Success with Geophysics: Archaeology

***FastTIMES** welcomes short articles on applications of geophysics to the near surface in many disciplines, including engineering and environmental problems, geology, soil science, hydrology, and archaeology. In the four articles that follow, we glimpse how noninvasive geophysical methods have improved archaeological investigations.*

Ground-penetrating Radar Processing and Interpretation Techniques for Archaeology

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Introduction

Ground-penetrating radar (GPR) has recently gained a wide acceptance in the archaeological community as a method to quickly and accurately locate buried archaeological features, artifacts, and important cultural and geological strata in the near-surface. The GPR method has now become one of the primary tools for geophysical feature identification primarily because of its three-dimensional abilities, and the ability to work around modern cultural features such as buildings, fences, and metal objects without a great deal of interference. While radar energy depth penetration limits (to at most about five meters in most ground conditions) can limit GPR's ability to map very deep features, most archaeological features around the world are located within that depth range. Historically the archaeological community has used GPR to identify buried remains for protection and future preservation, or to identify them for selective excavation. Recently, GPR has gone far beyond this historical application and has been used as a tool for collecting "primary data" from archaeological sites, which can be used to test ideas about ancient cultures in much the way standard archaeological data can (Kvamme, 2003; Conyers and Osburn, 2006).

Figure 1. Collecting GPR data using a GSSI SIR-3000 system and 400 MHz antennas attached to a survey wheel.

Today's GPR systems are quite compact, easy to use, and can easily be transported around the world in a few check-through cases. Rarely have I been detained by customs personnel, as long as documentation is obtained in advance from a local in-country sponsor or institution, and the ownership of the equipment and its value is noted in the paperwork. All GPR systems used today are digital and compact. Antennas are usually attached to a survey wheel or GPS system for distance measurement along transects (Figure 1). Reflection data can be quickly transferred to small flash drives and transferred to laptop computers for rapid processing and map construction using a variety of software written specially for archaeological applications. Prototype GPR systems have been developed that transmit reflection data wirelessly to a nearby computer, and maps of the ground are constructed in "real time" as reflection profiles are collected (Grasmueck and Viggiano, 2007). Multiple antenna arrays are also being explored to produce "real 3-D" data, imitating seismic acquisition and processing methods.

Collecting GPR Data in Archaeological Contexts

For archaeological applications, radar antennas are usually moved along the ground in linear transects and two-dimensional profiles of a large number of reflections are created, producing a profile of subsurface stratigraphy and buried features along each line (Figure 2). Antenna frequencies close to 400 MHz are the most widely used for archaeology. They transmit energy to about 3- to 4-meters depth in many ground conditions and have a feature resolution of about 30 to 40 cm, which is usually ideal for archaeological identification. With the 400 MHz antennas transect spacing is usually 50 cm or less, which creates a footprint of energy transmission in the ground giving complete coverage of buried materials. When data are acquired in a series of transects within a grid using this transect spacing, radar reflection wave amplitude maps can produce very accurate three-dimensional images of buried features and associated stratigraphy.

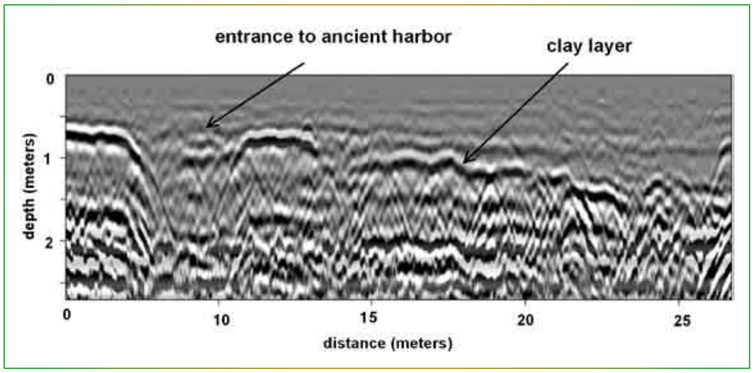

Figure 2. Reflection profile across an ancient harbor in Israel. Homogeneous near-shore sand overlying the clay produces very few reflections. A gravel layer below the clay layer produces many hyperbolic reflections, generated from each large gravel clast. In this profile the entrance to an ancient harbor, dredged through the clay and gravel, can be seen as a deep incision through those layers.

The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial of features, surface topography, and vegetation. It is common to be confronted with very different ground conditions than one would expect when called in as a consultant on other's projects far from home. I have found that many archaeologists are not aware of the geological or ground conditions suitable for geophysics at their sites. In cases of this sort my students and I are often told in advance that the ground surface is "clear" and the soil is "sandy," only to find that the site is covered in sagebrush or trees, and the soil is actually water-saturated clayey silt. This never ceases to amaze me, and I can only conclude that most archaeologists spend too much time gazing into their small 1 x 1 meter excavations and are not aware of the overall landscape or the nature of soils and sediments in the area as a whole. When this occurs, all one can do is modify collection and processing procedures from what would be optimum, and hope that one's experience can still provide usable results. Interestingly, we have found that wet ground conditions and even wet clay need not preclude the use of GPR, as was thought in the early days of the method's development. Our experience shows that excellent GPR data can be obtained even in totally saturated clay soil (Conyers, 2004b; Conyers and Connell, 2007). The limiting factor in cases like this is not clay or water *per se* but the mineralogy of the clay and the amount of dissolved salts in the water that affects energy attenuation.

One of the advantages of GPR surveys over other geophysical methods is that the subsurface stratigraphy, archaeological features, and soil layers at a site can be mapped in real depth. This is always very important in archaeological contexts because accurate depth is a crucial element in planning future excavations based on the results of a GPR survey. Velocity analysis is therefore extremely important, using a number of field collection and processing procedures (Conyers, 2004a).

Analysis of reflection profiles can be a very effective interpretation method, but is usually only possible after a good deal of experience with the GPR method. GPR profiles often do not "look like" what one would expect from stratigraphic layers or archaeological features, if one were comparing them to those visible, for instance, in the wall of a back-hoe trench. This is because as radar energy propagates in the ground it spreads out in a cone, and the resulting reflections are returned to the surface antenna from the front, back and sides, creating a somewhat complex profile with distorted planar reflections and an abundance of hyperbolic reflections. In addition, distorted planar reflections are caused by velocity variations both with depth and laterally that are usually un-knowable. The abundance of hyperbolas in many profiles is created from reflections within the conical transmission pattern from "point sources" in the ground such as rocks (Figure 2). These, and other factors that create a less than clear picture of the ground, must be taken into account when interpreting reflection profiles.

Profiles also contain high and low amplitude reflections created at the interfaces of materials that differ greatly in chemical and physical properties (Conyers, 2004a). If information is available about the lithology of buried sediments and soils, layers of interest can be identified and mapped throughout a grid (Figure 3). This can be of great value, as these types of data can place archaeological materials within a geologic context using an analysis of the depositional environments of individual layers, and therefore be used to show environmental changes over time. The placement of archaeological features in the ancient landscape using GPR stratigraphic analysis is one of the method's great values (Kvamme, 2003).

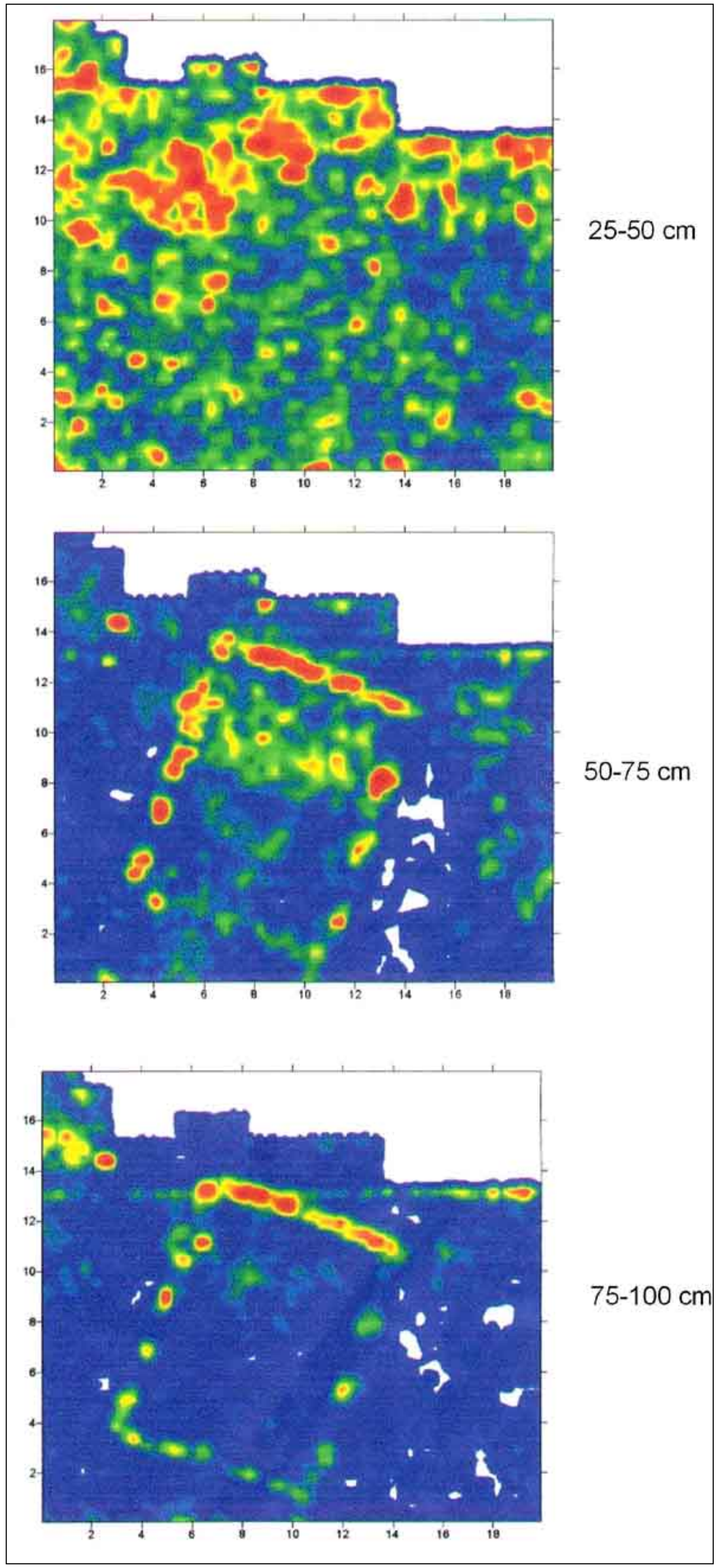

Figure 3. Example of amplitude slice-maps showing columns and walls of a buried Roman temple at Petra, Jordan in the lower slices from 50 to 100 cm depth. These images are about as good as they get with GPR in archaeology, as this cut-stone structure is covered by a layer of wind blown quartz sand and surface rubble. The buried structure is essentially intact.

Analysis and Interpretation of GPR Reflection Data

Standard two-dimensional reflection profiles can be used for some basic data interpretation, and given enough time, tedious profile-by-profile interpretation can be quite useful. However, it is often the primary goal of most GPR surveys for archaeology to identify the size, shape, depth, and location of both buried cultural remains and related stratigraphy (and do it quickly). The standard way to accomplish this goal just a decade ago was to visually identify and correlate important reflections within two-dimensional reflection profiles and then correlate them from profile to profile throughout a grid, creating a "manually produced" map of the subsurface. This can be not only time consuming but often inaccurate as it can contain human errors. Recently most archaeological GPR work has employed amplitude slice-map analysis, which creates maps of reflected wave amplitude differences within a grid in horizontal slices in the ground (Conyers, 2004a). The result is a series of image maps that illustrate the three-dimensional location of reflections derived from a computer analysis of the two-dimensional profiles (Figure 3). This method of data processing is very fast, and is usually the first type of processing that my students and I do after transferring reflection data to a computer. Using this method every reflection amplitude in every profile is compared and interpolated with every other amplitude along a defined distance in the same profile and in adjoining profiles within a grid to produce images of the spatial extent of high and low reflective buried features. This is done in "time slices" (within certain vertical windows, defined in nanoseconds of two-way radar travel time), which are converted to "depth slices" if velocity analysis has been performed (Figure 3). The result can yield very important images of buried objects or natural features that produce reflections of varying intensity. Cultural objects can usually be discriminated from natural features based on an evaluation of their shape, as can be readily identified in the buried Roman temple shown in Figure 3.

In most cases the buried archaeological features of interest are less readily identified than the temple shown in Figure 3, and individual reflections profiles must also be interpreted in order to identify the origin of reflections of interest that might be visible in amplitude maps. In this process, features visible in horizontal depth slices are evaluated by vertical profiles, and the three-dimensional aspect of reflective objects the ground can be discerned.

Amplitude slices need not be constructed horizontally or even in equal time intervals. They can vary in thickness and orientation, depending on the questions being asked. Surface topography and the subsurface orientation of features and stratigraphy of a site may sometimes necessitate the construction of slices that are neither uniform in thickness nor horizontal, or are modified to take into account antenna tilt and the resulting variation in the cone of transmission (Goodman and others, 2006).

Often it is difficult to predict in advance what archaeological features should look like as a series of reflections in GPR profiles. As an aid to interpretation, the complex nature of radar travel paths in the ground can be simulated in two dimensions using synthetic models (Goodman, 1994; Conyers and Goodman, 1997). In this method, predicted features are modeled on the computer and assigned values of electrical conductivity and relative dielectric permittivity. The computer can then simulate radar wave travel paths and wavelengths of energy based on selected antenna frequencies. The conical transmission pattern of energy spreading is also simulated, and the resulting reflections from buried objects or stratigraphic interfaces are modeled in a synthetic reflection profile (Figure 4).

Synthetic reflection profiles can then be compared to actual profiles from the field as an interpretation aid. When the synthetic profile shown in Figure 4 was compared to profiles collected in an olive grove in Tunisia (Figure 5), the exact reflection features predicted in the model were discovered. In this method,

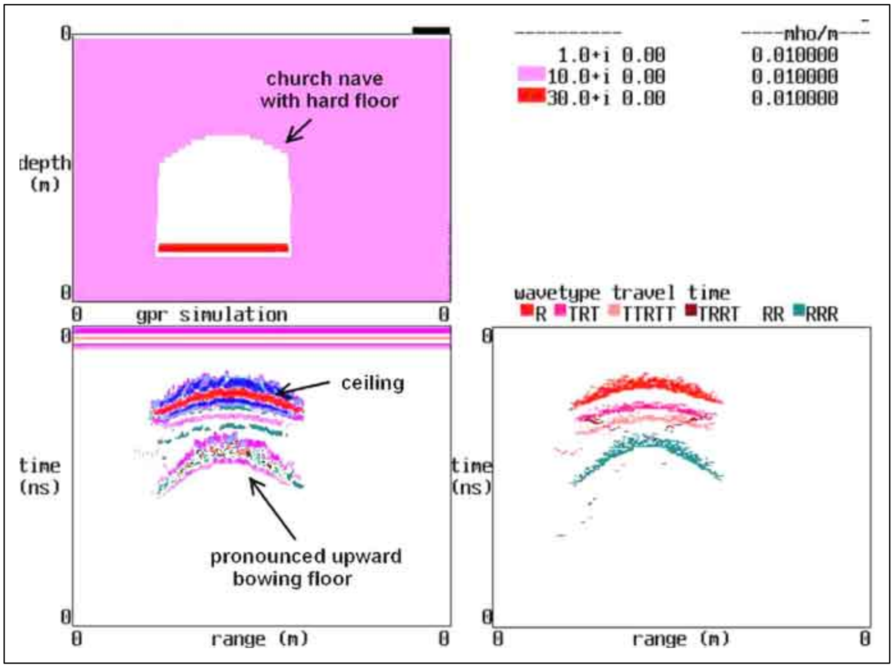

Figure 4. Synthetic reflection profile generation of an underground church in Tunisia. Only the ceiling, floor and walls of the church were simulated, producing reflections that accurately depicted the upward bowing ceiling, and a pronounced upward bowing floor. The floor reflection distortion is created by a velocity "pull up" as energy is transmitted at the speed of light within the church cavity, but at much slower rates elsewhere in the ground. The walls are invisible, as transmitted energy is passed parallel to them and if reflections occurred, the resulting waves were transmitted away from the surface antennas and not recorded.

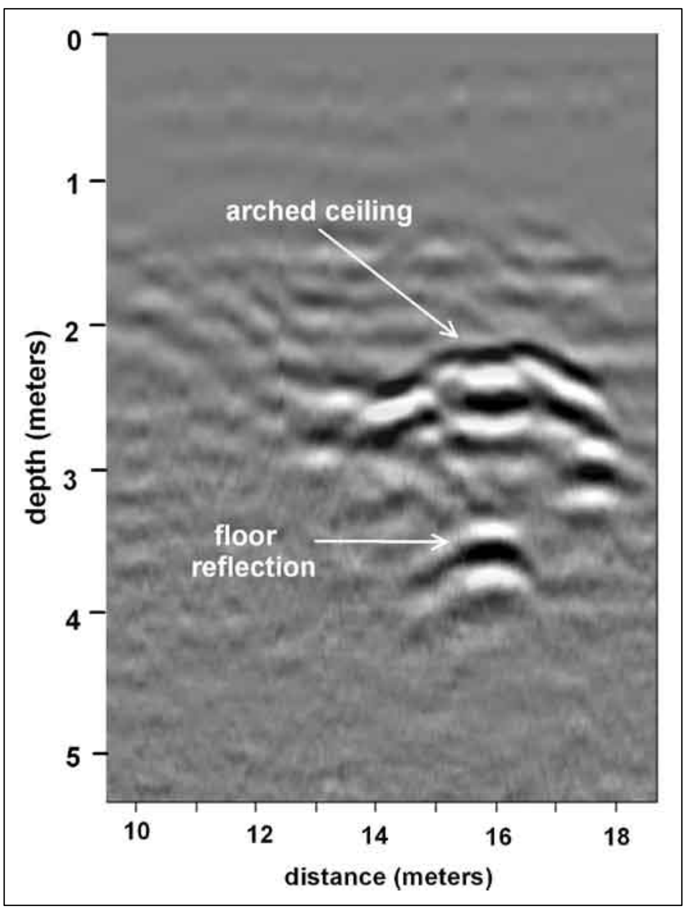

Figure 5. 270 MHz reflection profile across an underground church in Tunisia, which shows much the same reflection features as modeled in advance (Figure 4).

the comparison of the model to the actual GPR reflection profiles provided a great deal of confidence in the interpretation and a guide to excavations.

Other images that can be of value in visualizing buried archaeological features are isosurfaces (Conyers, 2004a). In this method, a three-dimensional package of reflections within a grid is analyzed in batch. All reflections of certain amplitudes are then displayed as "objects," while amplitudes below a certain threshold are made transparent. The resulting reflection features, which can often mimic actual archaeological feature in the ground that produced the reflections, are then displayed with artificial sunlight, and at varying angles of visibility (Figure 6). In this way a "virtual reality" image of features can be produced that can help greatly in interpretation, especially for archaeologists with no geophysical training.

A number of other interesting GPR processing and interpretation methods have been developed that show great utility in future archaeological applications (Conyers, 2006). Frequency filtering of reflection records allows for the display of only certain bands of energy, allowing either larger or smaller objects in the ground to be enhanced or filtered out (Grealy, 2006). In this way, certain objects or

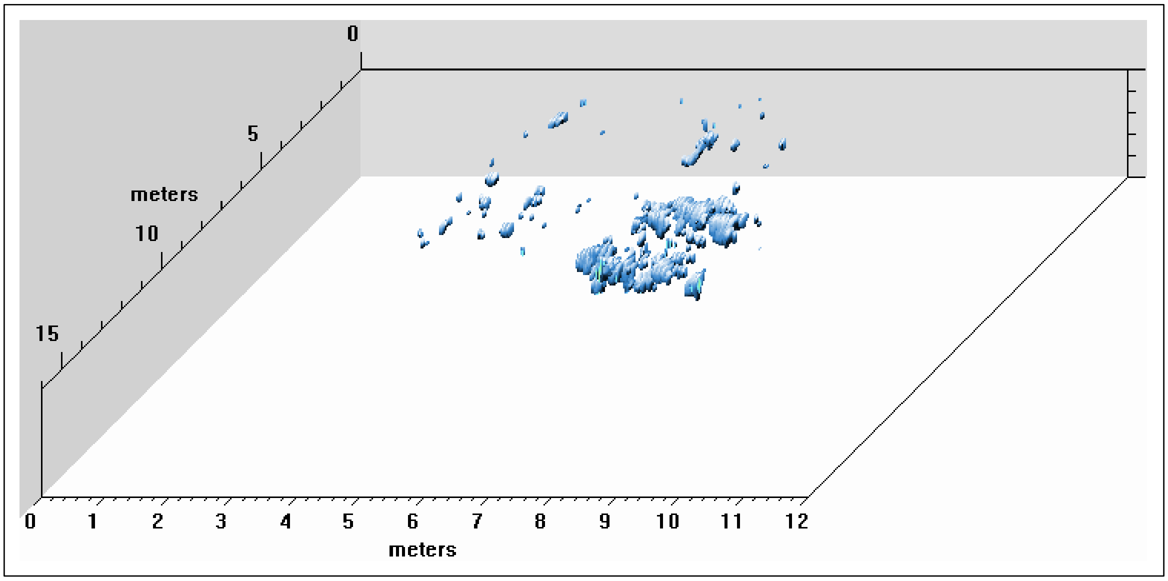

Figure 6. Isosurface map of the highest amplitude reflections from a pit-house floor preserved within sand dunes along the Oregon coast. Random stones, probably related to human activity in the dunes can be seen as small reflections scattered above and around the sunken house floor.

perhaps buried architecture at specific depths can be visualized and others removed or ignored. Reflections within the "near-field" of the antenna can also be used to produce maps of the ground using frequency filtering and background-removal and careful range-gaining processing (Ernenwein, 2006). In this way, reflection data recorded very near the ground surface, which just a few years ago was often ignored as unusable, can produce important images of shallow features. Experienced archaeological geophysicists are also beginning to appreciate the ability of GPR to discern buried features that are almost invisible to the human eye when excavated and exposed to view. Often the chemical and physical contrasts of these features are so slight that only low amplitude radar waves are reflected back to the surface. But careful analysis of these amplitudes can still provide accurate maps of very subtle features, as the digital information is available, even though it may not be visible to the human eye (Weaver, 2006).

An important re-direction in the use of geophysics for archaeology has been GPRs ability to test cultural models about the human past. Most archaeological geophysics is still focused on its original application of finding buried objects or features that can later be excavated using traditional methods. As most of us working in geophysical archaeology can today routinely produce accurate three-dimensional images of the ground, a few of us believe that it is now time to use this ability to test hypotheses about human activity across large areas, social organization and many other anthropological questions. For instance, if models of historic human activity can be related to the placement, orientation, shape and clustering of buried architecture, then GPR mapping is capable of accurately testing these hypotheses or developing new ideas about the past (Conyers and Osburn, 2006). GPR can potentially tell a great deal about archaeological sites without ever having to excavate, which will be of great benefit in the future as traditional archaeological digging becomes more expensive and often curtailed due to preservation issues.

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