High resolution GPR mapping of Late Bronze Age architecture at Kalavasos-Ayios Dhimitrios, Cyprus

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A B S T R A C T

At the Late Bronze Age site of Kalavasos-Ayios Dhimitrios in southern Cyprus, the subterranean remains of previously unknown buildings were recently discovered and mapped with ground-penetrating radar (GPR). Though the fine-grained calcareous substrate at the site was not necessarily ideal for GPR—exhibiting a high clay fraction, significant volumetric water content, and scattering rubble—the buildings were mapped in excellent resolution with sufficient detail to indicate walls, entry-ways, and other architectural details. This was achieved with a somewhat lower frequency antenna (250 MHz center frequency) than is commonly recommended in archeological geophysics. The 250 MHz system was employed in order to mitigate the potentially negative effects of the lossy substrate, which had proved problematic for past research using higher frequency antennas. Our work showed that excellent GPR results were possible in this substrate by simply lowering the antenna frequency, and that electromagnetic attenuation likely improved spatial resolution allowing for the detection of greater detail than might be expected. The resulting GPR findings offer a fresh perspective on this important archeological site, while indicating that conservative antenna selection is not only sometimes warranted, but may be crucial in some archeological GPR investigations.

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1. Introduction

Recent GPR surveys have successfully delineated a number of important architectural features at the Late Bronze Age site of Kalavasos-Ayios Dhimitrios (K-AD) in southern Cyprus (Rogers et al., 2012; Urban et al., 2013). The site exhibits a clay-rich, alkaline substrate with substantial embedded rubble and significant soil moisture content (as high as 27% VWC at 0.4 m). It has been previously noted in the archeological GPR literature that substrate conditions such as described above are poorly suited for GPR investigations (Conyers, 2013: 203–204), and it has long been known that electromagnetic attenuation, $\alpha$, is more pronounced with higher antenna frequencies, often leading to greatly reduced penetration depths (Davis and Annan, 1989; Jol, 1995; Smith and Jol, 1995; Leucci, 2008). In order to mitigate the anticipated effects of $\alpha$, in addition to scattering losses expected with the substrate at K-AD, a 250 MHz GPR system was employed for the investigation at hand: a somewhat lower antenna frequency than is most often recommended in archeological geophysics. While decreasing the antenna frequency may mitigate the effects of $\alpha$, however, it does so at the expense of spatial resolution (e.g. Jol, 1995). This approach is therefore generally viewed as a compromise where greater probing depth is gained only at a loss of spatial detail. The majority of literature on the application of GPR to archeology endorses antenna frequencies of 400 MHz or greater, thus favoring the prospect of superior resolution as might be required for archeological interpretation. For example, L. Conyers—the most widely cited source on archeological GPR—claims to have used 400 MHz and higher for nearly all investigations, stating that he has found use for lower frequency systems in less than 5% of field investigations (Conyers, 2012: 27). Additionally, Conyers has argued that with frequencies lower than 300 MHz, resolution adequate for archeological interpretation is not likely to be achieved:

“With those antennas, resolution is diminished, making many subtle changes in beds and archeological features all but invisible in GPR profiles and maps.” (Conyers, 2006: 144).

In contrast, Goodman and Piro (2013: 74–76) have recently noted that archeological GPR data can often be improved by lowering the antenna frequency and increasing sampling density. This approach is supported by the present study and has also proven effective in recent studies on similar sites. For example, GPR work in substrate conditions similar to K-AD has recently revealed the largest known Chalcolithic village plan in the lower Galilee of Israel, with GPR results indicating walls, rooms, and silos hidden beneath—in some instances—more than 1.0 m of clay (Urban et al., 2014); this was achieved with a 250 MHz system.

Like the aforementioned study, the GPR investigation at K-AD revealed many architectural features at a spatial resolution suitable for
archaeological interpretation. Further, this was achieved with a 250 MHz antenna in a setting where diminished performance in relation to soil moisture was previously observed with a 400 MHz antenna (Rogers et al., 2012), and failure was observed with a 500 MHz antenna. We argue here that the lower antenna frequency used for the present study likely mitigated the effects of electromagnetic and scattering losses that had in turn caused the previous problems observed with the higher frequency antennas. We also argue that at practicable transect intervals (i.e. not prohibitively close), the 250 MHz antenna provides horizontal resolution comparable to the 400 MHz antenna previously deployed at this site by Rogers et al. (2012), thus no architectural detail appears to have been lost by lowering the antenna frequency.

1.1. Archeological background

During the Late Bronze Age (1650–1100 BCE), the island of Cyprus witnessed a rise in social, political and economic complexity, with settlements becoming both urban in composition and international in scope (e.g. Keswani, 1996; Knapp, 1986, 1997, 2013). The site of Kalavasos-Ayios Dhimitrios (K-AD) is among the major Late Bronze Age sites found on Cyprus and may hold key evidence to understanding this transformation. Located at a confluence of routes that link the eastern portion of the island to the west, and the copper mines in the (southern side of the) Troodos Mountains to the coast, the site is well positioned as a potential hub for communication and trade (South, 1980: 23–6) (Fig. 1). The distribution of surface finds and architectural remains indicates that the site likely covered >11 ha and served as a significant regional center (Keswani, 1993), and excavations at the site from 1979 to 1998 unearthed parts of an urban center of the Late Cypriot II period (c. 1450–1200 BCE) (South, 1980, 1988, 1997) (Fig. 2). The potential inter-regional importance of KA-D is highlighted by Goren et al. (2003), who — on the basis of clay provenience studies — consider the site to be a likely source of communications sent from the King of Alashiya (generally assumed to be Cyprus: Knapp, 2013: 438) to
the Egyptian pharaoh during the 14th century BCE and the King of Ugarit during the 13th century BCE. Despite the site’s significance, the full extent of sub-surface archeological deposits remains in question. Architecturally, KA-D is known for a 30.5 m × 37 m monumental structure: Building X (Fig. 2). It has been suggested that this building, which exhibits evidence for the large-scale production and storage of olive oil as well as elite feasting, likely served as the site’s administrative center (South, 1980, 1995, 1997). The excavations headed by South also unearthed several tombs far to the west of Building X, immediately north of Area 3 (Fig. 2). Later GPR work immediately south of Building X identified a complex of additional architectural remains (Rogers et al., 2012).

1.2. Environmental setting

Köppen-Geiger climate classification of the region fits the criteria of Csa (warm temperate-dry summer-hot summer) as determined from Kottek et al. (2006). This typical Mediterranean climate combined with predominantly limestone bedrock fosters the development of the clay-rich, calcareous soil type found at K-AD. Previous soil mapping projects in Cyprus have identified the vicinity of KA-D as having soils that are highly to extremely calcareous (CaCO₃ > 30%) (Luken and Grivas, 1987) with a general soil classification in the region of calcareous lithosol (Soteriades and Grivas, 1970). It should be noted, however, that the soil specific to the survey area presents a finer, more homogeneous, appearance than a typical lithosol.

Diminished GPR performance has previously been noted in soils that have high concentrations of calcium carbonate, CaCO₃, (i.e. calcareous soils) due to increased electrical conductivity, σ (Grant and Schultz, 1994), one of the major factors in electromagnetic attenuation, α (Olehoft, 1984; Ward and Hohmann, 1991: 137–142). Such soils are also naturally associated with high pH. While σ is a measure of total ion activity, pH is a measure of activity of the hydrogen ion H⁺. In certain conditions, high pH can also indicate high σ. This is often the case with calcareous soils such as the substrate at K-AD, where pH is high due to the concentration of the salt, CaCO₃, which correspondingly increases σ when in solution (i.e. when sufficient soil moisture is present). Measurements of soil pH as an indicator of the dominant salt, CaCO₃, soil textural analysis to determine the clay fraction of the substrate, and measurements of volumetric water content (VWC), were undertaken at K-AD, within the GPR survey areas.

Soil pH was measured with a hand-held pH electrode, the type often used for agricultural applications. Soil was moistened with distilled (de-ionized) water (neutral pH of 7) to bring ions in the substrate
into solution. Twelve discrete readings were taken across the site at an ambient air temperature of 25 °C. All samples tested exhibited pH > 8, showing the soil to be alkaline as expected, exhibiting a pH range falling between the common values of sea-water and baking soda. The result of the pH measurements therefore indicated the expected high concentration of CaCO$_3$, likely occurring as the dominant salt in addition to smaller fractions of other salts known to occur in this substrate type which could also contribute to increased $\sigma$ when sufficient moisture is present (alkaline soils are associated with the base cations Ca$^{2+}$, Mg$^{2+}$, K$^+$ and Na$^+$).

Mobility of the available salts in the soil, however—rather than the simple presence of the salts—is the crucial factor determining $\sigma$. This is contingent upon the amount of water available in the soil; thereby allowing the ions to go into solution. The associated electrical properties are therefore time-dependent, often changing drastically with variable soil moisture content (Hubbard et al., 1997). Soil moisture was measured at various depths at 3 locations on the site. The ground was cored with a soil auger and volumetric water content (VWC) measured incrementally with a calibrated dielectric soil moisture probe. The analysis of VWC showed significant water retention in the substrate at K-AD, with VWC as high as 24% in the known depth range of archeological features (Fig. 4). (See Fig. 3.)

Clay content is another factor long known to adversely affect GPR performance (Daniels, 2004; Davis and Annan, 1989; Doolittle and Collins, 1995; Walther et al., 1986). Due to a high capacity to absorb and retain water, coupled with a typical abundance of exchangeable cations, clays are associated with high $\sigma$ (which varies by clay species) as well as high $\varepsilon_r$ (Doolittle and Collins, 1995; Saarenketo, 1998). A clay content of 35% or more is considered to be unfavorable to GPR performance in many circumstances (Daniels, 2004), with some past researchers even suggesting that a clay content of 5–10% could limit probing depth to less than 1 m (Walther et al., 1986). Documentation of soil texture at K-AD was undertaken with a 20 stage sieve that characterizes grain sizes ranging from gravel to clay. Five samples collected on site were dried and sieved. Percentages by volume were calculated for fractions of gravel, sand, silt, and clay. The analysis showed the

![Fig. 3. GPR survey areas 1 and 2.](image-url)
substrate to be dominated by silt and clay, with a textural classification of silty-clay (nearly 60% clay and less than 10% sand), in accordance with the USDA soil classification system (http://soils.usda.gov).

The above measurements indicated that at K-AD, significant salt concentrations coupled with water retention due to high clay content, could lead to poor GPR performance, likely explaining the observations of Rogers et al. (2012), who recommended only conducting GPR surveying at this site during the driest time of year (the season in which the above measurements were made). It should be noted that these measurements were not part of a standard protocol for assessing substrate suitability to GPR survey, and were not therefore used to develop actual values of electrical conductivity. The measurements were rather implemented to demonstrate with a few simple and readily available tools that conditions associated with attenuation (and poor GPR performance) are present at K-AD.

2. Methods

2.1. GPR data collection

Work at K-AD was undertaken with a Noggin series 250 MHz (center-frequency) instrument by Sensors and Software Inc. The antenna was deployed on a sled configuration and in-line distances logged with a calibrated odometer. Stacking was applied for random noise reduction. Areas to the immediate south (Area 1) and west (Area 2) of Building X were surveyed. In Area 1, a 40 × 30 m survey was collected at a 0.5 m transect interval. This was the survey area where Rogers et al. (2012) had previously discovered a complex of structures, and the transect interval used was the same as in that previous study, which had relied on a 400 MHz system. In the west a 17 × 30 m survey was collected at a 0.16 m transect interval in an area that had not been previously surveyed. Instrument parameters for both surveys included:

1. Total time window — 75 ns
2. Number of points per Trace — 187
3. Interval between traces — 0.05 m
4. Tx-Rx offset — 0.2794 m
5. Number of stacks — 8
6. Trigger method — wheel
7. Survey mode — reflection

2.2. Data processing

A variety of post-processing procedures were undertaken to maximize the usefulness of the GPR survey data. These were implemented with software products by Sensors and Software Inc., and included the following:

1. Gain — moderate to high spreading and exponential compensation gain (SEC-2)
2. Dewow
3. Velocity estimates (with hyperbola fitting)
4. Background subtraction (average of all traces)
5. Enveloping
6. Velocity migration

No topographic corrections were undertaken because variability in surface relief across the survey areas was limited at K-AD. Collected profiles were gridded and depth-sliced at 0.20 m intervals, and Hierarchical Data Format (HDF) files generated for 3-D volume rendering. Final figures were produced with Surfer 12 and Voxler 3, both by Golden Software Inc. For a detailed discussion of the data processing procedures described here see Jol and Bristow, 2003; Annan, 2004; Daniels, 2004; Jol, 2009; Conyers, 2013; Goodman and Piro, 2013.

3. Results

The survey of Area 1, a re-survey of the area investigated by Rogers et al. (2012), detected the same complex of features previously detected in the aforementioned study (Fig. 5), but with visibly improved feature continuity over the previously published results. The survey of Area 2 revealed a previously unknown structure in very high resolution — which has been designated as Building XVI following the naming convention used at K-AD (Fig. 5). Architectural detail revealed by these surveys was sufficient to develop archeologically useful interpretations. The plan of the newly discovered Building XVI, in particular, indicates a massive rectangular building with a large central room (perhaps an open court, given its size) with interior rooms accessed from this space on both its northern and southern boundaries (Fig. 5).

This discovery of a major new building complex of a (monumental) scale in keeping with the other large well-built structures at K-AD (a coherent structure greater than 25 m × 15 m), suggests that substantial parts of this remarkable site’s architecture may still remain unseen, with shallow overburden masking a great hidden potential for fresh insights and interpretations.

4. Discussion

Attenuation is caused by several loss mechanisms associated with the host medium. These include absorption losses related to electromagnetic properties, along with losses related to scattering in heterogeneous media and geometrical losses from the spherical divergence of the wave (Olehoff, 1984). For clay-rich substrates, $\sigma$, commonly ranges from 5 to 40, while $\sigma$ ranges from 2 to 1000 mS/m (depending primarily on moisture and mineral content), with an associated attenuation of 1–300 dB/m (Table 1). It should be noted from the table that observed attenuation in saturated sand of similar velocity to clay is significantly lower due to a much lower $\sigma$ (largely due to reduced cation exchange capacity (CEC)), even though $\sigma$, $\varepsilon$, may still be high. This demonstrates that water content alone is not necessarily as important as the combination of water content with soil type in determining attenuation (e.g. Davis and Annan, 1989), except perhaps at higher frequencies where permittivity dominates electromagnetic losses (e.g. 1.5 GHz) as indicated by the well known Cole and Cole (1941) phenomenon. Since $\alpha$ limits GPR capabilities, and these limitations are exacerbated as frequency increases, it makes sense to select a lower frequency when $\alpha$ is likely to be problematic. Given that $\alpha$ can also act to decrease wavelength, a primary factor in determining spatial resolution, good GPR resolution may still be achieved while reducing the effects of losses in attenuating substrates.

The fairly low GPR velocities observed at K-AD support the case of a substrate with significant moisture content; a factor that likely improved...
GPR resolution by increasing $\varepsilon_r$ (thus decreasing signal velocity). In non-magnetic media where velocity is known, $\varepsilon_r$ is sometimes determined by (Eq. (1))

$$\varepsilon_r = \left( \frac{\varepsilon}{\varphi} \right)^2$$

where $c$ is the free-air velocity and $V$ is the substrate velocity. Eq. (1) yields $\varepsilon_r$ values of 14–18, for some areas of K-AD and 20 or more for others with GPR velocities ranging from as low as 0.06 m/ns to as high at 0.08 m/ns as determined through hyperbola fitting. The determined values of $\varepsilon_r$ fit with the known properties of clay at various moisture contents (Table 1), and are high enough — with the typical range of $\varepsilon_r$ varying from 4 for dry substrate to 30 for saturated substrate (Daniels, 1996) — to indicate that significant moisture is retained in the substrate even during drier seasons (as was observed with VWC measurements) (though the above is a commonly used convention, it should be noted that this represents an idealized low-loss case thus not fully accounting for the effects of $\sigma$ on $V$ — for a more thorough discussion consult Annan, 2009).

Since resolution is largely a function wavelength $\lambda$, itself determined by both velocity $V$ and frequency $f$ (Eq. (2))

$$\lambda = \frac{V}{f}$$

increasing $f$ or decreasing $V$ will decrease $\lambda$, thus improving resolution.

Table 1
Electrical properties and velocities of common earth materials (After Davis and Annan, 1989).

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric constant</th>
<th>Conductivity (mS/m)</th>
<th>Velocity (m/ns)</th>
<th>Attenuation (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>Dry sand</td>
<td>3–5</td>
<td>0.01</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated sand</td>
<td>20–30</td>
<td>0.1–1.0</td>
<td>0.06</td>
<td>0.03–0.3</td>
</tr>
<tr>
<td>Limestone</td>
<td>4–8</td>
<td>0.5–2</td>
<td>0.12</td>
<td>0.4–1</td>
</tr>
<tr>
<td>Silt</td>
<td>5–30</td>
<td>1–100</td>
<td>0.07</td>
<td>1–100</td>
</tr>
<tr>
<td>Clay</td>
<td>4–40</td>
<td>2–1000</td>
<td>0.06</td>
<td>1–100</td>
</tr>
<tr>
<td>Granite</td>
<td>4–6</td>
<td>0.01–1</td>
<td>0.13</td>
<td>0.01–1</td>
</tr>
</tbody>
</table>

Fig. 5. GPR survey results. New architecture was revealed in high resolution (depth slices shown at 0.6–0.8 m). Area 1 in the south exhibits a complex of structures originally discovered by Rogers et al. (2012), but the new survey exhibited greater detail and feature continuity. Area 2 in the west exhibits the newly discovered Building XVI. The survey of Area 2 exhibits sharper detail than Area 1 due at least partially to closer transect spacing.
When $V$ is known, vertical resolution can be estimated spatially as a fraction of $\lambda$, with the common convention of estimating vertical resolution as $\lambda/4$ and a more conservative estimate as $\lambda/2$. In estimating the likely vertical resolution achievable at K-AD, for example, the center frequency of 250 MHz and the estimated velocity range (determined through hyperbola fitting) of 0.06–0.08 m/ns could be used to first determine wavelength (estimated to average 0.32 m — it should be noted that this is close to the same wavelength as a 400 MHz center frequency at $\varepsilon_r$ of 5). The likely vertical resolution would therefore fall somewhere between 0.08 m ($\lambda/4$) and the more conservative 0.16 m ($\lambda/2$), with the idealized center frequency. The observed frequency spectrum, however, in contrast to the idealized center frequency of the antenna, exhibited an average peak frequency of 200 MHz (in Area 1) and 300 MHz (in Area 2) as determined from Hilbert analysis of the signal mean for each area. Thus, the actual resolution was likely somewhat higher for Area 2 than reported above, and somewhat lower for Area 1 than reported above. This may also at least partially explain why a somewhat sharper result was achieved in Area 2.

Horizontal resolution $\Delta_h$ has also been estimated by several conventions which have been summarized by Rial et al. (2007), all of which primarily hinge on $\lambda$, with resolution typically decreasing with distance from source (e.g. with Fresnel zone methods). Several approaches assume a low-loss condition in which $V$ is determined only by $\varepsilon_r$. For the situation at hand, where a more conductive substrate is expected, an estimate that accounts for the effects of total electromagnetic attenuation may be preferable. An estimated horizontal resolution of 0.14–0.32 m was determined for a range of depth $z$ varying from 0.2 to 1.0 m, using \[ \Delta_h = 4z\sqrt{\frac{\ln 2}{\left(2 + \alpha z\right)}} \] from Daniels (2004) with a hypothetical $\alpha$ of 100 dB/m (from the lower 1/3 of values given for clay in Table 1). As the actual conductivity was unknown, the actual resolution may have been somewhat better or worse than the above, though we expect on the basis of the known texture, pH, and VWC, that the attenuation value used above is reasonable.

From the above discussion two points should be obvious:

1. Shallower features in lower velocity media can be resolved at a level of horizontal detail that is sometimes limited more by transect interval than antenna frequency, therefore increasing antenna frequency as a strategy for improving $\Delta_h$ makes no sense unless correspondingly smaller transect intervals (which are often impractical in terms of time available and fieldwork context) are also introduced.
2. Lower antenna frequencies when applied in lower velocity media can often achieve comparable resolution to higher frequencies in higher velocity media. A 300 MHz signal in a medium with an $\varepsilon_r$ of 25 (e.g. moist clay) will have a $\lambda$ of 0.2 m, for example, while a 500 MHz signal in a medium with an $\varepsilon_r$ or 5 (e.g. dry clay) will have a $\lambda$ of 0.27 m.

Estimations of resolution, however, will not necessarily predict achievable resolution (with great precision) under real field conditions as many variables can affect resolution (e.g. noise in signal, physical properties of targets, dimensions and orientation of features, surface topography, etc.), not to mention that velocity typically varies with depth, and also often varies horizontally, altering the outcome of any estimates of average resolution. Further, the dominant frequencies in a given medium cannot always be immediately assumed from the center frequency of the antenna (and therefore should be determined empirically). Determining the optimal transect spacing for a given site in relation to the anticipation of achievable resolution may therefore be a difficult or impossible task in many circumstances given the number of unknown factors. In practice, the safest approach is to collect dense data using closely spaced transects as suggested by previous studies (e.g. Jol and Bristow, 2003; Neubauer et al., 2002; Novo et al., 2008). With these factors in mind, we chose the very close transect spacing of 16 cm ($\lambda/2$) for the densest of our GPR surveys (Area 2), and this indeed yielded sharper detail than Area 1 (at 0.5 m transect spacing), likely owing largely to this increased sampling density (but also possibly due to the somewhat higher average peak frequency observed in Area 2). The survey of Area 1, however, did yield greater detail than the previously published results from the same survey area (Rogers et al., 2012), with the latter study using the same transect interval (0.5 m) but a 400 MHz antenna. In this instance, the improved resolution seen with the 250 MHz system was likely due to a somewhat broader illumination area affording better coverage (i.e. the 400 MHz data likely required interpolation over greater distances than the 250 MHz data). Velocity estimates recently undertaken using hyperbola fitting on data presented in Rogers et al. (2012) exhibited the same range (0.6–0.8 m/ns) as was determined in the data sets reported in the study at hand, thus indicated similar sub-surface conditions. It should be noted, however, that the velocities reported by Rogers et al. (2012) are incorrect by at least a factor of 10, with reported velocities being 1.5 m/ns for a dry year and 1.12 m/ns for a wet year (Rogers et al., 2012). Correcting these values by an order of magnitude, the velocities are still approximately $2 \times$ what is suggested by hyperbolas visible in the published profiles. These velocities were incorrectly used to infer very low permittivity in the medium and therefore low moisture retention in the substrate (Rogers et al., 2012), a finding which is contrary to both the results of the present study and a re-examination of these previously reported GPR results, as well as the direct measurements of soil moisture at K-AD.

5. Conclusion

Archaeologically, the discovery and high resolution delineation of architecture at K-AD, by providing key pieces of new evidence for the urban fabric in the heart of one of the main centers of Late Bronze Age Cyprus, illustrate the power and potential of carefully formulated and articulated GPR survey to inform us of urban structure at major archeological sites without extensive excavation — thus saving time and cost, while creating an important tool for managing cultural resources. From the GPR data, a thorough assessment of the archeological remains was possible, without a disturbance of these fragile features. The high resolution of the GPR reconstruction enables a great deal of architectural detail, including not only the layout of walls, but in some instances the placement of entry-ways, and even the positions and sizes of individual stones, to be recovered. Recent studies of Late Bronze Age built environments on Cyprus demonstrate that the spatial analysis of such architectural details can yield important new insights into social interaction and power relationships during this transformative period (Fisher, 2009, 2014; Manning et al., 2014), thus defining a prominent role for non-invasive geophysical methods in future research on the island.

Methodologically, our findings have shown that excellent resolution is possible at antenna frequencies below 400 MHz in contrast to claims otherwise, and that in many conditions, transect spacing may be more important than antenna frequency (within reason) in determining the level of horizontal detail revealed by a GPR survey. It can also be surmised in comparing the results of Rogers et al. (2012) that 250 MHz achieved better coverage than 400 MHz with the same transect interval and under similar field conditions, likely due to reduced attenuation with the lower antenna frequency, and also more complete coverage between transects (i.e. somewhat larger illumination area—transect spacing was the same for both surveys).

In an ideal situation, a range of antennas would be available in the field and a thorough study of soil properties would be undertaken at a given site in advance of GPR surveying. In many instances, however, these approaches are not feasible due to constraints of time and funding or availability of equipment, not to mention the difficulty of transporting
extraneous equipment to remote field sites. In such instances where poor GPR performance may be anticipated due to qualitatively known properties of the substrate, conservative antenna selection, combined with dense data collection (i.e. closely spaced transects) appears to be the safest approach for ensuring a successful GPR investigation.

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