LÖDÖSEHUS: GEOPHYSICAL METHODS FOR DESCRIBING ARCHAEOLOGY AND NEAR-SURFACE GEOLOGY AT THE SITE OF A MEDIEVAL CASTLE IN LÖDÖSE, SW SWEDEN

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ABSTRACT

Near-surface geophysics is a well established method for mapping the geological conditions in the subsurface. The use of geophysics is also a commonly used method in archaeological surveys, although traditionally not as much in Sweden. Ground-penetrating radar (GPR) is however gaining more popularity and is arguably the most used method in archaeology due to the amount of data that can be gathered in a short amount of time and with little effort. This study was done mostly with GPR together with a resistivity and induced polarization (IP) survey with the aim to compare the methods with each other. Data gathered with the GPR can be visualised in 2D and 3D and it is therefore of great interest to compare these data forms. The study area is located in Lödöse, SW Sweden, which was one of the most important cities in medieval Sweden. The survey presented in this thesis was done over the former courtyard and outer bailey of a castle with a triple moat system once called Lödösehus. Today there are no visible remains of this castle and only a small part of the outer bailey has been excavated. The 3D GPR data showed previously excavated structures along with two larger, previously undiscovered structures. The 2D GPR data showed reflections from two of the moats and identified anomalies in the 3D data as postholes and structures. The resistivity survey potentially identified an unexcavated moat and showed that the top 5 meters of the soil has unusually high resistivity values for clay. This indicates a high degree of leaching of salts or thick deposits of anthropogenic waste which could explain the exceptional penetration depth with the GPR in an area of clay. The IP survey showed an area of electrical chargeability in connection to the potential moat that was found in the resistivity survey, indicating the possibility of metallic objects in the area. This study has greatly increased the archaeological knowledge of Lödösehus and provides exact locations of previously excavated structures. Furthermore, new areas of interest have been identified for future excavation in order to learn more about the history of one of the largest cities in medieval Sweden.

Key words: *Near-surface geophysics*, *Ground-penetrating radar*, *Resistivity*, *Induced Polarization*, *Archaeology*, *Leached clay*, *Medieval castle*, *Lödösehus*, *Lödöse*, *Sweden*

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Furthermore, I (Fredrik) would like to thank Alaël, the love of my life, who supported me in every way imaginable through the process of writing this thesis and for making every day feel like a Friday; My mother, Eugenia, for her constant support throughout my life and for reminding me of holding my head high and never lose sight of my objectives; My sister, Michelle, who taught me the discipline of studying and who is always there for me when I need someone to confide in, My father, Jörgen, for gifting me a passion for history and archaeology and from whom I always learn something new; My friend, Kyle, whom I met on a narrow street in McLeod Ganj in the Himalayas years ago and made sure that this thesis is written in the English it deserves to be; My dog, Zorro, for reminding me of the value of living in the moment and being happy for the little things in life.

CONTENTS

1 INTRODUCTION

This is a report that is one part of a larger study that was done on in two areas in Lödöse, SW Sweden. This report will be focused on Lödösehus, the castle that once stood on a hill overlooking the medieval town of Lödöse. The other part, The Monastery Hill, will be covered in Möhl & Andersson (2021). All data that was gathered, processed and interpreted in both papers has been done so in close collaboration.

1.1 Geophysics in archaeology

A question that always benefits from being answered by earth scientists or geotechnical engineers is what appears beneath the ground's surface. This is generally done by drilling, soundings or test pits, which can provide point data that can be combined into models. In some cases, there is a need to construct a full image covering all data points in the study area without disturbing the sediment (or at least to get data points between drill holes). This is where remote measurements like geophysics come in to map the subsurface (Musset & Khan, 2000, p. 4). There are several different tools used in geophysics that all have different applicability with their associated pros and cons.

The development of geophysical techniques and equipment often has its roots in oil and mineral exploration, but these have since been adapted to nearer-surface investigations in environmental and engineering surveys. For geophysics to work at its full potential, there is a need for a measurable contrast of the physical properties between different mediums. Archaeological remains in the subsurface provides a sharp contrast to the surrounding sediments and for this reason, geophysics is also used in archaeology (Milsom & Eriksen, 2011, p. 1).

Despite Sweden being one of the leading countries in the development of near-surface geophysics, geophysical surveys are not commonly used in archaeology, perhaps with the exception of simple metal detectors. One reason for this is Sweden's geology and land cover. Approximately three quarters of the land surface is covered by forests and other wooded areas that generally prohibit effective measurements. Also, the Weichselian glaciation has left a surface cover of till and other glacial sediments. The combination of forests and unsorted, heterogeneous sediments has made it difficult to gather data of both quality and quantity. Further problems can occur where the depth to bedrock is shallow, which can affect the collected data, or where a thick layer of clay is present, that may limit the penetration depth of some surveys. Still, there are numerous archaeological sites in Sweden with promising geophysical survey conditions. Geophysics has previously most likely not been used due to bad initial experiences and tradition (Viberg et al., 2011). However, geophysics in Swedish archaeology is becoming more popular, especially the use of ground-penetrating radar (Rundkvist & Viberg, 2014).

This master thesis will hopefully shed light on the potential of geophysical surveying in archaeology. Since ground-penetrating radar has been of great success in Sweden in recent times, (e.g. (Karlsson et al., 2014; Viberg & Wikström, 2014; Westergaard et al., 2019)), it is of interest to investigate if other geophysical instruments, such as resistivity and induced polarization, can be proved to be of use. The benefit of geophysical instruments are myriad: they are non-destructive, can pinpoint areas, thus allowing archaeologists to know where to and where not to conduct an excavation, they can provide complementary information to excavations, and they can also find areas of interest that would otherwise remain undiscovered (Viberg et al., 2011). The use of geophysical surveys are also indirectly recommended by the Council of Europe. The Valletta Convention states that non-destructive methods of investigation should be applied wherever possible to protect the archaeological heritage (Council of Europe, 1992).

Two different geophysical methods will be used in this study: ground-penetrating radar (GPR) and resistivity/induced polarization. The geophysical aspects of the different tools will be tested by the archaeological objects. Since ground-penetrating radar was mainly used in this study, a key question will be if data is best interpreted with 2D or 3D visualisation. Furthermore, since a complementary resistivity and induced polarization survey was conducted, another question to be considered will be if these methods serve as a valuable tool for archaeological surveys. Known archaeological features mapped from previous excavations will be used as a guide to interpret and understand the geophysical data surveyed over areas not yet excavated.

1.2 Geological setting of Lödöse

Lödöse is located in the Göta river valley (Figure 1.1). The area was covered by kilometers of thick ice during the last glaciation. The ice started to retreat from the Gothenburg area around 14,500 years ago and the Göta river valley was completely ice free 2,000 years later (Klingberg et al., 2006). At this point the land started to rise owing to isostatic forces, but the valley was still under water with marine and archipelagic conditions. The water was calm with relatively weak currents since the valley was protected by a large island to the west. The salinity was high in the deep water, while the surface water was brackish. As the isostatic rebound continued, the valley had 11,000 years ago become a strait between the main land and the large island in the west (Klingberg et al., 2006).

Thick layers of clay were deposited in the deeper water. Cohesive soil layers 60-80 meters thick are commonly found in this area (Fredén, 1986, p. 42). The depth to bedrock can be even deeper locally, for example south of Lödöse where the depth can be over 100 meters. The soil mainly consists of glacial clay with post-glacial clay overlying it (Fredén, 1986, pp. 42, 50). Gravel and pebbles can occur in the clay. These would be dropstones that have been deposited by melting icebergs (Klingberg et al., 2006). Non-cohesive soil can also be found between the bedrock and the clay (Figure 1.3). This is the case in Lödöse, where a drill core from the construction of the old motorway measured 33 meters of cohesive soil and 9 meters of non-cohesive soil before reaching the bedrock (Fredén, 1986, p. 42). The bedrock consists of red granitic augen gneiss (p. 22). Fluvial sediments can be found around watercourses, like around the Gårda stream that flows through Lödöse. They consist of alternating layers of clay, silt and sand as well as gyttja with thin layers of organic content. The thickness is usually around 1 meter (p. 52).

As the isostatic rebound continued, the strait became a bay around 10,000 years ago when lake Vänern became disconnected from the ocean (Klingberg et al., 2006). As time went on, a river started to form (the Göta river), forming deltas as the mouth of the river shifted to the south. The clay particles flocculated in contact with the saline water, leading to a relatively fast sedimentation. The ground in Lödöse is therefore believed to have been a fine-grained delta with its flat plains of clay. While isostatic rebound is still occurring in Scandinavia, the Göta river valley has looked more or less the same for the last 2,000 years (Klingberg et al., 2006).

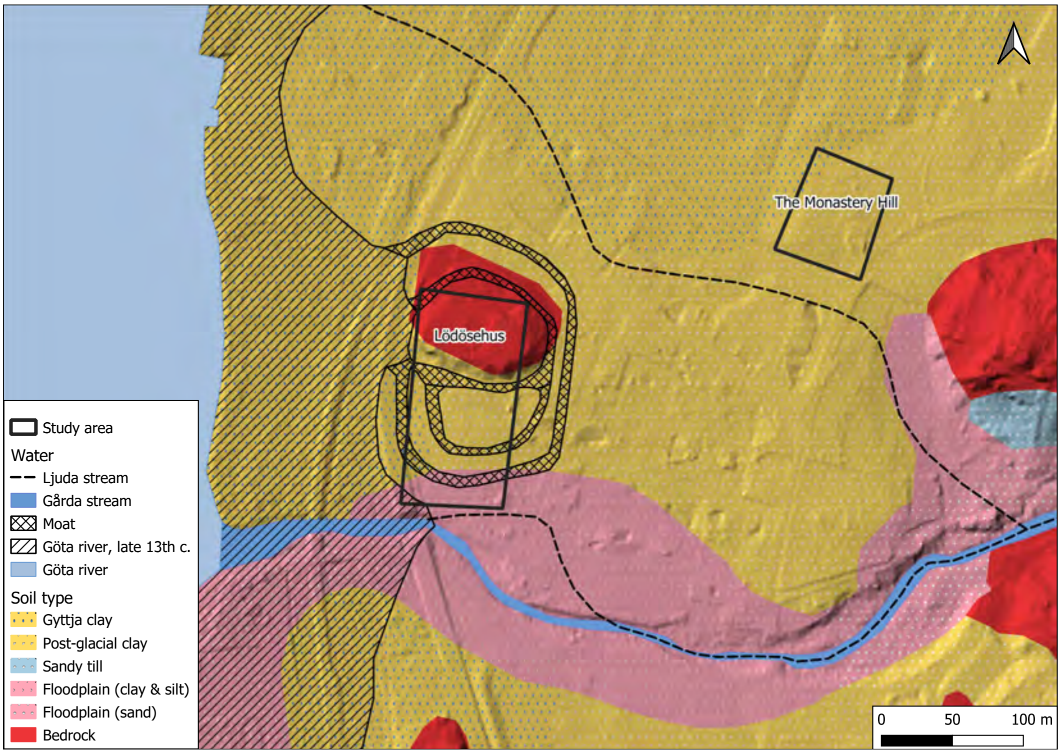
Figure 1.1: Overview map of the localities mentioned in this report. The study area is located in Lödöse. Bohus Fortress is also included on the map, which was an important fortification in medieval times. © ESRI; Lantmäteriet

Geological maps of Lödöse containing the different sediment types and the depth to bedrock are provided in Figure 1.2a and 1.2b. The backside of Lödösehus (the park-like lawn behind the villa) is mainly post-glacial clay with some gyttja clay, but there is also fluvial sediments of clay and silt in the southern part close to the stream. The depth to bedrock is around 20 meters in the northern part of the park-like lawn and goes down to around 40 meters in the southern part. The courtyard of Lödösehus (the tarmac in front of the villa) is situated on bedrock, therefore no soil layer is mapped. It is important to point out that the map of the depth to bedrock is an interpolated model based on point observations, seen as the black triangles on the map.

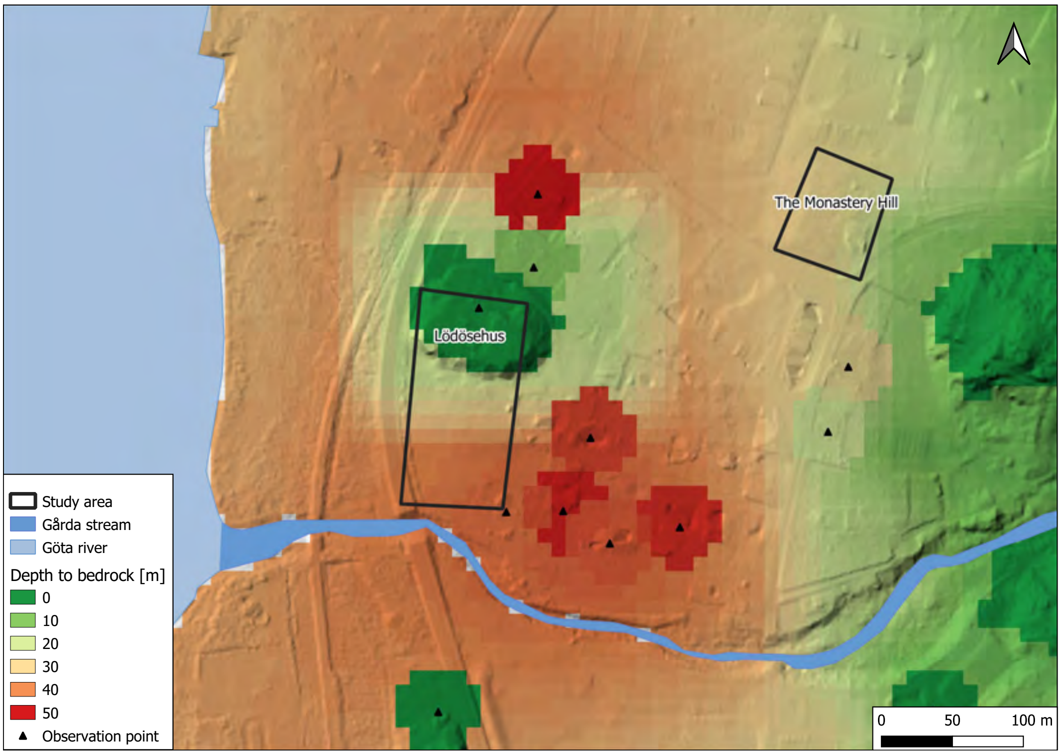
The Monastery Hill is also marked on the map. This area was also surveyed in connection to this study (Möhl & Andersson, 2021).

A standard stratigraphy in the Gothenburg area can be seen in Figure 1.3 (Stevens et al., 1991). This is a generalisation. The same features are not shared on all localities, but most areas have been affected and evolved in similar ways by the deglaciation. This figure is therefore a suitable representation of the geology in Lödöse. As described above, the figure shows the bottom layer to be non-cohesive soil (diamicton and sand) and cohesive soil layers (clay and silt) of different kinds overlaying it. Sand lenses can occur between the clay layers. High organic content can be found in the uppermost layers (post-glacial clay or gyttja) as well as sandy layers.

Added to Figure 1.2a is the water level of the Göta river in the late 13th century, demonstrated by the diagonal lines. The water level was higher than it is today, partly because of the land rise due to isostatic forces, and partly because the outflow from Lake Vänern is controlled today, affecting the water level in the river (Åström et al., 2011). Moats were built around the castle Lödösehus as a fortification. They were connected to the Göta river as seen in the map. The Gårda stream was in the past called Ljuda stream and consisted of two branches, one northern and one southern, that surrounded the inner city, as seen as the dashed lines. The southern branch flowed closer to Lödösehus and acted as a natural moat. The northern branch of the Ljuda stream explains why floodplain sediment is found around the area of the beginning of that branch.



(a)



(b)

Figure 1.2: The study area in this thesis is marked as Lödösehus. The study area marked as The Monastery Hill is presented in Möhl & Andersson (2021). (a) Map of the sediment types in Lödöse (© Lantmäteriet; SGU) together with water levels and old streams and moats from the 13th century (Ekre, 2007, p. 109). (b) Map showing a model of the depth to bedrock in Lödöse. © Lantmäteriet; SGU

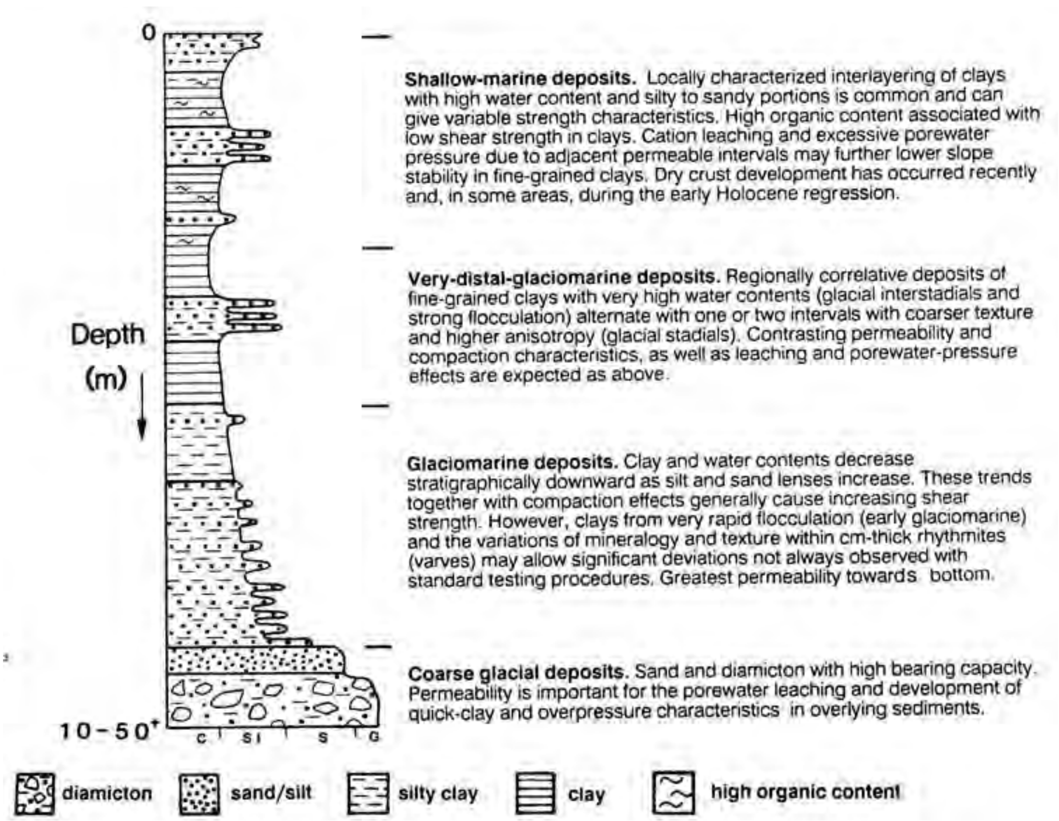


Figure 1.3: Common stratigraphical features in the Gothenburg area (Stevens et al., 1991).

As mentioned above, clay layers are very common in the Göta river valley. Clay particles are thin and sheet-like and have a negative electrical charge. As the clay particles flocculate in salt water, they do so in units that create pore spaces that retain water (Sällfors, 2013). As the former marine environment becomes land due to the isostatic rebound, the groundwater and precipitation percolates through the sediments which leaches the salts from the clays. This weakens the structure of the units, increasing the sensitivity of the clay and can ultimately lead to the formation of quick clay (SGI, 2020). High sensitive clays are common in western Sweden and quick clay is present in many places along the Göta river (Fredén, 1986, p. 43). There have been ten landslides along the Gårda stream, east of Lödöse (SGU, 2021). One of them was a large landslide that happened in 1953, called the Guntorp landslide, which disrupted the railway services for two months (Fredén, 1986, p. 48). A clay with a sensitivity of 50 or higher is considered to be quick clay. The clay in the area of the Guntorp landslide has been measured to have a sensitivity of 400 (p. 43). No landslide has been documented in Lödöse though, but the risk level for a landslide along the Gårda stream near the Göta river is deemed to be moderate (using a scale of low - moderate - high). The risk of a landslide occurring away from the stream is considered to be low (SGI, 2012).

1.3 History of Lödöse

The name Lödöse stems from the stream flowing through it. The stream is today called the Gårda stream (Gårdaån), but during the medieval ages it was called the Ljuda stream (Ljudaån). Lödöse is located by the stream's estuary, and the old Swedish word for estuary is ”os”. Therefore, the name Lödöse is believed to come from Ljudas os, or Ljudas's estuary (af Ugglas, 1931, pp. 19–20).

Nowadays, Lödöse is a small urban area. However, it was once one of the most important cities in medieval Sweden. Situated by the Göta river (Figure 1.1), it was the kingdom's only connection to the open sea because at the time Bohuslän belonged to Norway and Halland to Denmark, which constitutes the west coast, until 1645 (af Ugglas, 1931, p. 21). The issue of when Lödöse was founded is disputed. It is mentioned as Ljodhus in old Icelandic texts, such as Njál's saga, which suggests that Lödöse already existed as a larger town in the early 11th century (p. 25). This is supported by archaeological findings that make a strong case for Lödöse being present and flourishing in the mid 11th century (Ekre, 2007, p. 110). However, af Ugglas (1931, pp. 27-30) believes it rose to prominence after the Norwegian town of Kungahälla fell in 1135. These circumstances gave Lödöse the opportunity to prosper and Sweden could strengthen its position in the area. In any case, the 12th century is considered the beginning of Lödöse's history, with three stone churches built, one in the north, one in the east and one in the west (Figure 1.4).

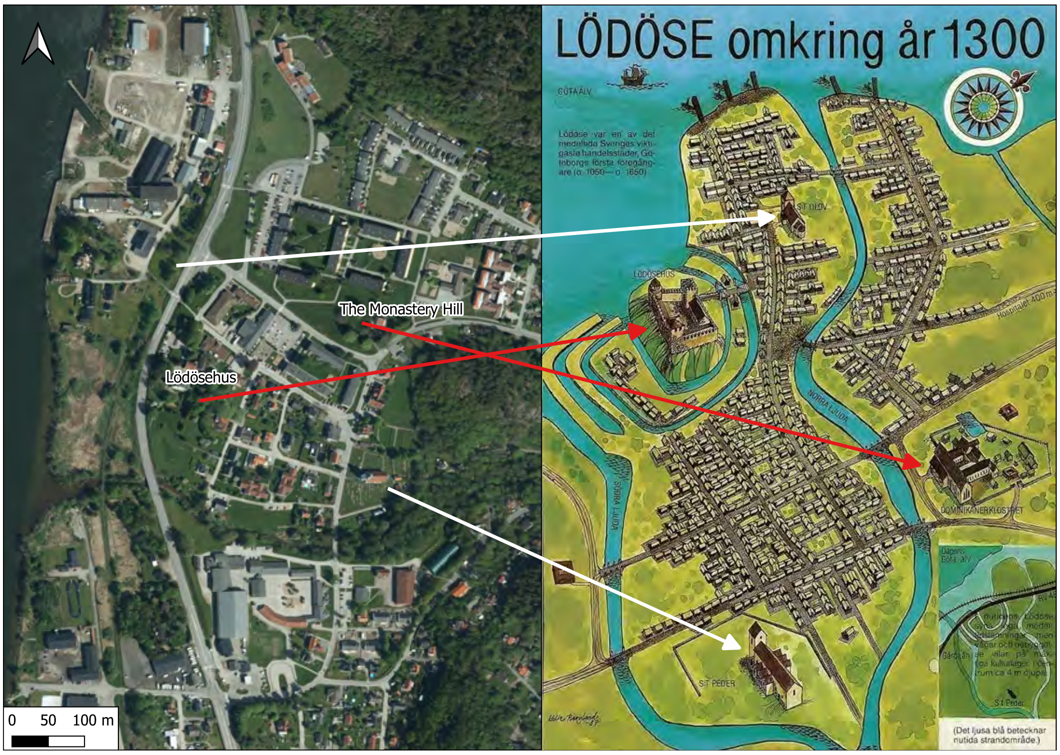


Figure 1.4: A comparison between an orthophoto (© Lantmäteriet) of Lödöse and an interpretation of Lödöse around year 1300 (© Lödöse Museum). The two study areas, Lödösehus and the Monastery Hill (described in Möhl & Andersson (2021)), are shown with red arrows. Two other churches, St. Peder (still in use, but rebuilt) and St. Olov (demolished), are shown with white arrows.

The archaeological discovery of a leather underlay for bracteate striking, along with dendrochronological dating from timber found in the same stratum, has established that Lödöse was a site of coin minting from the 1150s up until the 1360s. A bracteate is a single sided embossed coin. This makes Lödöse the earliest and most permanent site for the minting of coins in medieval mainland Sweden, only rivaled by Visby(?) on the island of Gotland (Ekre, 1991b, pp. 41, 47). A castellum was also built around the same time, which was later rebuilt in the 13th century as a castle named Lödösehus (Carlsson, 1995, pp. 156–157). In 1243, a Dominican Monastery complex with a church was founded according to written sources (af Ugglas, 1931, p. 209). Lödöse was thus of great importance with a population of up to 2,000 people until year 1350 when the Black Death came and development came to a halt. Afterwards, the city had periods of both prosperity and hardships, before being destroyed by the Danes in 1453 (Ekre et al., 1994, p. 10). A large proportion of the population of Lödöse was instead moved in 1473 to New Lödöse, today's Old Town in Gothenburg (Figure 1.1). Lödöse however served as a military fortification all the way up to the 17th century (Ekre, 1991a, pp. 56–57).

1.3.1 Lödösehus

In 1227 there was a war over the throne in Norway that had been being waged since the early 12th century. The Birkebeiner party supported Håkan Håkansson, a contender to the Norwegian throne. Håkan's antagonist, Knut Kristenson, had sought refuge in Lödöse and in an act of revenge and persecution, the Birkebeiners attacked Lödöse and burned down a castellum (Ekre, 1991a, pp. 54–55).

This is the first written account in which a fortification in Lödöse is mentioned. A castellum is a defensive tower, usually circular or quadrangular. They were constructed using either stone, wood or a combination of both, with a defensive wall around it. A castellum's purpose was not a residential one, but rather a last resort of defence in case of an attack (Ekre, 1991a, pp. 54–55, 66). It is not known when the castellum was built. It is however known that the oldest medieval mint in mainland Sweden was established in Lödöse in the 1150s which would have been a sound reason to build a castellum at the same time (Ekre, 2007, p. 110).

There are good reasons to believe that the castellum was replaced by a more fortified defensive construction soon after it burnt down. This argument is based on two assumptions, one being that during the 13th century, castellums in the Nordic countries (Sweden, Denmark and Norway) were replaced by more fortified and residential castles. The other assumption being that Lödöse is mentioned in written sources as "castrum Ludoise" (castrum being latin for military fortification), a place of such importance that the Swedish king Magnus Ladulås pledged it to the Danish king in 1278 in order to settle debts. Later sources from the 14th century mention Lödöse as a castrum where important events took place (af Ugglas, 1931, pp. 326–327).

The new castle built after the destruction of the castellum was what is known today as Lödösehus. The name Lödösehus appears first in written sources around 1280 when Magnus Ladulås pledged the castle a second time, this time to a Danish knight (Ekre, 1991a, p. 56). Based on archaeological findings, the castle was built of stone and brick (af Ugglas, 1931, p. 331). At the start of its existence, it served as a place where collected taxes were kept safe, but by the second half of the 13th century its purpose gradually changed to a military defensive fortification and a residence for the king on his visits to Lödöse.

Lödösehus served as the main castle in the county up until 1369, after which it is not mentioned in written sources. Royal visits to Lödöse are however mentioned, as in 1442 when an inter-Nordic meeting of representatives was held in Lödöse to elect a king of the Scandinavian union. This meeting was held in the Dominican Monastery. Normally, these types of meetings would be held in a castle although Lödösehus was not mentioned (Ekre, 1991a, pp. 56–57).

Lödösehus seemingly never regained its status as a county castle after 1369. The likely reason for this was the Hansa attack in 1368. During this time, Lödöse and the lands along the Göta river were a county under the Norwegian king Håkan who had an alliance with the Danish king Valdermar Atterdag. The Hansa attacked Lödöse in an act of revenge towards these kings, and it is logical to assume that the castle would have been a target of this attack. This, in combination with other defensive military fortifications being built along the Göta river, closer to the sea, eroded the importance of Lödöse and Lödösehus (Ekre, 1991a, p. 56).

Lödösehus was however reconditioned and refortified on different occasions after it was burnt down by the Hansa in 1368. It served as a military fortification for a couple of centuries after its days of glory up until the 1670s (Ekre et al., 1994, p. 20).

As of today, there are no visible structures left from the castle apart from two buildings in its vicinity that seemingly use parts of the walls as foundations. The place where the castle once stood is called Skanskullen and is a bedrock hill elevated 5 meters from the surrounding area.

In 1895, a wholesaler built a villa on top of the hill without performing any archaeological surveys of Skanskullen, destroying the visible remains of the bailey in the process (Ekre et al., 1994, p. 20). Because of this, larger scale archaeological investigations have not been performed at the site of the castle itself, apart from a one-day excavation slightly north-east of the villa. This excavation was carried out in 2008 as part of the construction of a playground. At a depth of 0.5 meter, the excavation unearthed wall foundations, animal bones, tile, ceramics and even a crossbow tip (Jefferey, 2017). Furthermore, in front of the villa on its north side, a reconditioning of the stairs to the entrance was done where plenty of bricks from a wall were found (Ekre, 1991a, p. 63).

Today, a park like lawn lies south of the villa. It is there where most of the archaeological information about Lödösehus has been gathered. Based on archaeological and infrastructural excavations, Ekre (1991) drew a map of how the castle and the area around it might have looked like (Figure 1.5). Excavations on the park-like lawn performed in 1916-1920 by af Ugglas revealed, amongst other things, wall foundations belonging to buildings of unknown purposes, postholes, hearths and moats. The excavations performed at the site were limited, but parts of a double moat system to the south were unearthed (Ekre et al., 1994, pp. 20–22). A third moat, going along the hill was theorized by af Ugglas (1931) and confirmed by later excavations. The eastern outer moat has been dated with the help of dendrochronology from wooden planks to have been built during the 1250s to 1260s (Ekre, 1991a, p. 62). Excavations of the eastern part of the moats resulted in findings of iron slag, indicating that there probably was a forge in the area south of the castle (Ekre et al., 1994, pp. 20–22).

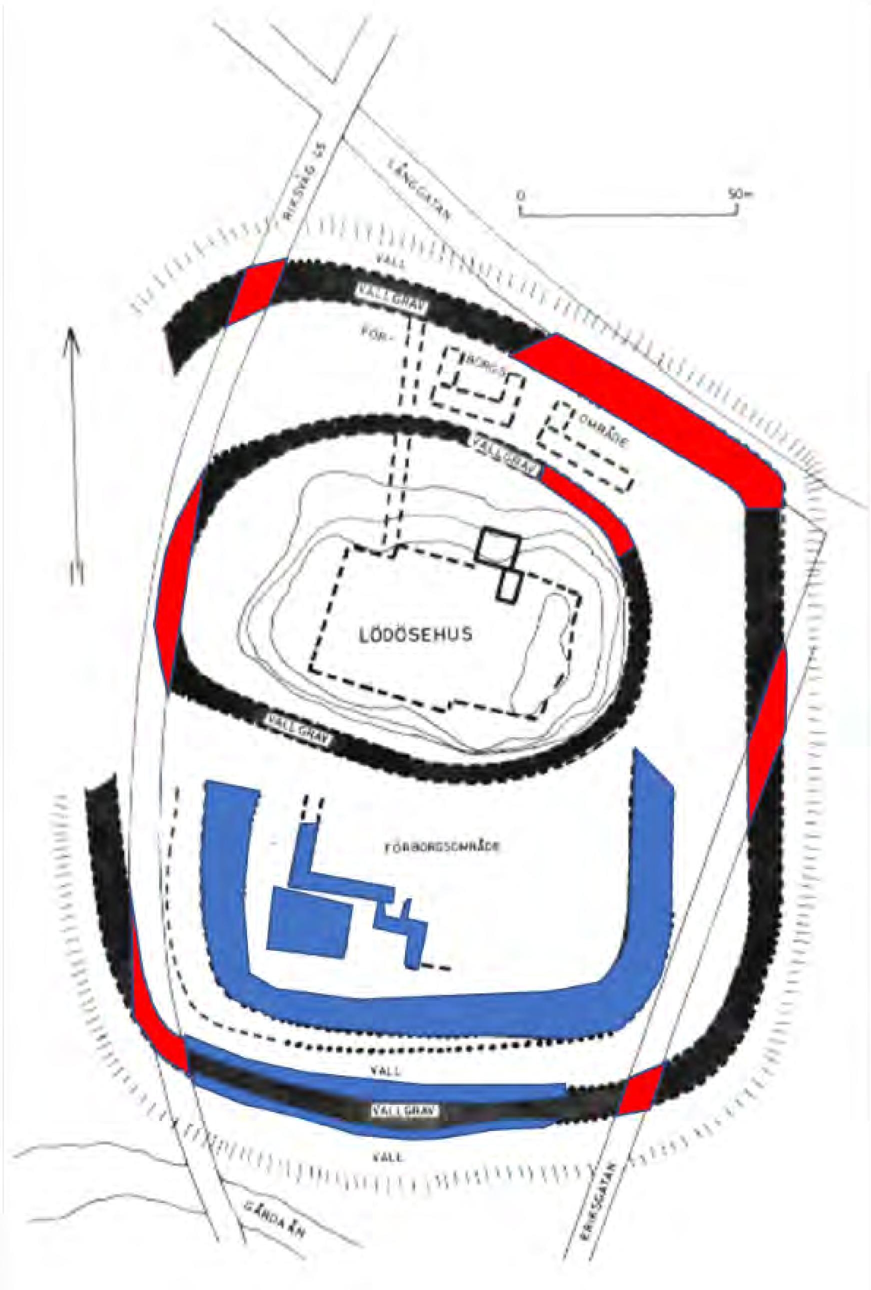


Figure 1.5: A sketch of Lödösehus drawn by Ekre (1991) based on excavations performed by af Ugglas (1931; in blue) and for infrastructure (red). Marked areas of excavations are interpretations based on pictures and written sources from the authors. The thick, dark lines labeled ”Vallgrav” represents the positions of the moats as Ekre assumed them to be, based on excavations. The blue square and linear structures to the south, within the middle moat, represents the wall foundations and other structures excavated by af Ugglas. The dashed lines are theoretical placements (Ekre, 1991a, p. 61). Today, the park like lawn is situated in the area to the south of the inner moat and the villa stands where the text 'Lödösehus' is written

2 METHOD

2.1 GPR

The top few meters of ground are often the most important in archaeology, since it is here most archaeological features are found. The shallow depths are where ground-penetrating radar (GPR or ”radar” for short) has great abilities to produce images in either 2D or 3D. This instrument has therefore become of great importance in archaeological surveys (Conyers, 2018, p. 18).

A GPR is an instrument with antennas that transmit and receive electromagnetic waves from the surface into the ground. The instruments come in different sizes dependent on the frequency of the antennas and the amount of antennas. The GPR used in this study is the MALÅ 3D Imaging Radar Array, also called MIRA. It is an 8-channel radar, with five transmitter and four receiver antennas at a frequency of 400 MHz. This radar can either be pulled directly on the ground, or be pushed like a cart by attaching wheels to its sides. Survey lines are made in straight profiles over the area of interest. A measuring wheel is attached to it that records the distance of the profiles. It also uses a Leica RTK GPS to set coordinates to the surveyed area. Every survey line produces a 2D profile. A screen is connected to the instrument which shows the result of the profile in real time. A preliminary result is thus given directly in the field. This allows the surveyor to know if the instrument is functional for the specific study area, or if certain settings need to be changed or if another frequency (if available) needs to be used. To acquire a 3D model of the study area, several profiles are made adjacent to each other. The profiles are then processed and interpolated in a rSlicer (DECO Geophysical, 2007-2010, Version 2.1.101001), producing a 3D model. The filters used in the processing includes DC Removal, Time Zero Adjustment, Amplitude Muting, Amplitude Correction, Antenna Ringdown Removal, Interpolation, Migration and Amplitude Envelope.

The waves transmitted from the GPR into the subsurface reflect on different interfaces as they propagate downwards. This can, for example, be at stratigraphic boundaries, buried objects or archaeological features. When the waves reach the surface, they are detected and recorded by a receiving antenna in the instrument. The receiving antenna measures the time between transmitting and receiving a wave. This is called the two-way travel time (TWT) and is measured in nanoseconds (ns) (Conyers, 2018, p. 19). If the geological material is known, the TWT can be translated into meters, since the velocity of a wave is dependent on the medium it passes through (Musset & Khan, 2000, p. 229).

Some radar waves will not be reflected back at interfaces but continue further down into the subsurface to be reflected from a deeper interface instead. This will continue until the energy finally dissipates and the signal is lost (Conyers, 2018, p. 19). The penetration depth is dependent on the frequency of the antennas and the conductivity of the material. The frequency also determines the resolution of the radar image. The resolution increases with higher frequency antennas but at a cost of shallower penetration depth. Conversely, the penetration depth becomes deeper with low frequency antennas at a cost of lower resolution. The maximum depth however is not solely dependent on the instrument used but also on the properties of the subsurface. The radar energy decays rapidly in soils with high conductivity. There are several factors that influence the conductivity of a soil, such as the degree of water saturation, but most importantly the concentration of dissolved salts. A wet soil containing dissolved salts will have a higher signal attenuation. Clay, being a soil that can have a high water saturation and contain salt, will therefore have a shallow penetration depth (Doolittle & Collins, 1995).

Figure 2.1: The MALÅ 3D Imaging Array (MIRA) in the foreground on the park-like lawn behind Lödösehus. The villa built on top of the hill where Lödösehus once stood is seen in the background facing north

2.1.1 Measurement and Processing

To get as full picture as possible of the remains of Lödösehus, the tarmac in front of the villa (former courtyard) and the park-like lawn behind it (the outer bailey) were surveyed with the radar array mentioned above. With this instrument, all of the accessible areas could be measured in a short amount of time. An area of around 300 m^2 was surveyed in front of the villa and an area of around 3.600 m^2 on the backside. Since the collecting of data was made across several days, some areas were missed and will result as gaps in the data. Some gaps also occurs where obstacles were in the way, such as trees.

The results were processed in rSlicer (DECO Geophysical, 2007-2010, Version 2.1.101001) and exported as TIF files containing coordinates in EPSG:3007 SWEREF 99 12 00. Layers from different depths could then be imported to QGIS (QGIS Development Team, 2020, Version 3.10.12) to be further analysed.

To visualise the results and to aid interpretations, the noteworthy anomalies were digitized. The pixels in the radar images had colour values ranging from 0 to around 125, where the most prominent anomalies had values between 0 and 60. Contour lines were therefore made to circle all areas with a value of 60 or less. These lines were then converted to polygons. By doing this, anomalies from all depths could be shown at the same time.

To better understand the GPR data, maps of known sub-surface utilities were geo-referenced and digitized. Where the utilities matched the GPR data, some anomalies could be ignored and marked as non-archaeological. A map of the archaeological findings on the backside of the villa was made by af Ugglas (1931). The map contains all of his findings together with an interpretation of the moats. With the results from the GPR survey, the map could be geo-referenced and digitized. Where the archaeological features on the map matched the GPR data, conclusions could be made as to what the anomalies mean.

There was however a limited number of objects in the GPR data that could be geo-referenced with af Ugglas's excavation map. These objects were the E-W striking wall and the four large postholes mapped by him. This means that the excavation maps might not be entirely correct in placement when superimposed on the GPR data, especially the further the features are from the geo-referenced objects.

Maps of buried utilities, such as cables and pipes, were ordered from the database called Ledningskollen ("utility tracker" in English). Two companies sent information regarding their utilities, Skanova and Vattenfall, all of which were located in front of the villa (the courtyard of Lödösehus). However, the GPR data showed several utilities that were not drawn on the maps sent by the companies. These were digitized manually to visualize their occurrence.

2.2 Resistivity and IP

By passing an electrical current through the ground, the subsurface can be investigated in what is called a resistivity survey. From a control unit, cables are laid out along a straight line. Electrodes are then connected to the cables and pushed into the ground. The current is passed through the electrodes into the subsurface and the variations in potential difference are measured, given hundreds to thousands available combinations of potential and current electrodes. The potential difference is given as resistivity (the inverse of conductivity), which has the unit ohm-meter (ohm-m) (Musset & Khan, 2000, pp. 181–183). The current does not take the shortest path between the electrodes, but the easiest. It spreads out downwards and sideways, taking the path where the resistance is low. Most of the current will however be close to the surface (Musset & Khan, 2000, p. 185). Maximum penetration depth is partly dependent on the properties of the ground, but it is also determined by the distance between the outermost electrodes (p. 194). The larger the distance between the electrodes, the deeper the penetration, but with the cost of lower resolution. A higher resolution can be achieved with a shorter spacing of the electrodes, but then the penetration depth will be shallower (p. 198).

Resistivity surveys are often used for geological mapping, e.g. for finding quick clay, describing groundwater and potential ground contamination, or mineral prospecting, but also for other uses such as archaeological surveying. As long as there is a contrast in the resistivity of different materials, this method can be used.

Typical resistivity values of different geological materials are shown in Figure 2.2. Note that crystalline rock may have much higher resistivity; granite can have a value of 1 million Ω-m (Musset & Khan, 2000, p. 183). Quick clay is also added to the figure to be distinguished from clay in general. The resistivity value of clay is mostly determined by its salt content. Since a quick clay has been leached from salt, the resistivity will be slightly higher than in a non-leached clay. In south western Sweden, the lower limit of resistivity has been set to 5 Ω-m (even though quick clay with lower resistivity does occur) (SGI, 2018). The soil in Lödöse (the study area of this thesis) has the potential to contain quick clay. It will be determined if quick clay can be identified by the resistivity surveys as well as the material of the archaeological objects.

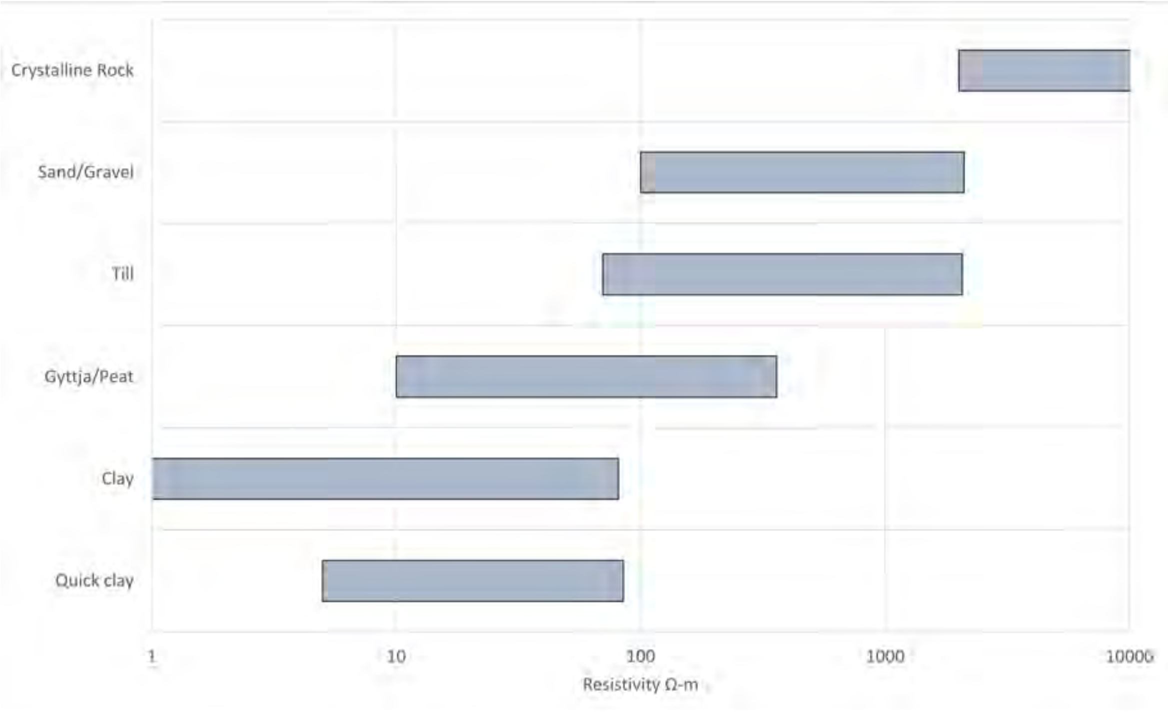


Figure 2.2: Typical resistivity values for different geological materials (SGI, 2018; Triumf, 1992).

Not added to Figure 2.2 is the resistivity of cavities. The reason for this is because it is highly dependent on if it is filled with either air, water or loose materials, or a combination of the aforementioned. An air-filled cavity will result in a high resistivity value, whereas a water-filled cavity will have lower resistivity (Musset & Khan, 2000, p. 421). The acquired resistivity value is therefore highly circumstantial.

Induced Polarization (IP) can be be surveyed together with resistivity, meaning that the same array is used. Induced polarization is commonly used to locate disseminated or massive ores. When an electrical current is passed through the ground and reaches rock containing the ores, the current will pass through the groundwater in the fractures. Where there are metallic minerals in the fractures, an electrical charge will be stored and released when the electrical current is turned of. The instrument then measures the discharge of the stored electrical charge. Since clay particles have an electrical charge, they might attract positive ions when a current is passed through the ground, storing a charge and then discharging it once the instrument turns off. The principle is that a conductive material in a matrix that is non conductive can be detected with an IP survey (Musset & Khan, 2000, p. 202).

This can be applied in archaeology to find materials that conduct electricity in the soil, such as metals.

Figure 2.3: The ABEM Terrameter LS in use for the survey on the Monastery Hill (Möhl & Andersson, 2021)

2.2.1 Measurement and Processing

To complement the GPR survey, one resistivity profile measuring 100 meters was made. The profile started in the exposed rock to the north, on which the villa stands, and ended by the end of the park-like lawn to the south. Induced Polarization measurements were also made to see if there are any objects with electrical chargeability in the subsurface. The IP measurement was made simultaneously to the resistivity measurement.

Different instruments and different types of measurements can be used for resistivity surveying. In this study, the ABEM Terrameter LS was used. Three or four cables are usually connected to the instrument. For this survey, three cables were used. Each cable has attachments for 21 electrodes, resulting in a layout length of 60 meters with an electrode spacing of 1 meter. The Gradient Plus array was used. This allows multiple measurements without the need to move the electrodes. Readings are automatically recorded using possible combinations of current and potential electrodes. Typically, roughly 848 datapoints will be stored for a four-cable array and slightly less for a three-cable array. Since the length of the profile (100 meters) measured more than the three cables (60 meter) the roll-along method was used. This allows the profile to continue with the same array (Gradient Plus).

The data was processed in Res2Dinv (Geotomo Software, 2012, Version 3.59) from which two models from the resistivity survey and one from the IP survey was made.

3 RESULTS

3.1 GPR

Results from the GPR survey are presented below. Superimposed drawings from af Ugglas (1931) serve as a key for understanding what is seen at certain localities in the GPR data. However, it requires a thorough analysis to determine what the other anomalies from the survey actually are. In those cases, where structures are seen to match the drawings it can be concluded, with confidence, that they are the same structures that af Ugglas excavated and thus be presented as such in the results. When structures are encountered that are not mapped, they will be presented here as structures or anomalies of archaeological nature. What they might be will be treated further in the discussion.

3.1.1 Courtyard

The results from the GPR survey of Lödösehus's courtyard on the tarmac in front of the villa are presented in this section (including Figures 3.1-3.14). First, 3D data will be shown (Figures 3.1-3.11) in a colour ramp from orange to purple. Anomalies that appear in any given depth with values between 0-60 are coloured in different shades of purple and it is these features that are noteworthy. After that, four 2D profiles (Figures 3.12-3.14) crosscutting interesting features will be presented. Profiles will be presented together with a map of the area showing the location of the profiles. The profiles have points marking every 10 meters. Point 0 is the start of the profiles. Every bar on the GPR profiles is 2 meters, both horizontally and vertically. Different kinds of anomalies can be seen in the data, some artificial and some presumably of archaeological interest. The known artificial features are presented first.

There are several utilities mapped in front of the villa. These are best presented with the GPR data at 0.22 meters depth. The same GPR data is presented in the two maps (Figure 3.1) with the utility locations in the lower map. The yellow dashed line is a mapped utility with a known location. This utility also appears in the radar image. The grey dashed line is a mapped cable with an approximate location, usually with an offset of roughly 2-3 meters. This cable can however not be seen at any depth in the radar images. The red dashed line is a utility with an uncertain location. The green dashed lines are utilities seen in the radar images that are not presented on available maps of utility locations. One of these utilities is probably a cable mapped with uncertain location.

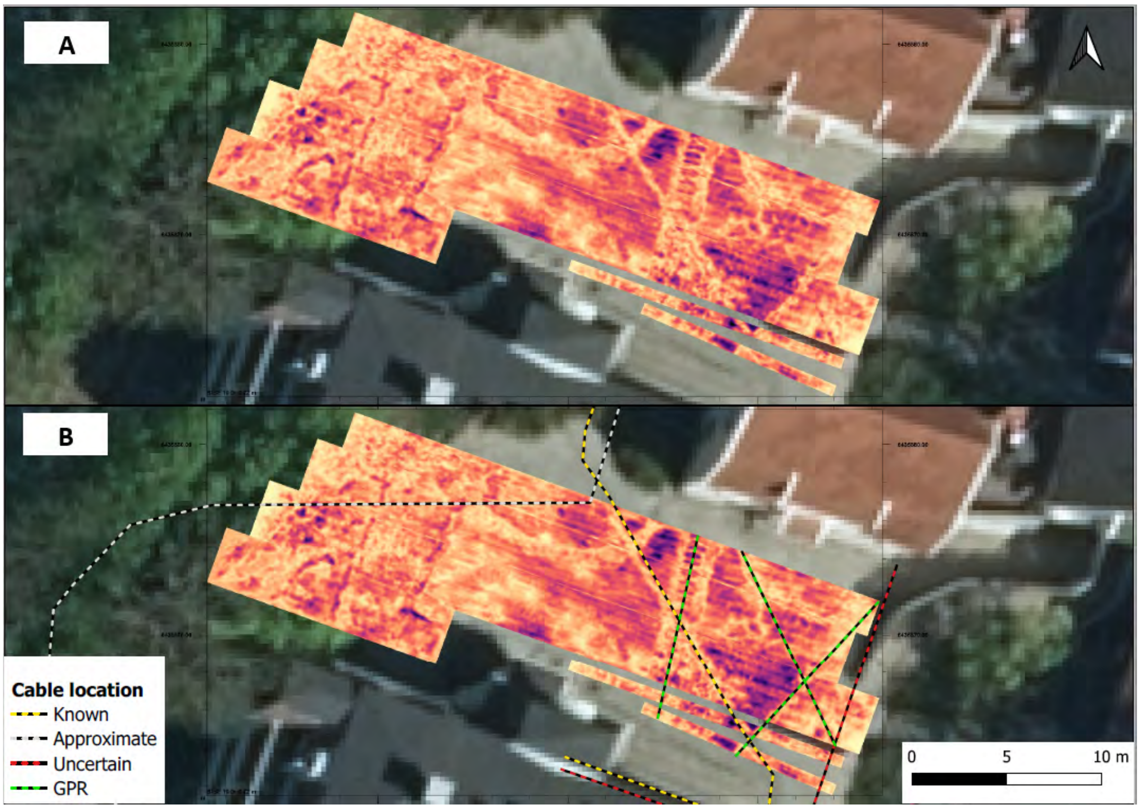


Figure 3.1: GPR data at 0.22 m depth with locations of utilities. Figure A shows noteworthy anomalies in purple at given depth. Figure B shows the location of the utilities superimposed on the data © Lantmäteriet

Radar images from various depths will now be presented together with the digitized anomalies. The polygons show the anomalies from all depths simultaneously.

Starting at 0.10 meters depth (Figure 3.2), one prominent feature can be seen to the left in the image. An irregular line is crossing the image in a NE-SW direction. This can be seen as the light-grey coloured polygon on the bottom map. This feature disappears quite quickly and can only faintly be seen at depth of 0.22 meters (Figure 3.3). It will instead be replaced by other features at greater depths. In the middle of the image, a bow-shaped feature appears. This feature will be more prominent at greater depths. To the right of the bow-shape, a ribbed object appears in a somewhat N-S direction. This was marked as a cable in Figure 3.1 on page 18, but has a different appearance than other visible utilities.

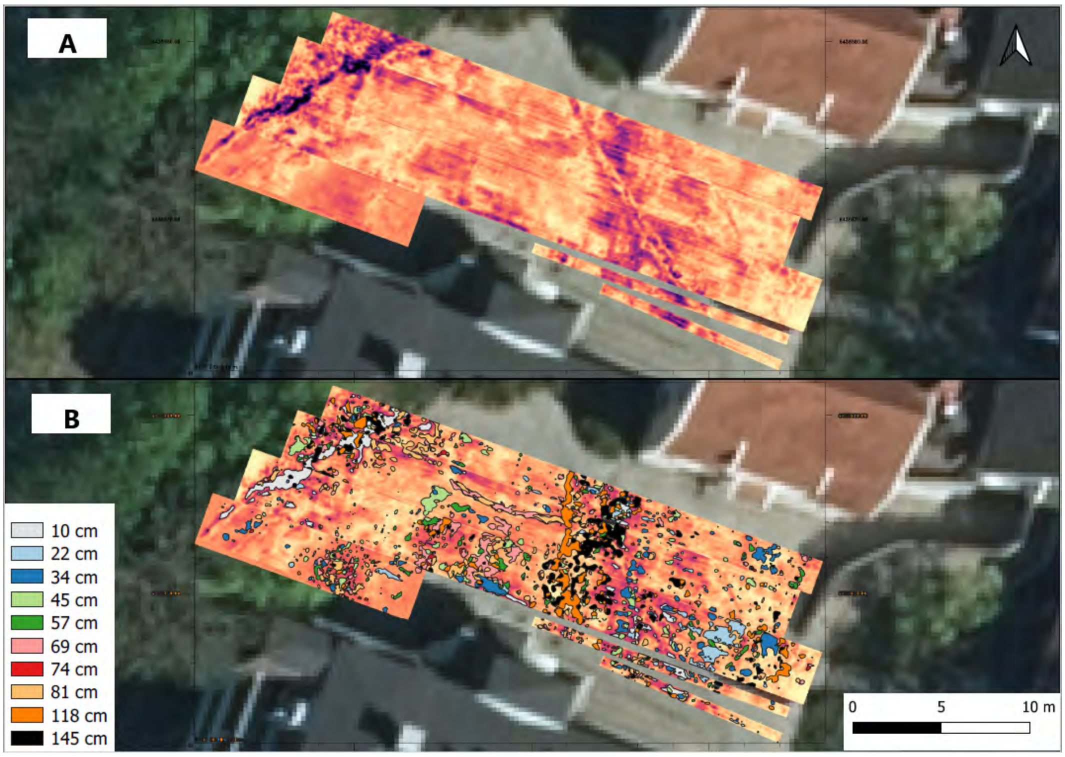


Figure 3.2: GPR data at 0.10 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

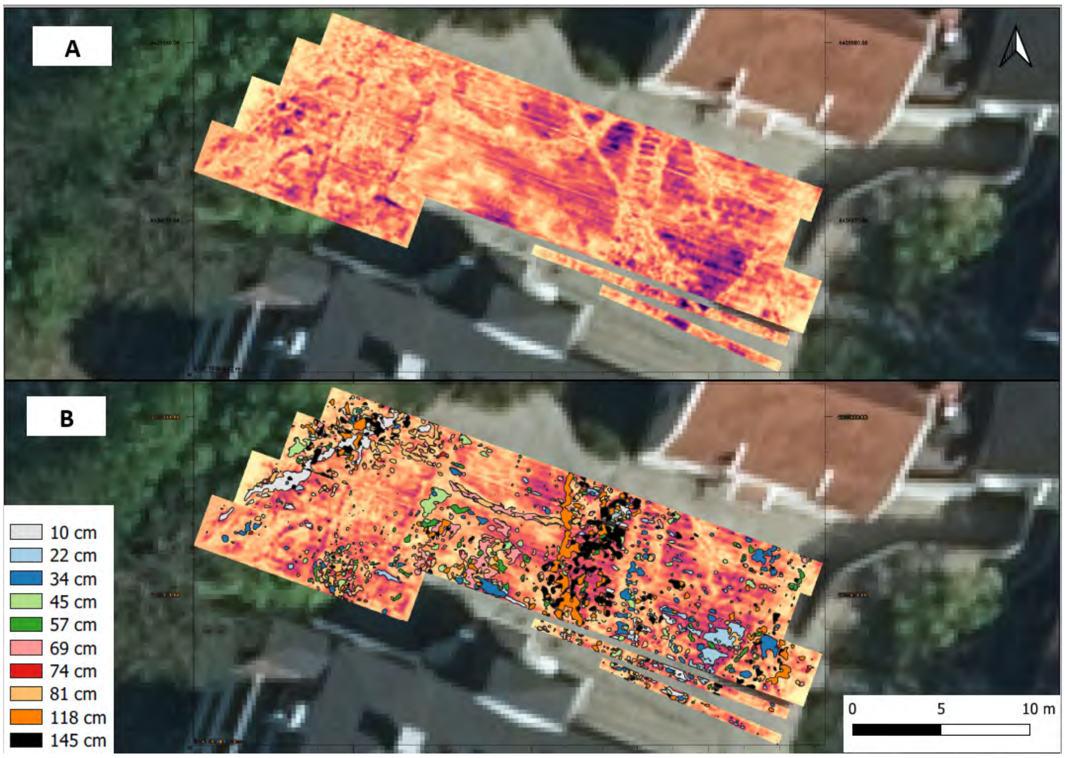


Figure 3.3: GPR data at 0.22 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

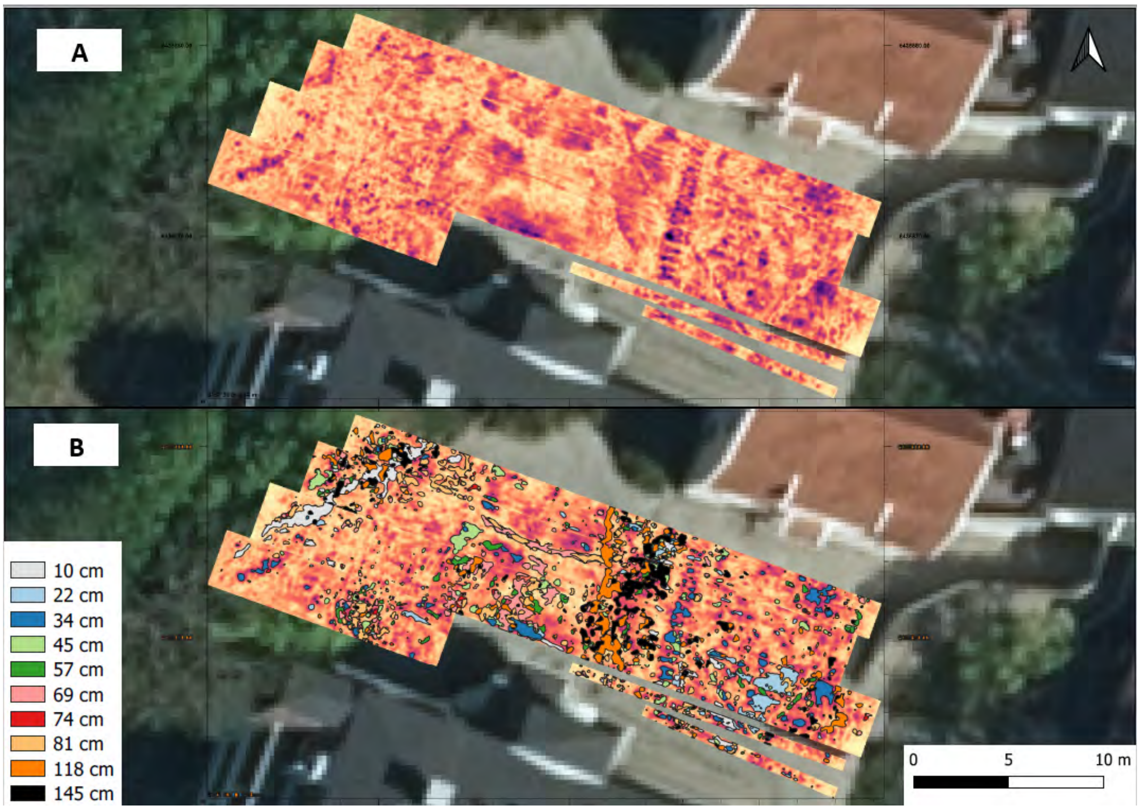


Figure 3.4: GPR data at 0.34 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

At 0.34 meters depth (Figure 3.4), a curved line appears to the left of the image, below the irregular line seen at 0.10 meters depth.

At 0.45 meters depth (Figure 3.5), point objects are starting to appear. Objects can be seen at the top left corner where the irregular line at 0.10 meter was located. At the bottom left side of the image, point objects forming a circle can be seen. This becomes clear when looking at the polygons where point objects can be seen in the area from almost all depths. The mentioned point objects become more evident at 0.57 meters depth (Figure 3.6).

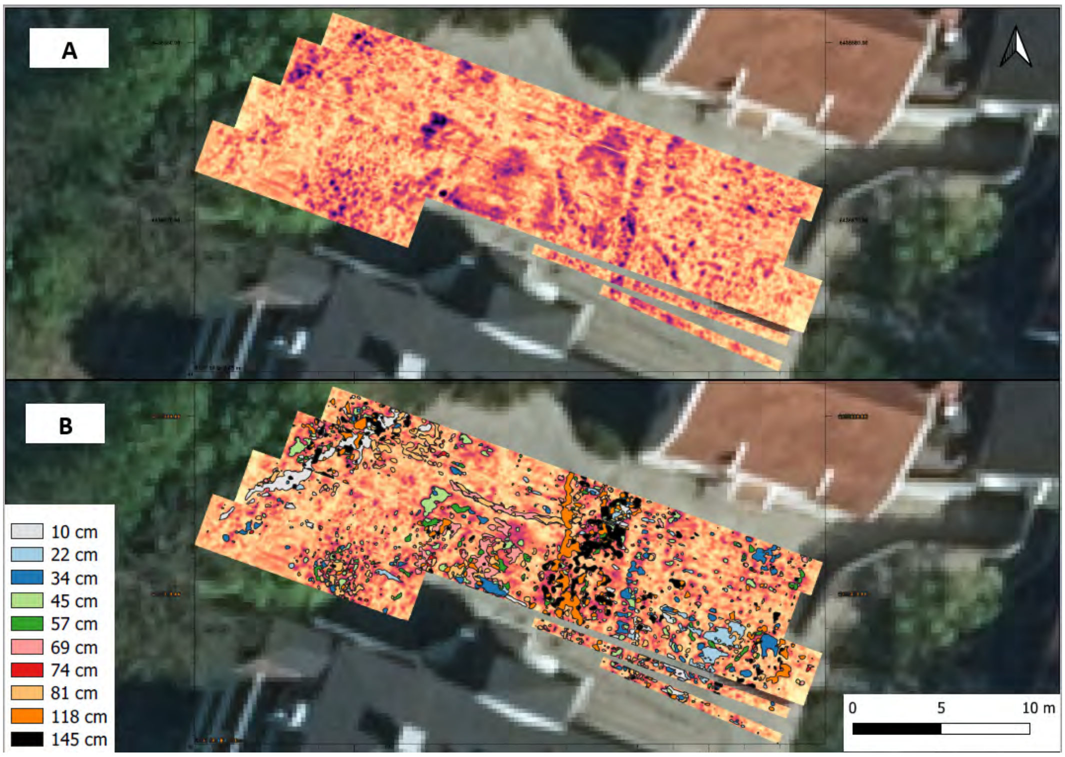


Figure 3.5: GPR data at 0.45 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

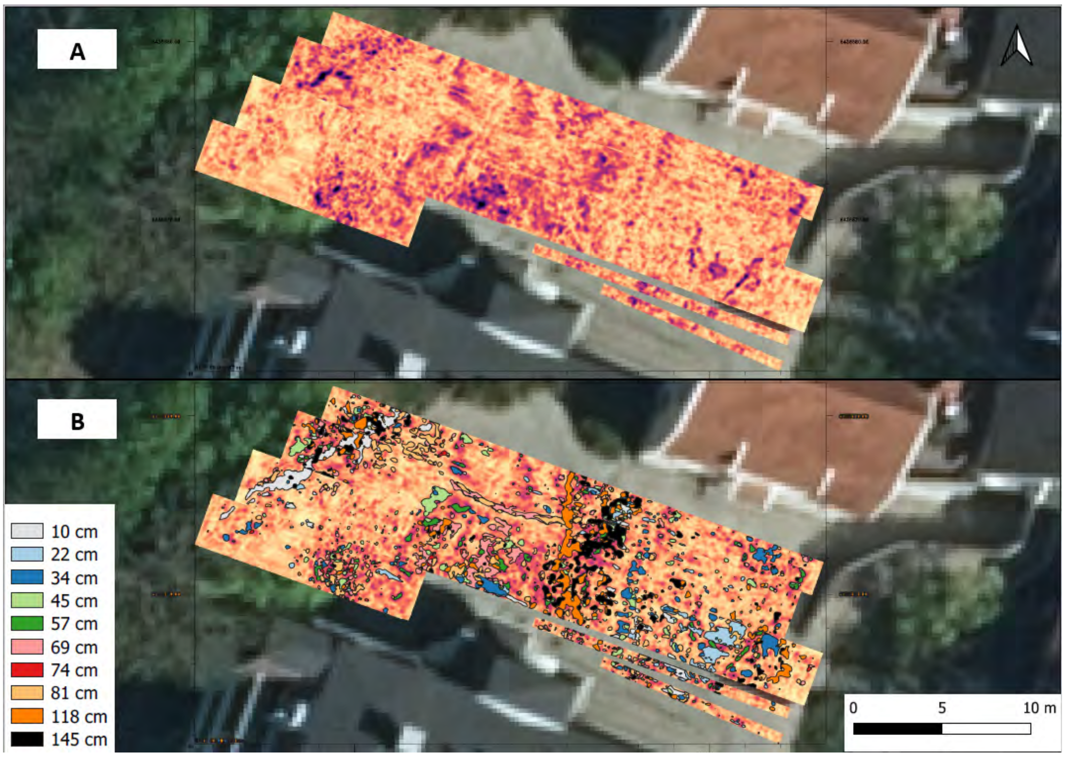


Figure 3.6: GPR data at 0.57 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

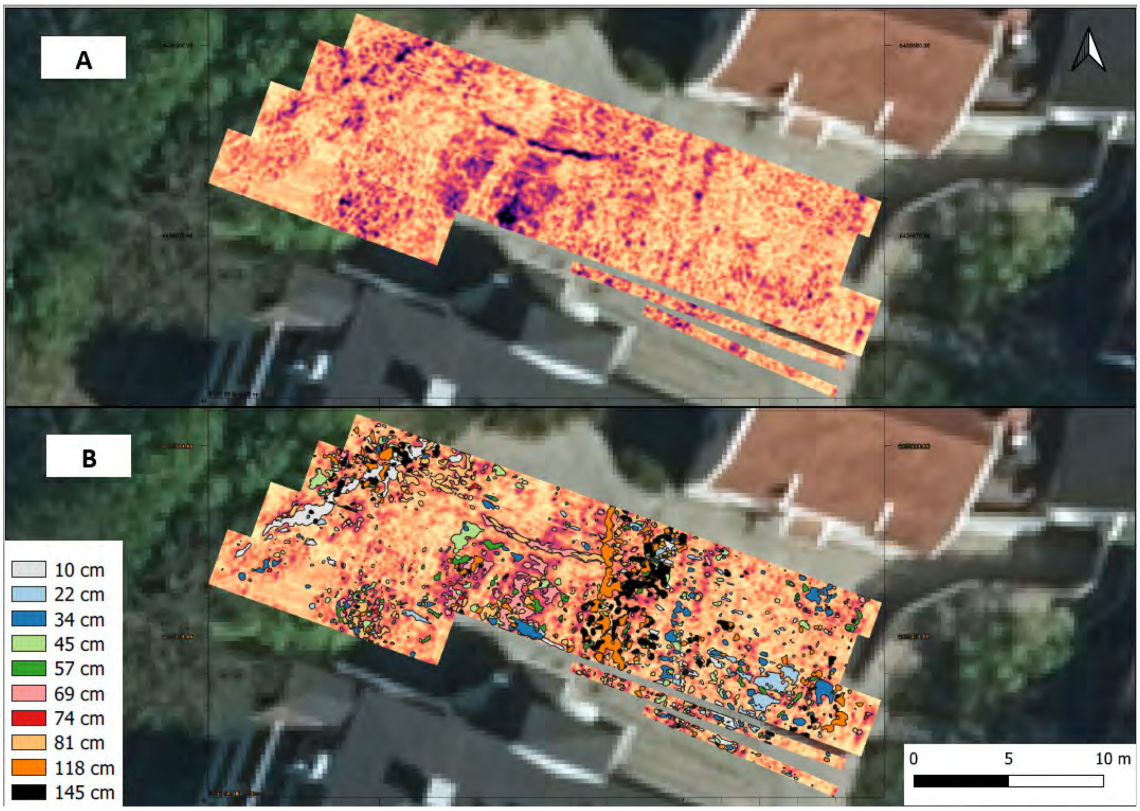


Figure 3.7: GPR data at 0.69 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

Looking at 0.69 meters depth (Figure 3.7), the data starts to become of greater interest. The point objects to the left are forming a somewhat straight line. The bow-shape in the middle visible already at 0.22 meters depth now has a prominent anomaly. Just below this feature, two halves of a circle can be seen. Both the bow and the circle are cut by a straight line. Looking at the polygons, the two semicircles form more of a rectangular feature.

The bow-shaped feature is no longer disrupted at 0.74 meters depth (Figure 3.8). The bow-shape can be seen how it extends to the left in the image at 0.81 meters depth (Figure 3.9), where it goes into a cluster of point objects. To the right of the bow-shape, new point objects are becoming visible, which will be more evident at greater depths.

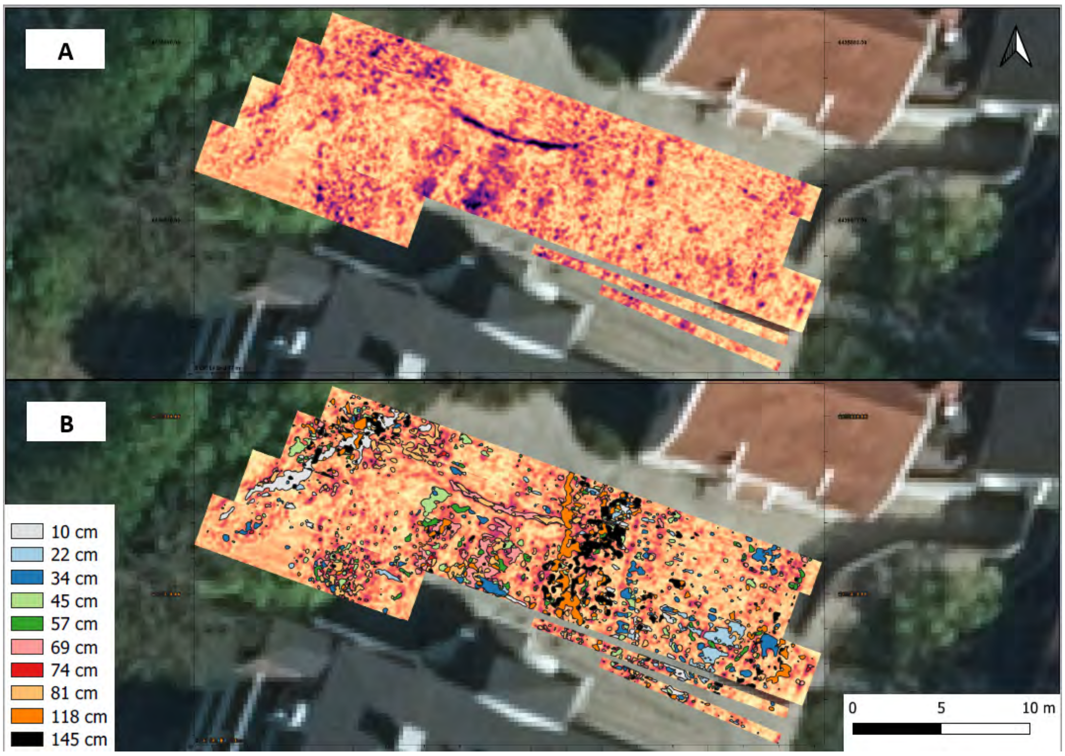


Figure 3.8: GPR data at 0.74 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

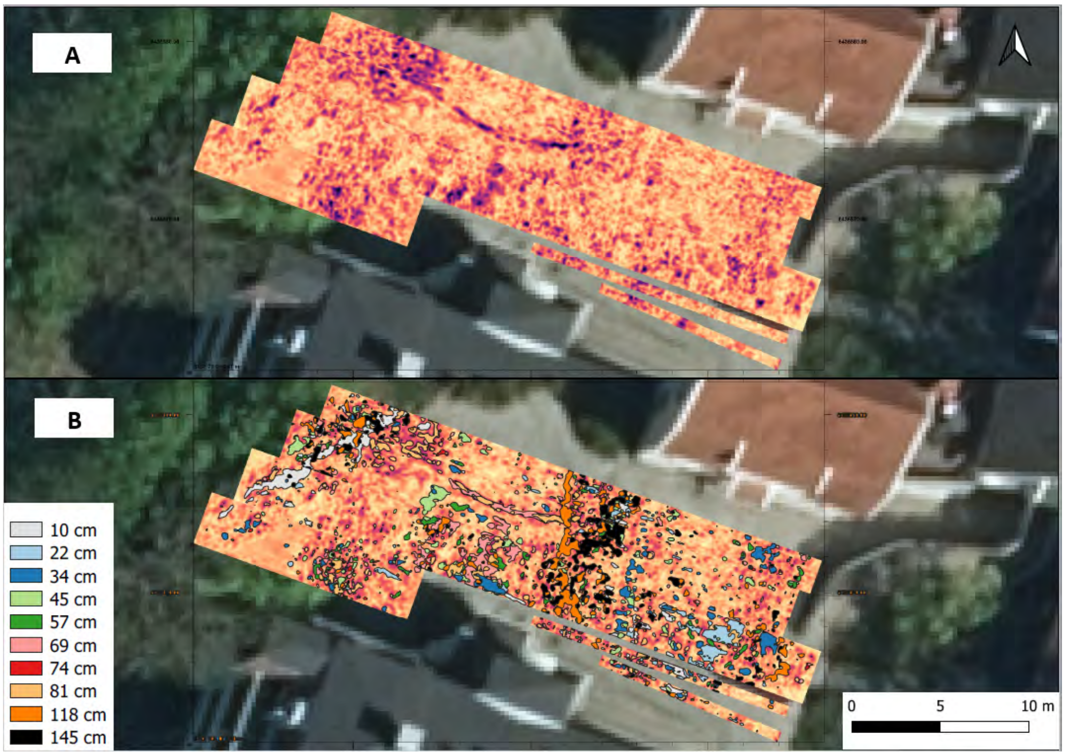


Figure 3.9: GPR data at 0.81 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

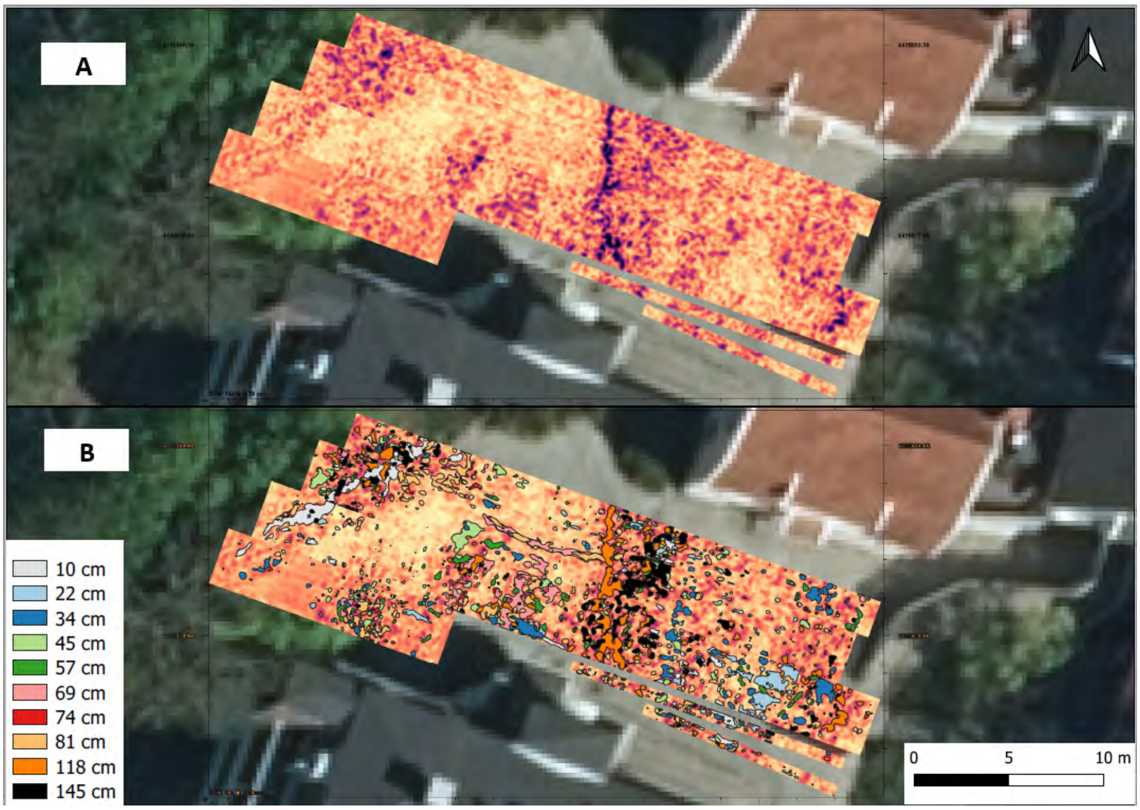


Figure 3.10: GPR data at 1.18 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

At a depth of 1.18 meter (Figure 3.10), the image looks almost completely different. Here, another irregular line appears, not too different from the irregular line in Figure 3.2 on page 19. This line can be seen as an orange coloured polygon on the digitized map. To the right of the line, a cluster of point objects can be seen.

At a depth of 1.45 meters (Figure 3.11), the cluster of point objects becomes prominent and can be seen as black polygons on the map with digitized polygons (B). A similar cluster of points can be seen to the left where different anomalies have been showing up at different depths.

Maximum depth penetration of radar waves given the local geology and instrument limitation is between 2 and 2.5 meters.

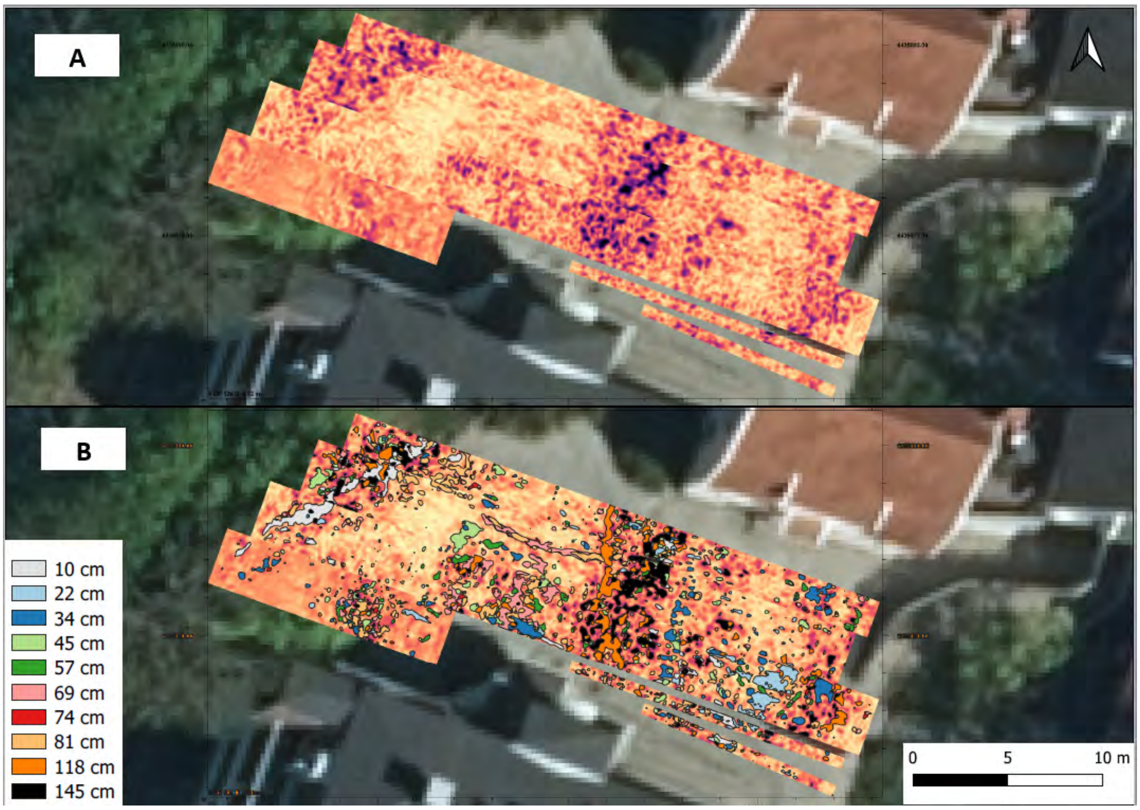


Figure 3.11: GPR data at 1.45 m depth. Figure A shows noteworthy anomalies in purple at given depth and figure B shows digitized anomalies from all depths simultaneously. © Lantmäteriet

In the first radar profile (Figure 3.12), three interesting features are crosscut. Between 0-5 meters along the profile, the irregular line striking in a NE-SW direction that first become visible at 0.10 meters (Figure 3.2) and later at 0.57 meters (Figure 3.6) is seen between 0-5 meters along the profile. The reflections reach a depth of below 1 meter. The utility mapped with an approximate location can be the cause of reflections appearing between 4-8 meters but it is not distinguished. The second feature seen is the bow-shape that become visible at 0.22 meters depth (Figure 3.3). It can be seen as the reflections between 6-16 meters along the profile and form planar reflections at 0.7 meters depth. The third feature appearing is the mapped utility seen at 20 meters along the profile and form a distinctive reflection at almost 2 meters depth. At 23 meters, a similar distinctive reflection appear over the ribbed object (Figure 3.3), although at 1 meters depth.

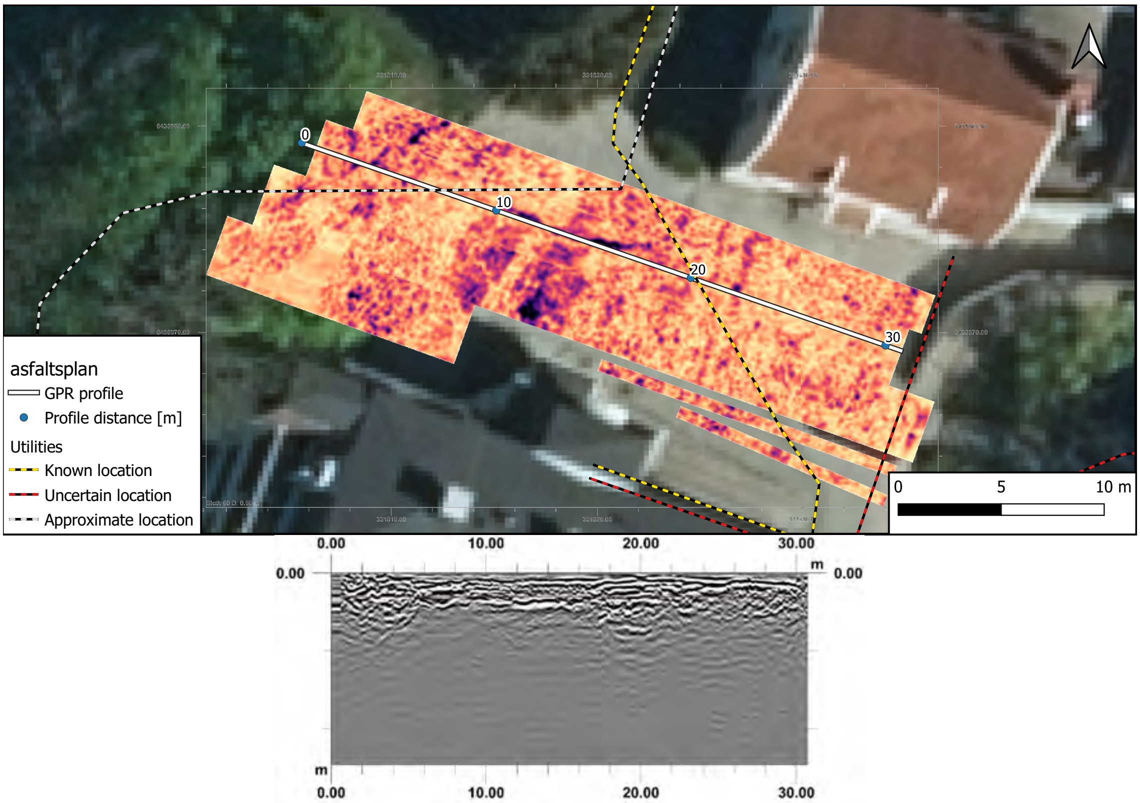


Figure 3.12: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 0.6 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

The second radar profile (Figure 3.13) crosscuts noteworthy anomalies that appear in the 3D data. The most prominent reflections are those seen at 2 and 32 meters along the profile with a depth that reaches over 2 meters. Both of these reflections are positioned over mapped utilities with uncertain and approximate locations. Between 10-17 meters reflections can be seen of the semi-circles that appears at 0.69 meters depth in the 3D data (Figure 3.7). These reflections show a layered stratification that stretch from 10-24 meters along the profile. At 25 meters the stratified reflections are interrupted by another reflection that coincides with a mapped utility. At 20 meters there are reflections from a different source that reach to a depth of 1 meter. These reflections coincide with the irregular line shown as an orange polygon in the 3D data at 1.18 meters depth (Figure 3.10).

In Figure 3.14, two shorter radar profiles are presented. The profile to the left is over the irregular line going in a NE-SW direction at 0.10 meters depth (Figure 3.2). As can be seen, the tarmac appears as layered reflections at surface level. At 0.6 meters, another layered reflection appears. Between these layered reflections, small hyperbolas can be seen.

The profile to the right crosscut the point anomalies that appears to the bottom left between 0.45-0.57 meters depth in the 3D data (Figure 3.5 and 3.6). These features are seen as a large hyperbola in the profile between 4-6 meters depth.

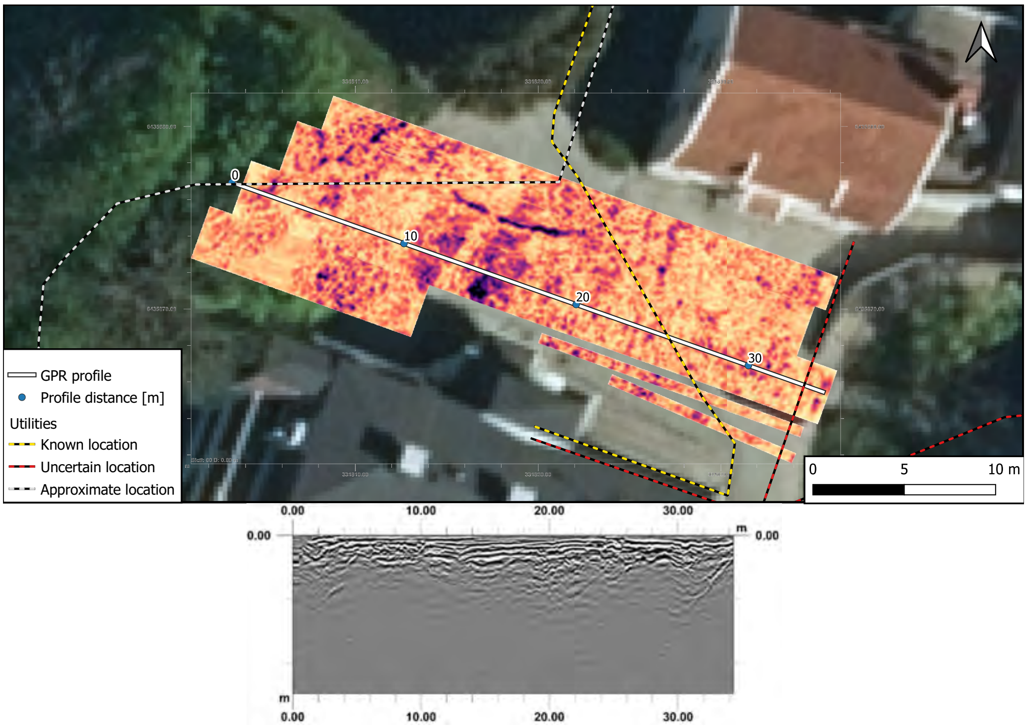


Figure 3.13: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 0.6 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

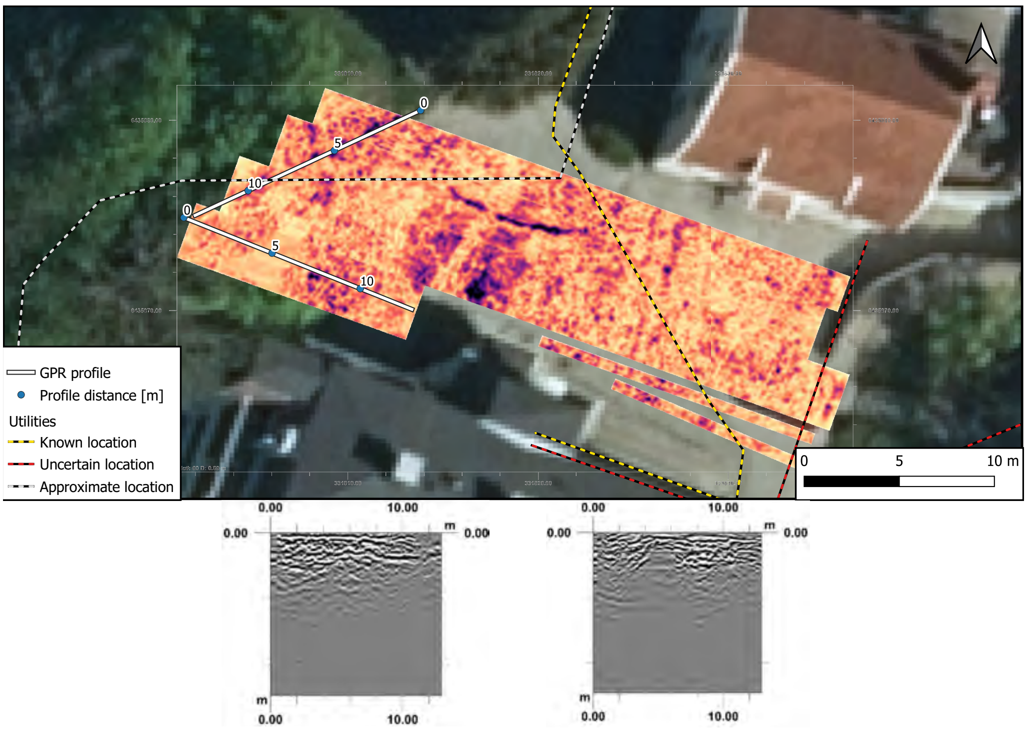


Figure 3.14: 3D GPR data (top) and 2D profiles (bottom). Profile going in a NE-SW direction is shown to the left and profile going in a E-W direction is shown to the right. The 3D data shows radar image at 0.6 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

3.1.2 The Outer Bailey

In this section, the results from the GPR survey on the outer bailey of Lödösehus are presented (including Figures 3.16-3.30). Today it is a park-like lawn behind the villa and will be referred to as such. One of the excavation maps drawn by af Ugglas (1931) is shown in Figure 3.15. The two light-coloured bodies encircling the area are the outer and middle moats. In the south-eastern corner is another light-coloured body, which is the margin of the Ljuda stream (Figure 1.2a) as it was during the castle's most functional days (13^{th}-14^{th} century). In the north-western corner, the structures excavated can be seen gathered in a relatively small area. In the north-eastern corner an excavated structure appear but since it was not covered by the GPR survey it will not be treated in this thesis.

Beginning from the top, the most eye-catching feature is the large wall going in an E-W direction. This wall will be mentioned as the E-W striking wall. The other wall, going in a N-S direction will be mentioned as the N-S striking wall. Where the two walls almost meet is a wooden floor which af Ugglas (1931, p. 364) believed a port gate once was situated.

Just south of the E-W striking wall are located three brick-built hearths. Only the westernmost of these three hearths was covered in the GPR survey due to a tree hindering the inclusion of the other two. Running in a N-S direction, south from the E-W striking wall, is a gutter that is crosscut by a wooden pole near its southern tip. The western end of the wooden pole rests on a rock and further west are four large postholes. South of these larger postholes are three smaller ones.

North of the four larger postholes are wooden planks and poles. North of these and west of the E-W striking wall is another hearth located built in bricks. Scattered over the survey area are several dark dots. These are smaller postholes.

In the south western corner of the survey area, just north of the middle moat, is a smaller hearth built of bricks and stones.

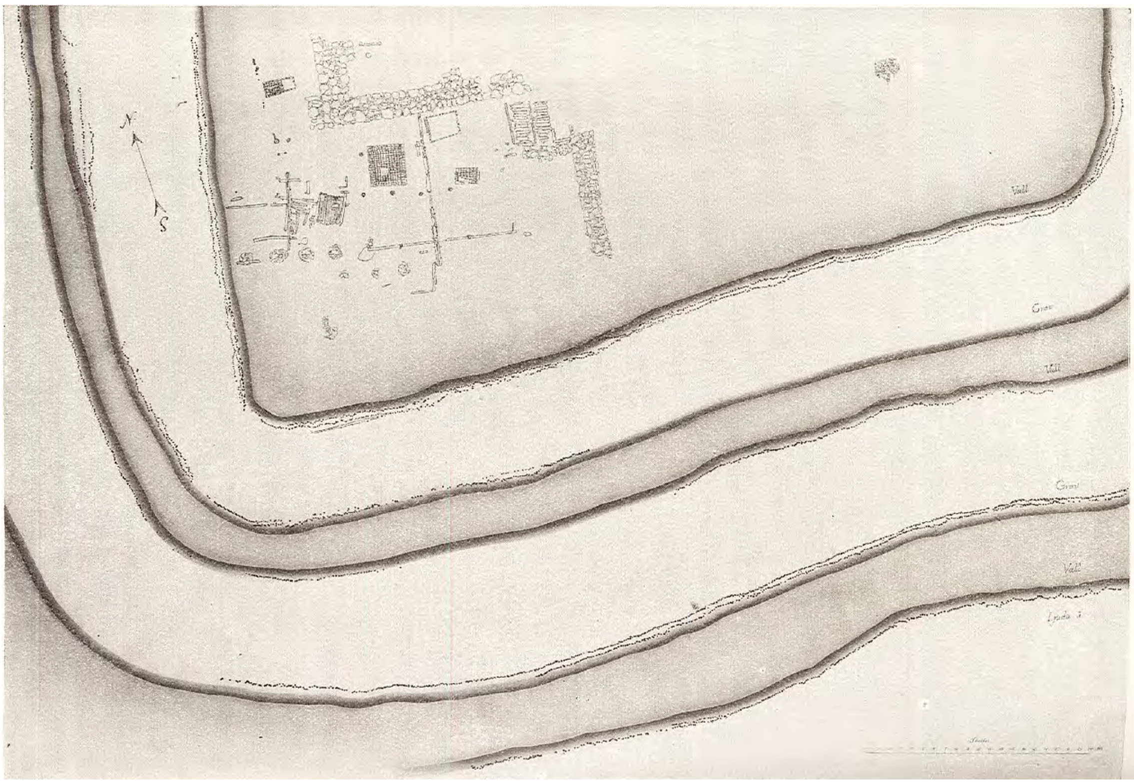


Figure 3.15: Excavation map from af Ugglas survey of the area behind the villa (af Ugglas, 1931)

The results are presented first by the known structures from af Ugglas's excavation maps that can also be seen in the radar data. Afterwards, unknown structures are presented. The presentation is done in this manner since known structures serve the function of helping interpreting unknown and potential structures that appear as anomalies in the data. To illustrate, figures of 3D GPR data are presented and in some cases where a more detailed analysis is needed, 2D profiles (cross-sections) are provided as well.

Profiles will be presented together with a map of the area showing the location of the profiles. The profiles have points marking every 10 meters. Point 0 is the start of the profiles. Every bar on the GPR profiles is 2 meters, both horizontally and vertically.

Figure 3.16: Digitized structures modified from af Ugglas (1931) superimposed on the GPR data at 0.70 m depth (A). GPR data at 0.70 m depth with anomalies appearing in purple (B). © Lantmäteriet

The E-W striking wall is clearly seen in the GPR data at a depth of between 0.60 and 0.70 meters (Figure 3.16). The mentioned wall, made of granite blocks, measured 19 meters (af Ugglas, 1931, p. 364). While the survey did not cover the entire wall due to vegetation, the wall did not appear in the data east of it, which confirms the length of the wall as af Ugglas determined it to be. The reflections of the wall in a GPR profile can be seen in Figure 3.17 between ca 55 and 65 meters on the profile.

At the same depths, the N-S striking wall starts to become visible (Figure 3.16) and continues to be so down to 1.50 meters. This wall appears clearer in the data on its southern parts with increased depth which corresponds to af Ugglas's notes that the wall has settled into the soil to the south (1931, p. 364).

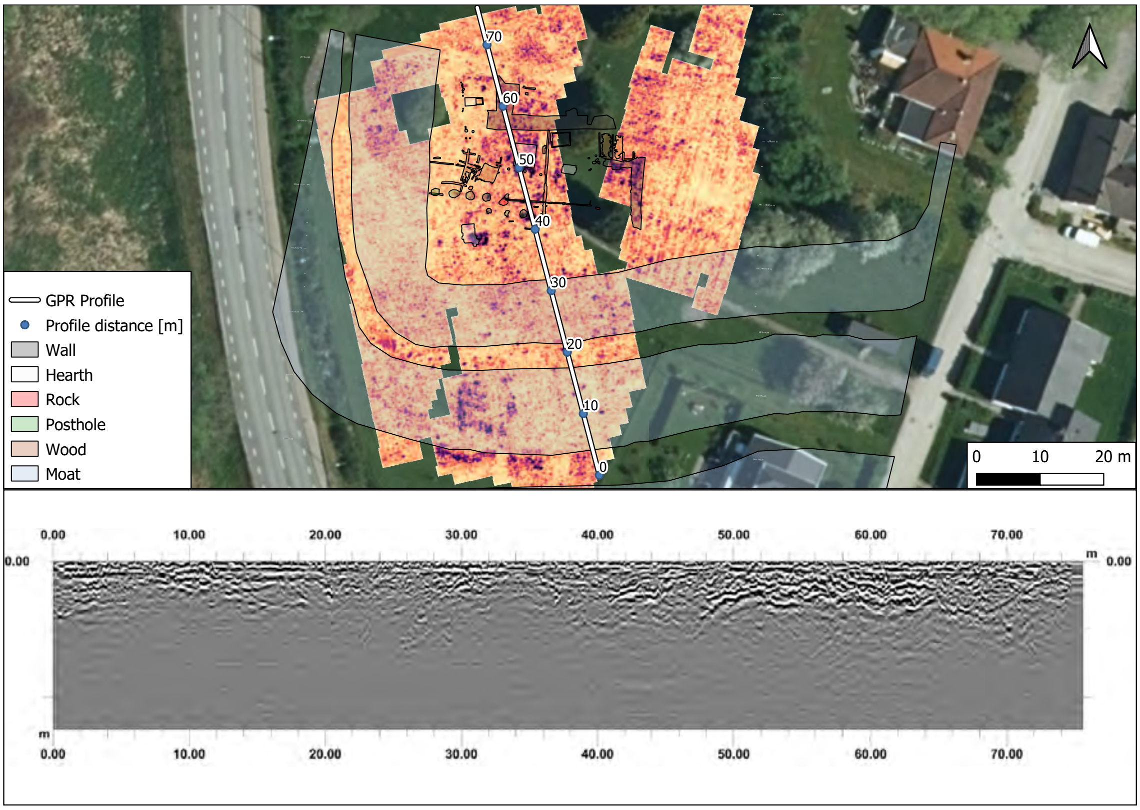


Figure 3.17: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 1 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

Just north of the E-W striking wall, there is a structure appearing at 0.70 meters (Figure 3.16) and continues to be clearly visible down to 1 meter. This structure appears to be rectangular in shape and has not been mapped by af Ugglas.

Some of the large postholes mapped by af Ugglas, even though not always aligned perfectly with the archaeological map, can also be seen in the GPR data at around 0.70 to 1.70 meters depth, most clearly visible at 1.30 meters depth (Figure 3.18).

The gutter going in a N-S direction from the E-W striking wall does not appear in the data. However, the western side of the log that crosscuts the gutter towards the south begins to be visible at 0.90 meters and more so at 1 meters depth. The stone upon which it rests to the west is visible already at 0.70 meters depth and continues to be so to 1.50 meters depth.

Figure 3.18: GPR data at 1.30 m depth with digitized structures modified from af Ugglas (1931) (left). © Lantmäteriet

The postholes, log and the stone upon which it rests becomes clearly visible on a GPR profile (Figure 3.19). The log can be seen as a straight reflection at around 1 meters depth and the postholes are visible as a U-shaped reflections pointing downwards. This is of interest since the reflections appears where established postholes are and serves as a tool for interpreting potential and unmapped postholes.

At the south-western corner, north of the middle moat and slightly south of the large postholes marked out by af Ugglas, is a crescent-shaped formation constituted by dark dots that could be postholes at 1.40 meters depth (Figure 3.20). When compared to the postholes above mapped by af Ugglas (Figure 3.19) there is striking similarities in the reflections on the GPR profiles.

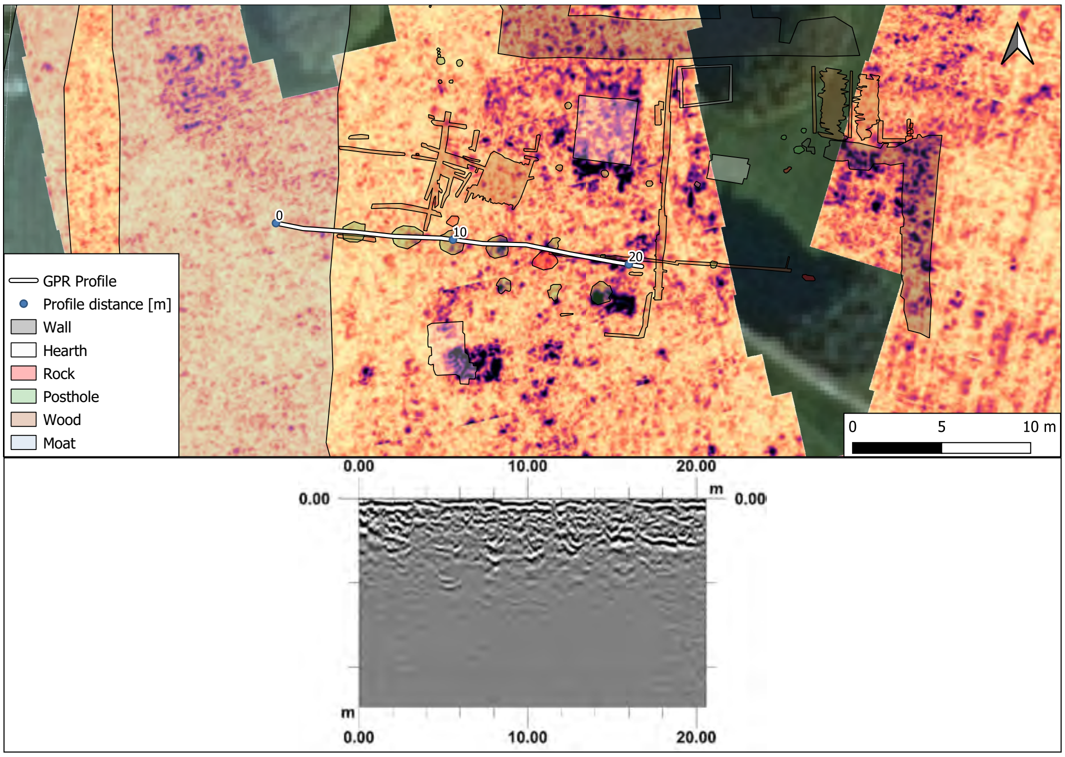


Figure 3.19: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 1 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

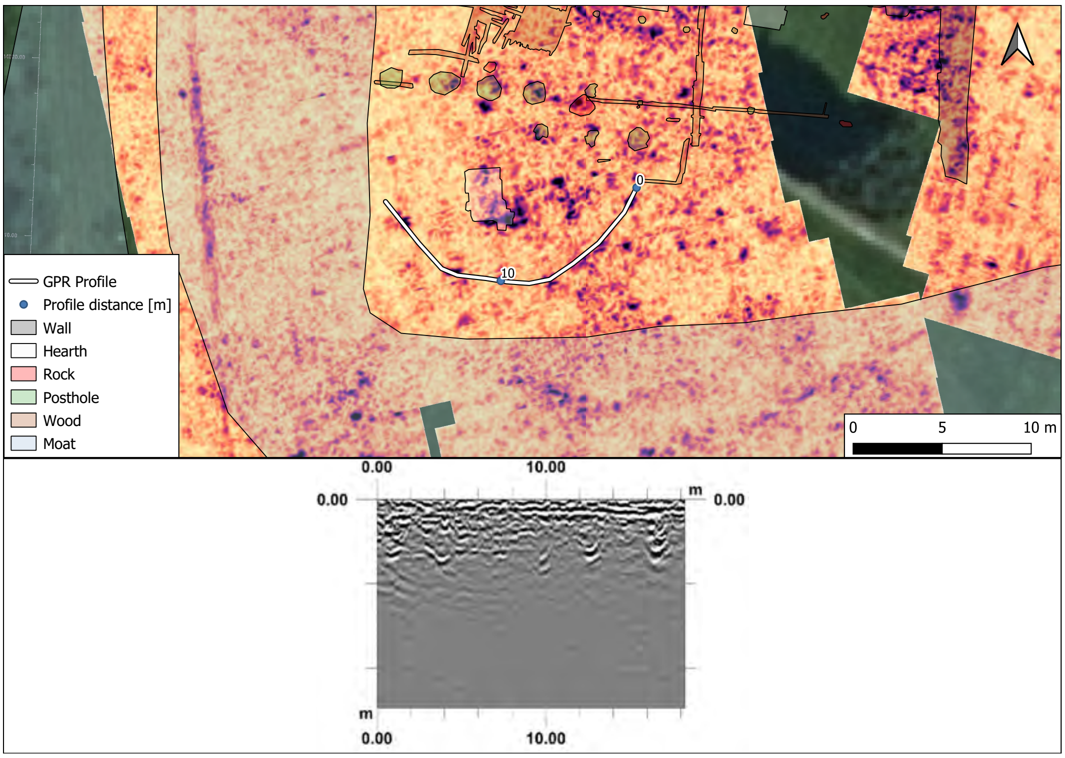


Figure 3.20: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 1 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

Anomalies resembling a structure where the larger of the hearths was uncovered by af Ugglas, just south of the E-W striking wall, start to become visible at 0.60 meters depth. The structure that appears is visible down to about 1.30 meters and dissipates afterwards. Even though the structure resembles the hearth excavated by af Ugglas, it does not entirely fit with the map drawn by him. When looking at Figure 3.21 at 0.90 meters, the reflections from the depth seems to be a quadrangular shape much like the hearth documented but larger than how af Ugglas mapped it.

Figure 3.21: GPR data at 0.90 m depth with digitized structures modified from af Ugglas (1931) (left). © Lantmäteriet

Other nearby structures however, such as the E-W striking wall, fit almost perfectly with the reflections from the radar data which makes the case of the large hearth not appearing in the data interesting. There are explanations as to why this might happen and it will be treated further in discussion. It can however with confidence be said that the structure that appears is of archaeological nature. This is further supported by looking at the GPR profile cross-cutting the hearth (Figure 3.17 on page 31). At 50-54 meters, where the hearth is located, there are clear reflections indicating the presence of something below the surface. The reflections are similar in appearance to those of the western wall that appears just above it.

At 0.70 meters, around eight dark dots are visible encircling the large hearth (Figure 3.16 on page 30). They are visible down to 1 meters depth, although they become larger and less distinguishable. Five of these dots were marked on the archaeological map by af Ugglas, surrounding the hearth, but were not described by him.

Further south, below the documented large postholes by af Ugglas, a structure starts to become visible at 0.80 meters and it is most clearly seen at 1 meters depth (Figure 3.17 on page 31). It is undocumented by af Ugglas, although it appears juxtaposed and rotated 90 degrees to a smaller uncovered and documented hearth. It is possible that it is the documented hearth but since the anomalies differ from it, it cannot be said for certain. It can be seen clearly in a GPR profile between 32-35 meters that there is a structure located in the soil there (Figure 3.22)

The hearth mapped by af Ugglas just west of the E-W striking wall, built entirely of bricks (af Ugglas, 1931, p. 381-382), does not appear in the GPR data.

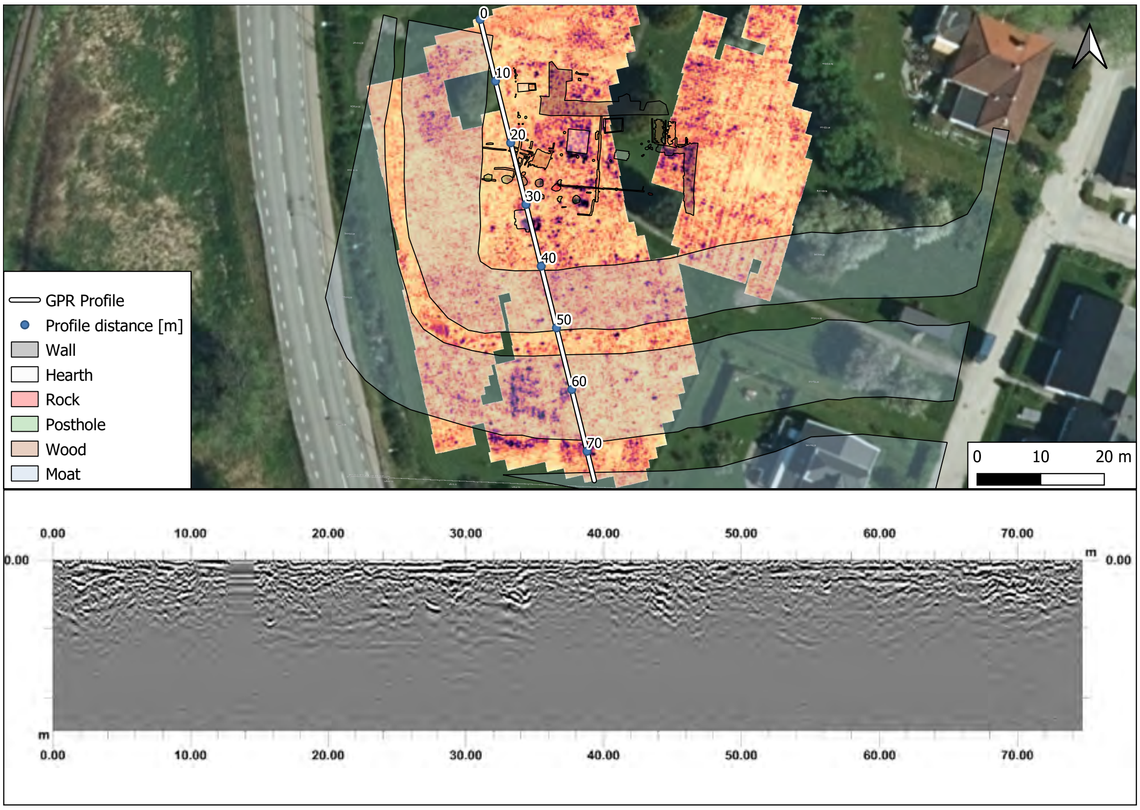


Figure 3.22: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 1 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

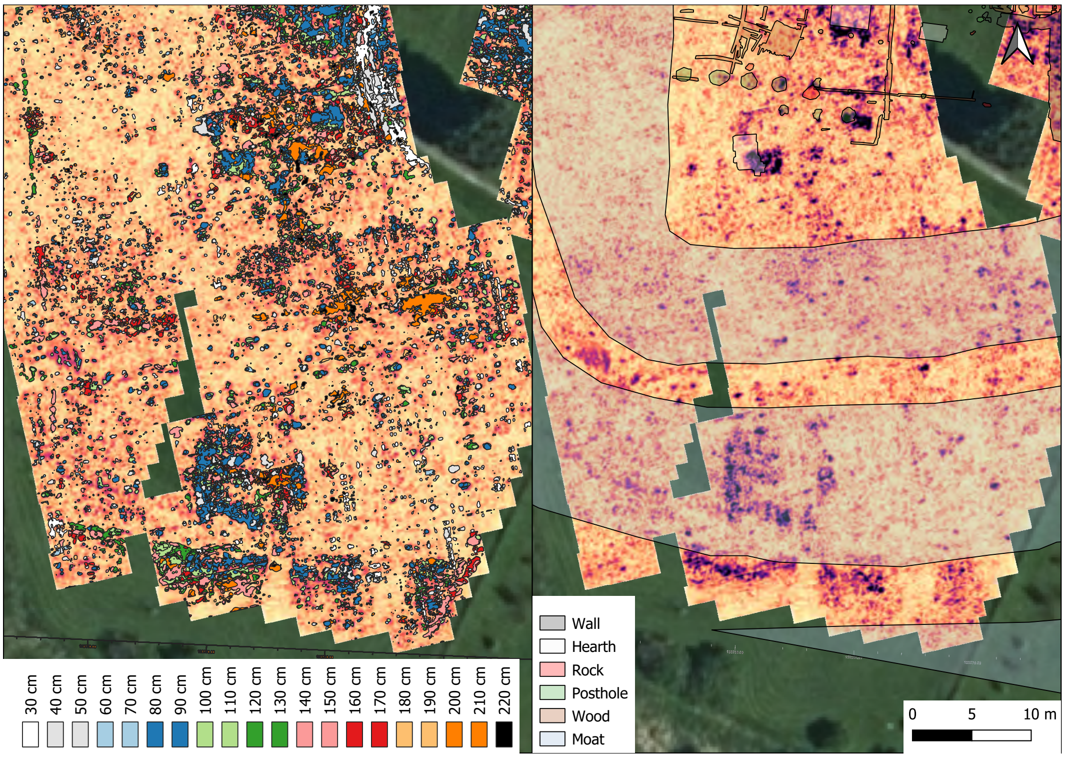


Figure 3.23: GPR data at 1 m depth. Polygons marking anomalies at every 10 cm depth from 30 cm to 220 cm put together (left). Digitized structures modified from af Ugglas (1931) (right). © Lantmäteriet

The moats can be distinguished in the 3D GPR data, although with difficulty. The margins of them are seen clearest between 0.6-1.5 meters depth but it is only when the excavation map is superimposed that it appears clearly that it is the moats that are the source of the anomalies. When anomalies are put together between the depths of 0.5-2.3 meters, clear structures appear within both moats, most striking in the southern part of the outer moat (Figure 3.23) and the north-western corner of the middle moat (Figure 3.25).

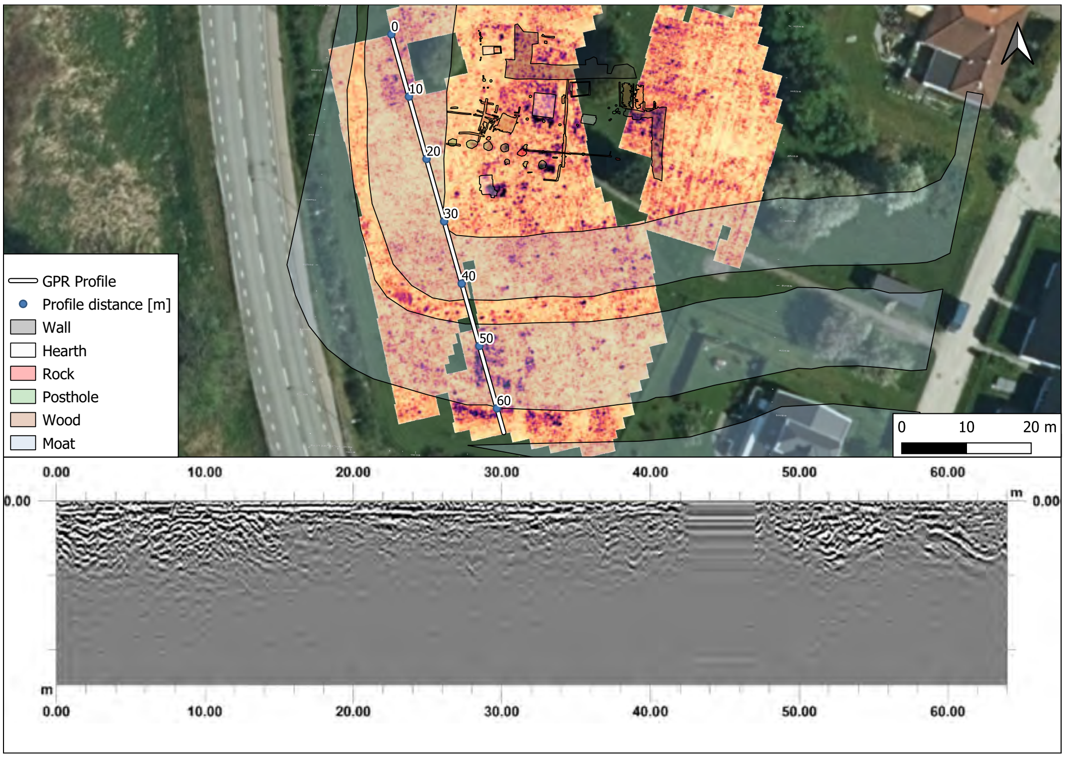


Figure 3.24: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 1 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

Seen on the GPR profile (Figure 3.24), at 50 meters there are clear reflections resembling those of the E-W striking wall. This, together with the anomalies from different depths are sufficient to conclude that the structure seen is of archaeological nature. As to why anomalies appear on different depths and together forming a structure will be treated further in discussion.

Another interesting aspect seen in Figure 3.24 is that at 60 meters a dipping reflection appears that does not correlate to the drawings made by either af Ugglas or Ekre of the moats. This reflection will be treated further in the discussion. The same profile (Figure 3.24) also shows an interesting reflection between 0-15 meters which falls within the middle moat as mapped by af Ugglas. Figure 3.25 shows anomalies from different depths put together in the north-western corner of the survey area. It forms interesting structures that together with the radar profile makes it likely that there is in fact an archaeological structure buried underground.

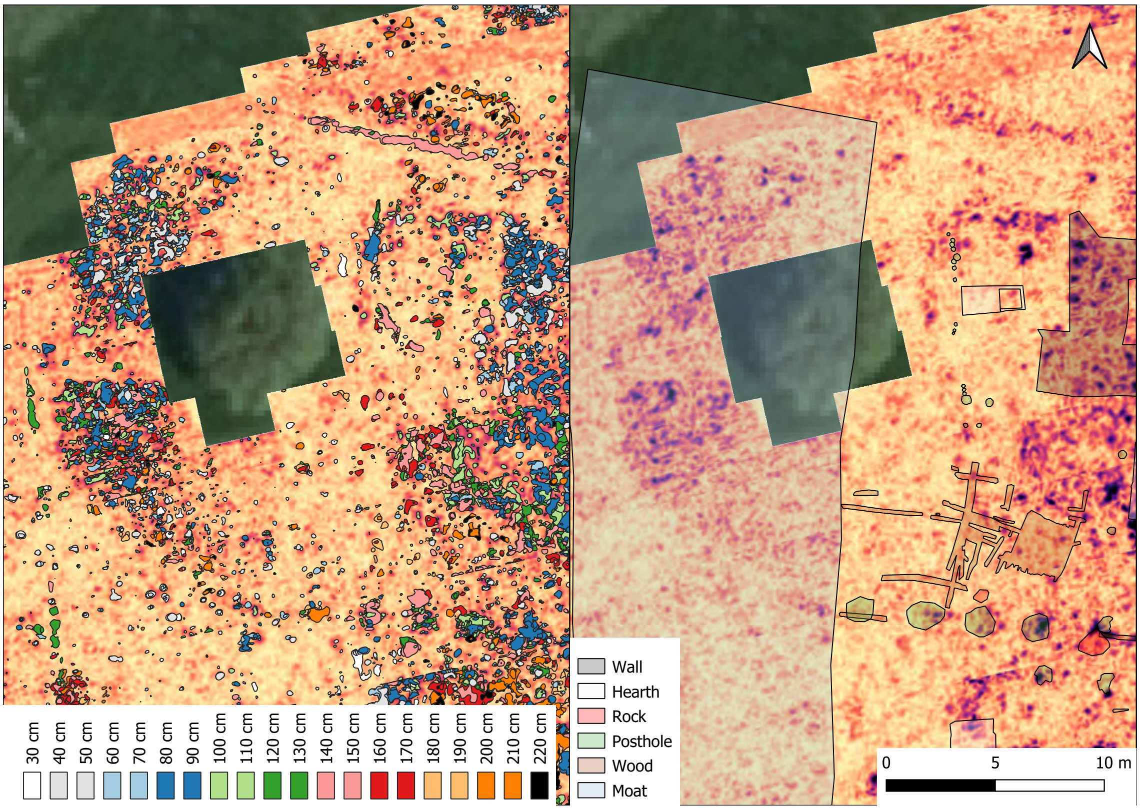


Figure 3.25: GPR data at 1 m depth. Polygons marking anomalies at every 10 cm depth from 30 cm to 220 cm put together (left). Digitized structures modified from af Ugglas (1931) (right). © Lantmäteriet

A profile going over the anomalies appearing along the margin of the outer moat is shown in Figure 3.26. These reflections appear at around 0.80 meters depth, are previously not mapped and of unknown origin. These anomalies resembles the structure found within the moat just north of them and appears at similar depths.

Straight lines appear between 1.20 meters and 1.70 meters throughout the survey area (Figure 3.27). Given the fact that these lines are undoubtedly straight, the nature of these are probably not of historical value but rather cables or pipes that have not been marked out and reported to the national database for utility placements.

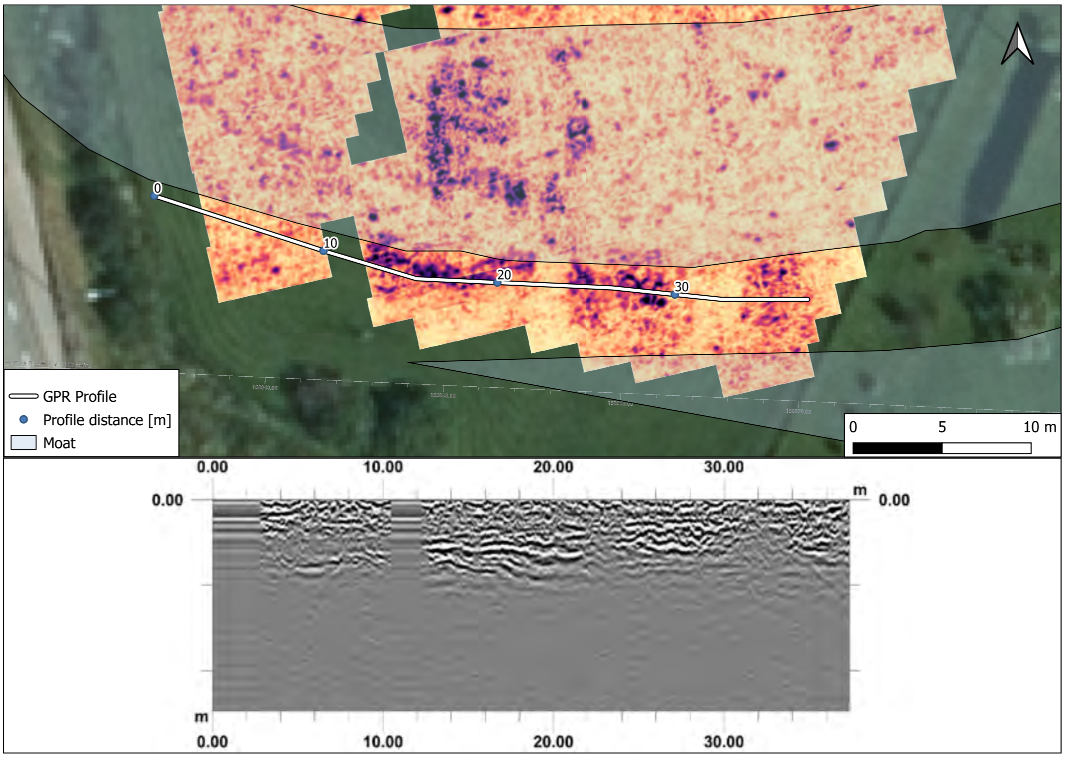


Figure 3.26: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 1 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

Figure 3.27: GPR map of the area behind Lödösehus. Lines shows where utilities were found with the GPR. © Lantmäteriet

The eastern section of the radar surveying was done over a gentle slope with step-like features that could be interpreted as terraces. These can also be seen in the data at shallow depths. Old aerial photos can give answers as to what these terraces have been used for. A photo from 1960 is shown to the right in Figure 3.28. An orchard visible and the terraces can also be seen. The red square shows the extension of the map to the left in the figure. This shows the radar data at 0.20 meters depth and lines of all cable- or pipe-like features that can be seen at various depths. The terraces can be seen as squiggly lines in the radar image. None of these utilities are documented in the data base of cable locations. Considering how many there are, it can be conceived that these belonged to the orchard.

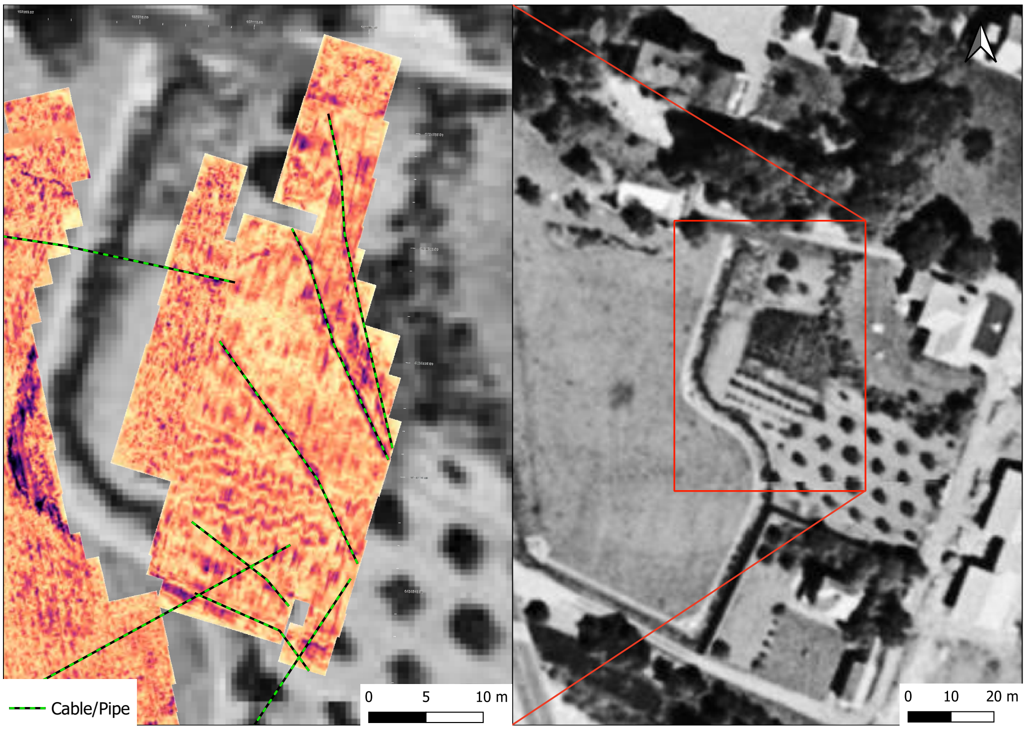


Figure 3.28: Aerial photo from 1960 together with radar data from 0.20 m depth with interpreted utilities. © Lantmäteriet

Anomalies appear most strikingly in the 3D data as a 6 meters wide and 13 meters long dense cluster in the eastern section, north of the N-S striking wall (Figure 3.29). More anomalies are visible throughout the eastern section, most notably in the northernmost area, although more scattered than the mentioned cluster. The anomalies become visible at 0.4 meters down to a depth of 2.3 meters, although most anomalies start to disappear at around 1 meters depth. Figure 3.29 shows the anomalies at a depth of 0.7 meters with a radar profile going through the dense clustered area. Reflections can be seen throughout the whole profile down to a depth of 2 meters and further in some places. An interesting reflection dipping towards the north can be seen between 1-5 meters. At around 22 meters, the profile crosscuts the N-S striking wall which is seen of the reflections.

Figure 3.30 shows another radar profile to the east of the previous one. Reflections appear between 0-15 meters to a depth of beyond 2 meters. Some of these reflections show as hyperbolas. Between 28-33 meters along the profile there is a reflection that dips towards the south, similar to the dipping reflection seen of Figure 3.29 between 1-5 meters along the profile.

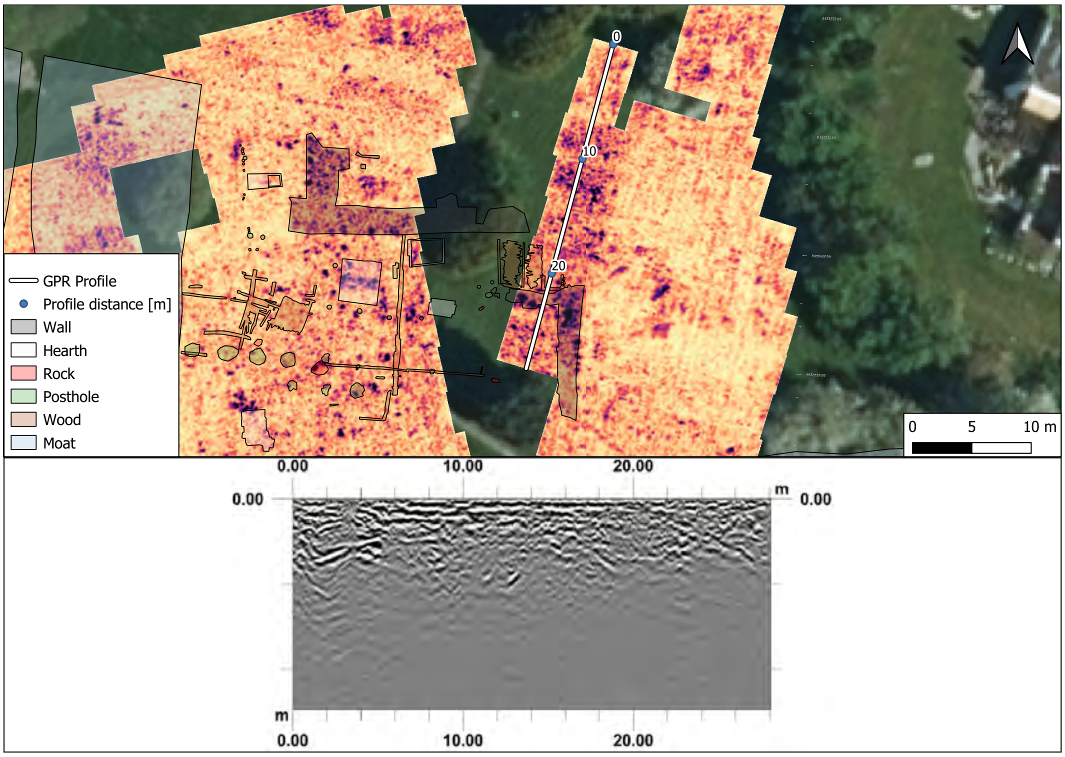


Figure 3.29: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 0.7 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

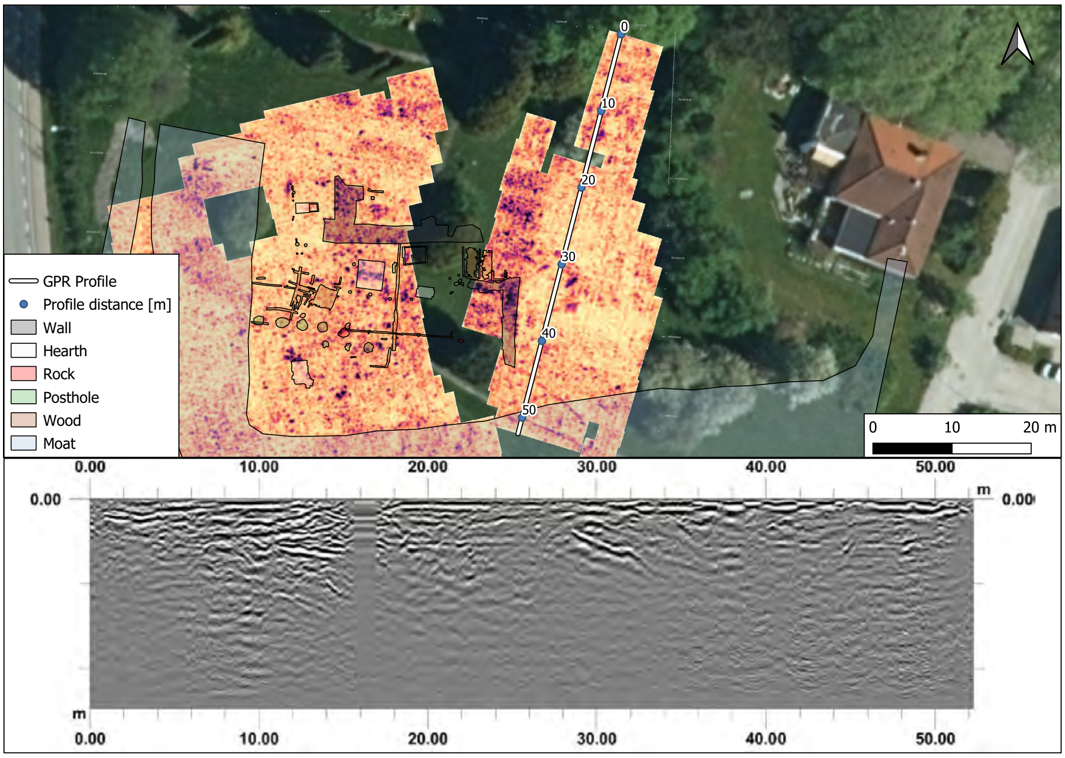


Figure 3.30: 3D GPR data (top) and 2D profile (bottom). The 3D data shows radar image at 0.7 m depth with the extent of the profile. The profile is marked at every 10 m. Each bar in the 2D profile on both the x and y axis represents 2 m. © Lantmäteriet

3.2 Resistivity

The results from the resistivity and IP survey are presented in Figure 3.32 on page 44 and 3.33 on page 45. The extent of the profile is shown in Figure 3.31. The profile measures 100 meters and the depth scale is given in meters above sea level with the line marking the distance along the profile as ground level. The values ranges from 0 Ω-m to 25449 Ω-m. North is to the left of the profile and south to the right.

Figure 3.31: The extent of the resistivity and IP profile behind Lödösehus superimposed on the GPR data and digitized structures modified from af Ugglas (1931). © Lantmäteriet

An overview of the resistivity profile in Figure 3.32 shows high resistivity anomalies in the form of red and purple bodies in varying sizes located close to the surface. Underlying these anomalies is a thick layer of low to very low resistivity soil (green, yellow and blue). The blue values (0-100 Ω-m) fall within the range of clay as seen in Figure 2.2 on page 14 which correlates to the information on the soil map (Figure 1.2a on page 5). As for the green and yellow values (175-350 Ω-m), they fall within the range of sand/gravel and till (Figure 2.2).

Since the start of the profile was put on the slope of the hill upon where Lödösehus stood, there is little doubt that the first 11 meters that show high resistance anomalies (750+ Ω-m) is the bedrock. Anomalies appear in different depths between the bedrock and the beginning of the area for the GPR survey (11-21 meters along the profile). Since no excavations have been performed here and no other data has been gathered, only two of these features can be identified. The asphalt road can be seen in Figure 3.31 just before the 20 meter mark which correlates with a shallow anomaly appearing between 17-18.5 meters. At 11.5-15.5 meters along the profile and at a depth that goes beyond other anomalies is a body of low resistivity (25-75 Ω-m) with similar values to that which is underlying the whole survey area. This falls within the value for clay. This will be treated further in the discussion. At the same position in the IP profile (Figure 3.33) anomalies can be seen which means that there is something that has electrical chargeability (e.g. geologic borders or anthropogenic additions to the stratigraphy) at this place of low resistivity values.

Between 38-46.5 meters along the profile, another high resistance anomaly can be seen which fits the E-W striking wall in the GPR data. An anomaly appears by the middle moat between 72-75 meters and between the middle and outer moat is a small anomaly between 80-81 meters. The largest anomaly appears as a high resistance body between 90-99 meters along the profile. These are the same structures that can be seen in Figure 3.26 on page 39 and the southern part of Figure 3.23 on page 36. This structure will be treated further in discussion.

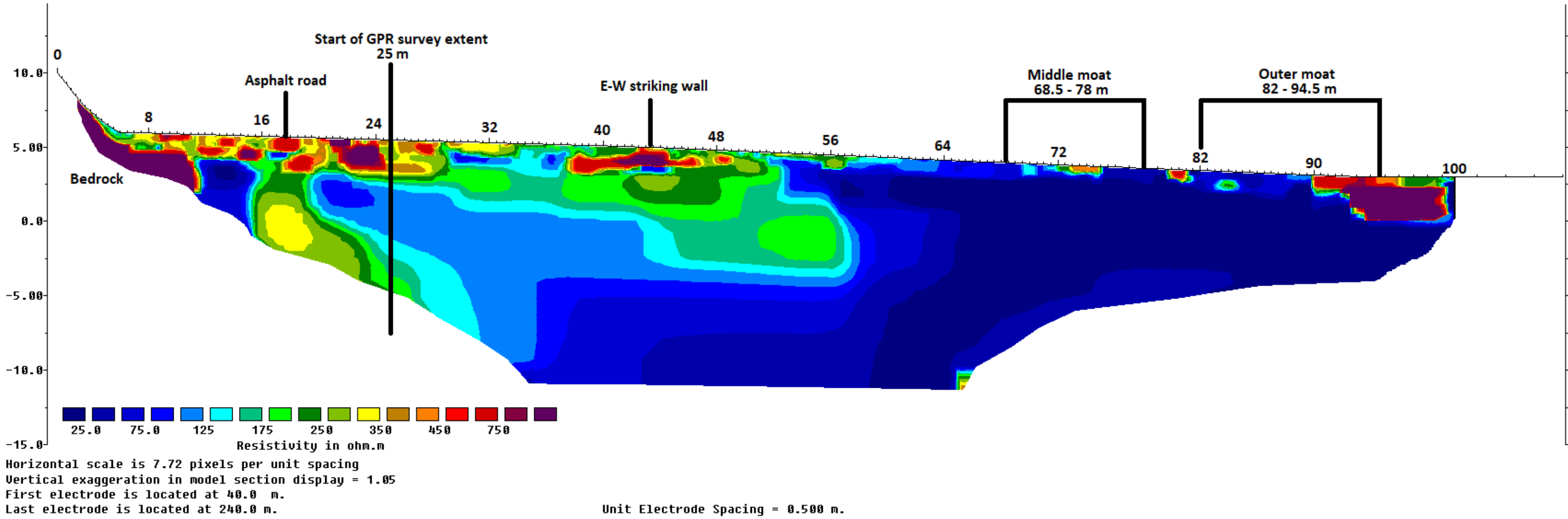


Figure 3.32: Resistivity profile of Lödösehus with known features from superimposed GPR and areal photograph. North is to the left of the profile and south is to the right. Low resistivity values is shown in blue to green, high resistivity values in yellow, red and purple.

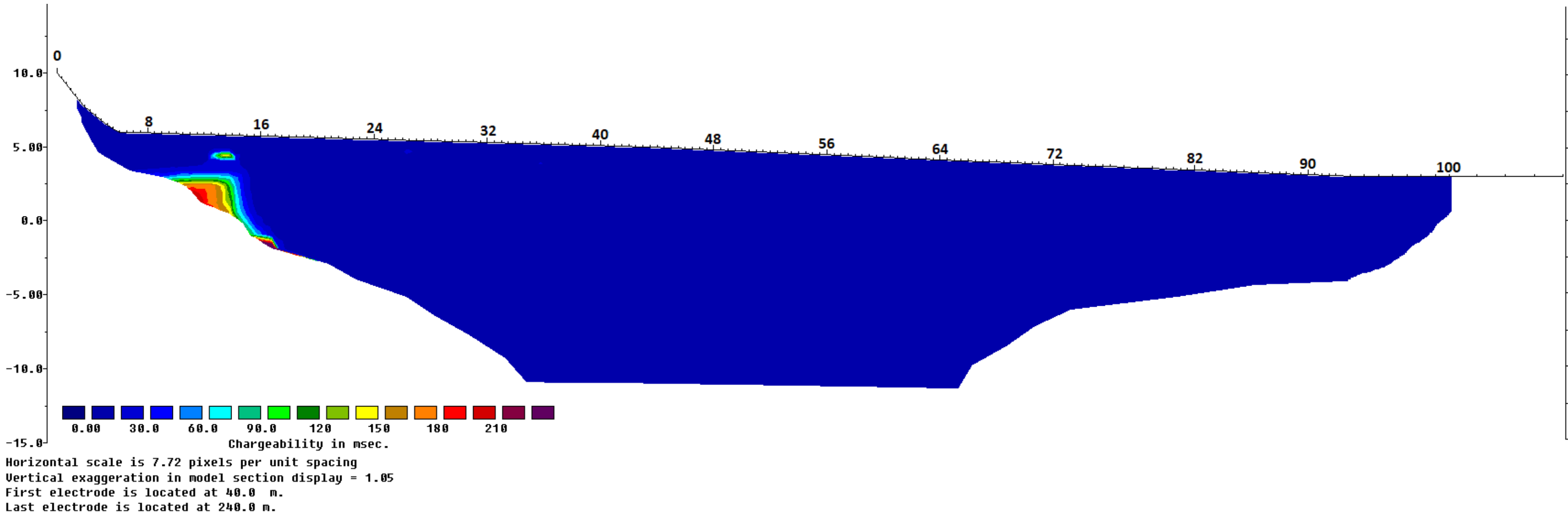


Figure 3.33: Induced Polarization profile of Lödösehus. North is to the left of the profile and south is to the right. Low values is shown in blue to green, high values in yellow, red and purple.

4 DISCUSSION

4.1 Geology

As mentioned in Chapter 2.1, clay with dissolved salts and saturated with water has a shallow penetration depth with a GPR. According to Musset & Khan (2000, p. 229), even a thin layer of wet clay or salt water will result in penetration depth of only a few centimeters. As seen in Figure 1.2a on page 5, the park-like lawn surveyed is situated mainly on post-glacial fine clay with the southern end being on top of floodplain deposits consisting of clay and silt. In the GPR data presented in Chapter 3, both in 2D and 3D, reflections and anomalies can be seen down to 2 meters and beyond. An example of this can be seen in Figure 3.17 on page 31. Naturally, penetration depth will be greater in the excavated areas since the soil has been disturbed in recent times and is therefore less compacted (Musset & Khan, 2000, p. 430). The park-like lawn has been used for farming, which would account for increased visibility in the top layer of the soil (af Ugglas, 1931, pp. 362–364). Furthermore, the cultural deposits containing pottery, leather and other sorts of human waste are in some places 4.5 meters thick in Lödöse (Ekre et al., 1994, p. 13). This would account for increased visibility with depth in GPR surveys since the cultural deposits are not undisturbed soils. However, the reason for this unusual penetration depth at Lödösehus with the GPR is probably due to the leaching of salts in the clay due to groundwater flow and precipitation. This is especially significant in the southern part of the survey area which is mapped as having floodplain deposits (Figure 1.2a on page 5). This would not only indicate a soil with higher permeability, but also a higher degree of leaching of the original post-glacial clay from the stream Gårdaån. Furthermore, the soil deposited is fluvially transported from a fresh water source with no salts bound to them.

Wooden objects that were excavated and mapped by af Ugglas were not visible in the 3D GPR data, except for one feature - the log that intersects the gutter. This could be due to most of these objects has rotted after being exposed to oxygen from the excavations. A radar profile crossing the wooden structures is seen in Figure 3.22 on page 35. Between 20-25 meters the profile intersects the mentioned wooden structures and reflections can indeed be seen down to around 1 meters depth. It is not however possible to conclude that it is the wooden structures that are seen and not just disturbed soil.

Another object that was not seen in the 3D GPR data was the hearth located just west of the E-W striking wall. The reason for this might be due to the construction of the hearth with cemented bricks. This could trap water that would remain for a longer period within the hearth. This would be the case even in periods of a lower groundwater table due to the slower rate of percolation through the cemented brick structure. Since water saturated soils have higher conductivity this causes a higher degree of signal attenuation and therefore shallower penetration depth of the GPR.

In a radar profile (Figure 3.30 on page 41) from the eastern section of the park-like lawn there are reflections forming hyperbolas between 0-10 meters along the profile. One of these hyperbolas is a utility that was found from the GPR survey (Figure 3.28). However, this area is in close proximity to Skanskullen (the bedrock hill). The hyperbolas could be due to boulders or till. Unfortunately, the survey did not get closer to the Skanskullen but it is possible that the soil close to it could consist of till.

The resistivity profile as shown in Figure 3.32 on page 44 was made with a colour scale to clearly visualize anomalies on the profile. There are seven bodies of high resistance ranging between the values of 450-750+ Ω-m to the left of the profile before the extent of the GPR survey. Only one of these features can be interpreted as the asphalt road based on the position of the profile when superimposed on an aerial photograph. To study these anomalies closer, a different colour scale was made as seen in Figure 4.4 on page 56.

Only three bodies of high resistivity before the GPR survey extent can now be seen; one between 14.5-15.5 meters (2000 Ω-m), another between 21-22 meters (3000+ Ω-m) at the surface and one body between 22.5-23.5 meters (2500 Ω-m). These might be structures since they show values similar to the E-W striking wall (at 43 meters) but they could also be boulders, till or lenses of sand/gravel given their position in proximity to the elevated bedrock. The resistivity values of the upper soil in in connection to the bedrock are around 500 Ω-m, placing it in the upper range of peat and mid-range of till and sand/gravel. An interesting feature is the anomaly appearing to the right of the interpreted inner moat (Figure 4.4 on page 56). This has a value of around 500 Ω-m which would place it in the range of gyttja/peat, till or sand/gravel. This might be a lens of till or sand/gravel but there is also a possibility that it is due to values from the underlying bedrock that was interpolated with the overlying soil.

The top five meters in both of the resistivity profiles (Figure 3.32 on page 3.32 and 4.4 on page 4.4) shows higher values than the underlying soil. This is probably due to the cultural layers with anthropogenic deposits being around 4.5 meters thick around the area (Ekre et al., 1994, p. 13). It could also be due the the groundwater table being generally low. However, there is a small gradient towards the south of the profile. The resistivity values are low in the southern part which indicates a higher water content. The higher resistivity values of the soil to the north falls within the range for quick clay which indicates that the clay has been leached of salts. The northern part of the park-like lawn therefore shows favourable conditions for the formation of quick clay.

4.2 Archaeology

4.2.1 GPR

Courtyard

The steep slope to the west in the data, which was the border for the GPR measurements, may not be a natural surface but a part of Lödösehus (A. Lazarides, personal communication, November 20, 2020). The slope is now covered by vegetation, and no further investigations were made in situ, but for the slope to be a former wall seemed likely. Parts of the old walls could be seen at the base of the houses in front of the villa, supporting this claim. Further support for this idea can be taken from the GPR data. At 0.10 meters depth, an irregular straight line, striking NE-SW, appears to the left in the radar image (Figure 3.2 on page 19). This is interpreted to be part of the wall. However, the line disappears just a decimeter further down but can be seen again at 0.57 meter broken into pieces (Figure 3.6 on page 21). Even deeper down, for example at 1.45 meter, clustered point objects are seen in this area (Figure 3.11 on page 25). It can be speculated that the line seen at 0.10 meters is the grey-coloured cable in Figure 3.1 on page 18. However, the irregularity of the line compared to other utilities seen in the data detracts from this assertion. The cable is also supposed to be mapped with an offset of roughly 2-3 meters, but fails to align with the radar image. The radar profile over the NE-SW striking line (Figure 3.14 on page 27) shows a layered structure at ground level and another at 0.6 meters depth with hyperbolas in between them. The lower layered structure is probably a wall and the top layered structure could be well sorted filling material. The hyperbolas appearing between the layered structure are most likely unsorted artificial filling material.

A similar feature to the one mentioned above is an irregular line appearing to the mid-right at 1.18 meters depth (Figure 3.10 on page 24). It shares similarities with the NE-SW striking line both in shape and that it is replaced by clustered point objects deeper down at 1.45 meters (Figure 3.11 on page 25). It would be interesting to see if these two lines connect to each other further north.

Since the castellum that was built before Lödösehus might have been circular, it is appealing to say that the bow-shaped feature appearing at around 0.70-0.80 meters depth (e.g. Figure 3.8 on page 23) would be a part of this castellum. However, it seems unlikely that it would have been placed at this location instead of higher up on top of the rock, further to the south. Since there was a moat surrounding the hill and this bow-shaped feature is found at the northern edge of the hill, it might be the foundation of a drawbridge that was facing the town. The radar profile shows clear, planar reflections of this feature, indicating that it is a structure at around 0.7 meters depth.

Not every feature can be studied and explained. It can be difficult to determine if one anomaly is an archaeological artefact or just artificial fill from the construction of the tarmac. An example is the semi-circles seen in Figure 3.7 on the 3D data and between 10-17 meters along the profile on Figure 3.13. They appear as layered reflection which is probably due to them consisting of filling material. The most interesting parts of the castle are probably found where the villa now stands. More detailed information about what Lödösehus might have looked like will remain a mystery. We will have to rely on archaeological interpretations from historical sources.

The Outer Bailey

It is not clear from his sources how deep af Ugglas dug. Based on his photographs however, an estimation can be made. The middle moat seems to have been dug out at a depth of ca 1.5 meters (af Ugglas, 1931, pp. 347–355) and the rest of the excavated features at a depth of ca 0.5-1 meters (pp. 363-384). Furthermore, he does not specify how the protocol was during archaeological excavations in regards to what is done to excavated material, both soil and archaeological finds. According to archaeologists today, during the time of af Ugglas excavations (1916-1920) there were no protocols of how to treat archaeological sites and finds (T. Axelsson, personal communication, February 15, 2021). This can cause different issues with the data gathered with the GPR. Mainly, were the excavated finds left in place or were they either removed from the site or moved within the site to facilitate further excavation? This might be the case for the hearth west of the E-W striking wall that cannot be seen in the GPR data.

The large hearth just south of the E-W striking wall uncovered and mapped by af Ugglas appears strange in the 3D GPR data. While the mentioned hearth does not appear as a structure matching the excavation map, the outlines of it appear, although larger than the hearth as mapped by him. It is possible that the anomalies in the 3D GPR data appears larger than the actual hearth because of the excavated area around the hearth is larger than the hearth itself. The soil that was used to fill the excavated area is causing the anomalies. Disturbed soil would be more loosely packed if not subjected to stress and therefore appearing as anomalies in the 3D GPR data when compared to undisturbed and packed soil. This could be the case for any anomalies, meaning that the actual size and position of structures encountered could be different than what it appears to be in the 3D GPR data due to the disturbed soil on top and around structures.

At 1 meter depth there is a clear, rectangular structure visible juxtaposed to the southernmost hearth excavated and mapped by af Ugglas. It is uncertain whether this structure is the hearth or something else but it does resemble the shape of the hearth, even though it is rotated 90 degrees relative to the one mapped. Without an excavation, there is no certain answer to this enigmatic coincidence. It is clear however from Figure 3.22 on page 35 at around 32 meters that there is a structure located at around 1 meters depth, right where the structure next to the mapped hearth is visible in the data.

Postholes were found and mapped by af Ugglas during his excavation. Postholes were used to drive down wooden piles into the ground for the purpose of building a protective fence or a house wall (af Ugglas, 1931, p. 368). The wooden piles have decayed with time but the postholes have been filled with soil that is less compacted than the surrounding soil (Musset & Khan, 2000, p. 430). It is therefore seen in the GPR data as anomalies.

It is not correct to assume that any dark dot appearing in the 3D GPR data can be assigned as postholes. These dark dot anomalies could also be stones, for example dropstones embedded in the post-glacial clay that constitutes the sediment in the area (Klingberg et al., 2006).

By looking at radar profiles in 2D, dark dot anomalies appearing in the 3D GPR data can be studied closer. A profile over the four large postholes was made that showed that they resemble U-shaped reflections (Figure 3.19 on page 33). The same type of reflections are shown in the profile in a crescent shape constituted by dark dots in the GPR data (Figure 3.20 on page 33). When there is an object that causes reflections during a GPR survey, such as stones or even postholes, they normally form a hyperbola (Musset & Khan, 2000, p. 437). The reason why the postholes do not show as hyperbolas and instead has a U-shape might be due to them being filled with loosely packed sediment that shows a contrast to the surrounding, more compacted soil.

Regardless, if postholes are seen as U-shaped reflections and objects like dropstones form a hyperbola, 2D radar profiles are evidently a crucial complement to 3D radar data in archaeological surveys.

Another fact to consider is that most of Lödöse has in recent history been a site of extensive agriculture, including the area of the survey. This must be considered when interpreting the data because the uppermost layer of the soil has been ploughed extensively. Stones that belonged to archaeological structures and got caught in a plough have been removed by farmers and either transported away or been placed somewhere else on the field, perhaps on a pile or a designated area (af Ugglas, 1931, pp. 362–364). However, in those cases where the dark dots form structures that appear in linear or, for example, crescent-shaped forms, it is more reasonable to assign them as postholes made in order to build house walls, fences, or similar, rather than stones moved by farmers and placed in these symmetrical forms.

The moats have not been excavated entirely, only parts of them, although which parts are unclear. Ekre drew a map based on around 15 excavations done in modern times, most of them for infrastructure, which encountered the moats (Figure 1.5 on page 10) (Ekre et al., 1994, pp. 60–62). Since these excavations were were undertaken for purposes other than archaeology, they were done around the area of the castle, where the modern roads are located. This means that the exact location of the moat system is not known at all parts but reliable enough to assume that the moats were placed where Ekre assumed them to be. The map af Ugglas (1931) made of the moats does not cover as much of their extension and differs in placement. However, since he actually did excavate parts of them on the park-like lawn south of the villa, his version of the moats will be the reference for further discussion.

The moats themselves, as they are mapped, were barely distinguishable in the 3D GPR data. However, there were interesting anomalies within and in proximity to the moats. Already at 0.50 meters there are anomalies in the southern part of the outer moat that persist to 2.10 meters. When the anomalies from different depths are put together, a rather interesting rectangular structure with three clusters of anomalies south of it manifests itself (Figure 4.1). Furthermore, in the north-western corner of the middle moat there are two clusters of anomalies which form structures (Figure 3.25 on page 38). This raises a couple of questions, mainly are the moats wrongfully mapped and what is the nature of the structures seen in these moats?

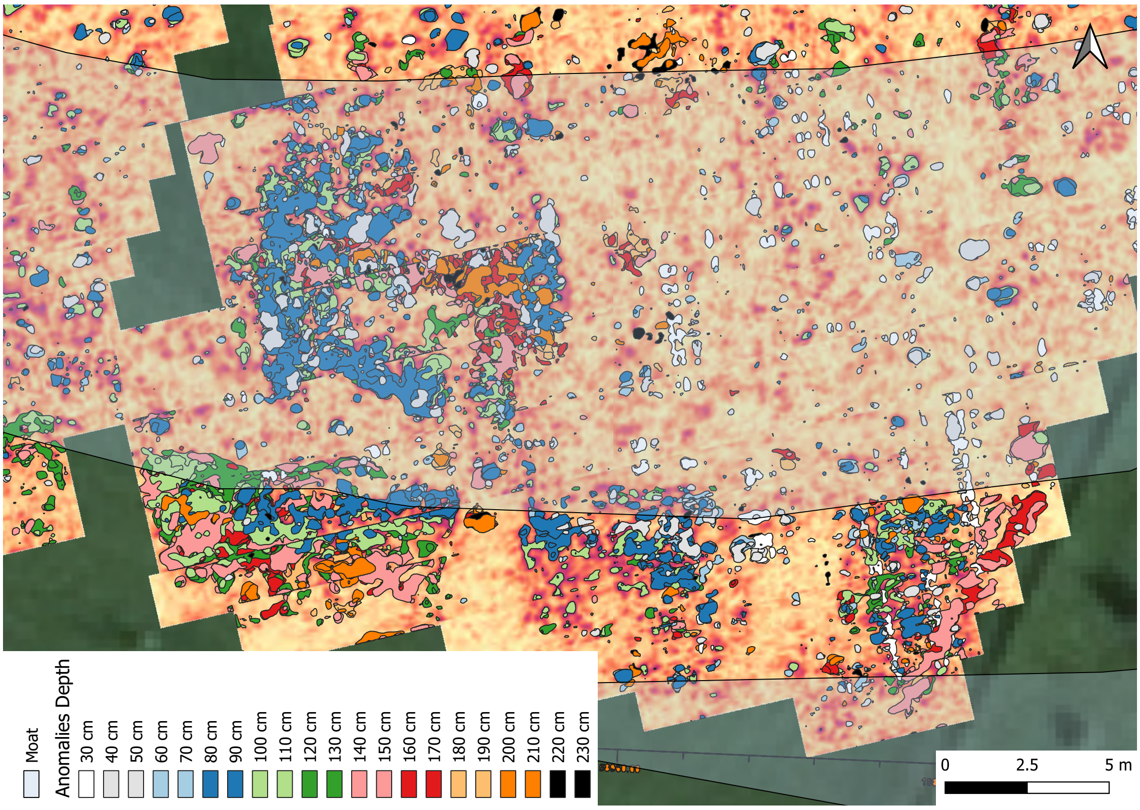


Figure 4.1: Structure shown by anomalies from every 10 centimeters between 0.3-2.3 meters depth in the southern part of the outer moat. © Lantmäteriet

To begin with the rectangular structure with three clusters of anomalies south of it, located in the southern part of the outer moat. These four structures become apparent when anomalies from every 10 centimeters are put together between 0.70-2.10 meters (Figure 4.1). If other structures are found at around 1 meters depth, and there is no considerable topography that might cause the difference, then it might indicate that these structures that can be seen down to 2.10 meters are of older origin. However, as can be seen on the soil-type map (Figure 1.2a on page 5), these structures are located in fluvial sediments (silt and clay) in proximity to the old margins of the Ljuda stream running south of the area. This could suggest that the structure has settled heavily due to being built on silt and clay. It could also mean that fluvial sediments have been deposited on top of the structure, causing it to settle more.

The explanation could of course be of a more simple nature, that these structures were built deeper than the other ones found in the survey area, perhaps because they were built in the moat.

The structures found in the north-western corner of the middle moat (Figure 3.25) show similar behaviour in the GPR data as the structure mentioned above. It appears clearly when putting anomalies together from a depth range of around 0.4-2.0 meters. When put together it is undeniably a structure that is seen. The radar profiles confirm this theory. As seen in Figure 3.24 on page 37 between 0.0-14.5 meters the reflections of the mentioned structure are seen. Between 48-56 meters along the same profile, the reflections of the structure within the outer moat are seen. Both these structures show reflections similar in composition to each other and reach down to similar depths. This could indicate that these two structures are of similar nature. Since af Ugglas (1931) does not mention either structure found within the moats, the GPR and resistivity data are the only tools available for interpreting them.

The subject of the moats being wrongfully mapped requires an analysis of the 2D GPR profiles cross-cutting them. As can be seen in Figure 3.24 on page 37, at about 58-64 meters along the profile, there is a dipping reflection that is similar in shape to what a moat, river bed or a ditch could look like. In fact, the dipping reflection seen between 58-64 meters is identical to some found on the Orkney islands, identified as ditches by the authors of Landscapes Revealed (Brend et al., 2020, pp. 57–61). This is the strongest argument for a different placement of the outer moat than previously mapped. In Figure 4.2, sections of the radar profiles in Figure 3.22 (top) and 3.17 (bottom) are presented showing the reflections that appears over the moats. Looking at the top profile, located slightly to the east of Figure 3.24, between 66-75 meters along the profile, reflections appear in a concave shape dipping downwards. Between 40-50 meters along the same profile and coinciding with the placement of the middle moat, there are similar reflections as seen between 66-75 meters, although less conspicuous. Furthermore, the reflections between 40-50 meters do not appear in the 3D data as clearly as those seen between 66-75 meters. This suggest that the nature of these reflections are different. Reflections are seen between 54-65 meters which could be reflections of the outer moat.

In the bottom profile on Figure 4.2, between 0-6 meters along the profile, there are reflections but they do not form a shape that could be interpreted as a moat. On the same profile between 20-30 meters, reflections that are concave can be seen that coincide with the placement of the middle moat. Furthermore, between 8-18 meters reflections are seen which would be from disturbed soil that was used to fill in the outer moat.

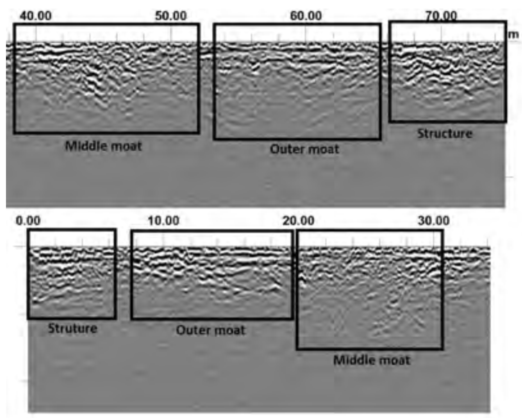


Figure 4.2: Comparison of reflections from the middle and outer moat as mapped by af Ugglas (1931) together with the structure appearing outside the outer moat. The top profile is taken from Figure 3.22 on page 35 and bottom profile is taken from Figure 3.17 on page 31.

Putting these anomalies together makes is hard to argue for a new placement of the moats based on the GPR data. Clear reflections appear in concave shapes that coincide with the placement of the middle moat. Reflections appear that also coincide with the placement of the outer moat, although they do not form a concave shape as those of the middle moat. These reflections are probably due to soil that was used to fill the moats and has therefore not compacted as much as the surrounding soil, thus showing clear reflections in the 2D profiles. These reflections are however not seen as clearly in the 3D data.

The reflections that appear south of the outer moat are the most clearly seen, both in the 2D and 3D data. This suggests that these reflections are from a different source than those of the moats. The anomalies appearing just south of the rectangular structure within the outer moat appear as three clusters in the 3D GPR data (Figure 4.1). A profile of these anomalies south of the outer moat is shown in Figure 3.26 on page 39. It is difficult to determine the nature of these reflections, whether they are caused by layered sediments or by a built structure. The resistivity profile (Figure 4.4 on page 56) can shed some light on this issue. Between 130-139 meters there is a body of high resistivity (3000+ Ω-m) which indicates that it is crystalline rock (Figure 2.2 on page 14). This will be treated further in chapter 4.2.2 on page 54.

The anomalies appearing in three clusters to the very south of the survey area are probably parts of a structure that has a connection to the rectangular structure found within the outer moat. According to Jefferey (2017), who excavated an area on Skankullen (the hill where Lödösehus was situated), the moats were refilled with soil in the late 13$^{\text{th}}$ century and Lödöse was refortified in the 16$^{\text{th}}$ century and in the 1670s. The excavations revealed walls that were built upon debris of bricks which she argues is because the walls were built at a later stage than the castle itself (Jefferey, 2017). This could mean that the structures and anomalies seen in the outer moat and just south of it could date back to either after the moats were filled in the late 13$^{\text{th}}$ century, the refortification in the 1670s or somewhere between. That would explain why the structure in the moat can be found at such depth (2.10 meters) since the structure, assuming that it is a building of some sort, was built upon unconsolidated soil that has caused it to settle heavily.

There is also the matter of the structures appearing within the middle moat on the north-western corner. Since no other data than that of the GPR was gathered over this structure, its nature will remain unknown.

There is a possibility that the structure appearing within the outer moat and the three clusters of anomalies just south of it could all be parts of a bridge fortification. The rectangular structure within the moat would have been a small defensive tower, acting as a barrier on the bridge. The three structures south of it could be foundations from a fortified bridge going in an E-W direction, parallel to the stream just south of the moat. This fortified bridge probably extended further east but due to a property the survey could not cover it. It is reasonable to assume that there would have been a bridge towards the south of the area to be used in times of peace or to stage a potential sortie. That would provide another explanation as to why this structure can be seen down to 2.10 meters depth since its foundations had to be built in the moat. This would also explain the dipping reflection in Figure 3.24 on page 37 as being some sort of foundation for the fortification.

An example of how this bridge fortification might have looked like can be seen in figure 4.3. The Figure shows the coat of arms of Lilla Edets municipality, to which Lödöse belongs. The coat of arms is inspired from Lödöse's medieval signet which dates back to 1411 (Riksarkivet, 2021). The fortification seen on the coat of arms is seemingly small and standing on water. If one would approach Lödöse from the open sea, one would come from the south along the Göta river. The first sight indicating that Lödöse had been reached would then have been the bridge fortification which could be a reason to why the signet of the medieval city would have looked like in Figure 4.3.

Figure 4.3: Coat of arms of Lilla Edets municipality, based on the medieval signet of Lödöse depicting Lödösehus (Riksarkivet, 2021)

4.2.2 Resistivity

As mentioned previously, a resistivity profile with a different colour scale was made to study the anomalies closer (Figure 4.4 on page 56). This profile will be the topic for discussion.

The possible bridge fortification shows values of 3000+ Ω-m to the east of the profile which can be interpreted to be an unknown structure made of crystalline rock that needs to be studied further (see section 4.3).

Juxtaposed to the bedrock, between 11.5-15.5 meters along the profile is a body of low resistivity with vales of 10-100 Ω-m. This could be the inner moat that never was excavated to the south of the hill upon where Lödösehus stood. The inner moat was however excavated to the north (as seen in Figure 1.5) in later times and was measured to be 3-4 meters wide (Ekre, 1991a, p. 60). The dimensions, placement, shape and low resistivity values present a strong argument for that anomaly to be the inner moat. Furthermore, ditches and other archaeological features that have been filled usually show lower resistivity values than surrounding soil (Musset & Khan, 2000, p. 430). The reason why the middle and outer moat do not show as anomalies like the inner moat might be explained by the surrounding soil being clay and thus there is no contrast in composition.

The potential inner moat shows interesting anomalies on the IP survey (Figure 3.33 on page 45). Large amounts of slag from a smithy have been found in a moat south-east of the area (Ekre, 1991a, p. 62). This can be the reason for the anomalies on the IP survey that coincide with what is interpreted to be the inner moat. Conductive material such as slag could have been thrown into the inner moat, meaning that there probably was another smithy in close proximity to the castle. However, since the interpreted inner moat shows values for clay it might be that the chargeability is due to clay particles being responsible for the anomalies. Since the bedrock at the beginning of the profile does not show the same anomalies, it is unlikely that it would be the bedrock responsible for the IP values.

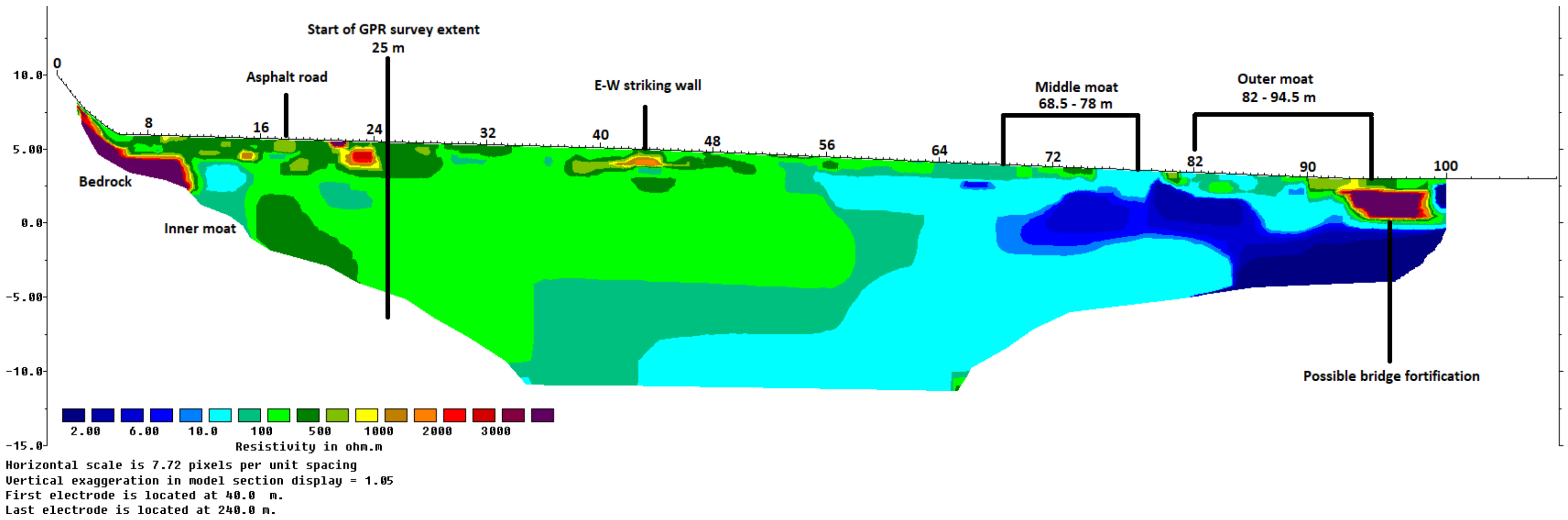


Figure 4.4: Resistivity profile of Lödösehus with known features from superimposed GPR and areal photograph. North is to the left of the profile and south to the right. Low resistivity values is shown in blue to green, high resistivity values in yellow, red and purple.

4.3 Future Excavations

For future studies, excavations are recommended. Ground-penetrating radar and resistivity are excellent tools in both geology and archaeology to map the subsurface. Geological knowledge is valuable in geophysical surveys in order to exclude geologic features and interpret anomalies as buried structures. However, in order to understand exactly what lies beneath the surface, excavations are the only way to find out. Geophysics in archaeology can narrow down a potentially large survey area down to precise locations where excavations can be carried out, thus saving the precious resources of time and money.

Figure 4.5: Marked suggested area for future excavation. Corners are marked with numbers where coordinates are given in Table 4.1 © Lantmäteriet

In Figure 4.5, an area marked in translucent white is shown where an excavation would answer several questions regarding the history of Lödöse. This is the site where the potential bridge fortification is situated. The area of the suggested excavation measures 150 m^2. Since the marked area was not excavated by af Ugglas (or anyone else), GPR and resistivity surveys can only confirm that these anomalies are part of a structure that can be found between 0.5-2.3 meters depth. Therefore, it should be excavated to at least 2 meters depth to obtain a clear picture of what lies beneath the surface. If it is a bridge fortification, the models and pictures of how Lödösehus once looked would have to be redrawn. It would perhaps also explain why the modern coat of arms of Lilla Edets municipality (Figure 4.3) depicts a fortification on water.

Table 4.1: Coordinates of the corner for the suggested excavation (SWEREF99 TM)

	X	Y
1	331803.350	6435755.068
2	331812.912	6435752.784
3	331799.666	6435740.238
4	331810.141	6435739.020

5 CONCLUSIONS

This study has proven that geophysical methods are a powerful tool in mapping archaeology in the subsurface and determining near-surface geological conditions. Ground-penetrating radar was the principal method used in this study and was complemented with a resistivity and induced polarization survey. To give the latter methods a more thorough evaluation, additional surveys would be needed. More about resistivity for archaeological and near-surface geological studies can be found in the other part of the larger study in Möhl & Andersson (2021).

Data gathered with GPR can be visualised in both 2D and 3D, each with their advantages. With 3D data, larger areas can be analysed and single anomalies can be seen in a larger context. However, only one wooden feature was seen in the 3D data and the disturbed soil in the moats were not clearly visible. To determine the nature of anomalies seen in the 3D data, 2D profiles proved to be useful in the case of studying postholes and the moats more closely. Reflections in the profiles did occur over wooden objects although it was not clear whether this was because of these objects or disturbed soil. For archaeological studies such as this, a combination of 2D and 3D data is useful to concentrate efforts in where to excavate and focus on further studies.

The resistivity and induced polarization profiles was a useful complement to the GPR survey. Where the terrain is difficult to reach with a GPR instrument, such as slopes and in dense vegetation, resistivity is a useful tool to map the subsurface. In determining the nature of the structure within the outer moat in the south of the study area, resistivity proved to be a helpful complement. Induced polarization did complement the resistivity survey in determining the nature of the low resistivity anomaly in proximity to the bedrock. However, resistivity and induced polarization surveys require more time to perform in comparison to GPR.

The penetration depth of the GPR was unusually high for a site with clay. This could be because of the cultural layers with anthropogenic deposits being up to 4.5 meters thick in the area and because of the leaching of salts in the post-glacial clay. The resistivity survey showed higher values in the top 5 meters of the soil which could indicate a lower groundwater table in the park-like lawn. Furthermore, the clay in the northern part had resistivity values which indicates favourable conditions for the formation of quick clay. The likely reason for this is a gradient towards the south which has caused a higher degree of leaching of salts in the clay.

In general, the knowledge of the outer bailey and courtyard of Lödösehus has greatly increased with this study. Previously excavated features can now be located with precision and new historically valuable features have been identified that require further excavations for the advancement of our knowledge on the subject matter.

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