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Non-destructive 3D prospection at the Viking Age fortress Borgring, Denmark

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ABSTRACT

Non-invasive methods are increasingly important for understanding archaeological sites and their contexts. Larger earth-built constructions are nevertheless still difficult to study without extensive excavations. At the recently discovered Viking-Age ring fortress Borgring in Denmark a suite of non-destructive methods was applied with the aim of understanding how this highly eroded earthen fortress was constructed, and investigating how the construction of such a large monument altered the landscape. The methods were 1) residual relief modelling of airborne laser scanning data, 2) electromagnetic induction (DualEM 421 s) survey combined with coring, and 3) soil magnetic susceptibility measurements all to produce a 3D model of the palaeo-landscape and the fortress.

We found that the narrow natural promontory was enlarged to make space for the construction of the fortress' rampart. The magnetic susceptibility of turfs from the rampart showed that both wetland and upland areas were alternately used for different compartments and explained the segmented anomalies comprising its construction. The combined results revealed a better archaeological understanding of the construction of the rampart, that the modifications of the landscape was somewhat comparative to the contemporary Fyrkat ring fortress site, and that the understanding of the landscape modifications were improved significantly by a multi-method 3D approach.

1. Introduction

Non-invasive prospection have proved crucial to the investigations of archaeological sites and their immediate surroundings, and the results of intensive geophysical and geochemical surveys demonstrate that these methods can successfully characterize highly eroded earthen sites. Prominent examples include studies of the ancient harbour of Rome (Keay et al., 2014), Cambodia's jungle-covered Angkor Wat complex (Evans & Fletcher, 2015), the multi-period city of Jerash, Jordan (Stott et al., 2018), and widespread early Holocene landscape modifications due to cultivation in Amazonia (Lombardo et al., 2020) while Scandinavian examples are reviewed by Stamnes et al. (in prep.).

Non destructive archaeological prospection methods are essential tools for archaeologists. Using airborne, satellite remote sensing and

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geophysical measurements permits the detection, characterisation and contextualisation of archaeological features without impacting those features. Furthermore, these techniques extend our understanding beyond the spatial constraints implicit in excavation. Using these methods in conjunction with targeted excavation and geoarchaeological investigations has engendered the investigation of entire landscapes, especially when machine learning is applied (Stott et al., 2019). Applications of airborne remote sensing and geophysical methods are increasingly applied elsewhere in Scandinavia on sites with comparable geological conditions and archaeological site types (Christiansen et al., 2016; de Smedt et al., 2013; Filzweiser et al., 2017; Rundkvist & Viberg, 2015; Risbøl et al., 2019; Viberg et al., 2020; Gabler et al., 2013). Although geophysical methods have long been used for archaeological investigations in Denmark, they have not been widely adopted. This is partly due to a methodological tradition that emphasizes intensive trial excavation over non-invasive prospection, the nature of the local archaeological record, and challenging geological conditions in the glacial landscape of eastern Denmark. Rural architecture has consisted of predominantly post-built timber structures since the Neolithic, and these are problematic to identify against a heterogeneous geological background, especially following centuries of plough truncation. Frequent igneous glacial erratics in morainic subsoil make identifying smaller discrete features problematic using magnetometry alone (Linford et al., 2007; Gaffney, 2008). Electromagnetic induction investigations (EMI) have proved invaluable for providing landscape context to archaeological sites and detecting larger features (Christiansen et al., 2016). However, the EMI method has rarely been used with high enough sampling density for the detection of the predominantly small archaeological features of interest. While ground penetrating radar (GPR) has shown great promise on the sandy glacial outwash and marine sediments in western Jutland (e.g. Filzwieser et al., 2017) its use elsewhere in Denmark is complicated by generally variable contents of clay, stones, glacial structures and soil moisture in heterogeneous glacial parent materials (Høyer et al., 2013).

Ring fortresses of the Trelleborg type are an important monument type from the late Viking Age in Southern Scandinavia. Constructed in the late 10th century, they are a systematic expression of the power of a highly organized society to coordinate and control resources (Roesdahl and Sindbæk, 2014; Ulriksen, 2011; Ulriksen et al., 2020), and as such are vital to our understanding of the formation of the Danish kingdom in the early Middle Ages. While there are differences in the size and construction of the fortresses, they all share common design elements that make them distinctive, particularly their precise geometric layout, with a circular turf and timber constructed rampart 120–240 m in diameter and 10–15 m wide, punctured by roads meeting in the centre, approximately aligned with the cardinal points of the compass (Roesdahl and Sindbæk, 2014). The sites are located on defensible ground, using natural features like watercourses and marshes. Ditches were dug where there are gaps in these natural defenses. At Trelleborg and Fyrkat substantial levelling deposits were required to accommodate the whole diameter of the fortress on the natural promontories the sites sit upon (Olsen and Schmid, 1977, pp. 49–52; Nørlund, 1948).

Non-destructive techniques are crucial for investigating the earth-built Trelleborg type fortresses as these sites are both large and potentially complex, meaning excavation can only provide limited insight. This was demonstrated by Brown et al. (2014), who used fluxgate gradiometry in conjunction with GPR to map numerous archaeological features at Aggersborg. At the site Fyrkat in Jutland EMI mapping was used to investigate the immediate landscape context of the fortress, delineating relict watercourses and beaches (Torp, 2011). The results of as yet unpublished geophysical surveys at the fortresses of Nonnebakken (Runge & Neubauer, 2020) and Borgeby in Skåne (Cinthio and Ödman, 2018), Sweden undertaken by LBI ArchPro and Rambøll are keenly anticipated.

At the most recently identified of these sites, Borgring on Zealand, Denmark (Fig. 1), non-destructive methods were key to the reinterpretation of the site as a Trelleborg type fortress. The fortress at Borgring was discovered initially from an aerial photograph taken during winter 1970, when a light dusting of snow revealed a heavily ploughed annular earthwork previously undetected in earlier images (Fig. 2). Here subtle remains of the rampart, only visible on the surface as an interrupted maximum 1.1 m high bank, could be identified. This revealed that the size and shape of the rampart was very much comparable to those of the other Trelleborg type ring fortress, but a small scale excavation at the site undertaken in 1971 concluded that it was likely a Roman Iron Age settlement (Goodchild et al., 2017). However, as described in Goodchild et al. (2017) this evidence had to be re-evaluated based on the Digital Terrain Model (DTM) derived from the airborne laser scanning (Lidar) data and a fluxgate gradiometer survey identifying a distinctive circular rampart and suggested cruciform internal street pattern indicative of the

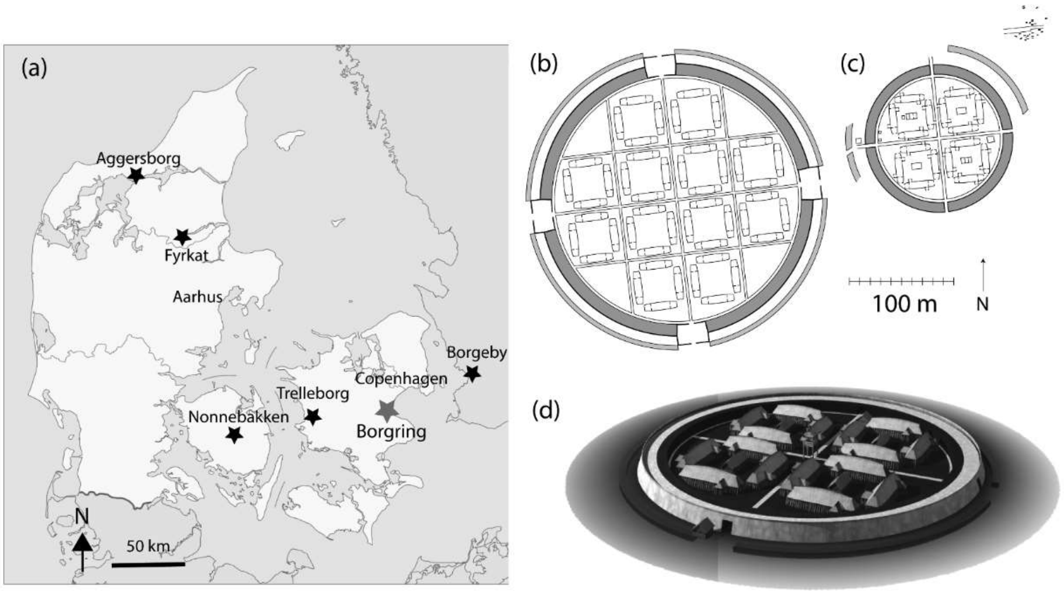

Fig. 1. (a) Location of the study site Borgring in Denmark (red star), and the confirmed Viking Age ring fortresses (black-stars), (b) an example of plans of recognized ring fortresses Aggersborg, (d) at Fyrkat, and (d) an archaeological reconstruction of the Fyrkat ring fortress (based on Roesdahl and Sindbæk, 2014; Olsen and Schmid, 1977).

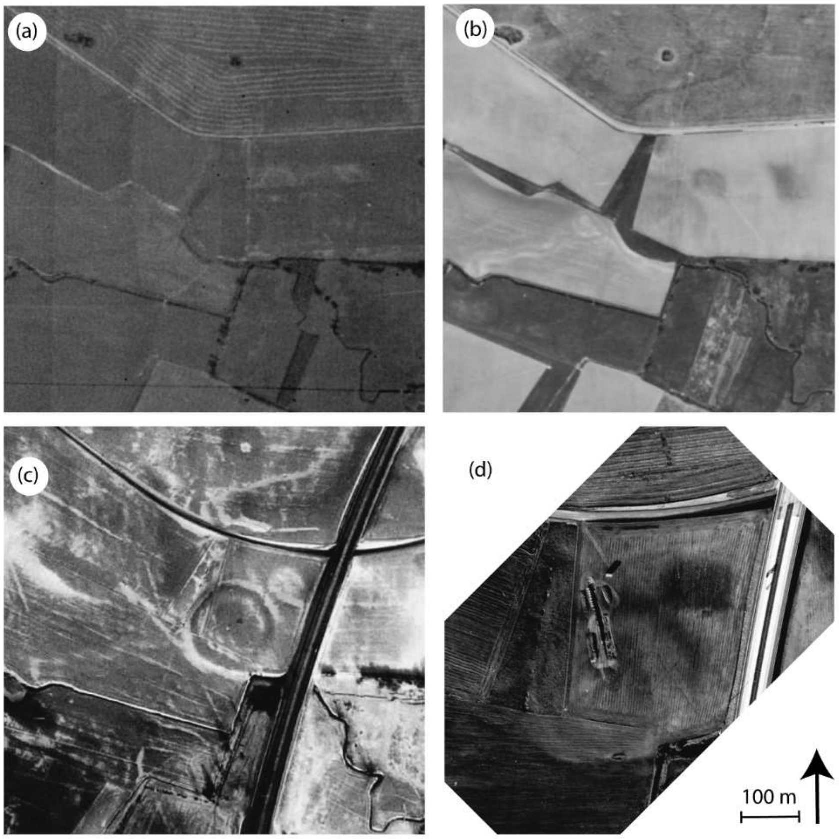

Fig. 2. Air images of the Borgring ring fortress taken before the first discovery in 2014. (a) Luftwaffe 1945, (b) Basic Cover 1954, (c) air officer V. Ruhl from winter 1970, and (d) during the 1972 excavation taken by the excavation team. The highway (E47/E55) east of Borgring was constructed in the late 1960s.

Trelleborg type ring fortresses dating from the Viking Age.

Here, we report an intensive campaign of integrated remote sensing, geophysical and geoarchaeological investigations undertaken at Borgring to gain a better understanding of the construction, use and context of the fortress. Our specific aim was understanding how the interior and the ramparts of a currently highly truncated earthen fortress was constructed, and to investigate how the construction of such a large monument altered the landscape. This was achieved by applying a suite of non-destructive geoarchaeological methods on this archaeological site on a very heterogeneous geological subsoil.

2. Materials and methods

2.1. The site and the archaeological context

The location of the study site Borgring is shown in Fig. 1 where also the locations of the other known Trelleborg-type ring fortresses are shown for comparison. A magnetometer survey reported by Goodchild et al (2017) was fundamental to the design planning of the subsequent research projects, as it enabled the targeting of excavations at the gateways of the fortress that ultimately confirmed its age (Christensen et al., 2018). The excavation undertaken afterwards revealed the turf construction of the Viking Age rampart and a number of features related to a Roman Iron Age settlement within it (Christensen et al., 2021). Subsequent excavation has confirmed the Trelleborg-type geometry of the rampart (Christensen et al., 2018; Ulriksen et al., 2020; Christensen et al., 2021), as the turf and timber construction method and layout of the gates very closely resembles those at the other fortresses. The pollen spectra of the growing surfaces of rampart turfs were also analysed in an attempt to identify the environment and the results indicated that they were harvested from a non-forested, dry agrarian landscape which was persistently grazed (Mortensen et al, 2021).

Radiocarbon dates acquired from timberwork in stratigraphically secure contexts at the Northern gate indicate that the trees were felled in the 10th century (Christensen et al., 2021), proving that Borgring is at least broadly contemporaneous to the other fortresses with a strict geometric layout (Fig. 1). The archaeological excavation findings and regional context are reported in Christensen et al., (2018), Ulriksen et al., (2020), Christensen et al. (2021), Jessen et al. (2021), Ljungkvist et al., (2021), Mortensen et al. (2021), and Sulas et al (2020).

Borgring is situated at a strategically important point overlooking the Køge Ådal river valley (Ulriksen et al., 2020), at a gap in the prominent but discontinuous esker running along the northern bank of the valley (Gravesen et al., 2017). This part of the moraine plateau on the northern bank of Køge river is located in between a several metre deep Ice Age erosion gulley towards the west and a less prominent valley northeast and east of the Borgring, both likely also remoduled by late-glacial nivation processes. Jessen et al. (2021) found that the uppermost sediment layers at and around Borgring were poorly sorted clays with inclusions of both silt and sand, and significantly more heterogeneous than indicated by the Geological Survey' Soil Map (Fig. 3B). These deposits were up to 1.5 m thick and covered large areas predominantly in the depressions, in the gully to the west and the valley floor. These post-Viking Age deposits were intentionally deposited to optimise the cultivation potential of the area.

A pilot study using multi-element soil geochemistry mapping combined with a strong acid extraction and and analysis by Inductively Coupled Plasma Mass Spectroscopy similar to Nielsen & Kristiansen (2014) was performed to detect anthropogenic elemental signals in the soil (Clausen, 2016). However the soil elemental signals could only be attributed to geological heterogeneity of the site and an Iron Age settlement predating the construction of the fortress, and not the use phase of the fortress (Clausen, 2016). The reason was likely a combination of weak archaeological signals, sampling of topsoil (0–10 cm) due to the

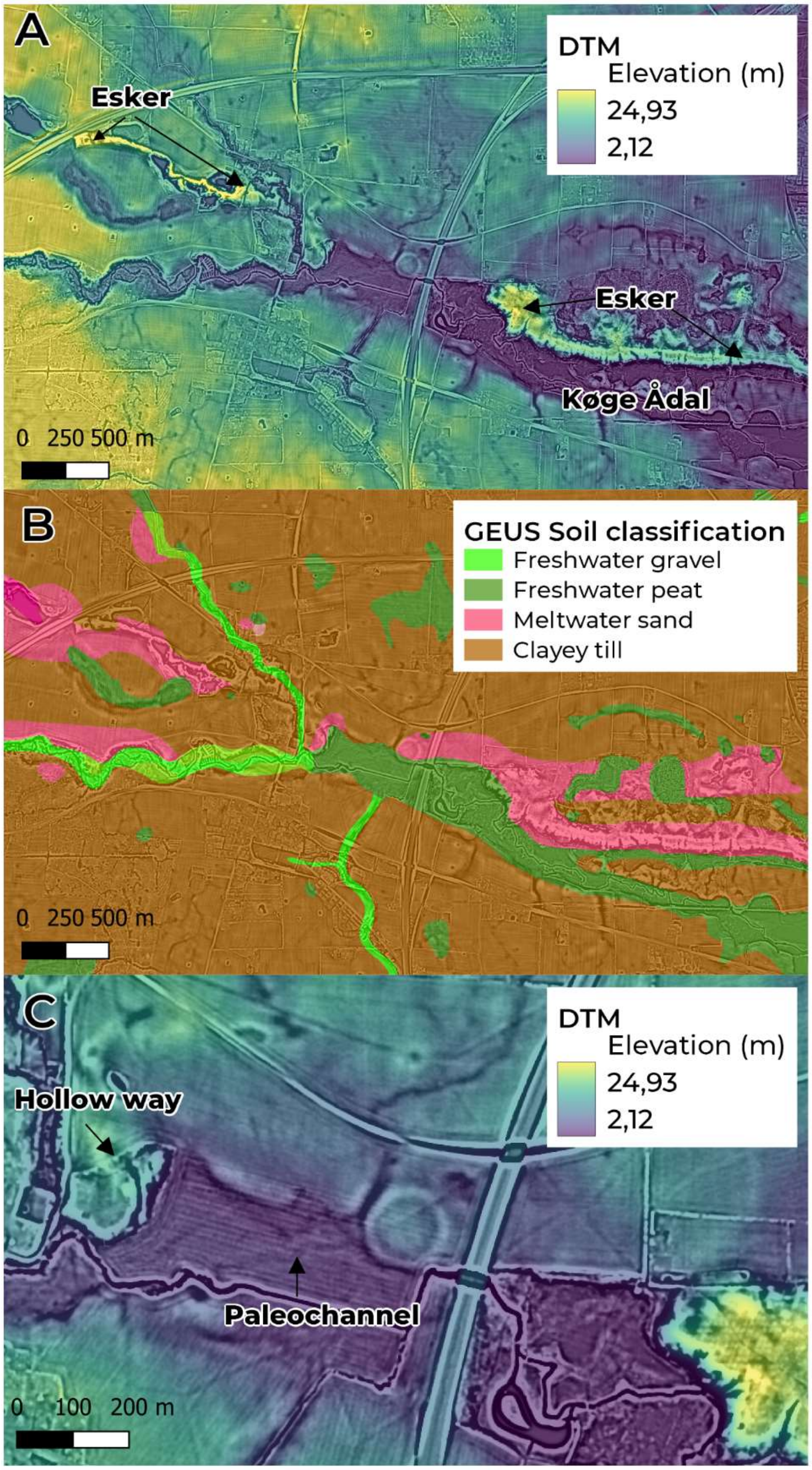

Fig. 3. Surface features at the Viking Age ring fortress Borgring and the surrounding landscape including the prominent esker to the southeast and far northwest corner, shown by a residual relief (RR) model. (a) on top of a false-colour digital elevation model (0 m above sea level blue to 40 m. a.s.l. red). (b) on top of the geological soil map (brown: clayey till, red: meltwater sand, dark green: peat, light green: freshwater sand). (c) Detail view of residual relief and terrain models showing fortress and its immediate environs. Background maps from Danish Agency for Data Supply and Efficiency.

very deep modern plough-layers/A-horizon, and strong signals from the heterogeneous Ice Age esker.

2.2. Topographic and soil data

Fig. 3a show a residual relief model based on an Lidar derived DTM from the 2014 (0.4 m spatial resolution) and 2007 (1.7 m spatial resolution) national surveys that were used to derive residual relief trend removal using convolved Gaussian filters at 2σ and 5σ using the Python programming language (Doneus et al., 2008; Hesse, 2010). This emphasised small changes in topography indicative of archaeological and geomorphological features while removing smaller scale, high frequency variation resulting from survey noise and cultivation patterns. Similarly, a low-pass smoothing filter using Gaussian weighting at 3σ and a 5 m kernel size was performed using the SAGA GIS package to smooth the DTM to remove high frequency variations as preparation for input for subsurface modelling using the electromagnetic induction data and coring data. Fig. 3b shows the publicly available soil map from the

Danish Geological Survey (GEUS).

2.3. *Coring and environmental archaeology at the ring fortress*

Systematic observations of excavation profiles and coring with a 30 mm open corer gave a detailed data-based understanding of the sediments and stratigraphy in the immediate vicinity of the fortress. These data were then fed into 3D modelling software allowing a reconstruction of the landscape prior to the building of the fortress, and the spatial extent of the modifications necessary to give a solid foundation to the ramparts (see coring details in Jessen et al., 2021).

2.4. *Electromagnetic induction survey*

The EMI data took three days to collect and is composed of 134,807 measurements with 1 m lateral distance (Fig. 4a) along driving lines. The line spacing was 1–10 m with the densest 1 m line spacing , covering the interior of the rampart and all areas within a distance of approximately 50 m from it. The used EMI instrument was a DUALEM421s which was mounted on two independent sledges and pulled behind a quadbike for efficient data collection. The collected data were carefully processed and inverted following the approach outlined by Christiansen et al. (2016) to ensure reliable interpretation of soil structures by calculating the depth of investigation for each model and removing all signals arising from human-made installations or the metallic quadbike when turning.

2.5. *Magnetic susceptibility of turfs in rampart*

In an attempt to identify the origin of the segmented anomalies comprising the rampart reported by Goodchild et al., 2017, an area (Trench 26) was excavated across a number of the segments and an intensive magnetic susceptibility survey of excavation surfaces was undertaken. These were conducted using the Bartington MS3 susceptibility meter and the MS2F and MS2D field coils. The MS2F was used on the surface of the trenches after topsoil removal. Measurements were recorded every 0.2 m along transects separated by 0.5 m, and the MS2D was used to record susceptibility on vertical profiles through the features on the exposed sections at 0.02 m intervals. The surface measurements showed a coherent spatial variation correlated with the spatial extents of

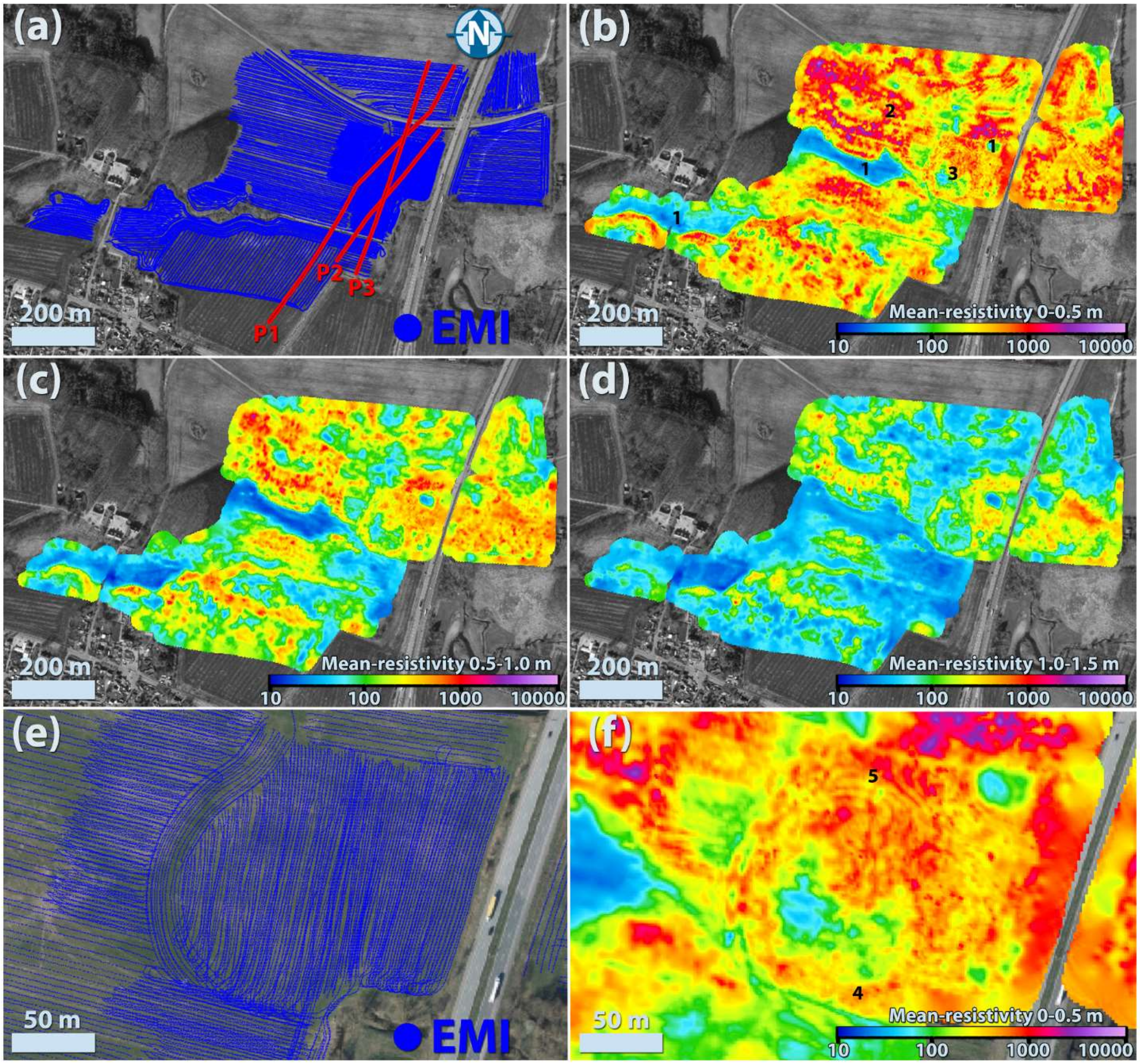

Fig. 4. (a) EMI measurements (in ohmm) and location of the three profiles shown in Fig. 5. (b) Mean-resistivity 0–0.5 m depth. (c) Mean-resistivity 0.5–1.0 m depth. (d) Mean-resistivity 1.0–1.5 m depth. (e) Zoom-in on data coverage on Borgring and (f) Zoom-in mean-resistivity map from 0 to 0.5 m depth at Borgring.

the archaeological deposits. However, in-situ measurement of the profile in the rampart (Trench 26) revealed very noisy data. This was likely as a result of the small sampling volume in heterogeneous fills, resulting in a large contribution from particles of highly magnetic gravels. To mitigate for this bulk samples of the fills were obtained, homogenised and sieved at 0.5 mm to remove inclusions, weighed, and measured using the MS2B dual frequency sensor in the low-frequency range to obtain mass-specific susceptibility measurements.

2.6. Modelling the rampart and surroundings in 3D

A depth model based on the inverted earth resistivity data from the EMI survey and the smoothed 2014 DTM was used to create a digital surface model estimating the buried ground surface prior to the construction of the fortress. Estimated depths below surface to the 100 ohmm boundary in the inverted EMI data were calculated using the Aarhus Workbench software package. This value was established empirically as representing the boundary between the infill and colluvium covering the river valley on the basis of the cores discussed above. The gridded depths from the inverted data were then subtracted from the smoothed 2014 DTM using SAGA GIS to produce a digital subsurface model, which indicated that the terrain at the time of the fortress's construction was considerably more rugged than it is today. In particular depressions on the north side of the esker appear to have been infilled by a large volume of sediment.

3. Results

3.1. Electromagnetic induction and 3D modelling of the landscape prior to fortress construction

The EMI results reveal highly heterogeneous soil structures throughout the study site. This is especially evident in Fig. 4b which depicts the mean-resistivity from 0 to 0.5 m depth. Conductive structures, which are highlighted by the number 1, are by means of boreholes correlated with organic silt from lake deposits. In the rest of the study area we mainly see soil structures with a resistivity of 100–500 ohmm (highlighted by the number 2). The resistivity differences in the till formations are caused by either a high sand/gravel content and/or saturation differences mainly driven by topography. The Borgring and rampart is clearly seen as a resistive unit in the maps (highlighted by the number 3). However, only the foundation is left, since the remaining part of the rampart has been eroded through time. This is especially evident in Fig. 4e and 4f which highlight the data coverage on the Borgring, and the resulting EMI structures in 0–0.5 m depth. Location 4 shows the rampart infrastructure, and even small-scale structures related to modern day land use can be seen as shown at location 5 which highlights plow structures. In Fig. 5a-c three cross-sections are shown running south-north on the rampart. The arrows on each profile indicates the approximate positions of the rampart.

3.2. Models based on airborne laser scanning

The residual relief model based on the Lidar data enabled us to better depict the fortress' near-perfect circular ring but also the extents of the contemporary deeply incised glacial valley west of the fortress and the small peat filled depression to the north-east became clearer (Fig. 3). The paleochannel, dated as contemporary to the fortress by Jessen et al. (2021), is clearly visible and presumably was an essential component of the fortress defenses.

The terrain model also clearly delineated the esker to the east and west of the fortress. This is relevant in terms of the placement of the fortress, as eskers historically provided convenient dry routes through the landscape (e.g. Doran 2004; O'Brien et. al 2015) and the fortress effectively controls travel along the esker.

No archaeological features are visible in the terrain model in the arable fields surrounding the fortress, as these have been heavily truncated by cultivation, evidenced by numerous lynchets and diagonal linear features resulting from tillage erosion in gathering pattern (Fig. 3). However, a short section of hollow way and a possible prehistoric burial mound are evident in the woodland 350 m to the west of the fortress.

3.3. Magnetic susceptibility of turfs

The magnetic susceptibility of the fills of the rampart revealed a strong correlation with the many smaller radial anomalies exhibiting both positive and negative magnetic gradients in the magnetometer survey. The archaeological excavations revealed the rampart was of heterogeneous construction, with the radial anomalies in the fluxgate survey corresponding to cells of differing materials used to construct the rampart. These were either dark coloured turfs and of low magnetic susceptibility (Fig. 8), or lighter coloured turf and infill with higher susceptibility. Both were mineral soils with a loamy texture and the

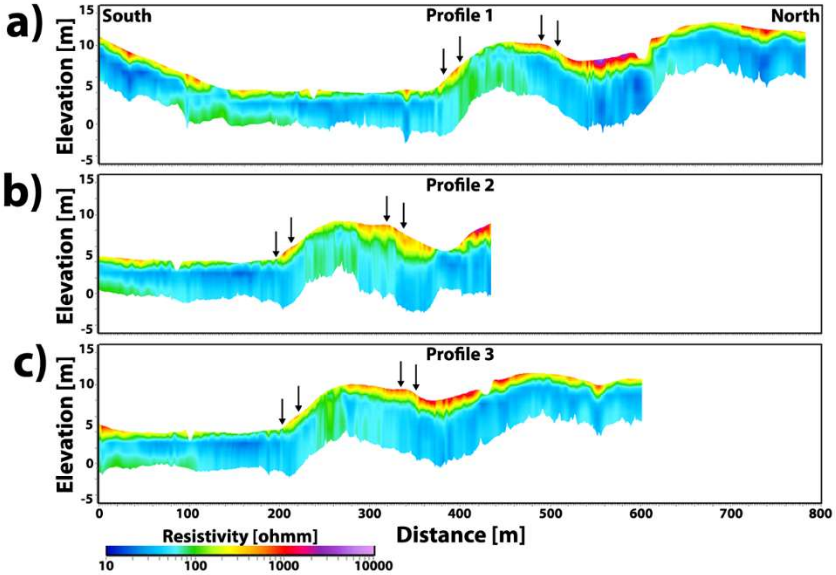

Fig. 5. 3D EMI profiles. The location of the profiles is highlighted in Fig. 4a. (a) Resistivity profile 1. (b) Resistivity profile 2. (c) Resistivity profile 3.

colour difference was caused by a smaller difference (approximately 1%) in soil organic matter content. In the gradiometer survey the former were identifiable as negative anomalies and the latter as positive.

This would seemingly indicate that the turfs used to construct the rampart were collected from different areas of the landscape. The very low magnetic susceptibility of the dark fills is indicative of waterlogged or gleyed soils (Maher, 1998; Hanesch & Scholger, 2005; Blundell et al., 2009), suggesting that these fills were likely extracted from moister soils, whereas the lighter coloured fills were likely acquired upslope of the fortress.

4. Discussion

4.1. Discussion of limitations, biases and strengths

A bias in respect to interpreting non-destructive investigation results at Borgring are the archaeological excavations from 1971 to 72 and 2014 (Goodchild et al., 2017). Here the excavated area is not exactly known from the first excavation investigating a part of the inside of the northwest quadrant and a section through the rampart to the outside of the fortress. Additionally, in 2016–2018 an area of c. 1400 m^2 was excavated over three different trenches. One trench covered the north gateway and a portion of the inside of the fortress, another trench opened the east gateway, while a third was cut in the southeast rampart. After the excavations the soil was redeposited in the trenches. However, the back-filling was by heavy machinery in the latter case which most likely re-distributed larger quantities of soil over larger areas but in thinner layers. Levelling out prehistoric monuments such as burial mounds and earth-built walls is a well-known phenomenon before the early 20th century in Denmark but we have no written indications that this took place at Borgring. However, written sources that might have elucidated this was unfortunately lost due to a fire in 1893 that destroyed the archive of the owner's estate, Vallø Stift.

At Borgring, the loamy and stony moranic subsoil, and the very heterogenous geological subsoil due to the esker (Gravesen et al., 2017) is likely a significant constraint on high-resolution non-destructive investigation by geophysical methods. As examples, the 5-m deep 100 Ohmm boundary west of the ring is believed to be entirely due to a 10 × 10 m spot of heavy clay, while solifluction-reworked fluvio-glacial silty layers underneath the east gate could likely explain some features seen in the EMI maps (Figs. 3 and 4) here.

4.2. Magnetometry data and re-evaluating traces of houses inside the fortress

The fluxgate gradiometer survey undertaken by Goodchild et al. (2017) identified a number of discrete features interpreted as possible pit houses, as well as the radial anomalies within the fortress rampart. No evidence of pit houses were identified during subsequent excavation, although a number of these anomalies did correspond with prehistoric cooking pits. The radial anomalies in the rampart were interpreted by Goodchild et al. (2017) as segmented timber cell structures similar to those found at the other Trelleborg type ring fortresses. However, the magnetic susceptibility readings obtained from the rampart fill indicate that these anomalies result from the fills of these cells being extracted from different areas of the landscape rather than a possible timber substructure.

At other ring fortresses, such as Aggersborg (Brown et al., 2014), magnetometry and GPR has been used in conjunction to successfully identify anomalies indicating a substantial number of features related to both the construction of the fortress and the pre-existing settlement. In particular, the surveys revealed elements of the fortress's street plan and radial structures within a portion of the rampart indicative of its construction. A large number of pit houses likely predating the fortress were also identified. These buildings are often readily detected in geophysical surveys by electromagnetic methods, using similar instruments (DeSmedt et al., 2013, 2014; Filzwieser et al., 2017), as they often exhibit strong contrast with the surrounding subsoils on sandy soils. This is due to a combination of pit houses of larger size, foundation stones and/or post-hole back-fillings, artisanal and metal production, and a tendency to be infilled with midden materials after the buildings go out of use (Sindbæk (2014). While results from Aggersborg are encouraging the surveys at Borgring (Goodchild et al., 2014; Figs. 3 and 4) did not successfully identify any arrangements of houses diagnostic of this type of fortress, which may result from the heterogeneous geology described above, low electromagnetic and magnetic contrasts, and the small scale of the features relative to the sampling density of the data as found in other investigations (e.g., Rundkvist and Viberg, 2015). However, subsequent excavation of the site, covering some 30% of the fortress's interior, did not identify any substantial structures contemporary with the fortress (Christensen et al., 2021) and Ulriksen et al. (2020) accordingly suggested that these buildings may not be present at Borgring and our data arguably support this conclusion.

4.3. The construction of the rampart

The EMI mapping provided detailed information on the rampart architecture and structures related to modern land use (Figs. 4–6).

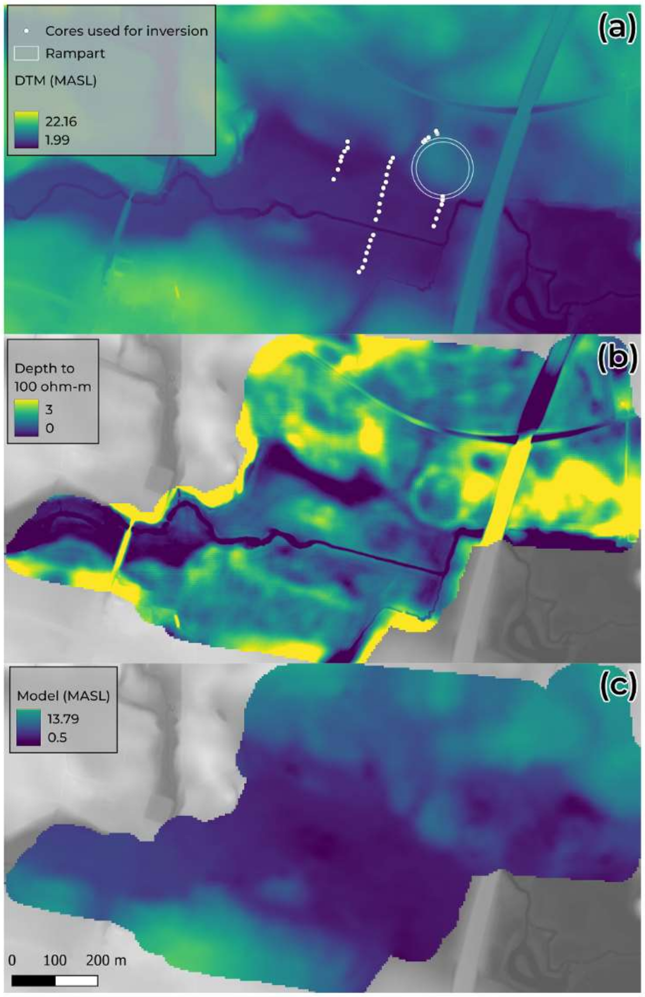

Fig. 6. Derivation of the electromagnetic induction (EMI) derived subsurface model showing the considerable accumulation of colluvium infilling in the valley, and the likely extent of deposited material enlarging the promontory the ring fortress is built on. (a) *o:* Lidar derived digital elevation model (DTM) and coring locations (b) Depth from surface to 100 ohmm boundary. (c) Subsurface model derived by subtracting depth to 100 ohmm boundary from the DTM.

Former lake deposits were likewise visible in the results, providing knowledge of the prehistoric waterways. Most importantly the EMI results could be used to reconstruct the buried ground surface prior to the construction of the fortress, indicating that substantial deposition of material was required to make space for the fortress.

The magnetic susceptibility and magnetometry surveys demonstrate that the material used to construct the rampart was extracted from different areas of the landscape. However, there is no clear spatial demarcation between where turfs were deposited in the rampart and where they were likely extracted from the waterlogged soils of the river valley or upslope on the glacial tills and meltwater sands. This possibly reflects the organisation of the construction where the material was deposited in wagon loads coming from nearby, upland areas as discussed in Mortensen et al. (2021).

Pollen analysis made on turfs used for the rampart shows great uniformity between the samples, indicating that they were harvested from the same vegetation type (Mortensen et al. 2021). The analysis likewise shows that the turfs were cut in an open, grazed agrarian landscape. Turfs with a low organic content seems to be preferred likely since they would reduce any later settling of the ramparts. If the turfs were harvested as close to Borging as possible to minimize the workload, the nearest dryland area would be located directly north of the construction site (Mortensen et al., 2021).

4.4. Archaeological implications

The Trelleborg-type fortresses are evidence for political evolution in the late Viking Age state formation at the transition to the medieval world, with military installations being a key parameter (Thurston, 2002) as a demonstration of power (Ulriksen et al., 2020). Most of the ring fortresses were located close to central fords leading major roads across river valleys. Considering Aggersborg, the traffic had to cross the Limfjord by boat. The size of each ring fortress was obviously not negotiable even if it did not fit the size of the equally important choice of building ground. Instead, large-scale pre-construction modelling of the landscape took place at least at four of the five Danish ring fortresses, including Borgring. Here, the construction workers initially had to transport an estimated 1900 m^3 of clay to the construction site in order to provide a solid foundation for the ramparts (Jessen et al., 2021). Then the gateways of timber and the rampart of turfs and soil were built. The soil multi element mapping (data not shown) suggested that there have been no major human activities inside the ring fortress. This is supported by the fact that neither the typical square blocks of houses nor the roads connecting the four gateways were found during excavation (Christensen et al., 2021). As a matter of fact, there was no waste left behind to indicate that people have stayed here in the late 10th century. All in all this may indicate that beside the rampart, the construction of Borgring was never finished.

The landscape has changed considerably since the Viking Age due both to natural processes mainly in the valley bottom but especially due to human induced tillage erosion and the intentional smoothing of the landscape by depositing large amounts of material to improve cultivation. The site investigation was, therefore, a complex and detailed assessment of the sediments and stratigraphy, as all data shows limited post-rampart construction activity, but the subsequent heavy erosion could have obliterated shallow surface features in places as discussed in Ulriksen et al. (2020). The model of the palaeo-surface of the site reveals an important context for the choice of the building site. Before the subsequent erosion and levelling, the summit and shoulder of this moraine plateau where the fortress was constructed in between two late-glacial erosion valleys was more prominently located along the river course. This would have presented the site both with high visibility and with defensive qualities. This may help to explain why the particular place was selected, despite the need for substantial landscaping. The extend of the levelling can be reconstructed with some precision from the EMI derived subsurface model (Figs. 6 and 7). The levelling indicated by EMI in the northeast quadrant (Fig. 9b) was only partly identified as such during the auguring and excavation (Jessen et al., 2021) suggesting that the EMI model might over-estimate the extend of the levelled area here. While substantial, the landscaping was hardly more extensive than seen at the contemporary ring fortress Fyrkat (Fig. 9). Despite the pronounced relief of the landscape, this was evidently a favourable and manageable location for the ring fortress.

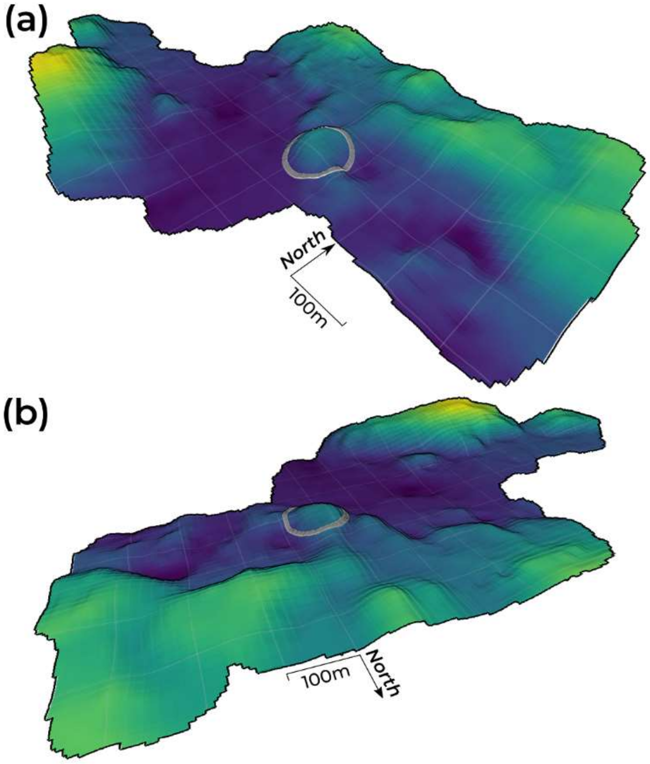

Fig. 7. Isometric 2.5D view of rampart location superimposed on subsurface model showing that the palaeo-surface of the morainic knoll the fortress was constructed upon was likely far more prominent along the river course before modern erosion than it is today, indicating why the site was selected for a fortress. (a) seen from southeast. (b) seen from northeast.

5. Conclusion

This Viking Age site located on a very heterogeneous geological subsoil and with a long history of erosion and re-deposition had major restrictions to non-invasive methods. The geoarchaeological investigation nevertheless revealed that: 1) 2D- and 3D-mapping are possible and cost-efficient when based on combined geophysical methods, coring and profile data, 2) on the loamy soil the EMI had difficulties distinguishing between archaeological sediments and geological subsoils, 3) mapping by soil geochemistry was not possible due to a combination of an Iron Age settlement and significant post-use erosion and re-deposition, and that 4) larger scale magnetic susceptibility mapping was better suited on this large earth-build construction, though it requires calibration from the identified features to reveal its full archaeological potential.

In an archaeological perspective the results support that the building ground for Borgring was chosen because it was the right spot in a strategic sense. The natural landscape's perceived spatial flaws were dealt with by pre-construction levelling of the terrain to fit the diameter of the rampart. Neither the location nor the size of the ring fortress seems hence negotiable.

CRediT authorship contribution statement

Søren M. Kristiansen: Conceptualization, Investigation,

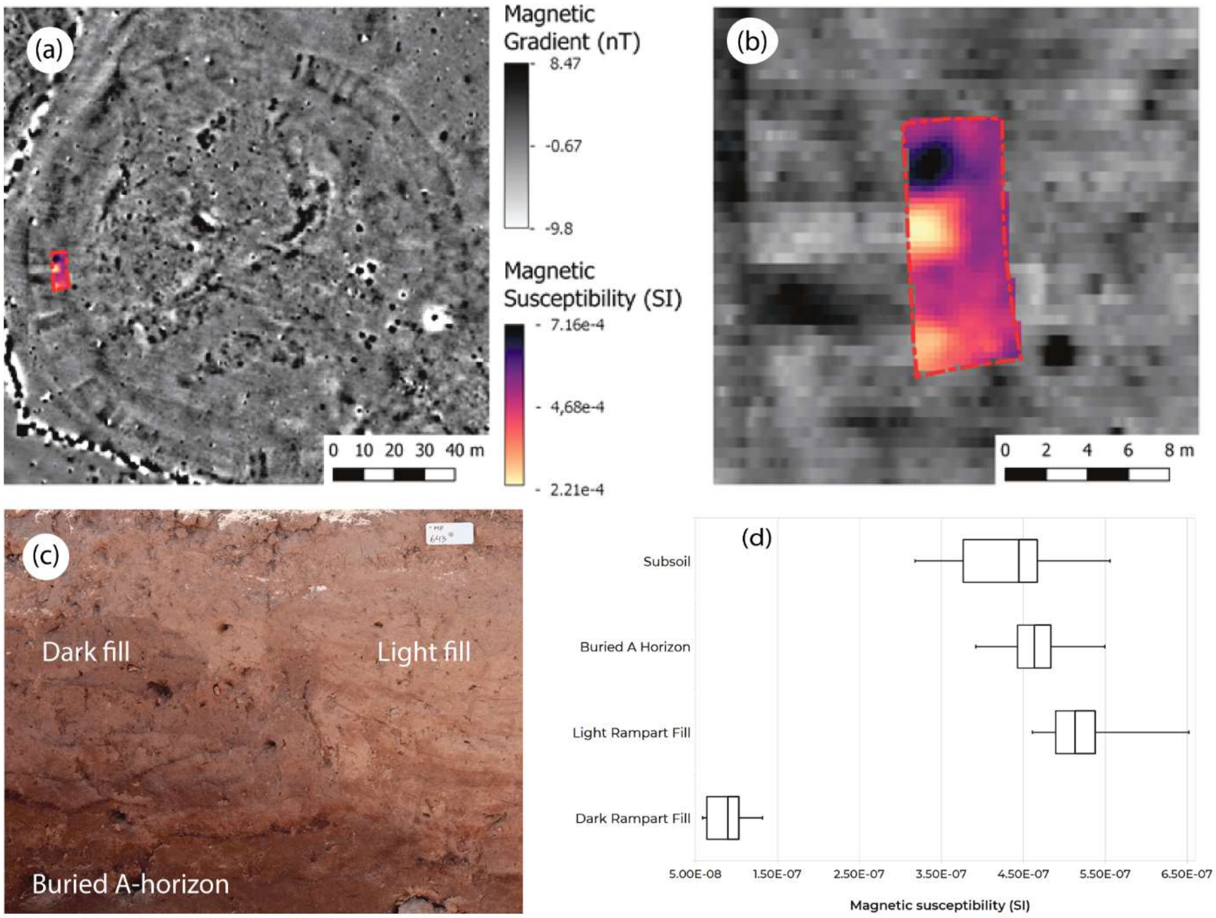

Fig. 8. Magnetic susceptibility data. (a) Fluxgate gradiometer magnetogram from Goodchild et al., (2017) revealing the circular, segmented rampart and the sampled excavation trench (trench 26, red square). (b) Magnetic susceptibility over the rampart after topsoil removal, (c) Image of profile in Trench 26 where the boundary between the ramparts' light and dark fill layers can be seen. (d) A magnetic susceptibility box-whisker data plot from the fill layers and the natural A-horizon soil surface underneath.

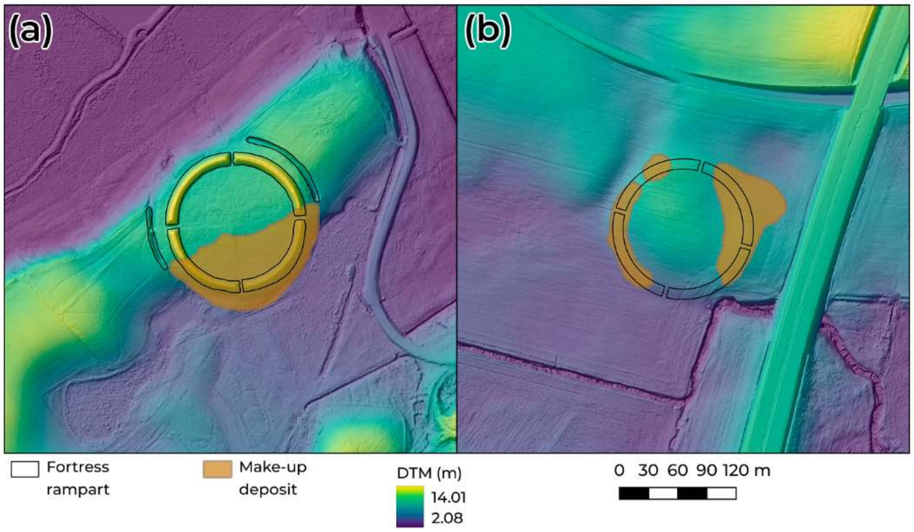

Fig. 9. Comparison between the Viking Age ring fortresses Fyrkat and Borgring, showing approximate extent of make-up deposits enlarging the natural promontory to make space for the fortresses. (a) Fyrkat. (b) Borgring. Fyrkat extent after Olsen and Schmid (1977).

Methodology, Project administration, Writing – original draft. **David Stott:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing. **Anders Vest Christiansen:** Methodology, Project administration, Writing – review & editing. **Peter Steen Henriksen:** Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Catherine Jessen:** Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Morten Fischer Mortensen:**

Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Jesper Bjergsted Pedersen:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Søren Michael Sindbæk:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing. **Jens Ulriksen:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

The data that supports the findings of this study are available upon request to the corresponding author.

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