Geological Challenges of Archaeological Prospecting: The Northern Peloponnese as a Type Location of Populated Syn-Rift Settings

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Abstract: The Northern Peloponnese is not only home of a series of ancient poleis that are being studied by archaeologists, but it is also located on the southern shoulder of the most active extensional crustal structure in the world; the Corinthian rift. This rift has shaped the Northern Peloponnese as we now see it today since the Pliocene. Normal faulting, the tectonic uplift of syn-rift sediments and sea level changes, has shaped a landscape of steps rising from the coast to the ridges in the hinterland that provides challenging conditions to a geophysical survey. Where we can find coarse grained slope and delta deposits of conglomerate on top of banks of marl on ridges and slopes, the lower marine terraces and the coastal plain as well as valleys show the protective caprock eroded and the marl covered by young alluvial deposits. These materials show only a small contrast in their magnetic properties, which reduces the importance of magnetic mapping for the archaeological prospection in this region. The human utilization of the coastal plain and the urban areas pose additional challenges. These challenges have been overcome through various approaches that are shown in exemplary case studies from Aigeira and Sikyon. Whereas a combination of magnetic mapping and ground-penetrating radar (GPR) works very well on the ridges and along the slopes where we find coarser sediments in addition to the magnetic mapping, it is not suitable in the coastal plain due to the attenuating properties of the alluvial sediment. Here, electrical resistivity tomography (ERT) proved to be very successful in mapping entire parts of a settlement in great detail. Seismic soundings were also successfully applied in determining the bedrock depth, the detection of walls and in the question of locating the harbor basin. In the presented six exemplary case studies, the following findings were made: (1) A fortification wall and building foundations at a depth of 0.4–1.2 m on a plateau northwest of the acropolis of Aigeira was found by 400 MHz GPR. (2) A honeycomb-shaped pattern of magnetic anomalies that suggested cavities could be identified as a weathering pattern of conglomerate rocks. (3) A rock basement 2.3 m deep and remains of an enclosing wall of the Aigeira theater area were found by shear wave refraction measurements. (4) Extensive ERT surveys detected several building remains in Sikyon like a potential building and grave monuments as well as several small houses. (5) A silted-up depression in the sediments of the coastal plane located through Love wave measurements, could be taken as evidence for either a silted harbor or a navigable riverbed.
Keywords: Aigeira; Old Sikyon; archaeogeophysical prospection; geological challenges; GPR; ERT; seismics

1. Introduction

Many important ancient poleis are located on the Northern Peloponnese (Greece) along the southern shore of the Gulf of Corinth, among them the ancient cities of Aigeira and Sikyon, which have recently been investigated archaeologically. The geophysical surveys being part of these studies are the subject of the present article. It deals with the causes and solutions of prospection challenges, which are primarily associated with the geological setting of the area of the Gulf of Corinth. As this is a type location for syn-rift tectonics, the presented prospection issues can be seen as exemplary cases, which can be transferred to other regions of similar geological character.

The similarities include typical sequences of host and deposited sedimentary rocks serving as construction material at the same time, as well as tectonic and weathering structure and topographic features. The Corinthian Rift is the most active extensional crustal structure in the world. It has shaped the Northern Peloponnese as we see it today since the Pliocene. Normal faulting, the tectonic uplift of syn-rift sediments and sea level changes have shaped a landscape of steps rising from the coast to the ridges in the hinterland. Common is also that especially the low lands are under intensive use of modern civilization, making prospection everything but an easy enterprise.

A review of [1] has shown that, until then, the application of geophysical methods was not a standard in archaeological studies. Since this time, the developments in geophysical survey techniques and equipment have strongly improved enabling multi-hectare surveying per day—if the environmental conditions are favorable. This progress established geophysical sounding as an archaeological research approach in its own right in assessing and studying cultural heritage covered in the ground ([2]). Often it is the first methodology applied in investigating a new site. Parallel to the perfection of established field technique new archaeological questions inspired the development or adaptation of so-far uncommon geophysical methods, and led to the understanding that a combination of different methods is often useful or necessary for solving the questions ([3]).

Although magnetic surveys are still the backbone of an archaeological survey it is often only in combination with other methods possible to interpret the geophysical results correctly. These complementing methods include ground-penetrating radar (GPR) (e.g., [4,5]), electrical resistivity tomography (ERT) (e.g., [6–8]), electromagnetic induction (EMI) (e.g., [9]) to different sorts of seismic methods ([10–13]). Whereas multi-ha-scale areas can be surveyed easily with magnetics and GPR in plain open area, the terrain conditions found on the Corinthian Rift are more difficult, and the rather small contrasts between geological background and the cultural remains mostly excludes the use of magnetics.

In this paper we address typical prospection tasks and challenges resulting from the Northern Peloponnese’s geologic history and related physical material properties. Solutions are presented in the form of a series of six exemplary case studies located along the entire topographical profile ranging from ridge and slopes over the marine terraces and the plain to the sea (Figure 1a). We use the archaeological site of Aigeira as a representative for a polis on the ridge and slopes and Sikyon as an example polis that is situated in the populated coastal plain of the Gulf of Corinth (Figure 1b,c). The geophysical-archaeological results of Aigeira and Sikyon are presented here for the first time in this generalized context.

As a starting point we provide an overview of the geological frame of the Northern Peloponnese region and the physical properties of the relevant present materials based on the literature and our own measurements. Then the example studies are presented. In the discussion, we address methodical items including the adaptability of the findings to other sites.
Figure 1. (a) Schematic topographic section. Marked are also the location of the exemplary cases presented in this article. (b) Overview of the location of Aigeira and the two main survey areas near the acropolis (A) and the area around the theater (B). (c) Overview of Sikyon with the two survey areas of the main settlement (A) and the harbor (B).

2. Geological and Archaeological Background

2.1. Geological Framework of the Northern Peloponnese

The Aegean is one of the seismologically most active regions due to ongoing tectonic deformation. It is in fact the most active extensional crustal structure in Europe. It is caused by the interaction of the Hellenic subduction zone in the southwest and the North Anatolian Fault zone in the northeast (Figure 2a; [14]). Since Miocene times, the NNE-moving African plate has been subducted under the Eurasian plate causing a back-arc extension that created the Aegean Sea ([15–17]). Additionally a gravitational anomaly in the subducted slab is proposed to be the cause for the ongoing tectonic uplift of the entire Peloponnese ([18]). Although the exact relationship to the Aegean expansion and the tectonic plate movement is still disputed ([19,20]), the Corinthian rift zone formed between the North Anatolian Fault (NAF) and the Kefalonian Fault (Figure 2a) in the Pliocene approximately 5 Myr ago (the exact point in time is still disputed [19,21,22]).

The rift expanded along a series of parallel normal faults creating a graben and thus enabled the formation of the Corinthian Gulf. The about 105–120 km long Gulf is up to 30 km wide, up to 900 m deep, and separates the Peloponnese from Continental Greece. Whereas the active part and the main fault lines of the Corinthian rift can nowadays be found offshore ([23,24]), older syn-rift sediments have been uplifted to elevations of over 1000 m during the Quaternary. These sediments are exposed in a 25–30 km wide belt along the Gulf’s southern shore and are less active ([14,15,25]). The resulting huge uplifted blocks are covered by deeply incised Plio-Quaternary syn-rift sediments that can be up to 2.8 km thick ([14,18,26]) and can be observed along the southern shore of the entire Northern Peloponnese.

Next to these huge steps marine terraces add topographic steps in some regions like east of Aigio and maybe most prominent in the Corinthia ([27]). In the Corinthia the arc-like terraces formed during eustatic sea-level changes in the last 350,000 years ([14,15,21]). Here, a series of 10 flat marine terraces with elevations of 10–400 m were mapped by Armijo et al. (1996) (Figure 2b).
Alluvial sediments can be found in many valleys and plains. The older sequence of these sediments and the regionally present paleosols can be attributed to the strong erosion of the post glacial warming period, whereas the younger alluvial fill is most likely related to land-use like deforestation and grazing ([28]).

Since the Classical period the alluvial fill is estimated by [29] to be about 1–3 m in depth based on excavations in the Voicha plain in the Corinthis. Whereas the total uplift (faulting superimposed on regional tectonics) of the region can be estimated to be around 1–5 m in the last 2000 years by studying harbor sites along the Gulf ([30–32]; see Section 3). This again shows how active the Corinthian rift remains.

![Figure 2](image.png)  
**Figure 2.** (a) General regional tectonic setting (after [14]). (b) Geological map of the syn-rift sediments after [33]. Marked are also the location of the archaeological sites mentioned in this article.

### 2.2. Stratigraphy and Physical Material Properties

For a geophysical survey in an archaeological context the entire geological history might only be of secondary interest. However, it often helps to understand the situation of the investigation site and the knowledge of the materials occurring in the survey area might be essential for the interpretation of geophysical results. It can also enable transferring experiences from one site to another, if the geological background is similar. Hence, it is worth knowing about the stratigraphic sequence and identifying the materials that are present at the archaeological site.

If we follow the classification of [34] the syn-rift sediments can be divided into three groups correlating to different phases in the rift evolution. This classification was established by studying the central part of the southern rift margin but is thought to be representative for the entire southern coast of the gulf ([34]).

The Lower Group is made of fluvio-lacustrine deposits from coarse conglomerates to fine lacustrine turbidites, which can be several hundred meters thick and are made of fine grained sediments like mudstone, siltstone, and even more common marl. Interbedded into this fine grained sediment are thin layers of conglomerate or sandstone.
The Middle Group is characterized by thick alluvial fan conglomerates and their equivalent giant Gilbert-type fan deltas with finer pro-delta deposits. The Gilbert-type fan deltas of the Middle Group are made of granule to pebble conglomerates interbedded with fine-grained deposits and pebbly sandstones.

The Upper Group shows next to smaller Gilbert-type fan deltas also marine terraces and red paleosols.

The involved materials can be summarized and categorized into the following groups: (a) mudstone, siltstone, and marlstone; (b) limestone, sandstone, and conglomerate; (c) marl, paleosol, and alluvial sediment. The consolidated fine-grained materials of group (a) make out the most of the syn-rift sediments and show, according to literature, similar physical properties in nearly every column in Table 1. The same is true for the more stiffer sediments of group (b). All present sediments have in common that they range at the lower end of magnetic susceptibility values. How these physical parameter are of consequence for the geophysical survey will be outlined in Section 3.

| Material              | $\kappa$ ($10^{-6}$ SI) | $\rho$ (Ωm) | $v_s$ (m/s) | $D$ (kg/m³) | $\epsilon_r$ | $\alpha$ (dB/m) |
|-----------------------|-------------------------|-------------|-------------|--------------|--------------|-----------------|
| Conglomerate          | 0–30                    | 10–10⁵      | 1800–2700   | 2300–2600    | 4–8          | 0.4–1           |
| Limestone             | 0–3000                  | 100–10⁵     | 1800–3800   | 1750–2880    | 4–8          | 0.4–1           |
| Sandstone             | 0–30 (20,900)           | 50–10⁵      | 300–2700    | 2000–2700    | 2–10         |                 |
| Marlstone             | 10–1000                 | 5–200       | 700–2300    | 2200–2700    |              |                 |
| Mudstone              | 10–1000                 | 5–200       | 1100–2300   |              |              |                 |
| Siltstone             | 10–1000                 | 5–200       |              |              |              |                 |
| Marl                  | 10–1000                 | 30–70       | 400–1500    | 1600–2300    | 4–20         | ca. 1–200       |
| Gravel                | 0–30                    | 50–10⁴      | 100–550     | 1400–2300    |              |                 |
| Alluvial sediment (silt) | 10–100                  | 100–300     | 1200–2200   | 5–30         | 1–100        |                 |
| Red Paleosols         | 10–100                  |             | 1200–2400   |              |              |                 |

2.3. Archaeological Sites in Respect to the Geological Framework

In the next section we give a short introduction into the archaeological sites of Aigeira and Sikyon already mentioned above (Figure 2b; Figure 1b,c), place them in the described geological context, and show their geological similarities and differences.

2.3.1. Aigeira

In the area of the modern villages of Aigeira and Derveni we find only a narrow plain along the Gulf of Corinth before the topography quickly rises in steps. These steps were created during the extension of the Corinthian rift by normal faulting, the deposition of delta deposits, but also by eustatic sea level changes, which created marine terraces in the area east of Aigio (compare Section 2.1).

Here at the eastern border of Achaia, we find the former settlement of Ancient Aigeira on a 420 m high marine terrace ([31]) and the neighboring terraces mainly to the north (Figure 1b). To the east and west of the hill the landscape is deeply incised.

The plateau of Aigeira is like the surrounding area made mainly of marlstone with interbedded thin layers of coarser material. However, it is capped by conglomerate delta and slope deposits of the Pleistocene Upper Group ([25,27]; Figure 2b), which most likely ‘saved’ it from the erosion that took place around the plateau. As a result the plateau is overlooking the Corinthian Gulf and the coastal plain.

This ideal strategic location is most likely one reason for the long settlement history from the late Bronze age until its fading in the late antiquity. Hence, making it one of the longest continuously inhabited sites in the area ([38,39]). Aigeira was mentioned by Pausanias and as Hyperesia in Homer’s
Odyssey and Ilias. The name of Hyperesia was changed to Aigeira after a ruse of war involving goats saving the polis from the threatening troops of Sikyon (7th c. BC; [40]).

Excavations in Aigeira are carried out by the Austrian Archaeological Institute in Athens (OEAI) since 1972 ([41]). Since 2012, a geophysical survey has been included in the studies, which mainly aimed at mapping remains in the subsurface such as buildings and fortification walls and possible cemeteries ([42]).

The oldest parts of the settlement can be found on the acropolis with its adjacent terrace, the so-called ‘Saddle’, on the highest grounds. In Hellenistic times the polis spread over an area of about 0.5 km$^2$ including the lower terraces. A theater and several temples were build on one of these terraces ([39,43]; Figure 1b). The building material here are roughly hewn conglomerate blocks as foundations and otherwise more finely worked blocks.

In Sections 5.1–5.3 we present three exemplary cases from different terraces in Aigeira that address these aims. Case 1 (Section 5.1) is located on an adjacent terrace northwest of the acropolis and addresses the aim of mapping a fortification walls and potential additional building remains. A possible cemetery site is located another terrace lower to the northwest (Section 5.2). On both of these terraces the conglomerate is not only present as bedrock but can also be found at the surface in a more or less cracked form. The third case (Section 5.3) is located northeast of the acropolis and on an even lower terrace than the other presented cases. Here, the conglomerate is not broadly present at the surface but forms the bedrock which is covered by a layer of marl or marly soil.

2.3.2. Sikyon

In contrast to the narrow coastal plain in Aigeira the coastal plain is approximately 3.5–4 km wide in the region of Sikyon. The topography also rises more slowly in many small marine terraces (compare Section 2.1). Only the approximately 150 m high plateau and higher grounds in the hinterland are covered by a layer of conglomerate whereas the terraces in the Corinthia are made of Pliocene-Pleistocene marl of the Lower and Middle Group and are capped of by mostly Pleistocene conglomerates and are covered by mostly Pleistocene conglomerates or the caprock has been eroded during the formation of the terraces causing badland erosion ([44]). The terraces and coastal plain are covered by alluvial sediment (Pleistocene and Neogene).

Here, Sikyon, a polis well known for ‘its artistic excellence exemplified in the now-lost works of her famous sculptors and painters’ ([29]) was located, with its acropolis on the triangular-shaped plateau. The Archaic and Classical city, however, were built on the lower terraces and the coastal plain between the rivers Asopus and Helisson flanking the acropolis and continuing to the harbor at the Gulf (Figure 1c).

After the polis was conquered by Demetrios Poliorcetes in 303 BC it was relocated to the acropolis plateau where the modern village of Vasiliko is located ([45]) and the part of the polis in the plain was abandoned and never overbuilt by any larger medieval or modern settlements ([45]).

Whereas Hellenistic-Roman Sikyon on the plateau has been researched and excavated for some years ([29]), only written sources and results of the rescue excavation by the Ephorate of Corinth existed so far about Archaic-Classical Sikyon, providing only little, in the way of comparable information.

The project ‘Finding Old Sikyon’ is a cooperation between the National Museum of Denmark, the Ephorate of Antiquities of Corinth, the Danish Institute at Athens, and the University of Kiel. It aims at identifying ‘the course of the city walls, the location of the harbor, major public spaces, monumental architecture and dwelling quarters with houses, streets etc’ ([45]).

In Sections 5.4–5.6, we show three cases from the Sikyon survey that present the different challenges that we encountered. The first case (Section 5.4) is located on a lower marine terrace made of marl and shows the influence of agricultural utilization on the geophysical survey. The second case (Section 5.5) shows the situation in the plain itself where alluvial sediment covers the archaeological remains. This alluvial cover was estimated by [29] to be 1–3 m thick; however, this is only based on few excavations and may vary. With the third case (Section 5.6) we finish our exemplary cases from ridge to
coast and address the situation of a silted-up harbor. Due to the tectonic uplift and the sedimentation
the former harbor basin is nowadays expected to lie under the outskirts of modern day Kiato.

Compared to Aigeira the materials involved in the cases of Sikyon are slightly different. We have
of course the marl terraces but they are covered by alluvial sediments. Hence, the material contrast
between the conglomerate, again most common building material, and the alluvial sediment is probably
more important for the geophysical survey.

3. Challenges and Solution Approaches

Having outlined the geological setting, archaeological background, and the physical rock
properties we now combine this information for working out the resulting challenges of archaeological
prospection. Here, we distinguish the situations on the ridge and the slopes and the situation in the
plain and in the urban areas. Some general challenges result from the location in the geological past,
such as the seismicity that comes with regularly earthquakes, which of course affects the conservation
state of the archaeological remains. Remains can be collapsed or buried in the past, which might make
the detection or interpretation more difficult. The development of both Aigeira and Sikyon has to be
regarded in context of past and present earthquake activity.

3.1. Ridges and Slopes

The small terraces on the ridge and slopes can make a large-scale geophysical survey technically
difficult. Additionally the steep scarp edges that separate single terraces can present a challenge as
well since targets such as fortification walls are often hidden in the outer edges of these terraces, so that
one always has to keep the safety of survey personnel involved in mind. However, these are challenges
one can solve with patience and caution and are not further discussed in this article.

In Section 2.2, the physical properties of the involved materials from the literature were
shortly addressed. In the following we include rock properties found at ridges and slopes not only
from literature (Table 1) but from our measurements in Aigeira (Table 2).

As mentioned before the materials that can be found on the lower ridges of the Northern
Peloponnese show all rather small magnetic susceptibilities (Table 1) with values of \( \kappa = 0 \) to
3000\((10^{-6}\text{SI})\). The measured values from Aigeira are found indeed at the lower limit of the range of
literature values. The conglomerate shows susceptibility values of \( \kappa = 0 \) to \( 8(10^{-6}\text{SI}) \) and the marl
values of \( \kappa = 4 \) to \( 9(10^{-6}\text{SI}) \), so they are not only small but also overlapping, making the detection of
a conglomerate building questionable that is embedded in marl.

| Site   | Material      | \( \kappa \times 10^{-6} \text{SI} \) | \( \rho (\Omega \text{m}) \) | \( v_s (\text{m s}^{-1}) \) |
|--------|---------------|---------------------------------|-----------------------------|-----------------------------|
| Aigeira| conglomerate  | 0–8                             | 140–7500                    | 400–2000                    |
|        | marl          | 4–9                             | 40–180                      | 150–250                     |
| Sikyon | conglomerate  | 6–8                             | 50–540                      | 500–820                     |
|        | alluvial deposits | 25–53                 | 4–60                        | 80–300                      |

This fact reduces the importance of magnetic mapping, which is otherwise the backbone of most
archaeogeophysical surveys. However, it might still be useful in identifying areas of interest. In
this case different geophysical methods like ground-penetrating radar (GPR), electrical resistivity
tomography (ERT), or seismic measurements have to be considered.

The literature values of the specific electrical resistivity show that the stiff coarse-grained rocks
such as conglomerate are higher than the ones of the finer-grained materials like marl \( (\rho = 10 –
10^5 \Omega \text{m} > \rho = 5 – 200 \Omega \text{m}; \text{Table 1}) \). This is also confirmed by the measured values from Aigeira
(\( \rho = 140 – 7500 \Omega \text{m} > \rho = 40 – 180 \Omega \text{m}; \text{Table 2} \)). Therefore, the application of an ERT survey would
be an option to map buildings made of conglomerate.
Since ERT surveys show a rather small measuring progress, it is normally worth to try the application of GPR first. It provides a higher resolution in the upper meters and a faster measuring progress as long as the attenuation is not too high and with resistivity values up to 180 Ωm this should not be the case.

The first exemplary case from Aigeira (Section 5.1) addresses this challenge of an inconspicuous magnetic map, where GPR proved to be a good solution to map archaeological structures.

The geological past and the tectonic processes resulted in a pronounced heterogeneity of near-surface rocks on top and along the flanks of the mountain range. There, spatial scales are comparable with anthropogenic structures so that weathering forms of the conglomerate rocks resemble man-made structures.

Here, the exemplary case presents an anomaly pattern in the magnetic map that resembles a system of prehistoric chamber tombs in form and size (Section 5.2). Furthermore, it shows how important it can be to apply different geophysical methods in combination at a single site to not mislead the archaeological interpretation and further studies.

The thickness of the sediment cover might vary from terrace to terrace and therefore the target depth might also be different at each site. So it might be of interest to know the depth of the bedrock. GPR is of course one option, but the sediment thickness can easily exceed GPR penetration depth leading to ERT being the better option. However, if the bedrock is too strongly weathered, the electric currents can run through the cracks. Hence, the application of seismic soundings is favorable, alone or in combination with an ERT survey. The measured values for the shear-wave velocity in Aigeira are smaller than the literature values for both materials indicating indeed the presence of mainly weathered conglomerate \( v_s = 400 - 2000 \text{ m s}^{-1} \) and marl with a lower degree of compaction \( v_s = 150 - 250 \text{ m s}^{-1} \) at the near surface of Aigeira. The result is a promising contrast in density and shear-wave velocities of conglomerate and marl.

Hence, it should be possible to determine a boundary between the two units or even to detect archaeological conglomerate structures if the required resolution can be achieved (Section 5.3). The latter could also be of interest, if walls lie below the GPR penetration.

### 3.2. Plain and Agricultural or Urban Area

Main geological features in the coastal plain as we can find it with the Voicha plain between Kiato and Corinth are marine terraces, the alluviation of the plain, and the uplift of the Peloponnesse and with it the coastlines.

The coastal plain and the lower marine terraces are widely covered by alluvial sediment, which we do not find on the higher grounds of the slopes and on the ridges. Therefore, we have to reevaluate and partly modify the geophysical prospection approach discussed so far. The literature values and the measured values from Sikyon show, that the alluvial sediment has a magnetic susceptibility of \( \kappa = 25 \text{ to } 53 \text{ (10}^{-6} \text{ SI)} \). Therefore, the contrast to conglomerate blocks \( \kappa = 6 - 8 \text{ (10}^{-6} \text{ SI)} \) as the main building material is approximately six times larger than on the ridges (Aigeira). Hence, we can expect a higher informative value of a magnetic survey in the plain compared to the slopes and ridges. However, this will also depend on the thickness of alluvial sediment covering the archaeological remains. Here, a possible thickness of up to 8 m ([29] estimated 1–3 m) was considered in the beginning of the Sikyon project. Since the sensitivity of gradiometer measurements decays strongly with depth, a magnetic survey will therefore not suffice on its own and will have to be applied in combination with other geophysical methods.

Alternative geophysical methods could be GPR, ERT, and seisms, depending on the task at hand. If we go back to the material properties found in literature (Table 1) we see that the alluvial sediment and the marl we found on the ridges do not differ greatly. If we however compare the measured values (Table 2), we see that the specific electrical resistivity with \( \rho = 4 \text{ to } 60 \Omega \text{m} \) is smaller for the alluvial sediment compared to the marly soil on the ridge of Aigeira. This might of course effect the applicability of ERT and GPR surveys in the plain. Based on experience the smaller values should not
highly effect the resolution of an ERT survey, but the applicability of a GPR survey is known to suffer
due to a higher attenuation in a conductive first layer.

The exemplary case addresses the challenge of a magnetic map, that does give information about
the archaeological remains, but only in combination with an additional ERT survey all details are
uncovered (Section 5.5).

The first exemplary case, however, will focus on another problem that diminishes the importance
of a magnetic survey and that is the anthropogenic utilization of the plain for agricultural purposes
(Section 5.4). It is widely used by densely planted orchards, which profit from the fertile conditions
the alluvial deposits provide. That does not only make the magnetic survey comparably slow, due to
lacking GPS connectivity, but it also leaves gaps caused by the trees, so that the interpretation is made
more difficult. However, the main problem in this region is not the trees itself but the accompanying
irrigation system that is installed using often hidden metal spikes. The result is often a magnetic map
that cannot be interpreted at all.

The only option is to apply another geophysical method. Since GPR is most likely to be affected
by the conductive soil, the best option is a 3D ERT survey to map archaeological remains.

As mentioned above the tectonic uplift of the Northern Peloponnese (compare Sections 2.1 and 2.3)
also caused an evolution of the coastlines between antiquity and today. The study of ancient harbors
has revealed how large the uplift rates have been since the Classical period. In the harbor of Lechaion
(western harbor of Corinth) exposed lithopaga molluscs and beachrock were found in a height of
1.1 m above sea level ([30]). For the proposed harbor of Ancient Aigeira at Mavra Litharia marine
conglomerates with cemented pottery fragments were found at a height of 2 m above sea level ([31])
and a more recent study shows an even greater two phase uplift of an ancient jetty to be 5.35 m since
the harbor was functioning in Roman times ([32]). For the Sikyon coastline we can therefore expect an
uplift of around 1.5 m ([29]) or more ([32]).

This uplift combined with the progressive silting of the plain will have most likely caused the
silting-up of the former harbor of Sikyon. The harbor basin is therefore expected to lie about 100 m
inland from the modern coastline on the outskirts of Kiato.

In general silted-up harbor basins, canals, and river beds can be distinguished from the
undisturbed geological layers, due to the fact that they usually show a lower degree of compaction
and mechanical stiffness. Therefore, they are detectable using seismic soundings, which determine the
propagation velocity of shear waves in the subsurface, as shown in previous successful surveys, for
example Miletos ([12,46]), Selinunte ([47]) or the former river beds of the Rhine ([48]).

Another method that has proven successful to investigate silted-up harbors is ERT, for example in
Ostia Antica ([7]). The lateral resolution may decay with increasing water saturation. However,
in combination with seismic soundings an electric sounding might improve the identification
of subsurface soil types and might even provide information about the water saturation in
subsurface soils.

The fact that the harbor basin is supposedly located in an urban area poses additional challenges
for the geophysical measurements. Many areas are not accessible due to buildings or private properties,
many surfaces are sealed, and particularly disturbing for seismic measurements is the noise that comes
with an urban area. However, the exemplary case will show, that even noisy seismic data can still
show results by being open to adapt the analysis strategy and analyze the surface waves instead the
first arrival times (Section 5.6).

4. Methods and Equipment Used in the Aigeira and Sikyon Surveys

Obviously, a wide array of geophysical methods is necessary to approach the geological and
anthropogenic challenges which present themselves on the Northern Peloponnese. Here, we want
to give general information about the used equipment, measurement configuration, and applied
processing flows. All georeferencing of the geophysical data was realized using a Leica DGPS system
in the Greek coordinate system EGSA87.
4.1. Magnetics

A magnetic survey is still necessary to map areas in the ha-scale per day to get an overview of the situation and identify hot spots of the settlement even if more detailed information cannot be achieved. The magnetic surveys were conducted using a handcart which holds four to six fluxgate gradiometer (0.65 m vertical spacing; by Foerster) in a horizontal spacing of 0.5 m and an in-house built datalogger. Inline 20 measurements per second were taken (Figure 3). The magnetic and position data are synchronized using an in-house software, which is also able to monitor the measuring progress in real time. The processing of the data was accomplished using an in-house software and consisted of (1) synchronization of magnetic and GPS data using the time stamps, (2) control of GPS quality, (3) removing the offset by subtracting the mean value inline over the whole profile (or in case study 1 in Section 5.1 over 200 samples). The resulting magnetic maps show a pixel resolution of 0.2 m × 0.2 m.

Accompanying susceptibility measurements were carried out with a Bartington MS2D probe.

4.2. GPR

As outlined before (Section 3) the application of GPR and ERT surveys is necessary to get sufficient results for an archaeological interpretation. The GPR surveys in the following exemplary cases were conducted using a 400 MHz antenna and either a SIR20 or SIR4000 registration unit (all by the company GSSI). A line spacing of 0.3 m was used for the areal measurements (Figure 3). The processing of the data was accomplished using an in-house software and included the following steps: (1) zero-time adjustment using the direct wave, (2) interpolating of coordinates and setting of a trace spacing of 0.02 m, (3) removal of horizontal stripes by subtracting a mean trace, (4) determination of the propagation velocity using the curvature of picked hyperbolas, and optionally (5) migration of the data with the following application of a dip filter.

4.3. ERT

The electrical resistivity tomography soundings were performed using a RESECS multielectrode-registration unit (by the company Geoserve). An electrode spacing of 1 m was used inline as well as a line spacing of 1 m (Figure 3). As for electrode configurations a combination of dipole-dipole for a high lateral resolution in the shallow subsurface and Wenner-beta for deeper penetration without losing too much lateral resolution was selected.

The inversion of the collected data was accomplished using the BERT software (Boundless Electrical Resistivity Tomography; [49,50]) by inverting the 2D profile using the combined data of all applied electrode configurations with assigned coordinates and topography. The inversions settings (see Table 3) were tested to accomplish stable results and then used for all profiles of the investigation site. The inverted 2D profiles were then combined to a 3D data set for visualization as depth section but also as areal depthslices.

Table 3. Parameters used for the electrical resistivity tomography inversion with the BERT software (Boundless Electrical Resistivity Tomography) in the exemplary cases.

| Parameter                                              | Value |
|--------------------------------------------------------|-------|
| Size of cells at the surface (in electrode spacing)    | 0.2   |
| Recalculation of the Jacobian matrix in every iteration| Yes   |
| Regularization strength (lambda)                       | 10    |
| Robust and blocky model (L1 norm)                      | Yes   |
| Vertical constrains (zweight)                          | 1     |
Figure 3. Overview over the measurements arrangements of magnetic mapping, ground-penetrating radar (GPR), and electrical resistivity tomography (ERT). For the case studies 1, 2, 4, 5 the arrangement of the measuring areas with indicated profile orientations is shown. The location and orientation of the seismic profiles of case study 3 and 6 can be taken from the corresponding result illustrations in Sections 5.3 and 5.6.

4.4. Seismics

Seismic soundings for the determination of propagation velocity of shear waves were conducted using a sledgehammer source by horizontally hitting a steel bar generating body-waves and surface-waves (Love-type) as well as 24-channel Geodes (Geometrics) and 10 Hz horizontal geophones. The receiver spacing was 1 m with shot points at every receiver point. Here, the exception is profile P3 in Case 4 (Section 5.3) with an receiver spacing of 0.25 m and only nine shot points along the line, due to terrain challenges and time restrictions.

To interpret the collected data different processing approaches were applied. In general the first onsets in arrival time of the shear-waves were picked for each shot gather along the line. The wavefront inversion tool of ReflexW ([51]) was used to get a depth section according to shear-wave velocity in the subsurface. This model was than interactively improved by using the FD-vidale ray-tracing algorithm...
(\Delta X = 0.1 \text{ m} \text{ and using the exact rays option}) which is also implemented in ReflexW. In the last exemplary case (Section 5.6), however, the described method did not result in sufficient results. Due to noise and low velocity layers it was not possible to look deep enough. Therefore the strong Love-waves were analyzed using a Multichannel Analysis of Surface Waves (MASW) approach ([7]). Along the profile shots were selected to extract a local wavefield by applying a gauss taper. A slant-stack was used to transfer the wavefield into a frequency-slowness spectrum. The width (approx. 12 m) and center offset (approx. 15 m) of this local wavefield were adjusted for each shot to achieve smooth slowness-frequency spectra along the seismic line in a spacing of 5 m. The fundamental mode in the resulting p-f-spectra was picked and modeled in 1D before combining them again into a 2D depth-section.

5. Prospection Results from Ridge to Plain

In the following section, we address the introduced prospection challenges and subsequently present the realized solutions for six exemplary chosen cases from Aigeira and Sikyon that cover the entire range from the mountain side of Aigeira down the marine terraces to the plain and the silted-up harbor of ‘Old Sikyon’ (Figure 1a).

5.1. Case Study 1—Plateau Northwest of Aigeira’s Acropolis: Marginal Magnetic Contrast

The small to vanishing magnetic contrast between building material, namely ashlars of the local conglomerate rock with susceptibility values of \( \kappa = 0–8 \left(10^{-6} \text{ SI}\right) \), and the surrounding marl with values of \( \kappa = 4–9 \left(10^{-6} \text{ SI}\right) \) (cf. Table 2) are found all over Aigeira. The magnetic map of the acropolis surroundings (Figure 4a) shows some geological structures but only few archaeological structures were found using magnetic prospection.

The following case shows this insufficiency of the magnetic survey in more detail. The site is located on a plateau northwest of and two terraces underneath the acropolis (Figure 4a) and at its northwestern break-off edge of the plateau stone ashlars are visible that are most likely connected to a fortification wall. The geophysical survey aimed at tracking this potential fortification wall in the subsurface and to obtain as much information about additional settlement remains as possible.

Magnetic mapping was applied to get a quick overview of the entire plateau. The resulting magnetic map (Figure 4b) shows some anomalies (M1-4), but no clearly identifiable archaeological structures.

Therefore an additional areal GPR survey was conducted to get more information about the terrace and a better understanding of the identified structures in the magnetic map. The resulting timeslice of 8–10 ns (approx. depth: 0.3–0.5 m) shows a thin lineament around the plateau (Figure 4c, R5) that correlates with the stone ashlars at the break-off edges in so far that the ashlars could be part of the outer shell whereas the GPR structure could be interpreted as the inner shell of a fortification wall that surrounds the entire terrace. The timeslice of 10–20 ns (approx. depth: 0.5–1.0 m) shows even more clearly additional structures proving that the whole terrace was built on earlier (Figure 4d, R1-4 and R6-7).

In regard to the inconclusive magnetic map some correlations can be seen between the structures in both the map (Figure 4b) and the GPR timeslices (Figure 4c,d). The GPR structures R1, R2, and R4 correlate with the negative magnetic anomalies M1, M2, and M4. Hence, these magnetic anomalies can finally be associated with building remains, which was not possible without the GPR survey. Additionally, the structure R3, which represents a series of linear gaps surrounded by an area of high reflection amplitudes, correlates with the positive linear magnetic anomaly M3. Although the lineaments appear to be too parallel to just be random, an interpretation should not be easily made. Because the patchy character of the GPR structure resembles patterns found in other survey areas in Aigeira, for example on the ‘Saddle’ but also in the next exemplary case (Section 5.2). Here, the patchy high reflective areas in the GPR are caused by the conglomerate bedrock and the non reflective areas...
by a marly soil that deposited in the cracks. The parallel lineaments embedded in the patchy pattern might therefore be a sign of anthropogenic carvings in the bedrock later refilled by a marly soil.

Figure 4. Case 1: Second lower terrace northwest of Aigeira’s acropolis. (a) Sketch of the first survey area in Aigeira (cf. area A in Figure 1b) with the magnetic map. The site location is marked (cf. Figure 3). (b) Magnetic map with marked anomalies (orange dotted lines). (c) Ground-penetrating (GPR) timeslice of 8–10 ns (approx. depth: 0.3–0.5 m) with marked structures (blue dotted lines). (d) GPR timeslice of 10–20 ns (approx. depth: 0.5–1.0 m) with marked structures (blue dotted lines).

5.2. Case Study 2—Plateau Northwest of Aigeira’s Acropolis: Cemetery or Weathering Structure

Another terrace underneath the acropolis and about 20 m to the northwest of the previously presented case site (Section 5.1), the second study area is located (see Figure 5a).

The magnetic map (Figure 5b) shows a honeycomb-shaped pattern of low magnetization in the ‘cells’, which are surrounded by highly magnetized ‘walls’. The amplitude difference of the ‘walls’ and ‘cells’ is with its 14 nT (cf. Table 4) remarkable high for the location of Aigeira. Since this pattern and its location outside of the Late Bronze Age settlement resembles a prehistoric cemetery (Figure 6b), further investigations have been carried out to obtain more information about the physical properties of the subsurface.

The resulting timeslices of the GPR survey show a similar pattern (Figure 5c). In this case the ‘cells’ correlate with high reflection amplitudes and the ‘walls’ correlate with low reflection amplitudes and high attenuation as can be seen in the related radargrams (see Figure 5e (left)). This attenuation can be shown by the comparison of amplitudes for ‘cells’ and ‘walls’. The ‘walls’ show only 17% of the ‘cells’ amplitudes in the depth range of 0.5–1 m indicating a strong attenuation between the ‘cells’. The radargrams with their many internal reflection indicate that the cells are not caused by open cavities. However, refilled cavities cannot be ruled out as a plausible qualitative interpretation. The anomalies can be found below a depth of about 0.4 m.
An additionally conducted ERT survey shows also a correlating pattern of high resistivity values (500 – 8000 Ωm) in the ‘cells’ and more conductive ‘walls’ (100 – 250 Ωm) (see Figure 5d) with the amplitude of the ‘walls’ being 36% the strength of the ‘cells’.

The interpretation of the physical properties derived from the applied measurement methods (Table 4) can lead to different interpretations if they are compared to the properties of the geologically present materials.

They could be explained by refilled or partly sanded-in cavities in the surrounding compacted marlstone, which could very well be an indication for a prehistoric cemetery, e.g., Mycenaean chamber tombs (cf. Figure 6b).

Figure 5. Case 2: Third terrace underneath and northwest of Aigeira’s acropolis. (a) Sketch of the first survey area in Aigeira (cf. area A in Figure 1b) with the magnetic map. The site location is marked (cf. Figure 3). (b) Magnetic map. (c) Ground-penetrating radar (GPR) timeslice. (d) Electrical resistivity tomography (ERT) depthslice. (e) Radargrams of P43 and P75 as well as the ERT depth sections of P7 and P11, which include only valid measurements with a standard deviation \( \sigma < 5 \Omega m \). Their location is shown in panel (c) or (d), respectively. (Source of satellite images (b–d): Google Earth)

However, a second interpretation of the physical properties (see Tables 2 and 4) is possible and in view of the present geological heterogeneity maybe even more plausible. As said above the physical properties of the ‘walls’ fit the local marlstone; however, the properties of the ‘cells’ can also be explained by a weathered and cracked conglomerate. Here, the conglomerate is cracked
and broken into blocks comparable to features that can be found all around the higher grounds of Aigeira (cf. Figure 6a). The edges might be weathered further widening the gaps between the blocks. These gaps were then refilled by a marly soil that was eroded from higher grounds.

![Figure 6](Image)

**Figure 6.** (a) Cracked conglomerate rocks in the vicinity of the investigation site. (b) Drawing of two exemplary chamber tombs on the Peloponnese (after [52]).

**Table 4.** Summary of physical properties derived from the geophysical measurements (cf. Figure 5). The values are averaged and rounded for three cell-wall-pairs over an circular area of 0.8 m² over a depth range of 0.5–1 m (for ground-penetrating radar and electrical resistivity tomography). The contrast column shows the percentage of the amplitudes of the wall in reference to the amplitude of the cells. For the magnetic anomaly the absolute difference is taken as reference.

| Method                      | Cells   | Walls   | Contrast |
|-----------------------------|---------|---------|----------|
| Magnetic anomaly amplitude  | −10 nT  | 4 nT    | 25%      |
| GPR reflection amplitude    | 4200    | 730     | 17%      |
| Specific electrical resistivity | 1000 Ωm| 370 Ωm  | 36%      |

Recent corings served as ground-truthing and found no indications of chamber tombs but confirmed the view of a geological interpretation of the geophysical data.

However, this case study shows the insufficiency of a simply qualitative interpretation of one or even two or three geophysical data sets, especially in a heterogeneous environment like the Northern Peloponnese where geological structures can have similar dimensions as anthropogenic structures.
5.3. Case Study 3—Aigeira Theater Area: Bedrock Depth

In the Hellenistic public center (cf. survey area B in Figure 1b) with its theater and temple buildings the tasks for the geophysical survey were diverse. Next to the mapping of possible building remains, the bedrock depth was of particular interest since it helps to reconstruct the ancient topography and equals the maximal depth of the archaeological remains.

Areal GPR measurements were able to detect building structures in the area of interest, but the penetration of the radar waves (a 400 MHz antenna was used) was not sufficient enough to map the bedrock. Therefore, seismic shear wave measurements were conducted. The refraction analysis of the two crossing profiles (P1 and P2 in Figure 7a,b) results in a depth section in terms of shear wave velocities, which are specific for different types of materials.

Figure 7. Case 3: Theater area northeast of Aigeira’s acropolis. (a) Sketch of the second survey area in Aigeira (cf. area B in Figure 1b) with the magnetic map. The locations of the seismic profiles is shown here. (b) Depth section in regard of shear wave velocity of the crossing lines for bedrock investigation. (c) Seismic depth section (left) and GPR timeslice (8–10 ns; right) with a wall ‘W’.
Here, the section shows an upper layer with velocity values of $v_s = 100$ to $200 \ m \ s^{-1}$ and a second layer with a velocity of $v_s = 1000 \ m \ s^{-1}$ at about 2–2.5 m depth. This represents unconsolidated soil on top of the underlying solid bedrock.

The imaging of the bedrock is not the only possible application for seismic measurements, however. Since walls have a similar mechanical stiffness to that of solid rock the seismic method is also able to detect walls as shown in the third profile (P3 in Figure 7a,c). This profile runs over a slope, which was too steep and the ground too uneven for a GPR survey. The depth section shows an increase of shear wave velocities (‘W’ in Figure 7c (left)) exactly underneath the slope. The location of this anomaly correlates with an extrapolation of a lineament in the GPR survey conducted in the lower area (Figure 7c (right)).

5.4. Case Study 4—Sikyon Ayios Nikolaos: Human Utilization in the Investigation Area

The following first case from Sikyon shows another reason why magnetic maps in this region as in many other populated areas are not always archaeologically interpretable. Several fields or orchards on the plain and terraces of Sikyon were not suitable for magnetic prospection due the presence of typical metal objects that accompany human utilization, like, e.g., pipes, cables, irrigation systems, and general trash. Often these objects were spotted in advance of the prospection, but sometimes the metal was very well hidden so that the resulting maps were not usable for any archaeological interpretation. Figure 8b shows a magnetic map of one of the fields, where the iron spikes of the irrigation systems were only found after the prospection.

Figure 8. Case 4: Sikyon–Ayios Nikolaos. (a) Sketch of survey area A (compare Figure 1c) with magnetic map and the marked site location. (b) Results of the magnetic prospection. The blue box shows the electrical resistivity tomography (ERT) survey area shown in the neighboring panels (cf. Figure 3). (c) 0.6–1.2 m depth slice of the ERT survey. (d) 1.2–1.6 m depth slice of the ERT survey. Source of satellite images (b–d): Google Earth
Since surface findings of the archaeological survey ([45]) suggested that this area was of interest, other prospection methods had to be used. During the Sikyon campaigns a total area of approximately 11,000 m$^2$ was measured using ERT due to insufficient magnetic maps or to gain more knowledge about the specific magnetic anomalies.

In the case in question, the ERT depthslices show two anomalies (Figure 8c,d). In a depth of 0.6–1.2 m a structure of what appears to be a small building is visible in the southwest of the field (A; Figure 8c). In the northeast, a larger building complex can be found, which becomes even more dominant and clearer at greater depths as can be seen in the depthslice of 1.2–1.6 m (B; Figure 8d). However, the two anomalies do not appear to be connected and the fact that the northeastern structures can be found at greater depths than the smaller southwestern structure might indicate a difference in age.

The results of two excavation trenches in 2017 and 2018 show, however, that the walls of the small building in the southwest are not of the same made. The northeastern wall is build of monumental, fine limestone ashars (size: 0.75 m $\times$ 0.44 m $\times$ 0.80 m), which indicates an important public or cult building, whereas the southwestern wall is only made of roughly hewn stone, which might indicate a difference in construction date ([53]).

5.5. Case Study 5—Sikyon Zogeri: Inconclusive Magnetic Map

The magnetic survey of one of the few larger open areas (Figure 9a) in the otherwise highly cultivated plain of ’Old Sikyon’ resulted in a magnetic map that shows archaeologically interesting lineaments.

In the northwestern part of this area two linear positive anomalies crossing each other can be found (A; Figure 9b). Due to its geometry and high magnetization this combined anomaly could indicate a crossroad with a foundation layer of burnt clay material. More to the south a wide minimum (B; Figure 9b) is running through the entire field in a similar orientation as one of the crossing positive anomalies. Another thinner linear minimum runs south of this wide minimum with a different orientation (C; Figure 9b). These two anomalies could be caused by walls of non-magnetic materials such as limestone or conglomerate. However, they differ in width, which might be an indicator for their actual width but also depth. The area around the crossroad as well as the area between the two lineaments in the southern part appear to have a ‘rectangularly organized character’, whereas the entire area between the crossroad and the anomalies in the south seem to be magnetically rather unobtrusive.

Since these described anomalies are of particular archaeological interest, additional geophysical methods were applied to gain further information. As GPR in addition to the magnetic mapping was successfully applied on the mountain side of Aigeira and on the higher grounds at Sikyon, it was also tested in the coastal plain of Sikyon. A small area was measured with a 400 MHz antenna as well as with an areal ERT test survey across the potential crossroad (Figure 9b,e). The results, however, were not satisfying, since the magnetic anomalies cannot be resolved due to a high absorption and therefore a lack in penetration (cf. Figure 5e). The high absorption is most likely caused by the electrically highly conductive alluvial sediments in the coastal plain which show very low resistivity values of 4 to 60 $\Omega$ m (cf. Table 2).

The ERT test was much more successful with sufficient penetration and resolution of archaeological remains. In consequence, a small ERT test survey grew into an intensive ERT survey of nearly the whole area and resulted in an astonishingly detailed map of building remains (cf. Figure 9c,d).

The tomographic map in regard to electrical resistivity in a depth of 0.4–0.5 m does not directly show the magnetic anomaly of the crossroad, but its surroundings with smaller houses can be reconstructed in great detail (A; Figure 9c). Furthermore, the rectangular character around the crossroads in the magnetic map correlates with what appears to be a series of small houses (D; Figure 9c). The depthslice also shows detailed building contours in the center of the investigation area, where the magnetic map is unobtrusive. The western half shows a large, possibly non-private
building complex which aligns nicely with the smaller houses in the eastern half and the structures to the north. In the south of the area the lineament C relates to the walls with the highest resistivity values of an extensive series of buildings which otherwise correlates with the rectangular character of the magnetic map.

Figure 9. Case 5: Sikyon–Zogeri. (a) Sketch of survey area A (cf. Figure 1c) with magnetic map and the marked site location. (b) Results of the magnetic mapping. (c) 0.4–0.5 m depthslices of electrical resistivity tomography (ERT) survey. The amplitudes were normalized to join the individual partial areas together (cf. Figure 3). (d) 1.6–1.7 m depthslice of the ERT survey. (e) Ground-penetrating radar test; exemplary timeslice of 6–9 ns (left) and radargram of P15 (right). Source of satellite images (b–d): Google Earth

The fact that the magnetic survey is able to detect the southern building series, but does not show the large building in the center, shows again the importance of a multi-method approach in archaeogeophysical prospecting. It might also point to different building materials, since the walls of both buildings resolved in the ERT tomographic map show similar dimensions in the same depth.

In this depthslice the wider magnetic lineament correlates with a band of lower resistivity values but at greater depths (1.6–1.7 m) where the northern buildings already fade, it correlates with a
lineament of higher resistivity values (Figure 9d). This and the fact that this lineament divides the area into two regions of different building orientation lead to the first interpretation attempt that it could be related to the buried foundations of the former city wall with different phases of the city on either side.

Excavations in 2018 ([53]), however, did not find any wall foundations but what looks rather like a former creek with alternating layers of clay and gravel. A second excavation trench showed, that the southern building series (C; Figure 9c) is in fact not connected with the habitation quarters but rather a row of late Classical or early Hellenistic grave monuments, probably on both sides of a street. The excavation also revealed the presumed difference in building materials in this area. Whereas the central non-private building (E) is made of blocks in different sizes and materials, the front of the grave monument is entirely made of limestone.

5.6. Case Study 6—Sikyon Harbor Area: Silted-Up Harbor in an Urban Area

Due to the tectonic uplift of the Northern Peloponnese and silting of the Voicha plain the ancient harbor basin can be expected about 100 m inland from the modern coastline. The area is connected to the plateau of Vasiliko by a modern street that most likely runs along an ancient road (suggested by emergency excavations; [29,53]). Additionally an artificial hill and a late antique basilica can be found so that it resembles the situation observed in Lechaion only 15 km to the southeast ([29,54]).

A manual augering transect during a geoarchaeological survey ([53,55]) found an inlay of marine sediments about 100 m away from the coast (Figure 10b, C28–C30). The outer augerings C28 and C30 show a layer of alluvial sediment on top of a impenetrable layer in a depth of 1.4–1.8 m which was interpreted as the top of the delta sediment terrace. The central augering C29 shows a layer of clay in a depth of 1.9–2.6 m with intrusions of pebbles and snails. The augering ends with a layer of pebbles and sand in a depth of 2.85 m.

These findings motivated a geophysical survey in the vicinity of these findings for a further indication of the harbor basin. Several ERT and seismic profiles were conducted in the few open areas on the outskirts of Kiato. A classical first arrival refraction analysis shows a layer boundary at a depth of about 1–1.5 m (Figure 10d). However, by analyzing the dispersion of the recorded Love waves, it was possible to derive a velocity-depth-section also for greater depths (Figure 10).

The two combined seismic methods result in a consistent velocity distribution of the subsurface. The velocity-depth-section shows values of about 400 to 700 m s\(^{-1}\) at a depth of 2–5 m, indicating gravel or consolidated material like conglomerate. A 25 m wide channel-shaped depression with shear wave velocities of about 230 to 300 m s\(^{-1}\) cuts this layer apart. The velocities of this channel indicate silty material that might only have been deposited in slowly flowing waters such as a former lagoon, a harbor basin, or other navigable waterway.
6. Discussion

In the following section we will discuss the solution approaches in regard to success and the possibility to transfer these approaches to different locations. Therefore, we will focus on the following items:

1. Geological setting predetermining prospection approaches;
2. Heterogeneity of geological features versus anthropogenic structures;
3. Seismic sounding as an alternative;
4. Seismic surveying in the urban area;
5. Transferability of solution approaches to other locations.

6.1. Solution Approaches in Regard of Reduced Significance of Magnetic Mapping

The placement of the archaeological sites of Aigeira and Sikyon on the southern shoulder of the Corinth rift has created a geological setting (cf. Section 2), which strongly reduces the significance of magnetic mapping, usually regarded as the standard tool of archaeological prospecting.

The presented case studies in Sections 5.1 and 5.5 show that combined approaches including areal GPR or ERT measurements are necessary to make reliable statements about architecture and infrastructure at depth levels down to several meters.
However, in all three of these cases (this includes Section 5.4 although it is not a geological challenge) the solution approach to apply a second geophysical method in combination was successful. This in itself is not surprising, since a multi-sensor approach has been called for for a long time (e.g., [56]) and it has nowadays become a common practice to combine magnetic mapping with GPR and/or ERT surveys. On the other hand the different methods are of course sensible to different physical properties (Sections 3 and 4).

However, it is elucidating to see, that the need for a different geophysical method correlates with the special geological setting of the investigation area.

On the ridge and on the slopes the application with GPR proved successful (Section 5.1). Here, we were able to detect a fortification wall surrounding the terrace and additional building outlines on a terrace northwest of the acropolis and thereby proving that this terrace was indeed part of the settlement (Figure 4). In addition to our examples from Aigeira the success of GPR was also shown by [57] on the plateau of the Hellenistic Sikyon.

However, the application of GPR was not crowned with success in the coastal plain of Old Sikyon, because the conductive alluvial sediment resulted in a high attenuation of electromagnetic waves and therefore a lack in penetration and resolution of the method (Figure 9e).

Here, ERT proved to be the method of choice and with it we were able to map the outline of buildings in great detail (Section 5.5) which proves that the magnetic anomalies were indeed related to archaeological remains in the subsurface (Figure 9). We mapped several smaller buildings around the proposed street crossing, a change in building alignments that could indicate different phases of the settlement, and a large building that might be the first indication of a public building in the abandoned part of the former city in the plain ([53]).

The fact that the large possible public building is located in the central part of the investigation site, where the magnetic map is more or less unobtrusive, shows again the importance of the combination of geophysical methods. Especially but not only in regions with low magnetic contrast.

The case study in Section 5.4 showed another example of the reduced importance of the magnetic survey, but here it was the insignificance by the agricultural use of the investigation site. It showed not only the importance of a multi-method approach but also interdisciplinary approaches in the field of archaeology.

Whereas the magnetic map of the two cases described above showed at least a restless pattern if not clear anomalies, the magnetic map in this case study was utterly inconclusive due to metal spikes in the irrigation system (Figure 8b). Here, only an archaeological survey that was performed parallel to the geophysical survey motivated further investigations. Using ERT enabled us to detect two building features in the subsurface. Excavation showed that the northeastern wall of the southwest building is part of a public or cult building (A, Figure 8c).

6.2. Heterogeneity of Geological Feature Versus Anthropogenic Structure

The geological setting especially on the ridges results in geological features like weathering formations that show the same dimensions as cultural heritage remains like prehistoric chamber tombs (cf. Figure 6) and therefore result in ambiguous geophysical results, or at least results that cannot easily be interpreted one way or another. The case study in Section 5.2 showed that even after the application of three geophysical method it is not possible to make a 100 percent reliable statement about the nature of the subsurface feature due to the complex geological heterogeneity in this area.

The honeycomb-shaped pattern in the magnetic map with its remarkable resemblance to a system of chamber tombs drawn by [52] (cf. Figure 6b) and its location right outside the settlement lead to an intensive study of this particular investigation site. The amplitudes of the anomaly field are large for Aigeira with 14 nT peak to peak difference, which makes the anomaly even more remarkable. This pattern was confirmed by the application of areal GPR and ERT surveys.

However, if we compare the radargrams (Figure 5e) with different examples of known chamber tombs ([58,59]) we do not see the strong top or bottom reflection of an empty chamber but a confused
pattern of reflections over a depth range of about 0.5 to 1.0 m. Therefore we can rule out empty chambers, but although the field of 3D modeling of GPR waves shows promise, it is still difficult to predict how radarwaves would reflect in a 3D environment of a system of complexly refilled cavities ([60,61]).

The smaller resistivity values in the order of $\rho = 370.0 \, \Omega \cdot m$ found between the ‘cells’ in the ERT results could indicate a weathered conglomerate if we compare the values with Table 2, but the high GPR attenuation points to a highly consolidated marlstone. The higher resistivity values of 1000 $\Omega \cdot m$ (cf. Tables 1 and 4) of the ‘cells’ itself could be explained by cracked conglomerates as well as by loosely refilled cavities.

A qualitative interpretation of the three applied methods is not sufficient to reliably resolve the question if this feature is of geological or anthropogenic making. Here, additional corings served as ground-truthing and verified the geological interpretation of the geophysical data.

We will present these corings together with additional seismic measurements that were analyzed using full waveform inversion in a future article (Rusch et al. (in preparation)). The full waveform inversion revealed a high heterogeneity of the first meters of the subsurface and showed that the anomaly pattern is not a cemetery but indeed a structure of complexly fractured conglomerate blocks can be found in the subsurface ([62]).

### 6.3. Seismic Soundings as an Alternative

Seismic soundings are classic geophysical methods to image the subsurface that are used only rarely in the field of archaeological prospection. In Aigeira seismic soundings were successful in detecting the basement depth in the area of the Hellenistic theater. We were able to show that the basement runs more or less parallel to the modern surface in a depth of 2–2.5 m, which exceeds the penetration depth of the GPR antenna (400 MHz) used in the area. This is a classical field of application for seismic soundings as they are often applied for the imaging of lithological structure.

What is a more unusual application for seismic methods is the detection of walls in the subsurface. In the same area a wall was suspected to be hidden in a steep topographic step, which was not safely accessible for a GPR survey. Due to the small geophone spacing of only 0.25 m, only nine shot points along the line, and a simple data processing we were able to identify a local feature inside the slope with a significantly higher shear-wave velocity. That this feature must be a wall can also be seen in the fact that its location correlates with the extension of a wall in the results of the adjacent GPR slice.

These examples of case study 3 show that seismic soundings are not only a method to resolve lithological layering but are also applicable to detect walls in the subsurface if the right configuration is used. If the data is further processed by applying a full waveform inversion for example it is entirely possible that even more features will be revealed from this data set. This would be especially useful if walls can be detected below the penetration depth of GPR.

### 6.4. Detecting a Harbor Basin in an Urban Area

The situation of the silted-up harbor of Old Sikyon is challenging due to the fact that it is suspected under the outskirts of modern Kiato. The data quality of the measured seismic lines was highly affected by the urban noise. We were able to use the first arrivals with small offsets to determine a first velocity model of the upper layers. The data also showed signs of low velocity zones in the subsurface which could be an indication for an alternating layering sediments that can be seen in lagoons ([7]). To get information of deeper layers we evaluated the Love-waves (MASW) along the line. The result is a depth section with regards to shear wave velocity (Figure 10e) also for deeper layers. In both depth sections we see a significantly lower velocity of about $v_s = 300 \, \text{m} \cdot \text{s}^{-1}$ in the central area of the profile. This area is approximately 30 m wide and can be followed into depths of up to 10 m. The results of the Love wave analysis indicates a thin layer of higher velocity in a depth of approximately 5 m. Corings in the neighboring harbor of Lechaion revealed layers of coarser materials embedded in silty materials.
which [63] classify as tsunami deposits. Due to the close distance between the two locations it could be that such a layer can also be present in a potential Sikyon harbor basin.

A denser lateral sampling and an application of an inversion algorithm can improve the lateral resolution and the misfit of the Love-wave analysis result.

The velocities in the depression in the center of the profile shows values of about \(v_s = 230\) to \(300\) m s\(^{-1}\) and are therefore typical for fine grained sediments like silt or marine clay deposits. These fine-grained sediments are deposited in a slow flowing water regime like a riverbed or a lagoon. Therefore it might be a second indication towards the former harbor location or a navigable waterway.

To be able to say if this is really the former harbor basin, we have to be able to correlate the seismic results with the augering cores. Hence, additional measurements are necessary, but as we have seen the urban environment is challenging for a larger scale seismic survey.

This fact motivated test measurements with passive ambient noise methods which results will be presented in an upcoming article.

6.5. Transferability of Solution Approaches to Other Locations

If we now look at the transfer capabilities of this solution approach, we can clearly state, that it is in general becoming more and more common to combine different geophysical methods at the same site in archaeological prospection. However, if we take a step back from the general approach of combining several methods ([2]) and go back to the geological setting of the Northern Peloponnese and have a look at prospection in this region, the possibilities are the following.

The geological condition that present themselves along the southern shore of the Gulf of Corinth today were formed by the evolution of the Corinthian rift and its uplifted syn-rift sediments. In [34], the authors state that the classification of sediments that they introduced for the central part can be seen as representative for the syn-rift sediments along the entire southern shore. If we now correlate the findings regarding the more successful geophysical prospection method with the stratigraphic classification of the sediments (cf. Figure 2), it most likely results in a good indicator for the more appropriate method for the specific investigation site.

We can see that the investigation sites of Aigeira are located on the ridge where we can find sediments of the Lower and Middle Group (cf. Section 2.2), mainly fan deltas and slope deposits that are coarser grained at the near surface.

For investigation sites on the ridges or slopes in our experience a GPR surveys proves successful and is preferable to ERT surveys, due to the better resolution and higher production rate. Although ERT proved successful as well in detecting cultural heritage in the subsurface in Aigeira and the Hellenistic Sikyon [57].

We do not find these coarser grained sediments in the coastal plain of Old Sikyon. Here the Upper Group is dominant, mainly the marine terraces made out of marl and covered by recently deposited alluvial sediments.

As already explored above the lack of success of the GPR survey in the coastal plain is connected to the electrical conductive alluvial sediment in the plain (Section 5.5). So that we could go one step further and propose that this could be transferred to other locations on the Northern Peloponnese following the stratigraphy studies by [33], where these recent alluvial deposits can be found. In our experience in these regions 3D ERT surveys have a better chance of success in combination with magnetic mapping. The application of dipole-dipole and Wenner-beta configurations with a \(1\) m \(\times\) \(1\) m electrode spacing resulted in often very detailed maps of the cultural heritage in the subsurface (cf. Figure 9).

The slope and delta deposits on the ridges have provided us with a sometimes very complex heterogeneity in the geological background features (Section 5.2). Here, we were able to show, that it might even be necessary to apply even more than two geophysical methods at one site. Even then it may not be possible to make a hundred percent reliable statement about the origin of possible
subsurface features. Here, the spectra of methods might have to be expanded to ground-truthing to calibrate the geophysical results for a reliable statement.

However, the additional application of seismic soundings has also proven an important tool in the prospection in our surveys on the Northern Peloponnese. Here, not only for questions about lithology but also in locating cultural heritage. This can be said for the entire range from ridge to harbor. On the ridge and on the coastal plain S- and P-wave seismics were successfully applied and can therefore be used in areas with similar environments.

The solution approaches are of course not limited in their transferability to the Northern Peloponnese but can also be applied for investigation sites where materials with similar physical properties can be found.

7. Conclusions

The geological setting of the Northern Peloponnese on the southern shoulder of the Corinthian rift with its uplifted syn-rift sediments is not an especially friendly environment for a geophysical prospection.

The materials found in this regions show little magnetic contrast reducing the importance of magnetic mapping in the region, which is normally used as the standard tool in archaeological prospection.

We showed through six exemplary case studies that the optimal method to accompany the magnetic mapping varies along the topographical profile from ridge over the slopes and the coastal plain to the Gulf of Corinth.

On the ridges and along the higher slopes GPR proved suitable to detect cultural heritage to a depth of up to about 2 m. Using the magnetic mapping and GPR enabled us to locate a fortification wall around and a terrace with additional buildings proving that the terrace that was not further investigated beforehand was part of the ancient settlement.

The alluvial sediment in the coastal plain caused a too high attenuation for GPR to be useful in archaeological prospection. Here, ERT proved to be very successful and extensive 3D ERT survey resulted in detailed maps of building features and whole settlement parts with different building alignments. Excavation showed that the southern building structures belong to late Classical or early Hellenistic grave monuments. Additionally, the first potentially public building in the abandoned part of the city in the coastal plain was located.

The geologic setting in Aigeira is a good example for a situation where even a multi-method approach might still leave open questions regarding the qualitative interpretation of survey results due to a highly complex heterogeneity of the weathered and cracked conglomerates. Here, either extensive modeling for a quantitative interpretation or ground-truthing is needed.

Next to the more classical method in archaeological prospection shear wave seismics can be applied successfully to locate deeper structures such as ancient waterways or possible harbor basins. Furthermore, major walls may be located at depth levels deeper than the radar and geoelectric detection ranges. The resolution of the seismic method in this area of investigation will be improved in the future by the application of full waveform inversion.

Using Love wave analysis, a silted depression was found along a seismic profile near the modern shoreline, which may be regarded as evidence of a former harbor or of other navigable infrastructure of Sikyon. However, due to the urban setting, this sedimentary structure could not be tracked yet over a larger area using active seismic measurements. As an alternative, passive seismic measurements may be applied in the future, in which the ambient seismic noise of the city is used to investigate the subsurface layering.

Since we find a similar geological setting along the southern shore of the Corinthian Gulf, the shown prospection approaches can be transferred to other investigation sites on the Northern Peloponnese as well as to different locations with materials that possess similar physical properties as the material presented in this article.
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