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On the interpretation of geophysical data and the suggested presence of a western moat at Gråborg on Öland

By Andreas Viberg, Christer Gustafsson and Jarrod Burks


In 2007 a magnetometer survey was carried out at the ring fort Gråborg on the Swedish island of Öland. The results were interpreted as indicating the remains of over 60 buildings, several roads, wells and a large moat outside the fort’s north-western gate. In 2011 these interpretations were severely criticised, and it was suggested that the moat-like anomaly in the geophysical data had actually been caused by a lightning strike. It was also suggested that none of the other interpreted features were actually supported by the presented magnetometry data.

This paper presents the results of a ground-penetrating radar (GPR) survey of the same area. The GPR data were collected in 2014 using the multi-antenna Malå Imaging Radar Array (MIRA) system, covering an area of approximately 3.8 ha. The results show that the ground inside and outside the fort’s walls is heavily disturbed by farming. Most of the underground features visible in the data can be interpreted as drainage ditches and power cables, but a few linear features are identified as being of possible archaeological interest. When comparing the radar data to the buildings, roads and wells suggested in the magnetometry interpretation, no apparent correlation can be established. There is furthermore no sign of any moat in the suggested area. The GPR results therefore support the idea that this moat-like feature is indeed the remains of a lightning strike.

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The ring fort Gråborg is on the Swedish island of Öland in the Baltic Sea (fig. 1). It is the largest Iron Age fort on the island, with a diameter of 170–220 m and an internal area of roughly 2.5 ha. Limited archaeological excavations and metal detector surveys indicate that the fort was built in the Late Roman Iron Age (AD 150–375) and was used until the Scandinavian Middle Ages (Stenberger 1933, p. 234; Malm 2003, p. 5). Rich historical records and maps survive, demonstrating that the interior of the fort has been farmed at least since the beginning of the 17th century.
(Tegnér 2008b, p. 44). Abraham Ahlvqvist (1822, p. 270) furthermore states that building foundations were visible within the fort before the area was subjected to farming. Today, nothing is visible above ground and the internal space consists of flat fields separated by drainage ditches (fig. 2). Masonry belonging to the fort’s outer perimeter wall survives, but in many places it has collapsed. The collapsed sections are today up to 20 m wide, but at certain well-preserved sections the original width and height can be estimated to roughly five and six metres, respectively (Swedish registry of ancient monuments, FMIS). Gråborg and its surrounding areas are now owned by the Royal Swedish Academy of Letters.

Because of its large size, only limited archaeological excavations have been carried out within the fort (fig. 2). These excavations took place from 1998 to 2002 and provided evidence of a possible building next to the perimeter wall in the east (trench 1 in fig. 2), as well as other possible settlement remains within the fort (Malm 2003). However, all of the excavated trenches also revealed clear evidence of intensive farming, which has over the years had a detrimental effect on the preservation of subsurface structures inside the fort. In addition to excavations, metal detector surveys have been carried out both inside and outside the walls (e.g. Erlandsson 2015).

Geologically, the area consists of clayey glacial till soils and limestone bedrock. The bedrock within the fort is very superficial and visible at ground level near the large clearance cairn (cf. fig. 8). During the 1998–2002 excavations, culture layers of 0.4–0.6m thickness were excavated before the team reached the underlying soils and bedrock.

In 2007 the Academy of Letters funded a large-area geophysical survey both inside and outside the walls. It was carried out by the Swedish company SAGA-geofysik, who used a magnetometer (Bartington dual gradiometer 6c1-2) to cover
roughly 17 ha of land. The data were collected every 25 cm inline, in survey transects separated by 1 m. The results were described as spectacular and were interpreted as providing evidence of more than 60 buildings, a large number of roads, a well and a roughly 120 m long structure interpreted as a wide moat (fig. 3). This interpretation was published on the company website (http://www.geofysik.com), in a short article in the popular journal *Populär Arkeologi* (Danielsson 2007), and in a book on Gråborg published by the Academy of Letters (Tegnér 2008a).

These results and interpretations were subsequently severely criticised by Immo Trinks & Anders Biwall (2011b), who claimed that “none of the presented interpretations were supported by a corresponding, plausible physical anomaly visible in the presented data” (p. 351) and that the interpretation of the magnetic data was more “based on wishful thinking than on factual data” (p. 353 f). They further suggested that the large moat-like anomaly should be interpreted as the site of a lightning strike rather than a cultural feature. Trinks & Biwall supported their position with reference to 2D ground-penetrating radar (GPR) measurements they had carried out on site in November 2008. They saw no signs of any large moat at the location in question (2011b, p. 352).

The critique of the interpretation of the magnetometry data was later called into question by Robert Danielsson (2012), property manager for the Academy of Letters, who welcomed the discussion but criticised Trinks & Biwall for not publishing their collected radar results, as well as for collecting them without the approval of the landowner. Danielsson (2012, p. 127) also pointed out that most discovered Lightning-Induced Remanent Magnetism anomalies (LIRM) are star-shaped and not nearly as long as the anomaly encountered outside Gråborg.

A quick look through the archaeological geophysics literature shows that LIRM anomalies can appear in several different shapes, not only as stars (e.g. fig. 4; Burks 2014; Burks et al. 2015 for a variety of different types). These anomalies are often much shorter than the one discovered at Gråborg, but examples from USA and Wales show they can extend for more than 90 m (e.g. fig. 4–5; Crew 2008; Burks et al. 2015). The current flow generated during a lightning strike typically follows the path of least resistance, and therefore often moves along the length of plough scars and other near-surface features that hold moisture or conduct electricity well. They can also follow the paths of deeper features, such as subsurface ditches or ancient stream channels that have been filled out.
However, in such cases we might expect the subsurface feature to appear in the data from other geophysical methods, for example GPR. In the case of Gråborg, the direction of ploughing is almost perpendicular to the measured magnetometer anomaly, suggesting that the large LIRM is following something else in the ground – possibly beneath the plough layer.

In order to investigate whether any building foundations, roads, wells or moats are indeed present underground at Gråborg, co-authors Viberg and Gustafsson surveyed the area in May 2014 using a motorised ground-penetrating radar system called the Malå Imaging Radar Array (MIRA). The surveys were carried out as a part of the project The Big Five, financed by the Swedish Research Council and the Academy of Letters (Viberg 2015). The project aims to survey several large ring forts on Öland in order to produce new information on the preservation and presence of possible subsurface features of archaeological origin. So far surveys have been carried out at Gråborg, Vedby borg, Löts borg and Bårby borg. An earlier survey in another fort on Öland, Sandby borg (Viberg et al. 2014), has shown that GPR is a suitable instrument for detecting fort-related features, for example, the stone foundations of buildings and roads inside the forts.

The MIRA system used in this project consists of nine transmitting and eight receiving individual antenna elements with a centre frequency of 400 MHz. The antenna elements are fixed in a box which is pushed across the survey area using a small garden tractor (fig. 6). Each survey swath results in 16 perfectly positioned individual data channels. Other system configurations are available depending on the desired swath width and antenna frequencies. The system used at Gråborg had a swath width of 1.36 m, and when the survey conditions are comparable to the Gråborg area, it is possible to cover 2–3 hectares per day at a very high resolution (see Trinks et al. 2010 for an extended discussion of the system). The instrument has been tested on several occasions in Sweden at sites including Birka, Uppåkra and Old Uppsala (Biwall et al. 2011; Trinks & Biwall 2011a; Trinks et al. 2013).

The 2014 surveys were encouraged by Academy of Letters and covered both the area of the possible moat northwest of the fort and the interior of the fort itself. The measurements covered approximately 3.8 ha: data were collected every 8 cm in-line with a crossline sample spacing of 8 cm (i.e. the distance between the antennas in the box). This offered the possibility of detecting and properly interpreting archaeological features roughly
16 cm in diameter. In order to ensure accurate spatial positioning, the system was connected to an RTK-GPS accurate to a couple of centimetres. The data were processed using the rSlicer software and the resulting Geotiff images were imported into ArcMap 10.2.1 for interpretation. The velocity for the time to depth conversion was estimated at 0.1 m/ns by hyperbola fitting in the rSlicer software.

The results of the radar survey are presented in fig. 7. The main impression they convey is that the areas both outside and inside the fort have been heavily affected by intensive farming. Most clearly discernible features discovered by the GPR represent power cables and drainage pipes at a depth of no more than 65 cm. Only faint remnants of possible archaeological features are present in the data. Nothing of note was observed in the data from 65–285 cm below surface. Two larger linear features are, however, interesting in the near-surface results. One passes through the middle of the fort and fits well with a ditch-like feature discovered during the excavations of 1998–2002. Another interesting linear feature is seen in the southernmost part of the fort. This feature follows the curvature of the wall and may by analogy to better-preserved sites identify the northern boundary of a group of buildings built...
against the wall (fig. 7–8). Similar linear features have been identified at Bårby ring fort (Viberg forthcoming).

Looking specifically at the area where the suggested moat should be, it is obvious that no such feature exists in the GPR data. A slightly darker linear area can be seen just west of parts of the suspected LIRM anomaly, but the two do not coincide, being over 7 m apart (cf. fig. 8). Even though electrical current from lightning has as noted been known to follow the direction of ploughing and subsurface streams or erosional channels, this does not seem to be the case at Gråborg as no subsurface features are visible in the data and the direction of ploughing is perpendicular to the LIRM anomaly. Such anomalies would also most likely be broken up by ploughing, if the current has travelled within the plough zone. Since the area outside Gråborg is ploughed regularly, and was in fact ploughed immediately after the 2007 magnetometer survey, the LIRM anomaly may have been negatively affected if it is shallow.

One possibility, which must be taken into ac-
Tab. 1. Peak anomaly strengths of ditch features in magnetic data from different sites in glacially impacted environments (Ohio, USA) similar to the Gråborg setting.

<table>
<thead>
<tr>
<th>Site (physiographic setting)</th>
<th>Peak anomaly strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holder-Wright Group (upland)</td>
<td>-2 nT</td>
</tr>
<tr>
<td>Hahn (floodplain terrace)</td>
<td>6 nT</td>
</tr>
<tr>
<td>Plain Hill (upland)</td>
<td>7 nT</td>
</tr>
<tr>
<td>Tremper Earthworks (glacial outwash terrace)</td>
<td>7 nT</td>
</tr>
<tr>
<td>Jones Group (upland)</td>
<td>14–15 nT</td>
</tr>
<tr>
<td>High Bank Works, Turpin Tract (glacial outwash terrace)</td>
<td>10 nT</td>
</tr>
<tr>
<td>Shriver Circle (floodplain terrace/glacial outwash terrace)</td>
<td>12 nT</td>
</tr>
<tr>
<td>Junction Group (glacial outwash terrace)</td>
<td>17 nT</td>
</tr>
<tr>
<td>Steel Group (floodplain terrace)</td>
<td>17 nT</td>
</tr>
<tr>
<td>Hopewell Mound Group (glacial outwash terrace)</td>
<td>18 nT</td>
</tr>
<tr>
<td>Reinhardt Group (upland)</td>
<td>25–29 nT</td>
</tr>
<tr>
<td>Winegardner Works (floodplain)</td>
<td>34 nT</td>
</tr>
</tbody>
</table>

count, is that soil-filled ditches and moats might not show up in GPR data because of a lack of physical contrast (e.g. if the ground is extremely dry). This has been shown on several occasions in Ohio, USA. Given that the LIRM anomaly roughly follows the outline of the fort and that such anomalies are known to follow the path of least resistance, the curving LIRM anomaly at Gråborg might point to the presence of a low-resistance ditch that has failed to show up in the GPR data. Co-author Burks has recently detected a LIRM following along a ploughed-down earthwork embankment wall, which was running at an oblique angle to the plough marks at the surface. However, we argue that this is unlikely in the case of Gråborg as two separate GPR surveys have been conducted over the anomaly (one in November and one in May), and given this seasonal spread some indication of a buried ditch should be apparent. In order to take every possibility into account, we recommend that the magnetometry and GPR data be complemented by an electrical resistance survey and/or a small test excavation. This will provide the final piece of the puzzle and put this question to rest.

Continuing the comparison between the GPR data and the magnetometry interpretations from SAGA-geofysik, the roads posited on the basis of the magnetic data likewise do not appear in the radar data (fig. 7). Nor do any of the suggested building foundations correlate with any possible posthole anomalies in the GPR data. From an archaeological point of view, the suggested buildings in the magnetometer data interpretations are quite peculiarly sized and do not fit with what is known about prehistoric or Medieval buildings on Öland. Furthermore, the only well that actually exists in the place suggested in the magnetometry interpretation is the stone-lined one inside the fort that is clearly visible above ground without the aid of geophysics. It was identified already by Abraham Ahlqvist (1822, p. 270) in the 19th century.

Note also that a metal detector survey was carried out in 2011, both inside the fort and in the field where the supposed moat and all the building foundations would be situated. Only five metal objects were found in the “moat field”, which does not support the idea of this being a densely populated area with several buildings on Öland. Furthermore, the only well that actually exists in the place suggested in the magnetometry interpretation is the stone-lined one inside the fort that is clearly visible above ground without the aid of geophysics. It was identified already by Abraham Ahlqvist (1822, p. 270) in the 19th century.

Apart from the possible areas of interest identified by the GPR, it is likely that the best loca-
tion for finding preserved building foundations within the fort would be under the rubble along the perimeter wall, as was the case in trench 1 (fig. 2). Elsewhere the radar data suggest that ploughing has effectively removed any building remains.

**Magnetometer survey of 2016**

In order to assess whether the large magnetic anomaly has indeed been affected by recent ploughing, a small test survey was conducted with a magnetometer in May 2016 (fig. 9). The area measured 50 x 27 m and was laid out over the central parts of the magnetic feature. A secondary goal was to measure the strength of the anomaly, as this might aid in determining its source. A single-probe Foerster Ferex 4.032 fluxgate gradiometer was used to measure the vertical gradient of the Earth’s magnetic field. The data were collected every 10 cm inline, in transects separated by 0.5 m. Post-survey data management and filtering was carried out in the software Data2Line, where the data were corrected for zero mean traverse (ZMT) and median filtered (5x5) before finished images were exported into ArcMap 10.4.1 for interpretation and map production.

The results show that the anomaly is still intact and unaffected by the ploughing. This indicates that the current has taken a deeper path below the plough zone and is not affected by the agricultural activities in the area. As for the strength of the anomaly it can be shown to have peak magnetic values of between +410 and -526.9 nT. As the typical magnetometer response for a soil-filled pit or ditch is commonly rather weak (tab. 1; Schmidt 2007, p. 26), it can be concluded that this anomaly does not represent a soil-filled moat.

**Conclusion**

Comparing the data from the magnetometer survey and its interpretation with the GPR data collected in 2014, it is clear that the suggested moat outside Gråborg is missing from the GPR data. Rather than a moat, we argue that the large bipolar feature in the magnetic data is most likely a LIRM anomaly, as previously suggested by Trinks & Biwall (2011b). LIRM anomalies can have a differing number of arms, sometimes only two, and they can extend for more than 100 m.

The GPR data also provide evidence that the suggested buildings, roads and wells, as presented in the previous magnetic interpretation maps, may also be misinterpretations. There are no indications of these features in the GPR survey results. Furthermore, a metal detector survey carried out in 2011 failed to find the numbers of metal objects that would be expected in a densely populated area. In the case of Gråborg, and based on the available archaeological evidence at this and other similar sites, the best chance for finding *in situ* preserved remains of buildings is under the rubble along the perimeter wall. A new magnetometer survey of the central parts of the suspected LIRM anomaly shows that the feature has an anomaly strength of more than 400–500 nT. Such
a strong response should be caused by a remanent magnetic feature rather than by a soil-filled moat with slightly elevated magnetic susceptibility.

We recommend that the previously conducted surveys be complemented by an electrical resistance survey and/or a small archaeological test excavation in the area of the large LIRM. These tests should finally put to rest the question of whether or not a moat is present outside Gråborg.

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References

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