 2010a,b). Almost the entire ice sheet melted away within a few thousand years with episodic short stops and even re-advances, which resulted in the formation of marginal moraines, of which the so called Ra Moraine is the most prominent (Mangerud et al., 2011). The Ra Moraine formed during the Younger Dryas stadial (c. 12.8–11.5 ka BP) and has a width from several hundreds of meters to a few kilometres (Mangerud et al., 2011). In the outer Oslofjord the Ra Moraine can be traced in Vestfold from Mølen (where it constitutes a source for the boulders of the burial cairns there) to Horten and continuing to Moss and Sarpsborg in Østfold (Fig. 1), 450 m northwest of the site at Borre (Klakkeg and Sørensen, 1991).

Post-glacial rebound related melting of the ice caused surface uplift to such an extent that, in Scandinavia, sea retreat must have been a noticeable process even in prehistoric times (Henningsmoen, 1979; Ekman, 2009). In the Oslo area, marine sediments can be found more than 222 m above present sea-level (Pirazzoli and Pluet, 1991; Vorren et al., 2008; Mangerud et al., 2011). Vertical crustal uplift due to post-glacial rebound reconstructed from levelling, tide-gauges and continuous GPS measurements is still around 8 mm yr\(^{-1}\) in the area of the Gulf of Bothnia and around 2–2.5 mm yr\(^{-1}\) in the southern Oslofjord in the area of Borre (Ekman, 1996; Dehls et al., 2000; Vestol, 2006; Ågren and Svensson, 2007). Even higher velocities for the vertical crustal movement are calculated from the permanent global navigation satellite system (GNSS) network (Kierulf et al., 2012). As the uplift rate of the post-glacial rebound is decelerating over time (Pässe, 2001; Persson, 2008, 2011, 2012) (Fig. 3), these numbers represent minimum values for the reconstruction of past shorelines. For example, the rate of sea-level change in the area of Larvik has decreased gradually from some 5 mm yr\(^{-1}\) at the end of the Bronze Age to ~3.5 mm yr\(^{-1}\) during the Viking Age (Sørensen et al., 2007). Archaeological excavations in the Viking Age portus Kaupang, 45 km southwest of Borre, showed that in 800 AD the shoreline was 3.6–3.8 m higher than today (Sørensen et al., 2007; Persson, 2008) (Fig. 3).

3.3. Raised beach-ridges

In many cases, shoreline displacement becomes visible through beach ridges, which are elongated accumulations of coastal
sediment deposited by waves and wind parallel to the coastline in the back beach area, but may also contain an intertidal component (Otros, 2000; Davis and Fitzgerald, 2004; Bird, 2008). It is still debated whether or to which amount they are created by storm or accretion by calmer swell on top of a berm (Woodroffe, 2002). Their actual size and shape depends on the velocity of shoreline progradation and amount as well as grain-size of sediment. They become preserved as a result of shoreline progradation and, consequently, series of beach ridges are common features of uplifting coasts or of accreting coasts due to high sediment supply (Woodroffe, 2002). The position of raised beach-ridges broadly indicates the maximum altitude of a former sea-level. Due to crustal uplift as a consequence of post-glacial rebound, Holocene raised beaches and beach ridges are common features in many coastal parts of Norway, including the Oslofjord area where Borre is situated (e.g. Klakegg and Sørensen, 1991; Pila, 2007).

4. Archaeological prospection methods

4.1. Airborne laser scanning

Airborne laser scanning is an extremely powerful and cost-effective method for the recognition and measurement of microtopography in open and especially in wooded areas (Ackermann, 1999; Wehr and Lohr, 1999; Turner and Kamerman, 2009) (Fig. 4). Archaeological and geological features only preserved as microtopographical structures, can be effectively visualised in detailed DTMs generated from such surveys. The laser scanner is mounted below an airborne platform – usually an aeroplane or helicopter. While flying over a pre-defined area in a meandering way, the scanner emits short infrared pulses towards the Earth’s surface, which are deflected by a rotating mirror across the flight path. From each laser pulse one or more echoes will return, where in most cases the last echo is reflected from the ground surface. The position and altitude of the scanner as well as its orientation in relation to a global coordinate system are determined by a differential global navigation satellite system (GNSS, e.g. GPS) and an inertial measurement unit (IMU). The high density of the measured points (up to several points per square meter) and their even distribution are crucial for the determination of highly precise and accurate surface models.

The Borre area was ALS scanned in 2009 by the Norwegian Institute for Cultural Heritage Research (NIKU) on demand from Vestfold County Council. Laser scanning of the area was conducted on 21st of April 2009 using a Leica ALS50-II operated by TerraTec AS. The flight was carried out 550 m above ground with a scanning repetition frequency of 142 kHz and a scan angle of 20° resulting in a point density of 10 points/m² (Risbøl, 2009), which resulted in a DTM with a resolution of 1 m. Data filtering has been carried out using the TerraScan software from Terrasolid.

To enhance the visibility of microtopographic features, such as heavily decimated burial mounds or beach-ridges in ploughed fields, the DTM was visualized in several ways, most importantly as hillshade (Fig. 5a), slope (Fig. 5b) and a local relief model (LRM) (Hesse, 2010; Stular et al., 2012) (Fig. 6). Here, the general (low-resolution) topography (represented by the low-pass filtered DTM) is subtracted from the high-resolution DTM. The result is a topographic model of the local microtopographic features, which can be enhanced by colour-coding (Fig. 6). The LRM is calculated applying various processing steps, where a kernel is used to define the low-pass filter. Depending on the kernel size, the resulting visualisations will differ. Therefore, different topographic settings (relief, size and structure of objects) will need different parameters to compute LRM. In this case, the low-pass filter had a Kernel size of 25 m.

In low relief areas, application of LRM produces clear and distinct visualisations, as can be seen from the example from Borre. Elevations above the mean terrain heights are colour-coded in red, while those below are blue. In this visualisation, burial mounds and extraction areas become more pronounced and beach-ridges are also enhanced (Fig. 6).

4.2. Ground penetrating radar

In May and October 2007, the Swedish National Heritage Board, UV-Teknik, conducted ground penetrating radar (GPR) surveys at Borre, discovering two Iron Age hall buildings outside the Borre park (Trinks et al., 2007). In May 2012, a series of GPR surveys were carried out at three selected areas inside the Borre park (Figs. 5b and 10): Survey area A was located across the northern slope break between mounds 5 and 4; area B was located 55 m south of mound 4 and area C was located across the slope break east of the burial site 170 m south of mound 4 (Figs. 5b and 10). The aim of the surveys was to acquire radar profiles across some of the prominent ridges in the landscape in order to determine their sub-surface make-up. The selection of the survey was based on preliminary assessments of the ALS data and on visual inspections on site.

The surveys were carried out using a Sensors and Software Noggin Plus system with a 500 MHz centre-frequency antenna mounted in a SmartCart configuration. Data was collected along parallel profiles set out at right angles to the topographical ridges, where the distance between individual profiles was set to 0.5 m, and the sampling distance in the direction of the profiles was 0.025 m. In survey area A 13 parallel profiles were recorded, in area B 11, and in area C 7 profiles. The length of the GPR profiles varied between 24 m in area A, 38 m in area B, and 24 m in area C (Fig. 5b). The strategy of surveying more than a single profile across the site ensured that a depth-slice visualisation of the data could be obtained. Furthermore, it served to ensure that an adequate number of profiles crossed the ridges so that these could be analysed and compared at a later stage in the project.
5. Results

5.1. ALS DTM documentation of archaeological features

The study area is located on a slope gently dipping from ~20 m above sea-level (asl) towards the sea (Figs. 1, 4 and 7). The ALS DTM clearly shows a considerable difference in the preservation of geological and archaeological features between forested areas and those exposed to modern ploughing (Fig. 5). The existence of mound 9 in the southwest and the continuation of the pronounced slope break parallel to the shoreline may indicate the continuation of the burial site towards the southwest (Fig. 10).

Fig. 4. Overview of Borre from the air. A) Orthophoto made by TerraTec AS on 11-07-2011 with 0.1 m resolution (http://www.norgebilder.no). Due to the vegetation only some of the large burial mounds are visible. B) Grey image of the same area showing a 1 × 1 m resolution ALS DTM measured on 21-04-2009 by TerraTec AS. Present day coastline digitized from the orthophoto shown in Fig. 4a. The large mounds and the site boundary towards the northeast and east-southeast are visible, but beach ridges and most of the small mounds can barely be seen.

Fig. 5. Different visualisation techniques of the ALS DTM of Borre. A) Hillshade presentation (illumination from the NW, 45° sun’s angle of elevation above the horizon) greatly improves the visibility of the burial mounds, slope breaks and beach ridges compared to the grey image in Fig. 4b. B) Hillshade with 50% transparent slope map above additionally enhances the perceptibility of many features. Location of GPR survey areas A, B and C are indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
The northeast boundary of the burial site is formed by a relatively straight, steep, up to 3 m high slope break towards a comparably lower area with preserved beach ridges (Figs. 5 and 6). Towards the coast to the southeast, the burial site is confined by a relatively straight slope break, parallel to the coastline between 7 and 5 m asl (Figs. 5 and 8). Fig. 10 summarizes our new interpretation of Borre based on ALS, GPR and ground check data, using and extending the numbering of the archaeological remains by Myhre (2003b, Fig. 1).

The different visualisations of the DTM (Figs. 5 and 6) reveal 7 large (diameter >30 m) mounds (Fig. 10, numbers 3–9) and additionally the remains of two similarly sized mounds which have been levelled previously (Nicolaysen, 1854; Myhre and Gansum, 2003) (Fig. 10, numbers 1, 2). The preserved size of the largest ones of these reaches some 7.5 m in height and more than 48 m in diameter. There are two medium sized mounds, measuring 19 m and 24 m in diameter (Fig. 10, numbers 11, 24).

Furthermore, 35 smaller mounds (diameter <13 m) are visible (Fig. 10). In total, 11 potential burial mounds have been located in the ALS data, of which eight have been disproved by a detailed ground check in April 2013, with exceptional surface visibility because of low vegetation after a snow-rich winter. Thus, despite of several decades of archaeological research at Borre, it was possible to identify three new smaller mounds by ALS, compared to the map by Gansum (2007, Fig. 4). These newly located mounds are found on top of the slope break in the north (Fig. 10, numbers 41–43). Mound 14, indicated by Myhre (2003b, Fig. 1) is not visible in the ALS data of this study. The state of preservation of all mounds varies strongly depending on their exposure to modern ploughing. Almost all large burial mounds are surrounded by hollows, where material have been extracted for mound construction, with one to four causeways left on which one could reach the mound (Fig. 10). The ALS data can be used to quantify the volume of the mounds as well the hollows surrounding them. Alternatively, Draganits and Preh (2014) provide an analytical solution for the volume calculation of burial mounds.

Besides the burial mounds, observations of other archaeological features include: i) two medium sized stone cairn mounds in the northern part of the site with diameters of 26 m and 17 m (Fig. 10, numbers 32, 33); ii) two smaller stone cairn mounds with diameters of 7 m and 5 m (numbers 44, 45); iii) a 43 m long, ship-shaped stone cairn next to the cluster of smaller mounds in the south (number 25); iv) a triangular mound (number 40) situated directly on the eastern slope break and an elongated mound (number 46) directly west of it; v) a possible field clearance cairn (number 55); vi) a chamber grave (number 50) and vii) a small heap of stones dominated by slag on top of the ridge at Prestetangen (Fig. 10, number 56). The possible field clearance cairn, chamber grave and the slag pile were additionally located during a detailed ground check for the ALS interpretation in April 2013.

5.2. ALS DTM documentation of geological features

Today at the coast of Borre, waves dominantly move in a northerly to north-north-westerly direction, producing a northwards directed longshore current. During high-tide and/or storms, beach ridges are deposited, which are well preserved at the uplifting coast in this area. These beach ridges are low-topography features, barely visible on the ground, but in the ALS DTM at Borre, a succession of more than 15 beach ridges is visible from the present shoreline up to 21 m asl (Figs. 6 and 10). Even in the ALS data, beach ridges are hardly visible in the ploughed fields outside of the central park area, but they are quite well preserved inside and in the forested area north and south of the park (Jerpåsen, 1993). The ditches surrounding the burial mounds clearly cross-cut the beach ridges (Figs. 6 and 10) and thus they must be younger.

Generally, the beach ridges are rather similar in size and height, except those at 18 m asl and especially around 6 m asl, which are broader, taller and straighter compared with the others (Figs. 5–8). The upper prominent beach ridge is situated between the destroyed burial mounds number 1 and 2 (Myhre, 2003a, Fig. 8), while the lower prominent ridge represents the south-eastern boundary of the burial site, towards the sea (Fig. 5b). In detail, this lower structure forms a steep slope break between 7 and
5 m asl (Figs. 5–7). Between these two prominent beach ridges (between 6 and 18 m asl), beach ridges are relatively straight, with the exception at the northern limit of the burial site and between mounds 7 and 8 (Myhre, 2003a, fig. 8), where they are deflected slightly in an S-shape along west-northwest-east-southeast and northwest-southeast trending lines (Fig. 10). This deflection of the beach ridges is probably a result of wave refraction and diffraction on existing relief during their formation (Davis and Fitzgerald, 2004).

The later beach ridges below 5 m asl (Fig. 5–7) are much more irregular and in places disturbed compared to those above 7 m asl (Figs. 5, 6 and 10). The coastline directly east of Borre shows two prominent promontories, in strong contrast with the generally quite smooth coastline of this area. From north to south their microtoponyms (Myhre, 2003a) are Klokkertangen (at the northern limit of the burial site) and Prestetangen (south-east of the triangular mound) (Fig. 10). They form prominent west-northwest-east-southeast oriented ridges causing the beach ridges to deflect considerably, and especially at Prestetangen the beach ridges bend in a U-shaped manner. The relationship indicates that the west-northwest/east-southeast trending ridges predate the beach ridges which are deflected by the former. The two ridges exert a strong influence on the orientation of the beach ridges below 4.5 m asl towards the present sea-level (Figs. 5, 6 and 10). Additionally, directly to the north of the ridge at Prestetangen no beach ridges are preserved, and the area seems to have been lowered (Figs. 5, 6 and 10).

5.3. Ground penetrating radar results

The location of the GPR surveys is indicated in Fig. 5b. In area A, the GPR results show a signal penetration depth of approximately 1.2 m, indicating a layered sandy/humic overburden on top of a relatively strong absorbing, clayey substratum. The overburden is thicker in the western end of the profile (Fig. 9) compared to its sloping eastern part. Several distinct horizons can be seen in the data, possibly indicating former ground surfaces or geological stratification.

The same pattern can be observed in area B (Fig. 5b), with a clear thinning of the topsoil in the area of the steepest slope. In area C (Fig. 5b) a linear, perpendicular, strongly reflecting structure can be
observed in the data, coinciding with the location of a track-way visible in the ALS data. The analysis of the vertical GPR profile sections indicates a compacted layer at this location. Due to the limited extent of the GPR survey in areas A, B and C it is difficult to differentiate between possible humanmade structures and natural stratification. A larger survey, using a lower frequency antenna, would probably identify beach ridges and large scale constructions more clearly. However, a succession of gently sea-ward dipping sedimentary layers in the GPR data of Trinks et al. (2007) from the area with the hall buildings directly west of the burial site supports our interpretation of beach ridges visible in the ALS data.

6. Discussion

6.1. Shoreline displacement at Borre

Archaeological findings and radiocarbon ages indicate that the Borre burial site was in use mainly between 600 and 1000 AD (Myhre, 1992a, 2003a; Gansum, 2007). A detailed shoreline displacement study of the Borre area has not been carried out so far, but is highly desirable. However, for this period a number of shoreline displacement studies exist from the area of the Oslofjord between Larvik and Ski (Sørensen, 1979; Stabell, 1980; Hafsten, 1983; Anundsen, 1985; Sørensen, 1999; Sørensen et al., 2007), summarized by Pirazzoli and Pluet (1991), Pässe (2001) and Sørensen et al. (2007) (Fig. 3). Unfortunately, many of these shoreline reconstructions refer to uncalibrated radiocarbon dates, which have to be recalculated to calibrated dates (Pässe, 2001; Sørensen et al., 2007). Due to the different location of these studies resulting in different rates of glacio-isostatic uplift, Sørensen (1999) applied a correction gradient for the uplift observed at the Vestfold coast in north–northeast-ward direction between Larvik and Ski, which is the more important the older a site is. This gradient is \(-0.015 \text{ mm km}^{-1}\) at present (Olesen et al., 2004).

Lacking sea-level reconstructions for Borre itself, the comparison with shoreline displacement curves from nearby areas in Vestfold (e.g. Henningsmoen, 1979; Stabell, 1980; Hafsten, 1983; Pässe, 2001; Sørensen et al., 2007), suggests that the local sea-level between 600 and 1000 AD was c. 3.5–5 m higher than today (Fig. 3), just below the prominent slope break at the sea side boundary of the burial site (Figs. 5–8). Until detailed local research on the shoreline displacement at Borre has been carried out, these values should be used as an approximation.

Based on shoreline reconstructions for Vestfold (Hafsten, 1983; Pässe, 2001; Sørensen et al., 2007) the beach ridges seen in the ALS data at Borre below 20 m asl formed approximately in the last 5000 years, clearly indicating that the present day crustal uplift rate of 2–2.5 mm yr\(^{-1}\) in the area (Ekman, 1996; Dehls et al., 2000; Vestol, 2006), is just a minimum value (Pässe, 2001; Persson, 2008; Persson, 2011, Fig. 40; Persson 2012, Fig. 71), because uplift rates of Scandinavia due to post-glacial rebound were much higher at the beginning of the Holocene and have decelerated since then (Pässe, 2001; Persson, 2008, 2011, 2012). For example, in the empirical model of the glacio-isostatic uplift of Scandinavia by Pässe (2001), the uplift rate in the area of Borre at 2900 BP was still 15 mm yr\(^{-1}\). As a comparison the global sea-level increased <1.5 m in the last 4000 years (Fleming et al., 1998; Lambeck, 2010a,b).

6.2. Possible harbour location at Borre

Borre, with its exceptional burial mounds and associated hall buildings, is hard to imagine without a harbour during the Viking Age. Additionally, visibility calculations based on DTMs of Borre and surrounding areas show that the burial mounds are clearly visible from the sea, but only from a comparably small area on land. However, no harbour has been located (Keller, 1993, 1994; Gansum, 1995). Keller (1993) even speculated that the coastal conditions at Borre were so unfavourable for landing, that the burial site was merely intended to be seen from passing ships, but not for landing. However, a landing possibility would be favourable at least for the ships intended to be buried in the burial mounds. In this context it is worth considering the difference between anchorage, harbour, and port (e.g. Tartaron, 2013, 4).

One hypothesis discussed among archaeologists is that the northern slope break was artificially constructed by excavating the area north of it to create an artificial harbour basin. This idea is not supported by the evidence from the ALS-derived DTM for two reasons: (i) The altitude of the area north of the slope break is >5 m asl, which would be dry land during the Viking Age according
to post-glacial rebound and local sea-level considerations (see above and Fig. 12). (ii) In the supposedly excavated area beach ridges are still preserved in relief, which must have formed before the construction of the burial mounds. Also, the beach ridges are deflected at the slope break, indicating a relative chronological relationship, in which the terrace edge must predate the beach ridges. Consequently, the preservation of these beach ridges excludes large-scale excavation of material from there, and this feature most likely is the result of material deposition (Figs. 5–7, 12).

The northern boundary with its steep slope, therefore, seems to have been formed by the deposition of material in the area of the burial site and not by excavation in the area to the north (Figs. 5–7). The deposition of material there might have made use of an already existing natural elevation, as indicated by the deflecting beach ridges between 6 and 17 m asl north of the burial site boundary.

The interpretation of the ALS data provides constraints for a more probable location of a former harbour at Borre. The lower prominent beach ridge at 7–5 m asl is much larger and straighter compared to most of the surrounding ridges. In particular, its seaward slope is much higher and steeper than any other beach ridge (Figs. 5–8). Therefore, it is suggested that some sediment has been deposited on its upper side to improve its function as a seaward boundary of the burial site, when the relative sea-level was higher.

Below 4.8 m asl there are two west-northwest-east-southeast oriented, prominent ridges, presently forming the promontories of Klokkertangen and Prestetangen, east of the northern end of the burial site and the triangular mound, respectively (Fig. 10). The northern one is ~180 m long, the one east of the triangular mound ~170 m long. The exact width of the ridges is difficult to reconstruct due to sedimentation, but they are some 10 m across (Figs. 5–7). Peculiarly, these ridges are built by polymict, sub-rounded to rounded boulders up to almost 1 m in diameter. This can be clearly observed, especially at the northern ridge. The rock types of the boulders include different porphyrites, various types of gneisses, amphibolites, and sandstone (Fig. 11). In contrast, in the area between the ridges, boulder sized clasts are very rare. These boulders are very infrequent outside of the west-northwest-east-southeast trending ridges, as well as in the nearby beach areas and in the beach ridges in the whole Borre area. Therefore it is suggested that they have been brought there artificially from somewhere else, and the most likely source is the prominent Ra Moraine that passes west of the burial site less than 450 m from the ridges (Klakegg and Sørensen, 1991; http://geo.ngu.no/kart/losmasse) (Figs. 1 and 10). The preserved maximum altitude of the two ridges is about 4 m asl (Klokkertangen) and 4.5 m asl (Prestetangen). They cause considerable deflection of the beach ridges below 4.5 m asl to the present sea-level and therefore must predate the beach ridges. Especially, they are strongly deflected in a U-shaped way around two long and thin ridges, directly east of the burial site (Figs. 5, 6 and 10).

These two promontories are in contrast with most of the coast of the western Oslofjord in the vicinity of Borre. Between Åsgårdstrand and Horten the coastline is relatively straight with few natural harbours. The straightness of the coastline is also mirrored by the nautical map of this area, with isobaths being straight and parallel to the general trend of the coastline (NHS, 2011). Additionally, the place name Langgrunn indicates a long and shallow shoreline.

The unfavourable conditions for ships landing at Borre have already been discussed by Keller (1993). He mentions that the currents between Borre and Bastøy Island make for difficult waters. Viking Age ships were operated by sails and oars and they could land on sandy beaches or anchor in sheltered coves. The coast at
Borre is shallow and muddy with few boulders, and far from balmy. Landing here has only been made possible by the recent construction of the artificial harbour of Steinbrygga, directly to the south of the Borre site (Keller, 1993) and many modern artificial jetties exist in this area to provide wave protected landing possibilities and harbours. These are about 100–220 m long and some 10 m wide. The west-northwest-east-southeast trending ridges seen in the ALS are exactly in the size range of the modern day jetties.

Fig. 10. Hillshade with the archaeological and geoaarchaeological interpretation of Borre from ALS and GPR data as well as new ground check observations. The numbering of the archaeological remains uses and extends the one by Myhre (2003a, fig. 8). Twelve new mounds have been located based on ALS data, of which three are probably burial mounds. See text for further explanation.

Fig. 11. A) General view towards the south-southwest showing the sandy beach directly north of the Borre site and the abrupt change of shoreline orientation at the forested headland in the background. The beach consists almost exclusively of sand-sized sediment. B) Detail of the very coarse grained sediments of the headland comprising subangular to rounded polymict boulders <1 m size, including porphyrites, various types of gneisses, amphibolite and sandstone.
jetties in this area, and we believe that they have been made for the same purpose. Consequently, these structures are interpreted as Viking Age jetties built to provide safe landings at Borre. Possible analogue jetties from the Viking Age – some of them reinforced with poles – have been indicated from Hedeby (Denmark) (Gron et al., 1998), Birka (Sweden) (Clarke and Ambrosiani, 1991; Ambrosiani, 2008) and Kaupang (Norway) (Henningsmoen, 1979). An additional important feature in the ALS topography can be found directly to the north of the ridge close to the triangular mound (Figs. 5, 6 and 10). In this area there are no beach ridges preserved and a ~90 m long and 35 m wide area is deepened for about 1.4 m compared to its surroundings (Figs. 5–7 and 13). It is suggested here that this area has been dredged to provide continuing landing possibilities for ships during lowering of the local relative sea-level. Dredging operations in harbours are mentioned by Vitruvius in the first century B.C. (Hesnard, 2004) and several examples from ancient port excavations, e.g. Marseille, Naples, Sidon and Tyre, have been documented (Morhange and Marriner, 2010).

If we accept that the two ridges at right angles to the coastline are artificial, Viking Age jetties, their separation of ~220 m is quite far for a single landing site (Fig. 10). Therefore, it might be speculated that they protected two landing sites, one of which was a “privileged” landing site with direct access to the burial site in the area of the dredged surface north of the ridge at the triangular mound (Figs. 10, 12 and 13). As can be seen in Fig. 13, dredging at the Borre coast facilitating the landing of Viking Age ships is absolutely necessary for sea-levels below 4 m asl. The lack of post-Viking Age beach ridges in this location may indicate that this area has been kept accessible in later periods. The slope break at the eastern boundary of the burial site appears quite worn and is about 0.5 m lower, compared to most other parts of the slope break (Fig. 6). This wear could have been caused by people using the jetty east of the triangular mound, or even from dragging ships to the burial site. In this context, the small heap of stones dominated by slag on top of the ridge at Prestetangen, which have been discovered during the ground check in April 2013, could represent former ship ballast stones.

The beach directly north of Borre is quite sandy and is protected by the northern ridge (Klokkertangen) and could represent an additional landing site for Borre (Figs. 10 and 12). Supporting our interpretations is the detection of rock boulder heaps used as ballast stones in Viking Age ships as described by Kalmring (2010) from Haithabu.

Two west-northwest/east-southeast trending, less prominent features, at the northern limit of the burial site and between mounds 7 and 8 (Myhre, 2003a, fig. 8), show slightly S-shaped deflections of beach ridges between 6 and 16 m asl (Figs. 5, 6 and 10). They could indicate older constructions in this area, but neotectonic faults as described by Olesen et al. (2004) may represent a more likely geological explanation. The actual reasons for the bending, however, remain unclear.

Pre-Viking Age human activities
in this area is indicated by radiocarbon dates predating the burial mounds (Gansum, 2007; Østigård and Gansum, 2009), but without further research and detailed geophysical investigations the nature of this activity remains ambiguous.

The “Saga Oseberg”, which is a 2012 replica of the Viking ship excavated from the burial mound at Oseberg in 1904, has a draught of 0.92 m under the mid-ship keel and a draught of 1.30 m at the rudder (pers. comm. Geir Røvik, 2013). The “Gaia”, which is a 1990 replica of the Viking ship excavated from the burial mound at Gokstad in 1880, has a draught of 0.95 m under the mid-ship keel and a draught of 1.40 m at the rudder (pers. comm. Freddy Svanberg, 2013). The combination of these draught values of replica Viking ships with the topography of the area between the burial site and the present day coastline (Figs. 7, 10, 12 and 13) indicates that with sea-levels below 4 m asl the only navigable access to Borre is close to the triangular mound, in an area which probably was artificially lowered (Figs. 7, 10 and 12). Both profile and ship are drawn with 12× vertical exaggeration.

7. Conclusions

ALS derived DTMs are a fast and cost-efficient method for the documentation, visualisation and interpretation of even very low relief archaeological features in both unvegetated and densely vegetated areas. As the archaeological remains can be studied together with surrounding geomorphological structures, the geo-archaeological interpretation can provide important insights into site properties, human–environmental interaction and post-abandonment processes.

Another advantageous aspect of high resolution ALS-derived DTMs is the possibility of establishing relative chronologies based on cross-cutting relationships of both archaeological as well as environmental features. The ALS data show the existence of seven preserved and two destroyed large mounds (diameter >30 m). Additionally, there are two medium sized mounds (19 m and 24 m diameters) as well as 35 smaller mounds (diameter <13 m), of which three are newly documented. Further structures include four stone cairns, a triangular mound and a boat-shaped stone cairn.

The ALS DTM at Borre shows a succession of more than 15 beach ridges from the present shoreline up to 21 m asl. While the beach ridges between 6 and 18 m asl are relatively smooth and straight, the beach ridges below 6 m asl appear more irregular and in places disturbed. Especially, they are strongly deflected in a U-shaped way around two long and thin ridges, directly east of the burial site.

The northern as well as eastern boundary of the burial ground is formed by slope breaks. ALS data indicates that in both cases sediment has probably been deposited to strengthen already existing natural relief.

Two prominent ridges at right angles to the coastline are ~180 m and 170 m long and some 10 m wide. Beach ridges are strongly deflected around them and thus the former must predate the beach ridges. They consist of polymict, sub-rounded to rounded boulders up to 1 m in diameter comprising different porphyrites, various types of gneisses, amphibolite and sandstone. Such boulders are rare outside of these ridges and probably derive from the nearby Ra moraine. These structures are interpreted as Viking Age jetties built to allow safe landings at Borre.

Directly north of the southern jetty the area is lowered and no beach ridges are preserved. This area has probably been dredged to provide continuing landing possibilities for ships during lowering of the local relative sea-level. Replicas of Viking ships have draughts around 1.4 m, and thus this dredged area would provide the only navigable access directly to Borre at sea-levels below 4 m asl.

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