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Conclusion

Ground-penetrating radar can be one of the most complicated of near-surface archaeological geophysical techniques, but also one of the more rewarding, as it has the ability to map what is buried in the ground in three dimensions. Conditions, although, must be conducive for radar energy propagation in the ground, features must be distinct enough to be differentiated from the background sediment or soil, and at a depth that can be resolved with the equipment available. For all these variables to be met, the geological and archaeological features at each site must be physically understood so that the origins of the reflections in the ground can be correctly interpreted. In addition, an understanding of how reflections are created, and how acquisition and processing steps can enhance, or sometimes obscure, these reflections is crucial.

Huge advances in GPR acquisition and processing hardware and software have been made in the last few years, which can transform what used to be considered unusable or at best marginal reflection data into important maps and images of the subsurface. One of the most important of these advances is amplitude analysis, which can process tens or even hundreds of reflection profiles at once, creating usable databases from massive amounts of reflections within hours, or even minutes, of completing a survey. Without this type of data analysis, GPR data must be interpreted using visual analysis and hand mapping of reflections in many profiles, which can prove daunting for all but the most motivated researcher with a good deal of free time. But even though computer-processing techniques are faster and more efficient, the primary database (each reflection trace in each profile) must have been collected and processed correctly before undergoing this powerful data transformation step. The fun and reward always comes in the data processing, but unless good-quality reflection data are originally collected, and a great deal of care is taken in postacquisition processing, one can never be assured of high-quality (or at least usable) results.

In GPR data collection, a great deal of time must be devoted to choosing correct antennas for optimum depth resolution, setting up grids to make sure target areas are completely covered, and choosing correct setup parameters to optimize recorded data quality. A proper calibration of equipment for the infinite number of variables that can occur within buried geological and archaeological materials must be thoughtfully applied. Each site will present its own set of both equipment problems that will have to be overcome, as well as soil and sediment variations that need to be adjusted for, if final results of GPR mapping are to be at all useful. Most important, an understanding of "why" data were collected in a certain fashion is necessary, if profiles and maps are to be interpreted correctly. It is not at all useful to be able to say that a set of acquisition procedures and setup parameters were used because the data "looked good," as this observation does not lend itself to being able to say "why" the final products appear as they do. To make results explainable for the more general archaeological audience, an understanding for each site of how GPR energy is generated, transmitted, reflected, attenuated, and then finally recorded is crucial. Then each acquisition and processing step, and the final mapping and imaging procedures, must be also explainable in an understandable way, or the results of this powerful but sometimes complicated near-surface geophysical technique will always be in doubt.

Although most GPR practitioners usually "show off" only their prettiest amplitude slice maps and reflection profiles in the published literature or when giving talks, while ignoring the harder-to-interpret maps and profiles, all the data acquired should be considered a primary database, and they must be correctly understood for the final products to be correctly interpreted. A combination of profile interpretation, selective data processing, amplitude slice–mapping, and reinterpretation of reflection profiles comparing them to the slice maps is always necessary. Often amplitude slice maps are produced first so that interesting distributions of reflections of certain amplitudes in the ground can be immediately seen. But the origin of those amplitudes must be understood by studying each of the reflection profiles and relating the origin of reflections to what generated them in the ground, or mistakes in interpretation will likely result. So, even though GPR data today can be processed into slice maps many orders of magnitude faster than just a few years ago, the "old-fashioned" methods of profile reflection analysis must still be a part of the final interpretation process.

When poor reflection data are acquired, it is crucial to try to understand what happened and then learn from those failures. With GPR, the number of variables, some of which can be controlled for, and others that cannot, are infinite. If archaeological geophysicists are to overcome the stigma of being "operators of black boxes" that produce strange wiggles, which only they and others in the "geophysics club" can understand, then we must all try to understand our data, no matter what its quality, and be able to explain to others both our successes and failures.

Many years ago, a colleague working at a deeply buried Paleoindian site in Texas hired some geophysicists to conduct a GPR survey to define important buried stratigraphic layers. The consulting geophysicists spent all day working with their equipment in an intense but quiet fashion, collecting reflection data, and presumably interpreting the results in the back of their van. At the end of the day, they proclaimed to the archaeologists, who were expectantly waiting for results, that "GPR doesn't work here." They quickly loaded up their equipment and drove off in a cloud of dust, never to be seen again. The archaeologists were struck dumb, as they knew little about the GPR method, and were left with no results and only a fairly large invoice for services rendered. To this day they remain unenlightened about what, if anything, was accomplished that day, and, needless to say, they have never again used GPR. It is negative experiences such as this that we must do our best to keep from happening. The only way for this to occur is by first understanding all acquisition, processing, and interpretation methods, and then correctly and patiently explaining their outcomes to others.

It is also important to emphasize that archaeologists cannot arbitrarily employ the GPR techniques presented in the book without having to break the ground with a shovel and get on their hands and knees with a trowel and dustpan. Ground-penetrating radar analysis will never be able to replace standard archaeological methods and to be most successful the method should be integrated with them. Subsurface radar reflections will never be able to determine the age of an archaeological feature, what kind of pottery it may have in context with it, or the color of the pigment it is decorated with. Only excavations can yield this type of information. The method's greatest strength lies in its ability to discover and create accurate images of hidden features in three dimensions and produce maps and profiles of important stratigraphy between and surrounding standard archaeological excavations.

Many in the archaeological community may continue to employ GPR only as an "anomaly-finding" device to locate possible features that can later be excavated. Although this may remain an important usage, in the future GPR's maximum effectiveness will be when it can be integrated with detailed archaeological and geological information collected from excavations and stratigraphic studies. When this is done, the method becomes a valuable tool to accurately map the anthropogenic and natural environment of a site and to integrate those maps with other more standard archaeological data. Without knowledgeable integration of GPR products with information from archaeologists and stratigraphers working at any one site, GPR will remain only a "black box" method that creates interesting (and possibly important) two- and three-dimensional images of features under the ground.

The GPR method is also only effective as a mapping tool in certain environments under specific soil and moisture regimes. Its success or failure is premised on the knowledgeable application of the correct equipment, the appropriate acquisition parameters, and the interpretative ability of the archaeologist, geologist, or geophysicist. It is one matter to recognize GPR anomalies (which may or may not have significance) and quite another to correctly interpret the most important reflections in order to derive archaeological or environmental meaning.

In an attempt to specify some of the successes and failures of GPR, an assessment of the feasibility of imaging various features in the ground is presented in table 8.1. These qualitative assessments are derived from the published literature and personal experience, and it is hoped that others using slightly different techniques may produce better results for some of what might be considered the more marginal archaeological applications. In addition, this book has focused on only a very small fraction of the sites and conditions around the world where the method could be potentially applied. Also, each of the databases used to produce interpretations in this book were collected during specific times and under conditions that can never be perfectly replicated.

Usable GPR data have recently been collected in some areas or conditions where "GPR dogma" has in the past declared that no usable results could possibly be obtained, showing that the method has much broader applicability than previously thought. Some of those results are illustrated in this book. Table 8.1 must therefore be used only as a general guide for accessing the feasibility of GPR and can in no way be relied on as an exclusive guide to all situations.

The general feasibilities described in table 8.1 must be tempered by an understanding that the depth of targets as well as local ground conditions can drastically alter radar energy penetration depth and reflection amplitudes. A common

Table 8.1. Feasibility of Using GPR to Discover and Map Some Buried Archaeological Features and Stratigraphy

Archaeological Target	*Feasibility for GPR*	*Reasons for Assessment*
Pit dwelling filled with different material than the surrounding matrix	Good	Good velocity contrast between floor and matrix will produce strong reflections.
Trenches, buried moats, hollow tunnels	Excellent	Good velocity contrasts at interfaces with surrounding material of the void.
Buried excavation trenches	Moderate to good	Good velocity contrast when backfill materials are different than surrounding materials or are less compacted.
Fire pits with baked bottoms greater than about 1–2 meters in diameter	Good	Firing can create a baked surface that readily reflects radar energy.
Fire pits less than one meter in diameter	Moderate to poor	Usually too small to be visible unless pits are very shallow and high-frequency antennas are used.
Stone foundations buried in fine-grained material	Excellent	Vertical walls will create reflection hyperbolas from their tops and sides.
Clay, stone, or wooden structures buried by rocky material	Poor	Too many small reflections (clutter) are produced from the rocky material and can be confused for the features of interest.
Clay, stone, or wooden structures buried by wet clay	Usually poor	The high electrical conductivity of some clay will severely attenuate radar energy.
Clay, stone, or wooden structures buried by moist or dry fine-grained volcanic material	Good	Good velocity contrast between the structures and the surrounding material creates strong reflections.
Kiln floors or roofs	Excellent	The high temperatures in the kilns baked the surrounding material, creating an excellent radar reflection surface.
Buried living surfaces overlain by material of a different lithology	Good	An aerially extensive interface with a good velocity contrast will readily reflect radar waves.
Small stone tools dispersed in soils	Poor	Often target objects are too small to reflect enough radar energy to be visible. This may be overcome if a high enough frequency antenna is used.
Small metallic tools dispersed in soils	Moderate	If objects are not buried too deeply and high-frequency antennas are used, metal objects will create small but visible reflection hyperbolas; can also create very visible multiple reflections in profiles.

(*continued*)

Table 8.1. Feasibility of Using GPR to Discover and Map Some Buried Archaeological Features and Stratigraphy (*continued*)

Archaeological Target	*Feasibility for GPR*	*Reasons for Assessment*
Moderate to large metal objects	Excellent	Metal is a perfect radar reflector and will generate visible reflection hyperbolas, as long as they are not too deeply buried.
Small clay artifacts	Poor	Usually do not create a large enough velocity contrast with surrounding material to be visible as a reflection
Aerially extensive concentrated areas of pottery sherds	Moderate	Depending on their thickness and velocity contrast with the surrounding matrix, they can create a noticeable reflection that appears as one layer.
Burials filled with material that is different than the surrounding matrix	Moderate	Good velocity contrast at the interface of the two different materials may create good reflections; visible if burial is large and not too deeply buried.
Stone- or clay-lined burial crypts in fine-grained matrix	Good	Rock and clay usually make a good contrast with the surrounding material and burials are usually large enough to be visible with most radar frequencies.
Features within rock-lined chambers	Poor	Cap stones and rock lining will reflect most of the radar energy before it can enter the chamber.
Compacted mud or soil walls and floors buried by fine-grained material	Good	Good velocity contrast exists at the wall interfaces will create reflections.
Stratigraphic layers with thicknesses less than the transmitted radar wavelength	Poor	The top and bottom of the layer cannot be resolved because the wavelength of the transmitted energy is too long.
Stratigraphic layers thicker than the transmitted radar wavelength	Good	Both the top and bottom of the layer will reflect energy from the same transmitted waves.
Any feature below a thick, wet clay layer	Poor	Many thick wet clay units are very electrically conductive and will attenuate most, if not all, radar energy; but there are some notable exceptions, as not all clay is conductive.

misconception is that resolution of buried archaeological features or important stratigraphic layers is better near the surface and decreases with depth. Generally this is true, but in some cases, if the features of interest are located within the antenna's near-field zone, they may remain hidden. Processing steps can sometimes be applied to those obscure but important shallow reflections, and they can possibly be coaxed out of the database. These same features, however, if buried deeper in the ground might be visible with the same transect spacing due to the conical spreading of the radar beam that illuminates an ever-increasing surface area with depth. Usually the closer the spacing of transects within a grid, the better definition of buried materials, irrespective of antenna frequency.

Many believe that GPR surveys can only be conducted on level or nearly level ground. While it is always easier to work on a clear flat surface, uneven or rough ground should not preclude using GPR. Some successful surveys, conducted in areas with severe topographic variations, often yield surprising useful results. If detailed surface elevation measurements are obtained over the grid, profiles can be corrected for topography and archaeological features that would otherwise be difficult to discern in standard profiles may become apparent. On rough ground, if the recorded reflection traces are stacked in order to average out the minor surface disturbances, and background removal filters are applied to the data after collection, good reflection data can still be obtained. Lower-frequency antennas (less than 300 megahertz) are much less influenced by small changes in their roll and pitch when pulled over rough surfaces, which is not the case when using higher frequency antennas that are smaller in size. Even small surface irregularities that are not factored out by topographic corrections can severely disrupt subsurface reflections obtained from high-frequency antennas. No matter what the antenna size or frequency it is imperative to keep antennas in the same general orientation with the ground, or energy coupling changes will cause changes in the nature of reflected waves that can be confused with "real" changes in the ground.

It is extremely important that field acquisition time be allotted for equipment calibration and velocity tests prior to conducting a survey. When arriving at a site, it is always tempting to immediately begin acquiring reflection data before the field conditions are fully understood. This is especially true if the GPR equipment is being rented by the day or hour. Haste of this sort can many times yield unfortunate results, especially if it is discovered after returning from the field that important equipment adjustments such as trace stacking or time window adjustments were incorrectly made. The same is true with time–depth conversions that can only be accurately made if velocity measurements are obtained as part of a field data acquisition program at the same time as the reflection profiles are collected.

Each GPR survey will produce unique results, depending on the field conditions at the time the survey was made. Often there are variations in data quality in the same area from day to day. Soil and sediment moisture and other environmental factors can vary with moisture changes and surface conditions, and radar wave velocities and subsurface resolution will vary accordingly. If velocity tests are not made while in the field conducting the survey, they can never be accurately replicated, and after the fact, time–depth corrections can sometimes be only a matter of conjecture.

An understanding of the subsurface stratigraphy as it relates to the generation of reflections is also crucial in the interpretation process. This can only be accomplished if the stratigraphy in test excavations or outcrops is visible and studied. If possible, some GPR profiles in a grid should be acquired that can be "tied" to visible stratigraphy so that the reflections obtained in the profiles can be correlated directly to buried horizons of interest. If this is not done, the origin of individual reflections will always be in doubt, and some possibly important features may go unrecognized. In some situations, it may be difficult to get permission to excavate in order to observe and measure the stratigraphy, especially if the purpose of the survey is to map a site noninvasively. If excavation is not allowed in an archaeologically sensitive area, it may still be possible to extend survey transects to nearby road cuts or to excavations that are located away from the site but in a similar geological setting. As a last resort, it may be permissible to obtain stratigraphic information from auger probes or small diameter cores that may be correlated to reflections in GPR profiles.

Users of GPR should always take into account information about soil and sediment conditions from published reports or consult with geologists or soil scientists who have a familiarity with the study area. If soils are very clay-rich, especially when wet, or the features of interest are located quite deep in the ground, other geophysical techniques may be more useful than GPR. Recent work, however, has shown that even wet clay, if it is not electrically conductive, will still allow the passage and reflection of radar energy to surprising depths (Conyers 2004). Although many other geophysical mapping methods can still yield meaningful data where GPR fails, GPR is one of the only near-surface methods that can be accurately calibrated to give reliable depth information and produce three-dimensional maps.

During data acquisition, it is important, but many times difficult, to refrain from making judgments about the success or failure of the survey. It is always tempting to expound to onlookers about the origin of reflection anomalies that may be visible as raw profiles on the computer screen in "real time." Thoughtful processing and interpretation of the data after returning from the field is usually necessary for any accurate assessment of a survey's success. Preliminary conclusions based on a perusal of raw reflection profiles in the field are often inaccurate and any evaluation of the survey's success based on them can be both hasty and potentially embarrassing. After applying background removal filters, amplitude slice analyses, and other interpretative techniques to the reflection data, otherwise invisible features often appear in the most unlikely places. A detailed analysis of the data is almost always necessary and casual approaches to data processing and interpretation will likely result in flawed or failed surveys.

For stratigraphically or archaeologically complicated sites, an iterative process of computer manipulation and mapping combined with manual interpretation of profiles is almost always necessary. Individualized and sometimes sophisticated techniques must often be improvised to deal with the complexities of some sites. These processes may necessitate a cooperative analysis by a team of archaeologists, geologists, and geophysicists. This type of approach is often difficult due to economic and time constraints, necessitating that the archaeologist in charge of the survey be well versed in many of the techniques discussed in this book.