

Chapter 13

Ground-penetrating Radar for Archaeological Mapping

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Abstract: Ground-penetrating Radar (GPR) is considered one of the more complicated of near-surface geophysical techniques, but also one of the more precise, because of its ability to map buried archaeological features in three-dimensions. Data from many two-dimensional reflections profiles within a tightly spaced grid, can be processed to remove noise, migrate reflections to their correct subsurface location, and then enhance important reflections from subsurface interfaces of interest. Three-dimensional images can then be constructed that produce realistic isosurfaces and amplitude slice-maps of buried features. When GPR reflections are incorporated with information derived from standard archaeological methods, and corrected to depth in the ground using velocity analysis, GPR maps can be used to display a large amount of information from limited excavations to produce a great deal of knowledge from a very large area. At the Albany, New York, town sites, historical maps of the city were compared to GPR images to determine neighborhood changes over time and the changing cultural landscape of one city block from early settlement through the early 20th century. At two sites in California and Colorado no reflections recognizable as cultural or geological were identified in reflection profiles, but amplitude slice-maps delineated spatial patterns that were found to be highly significant. Complex stratigraphy associated with buried cultural features can also be mapped, as illustrated in reflection profiles from aeolian dunes in coastal Oregon.

1. INTRODUCTION

Ground-penetrating radar is a near-surface geophysical technique that allows archaeologists to discover and map buried archaeological features in ways not possible using traditional field methods. By measuring the elapsed time

between pulses of radar energy transmitted from a surface antenna, reflected from buried discontinuities, and then received back at the surface, two-dimensional profiles of buried stratigraphy can be produced. When the distribution and orientation of those subsurface changes can be related to certain aspects of archaeological sites such as the presence of architecture, use areas, or other associated cultural features, high-definition maps and images of buried remains can be produced. Ground-penetrating radar is a geophysical technique that is most effective with buried sites where artifacts and features of interest are located within 2–3 m of the surface, but has occasionally been used for more deeply buried deposits.

A growing community of archaeologists has been incorporating ground-penetrating radar (GPR) as a routine field procedure for many years (Conyers, 2004; Conyers and Goodman, 1997; Gaffney and Gater, 2003). Their maps and images act as primary data that can be used to guide the placement of excavations, or to define sensitive areas containing cultural remains to avoid. Archaeological geophysicists have also used the GPR method as a way to place archaeological sites within a broader environmental context and study human interaction with, and adaptation to, ancient landscapes (Kvamme, 2003).

Ground-penetrating radar data collection involves the transmission of high frequency radar pulses from a surface antenna into the ground. That energy travels at the speed of light in air, but quickly slows when it moves through the ground. At each interface where its speed changes, some of that energy is reflected back to the surface. The greater the velocity change, the higher the amplitude of the reflected radar-waves. The elapsed time between when radar waves are transmitted, reflected from buried materials or sediment, and soil changes in the ground, and then received back at the surface is then measured. When many thousands of radar-wave reflections are measured and recorded, as antennas are moved along transects within a grid, two-dimensional profiles of soil, sediment, and buried cultural feature changes can be created (Figure 1). When many tens or even hundreds of two-dimensional profiles are collected in a grid, three-dimensional maps can be constructed, making the GPR method one of the most precise tools for archaeological mapping.

The GPR method has recently become so accurate that the possibility now exists to test any number of working hypotheses concerning a broad range of anthropological, geological, and environmental questions important to archaeological interpretation. Some of those could be related to social organization and social change, when these cultural attributes can be directly related to the placement, orientation, size, geometry, or distribution of certain architectural and ancillary features on the landscape. Geological and environmental aspects of ancient landscapes such as soil changes and the nature of buried topographic features is also possible (Conyers, 1995; Conyers and Spetzler, 2002; Conyers et al., 2002a). Most importantly, the GPR method can gather a great deal of information about the near-surface in a totally non-destructive way, allowing large areas with buried remains to be studied efficiently and accurately, while

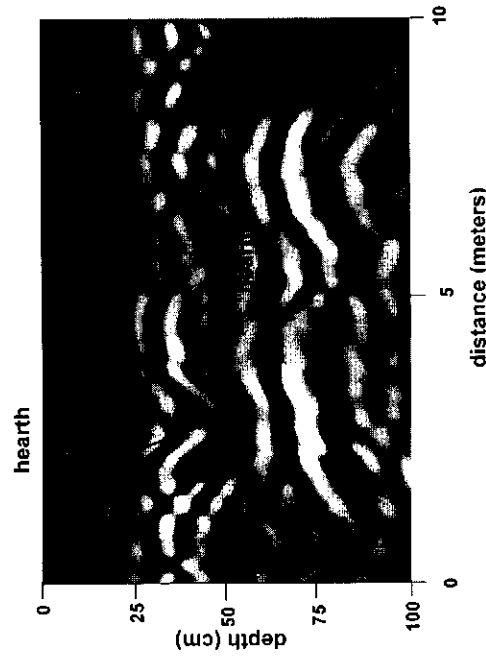


Figure 1. A two-dimensional GPR reflection profile showing a clay floor of a pit house buried in sand dunes.

The GPR method is especially effective in certain sediments and soils between about twenty centimeters and five meters below the ground surface, where the targets to be imaged are fairly large, hollow, linear, or have significant physical and chemical properties that contrast with the surrounding medium. Features as diverse as Maya house platforms and plazas (Conyers, 1995), burial tombs (Goodman and Nishimura, 1993), historical-period cellars, privies, and graves (Bevan and Kenyon, 1975), camp sites (Vaughan, 1986) and pit dwellings and kivas (Conyers and Cameron, 1998) have been discovered and mapped using the GPR method. Large-scale architectural features such as stone walls and floors, surrounded by homogeneous soil or sediment, are especially visible as GPR reflections, and very suitable for three-dimensional mapping and image production (Conyers, 2004; Conyers et al., 2002a, Goodman et al., 2004, Neubauer et al., 2002).

Modern GPR systems are quite compact and easy to use. The typical system consists of surface antennas, a radar system to produce pulses, a computer to process and save the data, a video monitor, and a power source. This system can be easily transported to the field by plane, car, and backpack. Processing of data can often occur on a laptop computer after reflection data are downloaded, often within a few hours after data collection.

2. THE GPR METHOD

Ground-penetrating radar (GPR) is a geophysical method that can accurately map the spatial extent of near-surface objects and archaeological features or

waves are propagated in distinct pulses from a surface antenna, reflected off buried objects, features, bedding contacts, or soil units, and detected back at the source by a receiving antenna. As radar pulses are transmitted through various materials on their way to the buried target feature, their velocity changes depending on the physical and chemical properties of the material through which they travel (Conyers, 2004a; Conyers and Goodman, 1997). The greater the contrast in electrical and to some extent magnetic properties between two materials at a subsurface interface (resulting in a stronger reflected signal), the greater is the amplitude of the reflected waves. When the travel times of energy pulses are measured, and their velocity through the ground is known, then distance (or depth in the ground) can be accurately measured to produce a three-dimensional dataset (Conyers and Lucius, 1996). Each time a radar pulse traverses a material with a different composition or water saturation, the velocity changes and a portion of the radar energy is reflected back to the surface, to be recorded at the receiving antenna. The remaining energy continues to pass into the ground to be further reflected, until it finally dissipates with depth.

The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography, and vegetation. It is not a geophysical method that can be immediately applied to any subsurface problem, although with thoughtful modifications in acquisition and data-processing methodology, GPR can be adapted to many differing site conditions. Although radar-wave penetration and the ability to reflect energy back to the surface is often enhanced in a dry environment, moist soils can still transmit and reflect radar energy, and GPR surveys can sometimes yield meaningful data even in totally saturated clay-rich soils. Recent research indicates that the amount and distribution of water in the ground is probably the most important variable that affects radar transmission and reflection (Conyers, 2004b). Often completely water-saturated ground will drastically slow radar wave velocity, but not attenuate the signal, if the material is not electrically conductive. Radar energy has been transmitted and reflected from depths approaching 3 m in totally saturated clay, when that clay is of a chemical composition that does not impede radar movement. In contrast totally dry sandy soil can potentially attenuate energy when it contains hydrous salts, as they are electrically conductive and will readily dissipate radar energy.

3. GPR DATA COLLECTION

To produce reflection profiles the two-way travel time and the amplitude and wavelength of the reflected radar waves derived from pulses generated at the antenna are amplified, processed, and recorded for immediate viewing or later post-acquisition processing and display. Most often this primary display is

in the form of two-dimensional profiles. During acquisition of field data, the radar-transmission process is repeated many times per second as the antennas are pulled along the ground surface or moved in steps. Distance along each line is recorded for accurate placement of all reflections in space within a surveyed grid. Reflection profiles are usually spaced between 50 and 100 cm apart in a grid, but recent research has shown that greater resolution is almost always a function of a more densely spaced grid (Goodman et al., 2004; Neubauer et al., 2002).

The depth to which radar energy can penetrate and the amount of definition that can be expected in the subsurface is partially controlled by the frequency of the radar energy transmitted. Frequency controls both the wavelength of the propagating wave and the amount of signal spreading and attenuation of the energy as it travels in the ground. Commercial GPR antennas range from about 10 to 1500 megahertz (MHz) center frequency. Proper antenna frequency selection can in most cases make the difference between success and failure in a GPR survey and must be planned for in advance. In general the greater the depth of investigation, the lower the antenna frequency necessary. Lower-frequency antennas are much larger, heavier and more difficult to transport to and within the field than high-frequency antennas but can potentially transmit energy more deeply into the ground. In contrast, high-frequency antennas are quite small and can easily fit into a suitcase but are capable of shallower transmission.

Subsurface-feature resolution varies with radar-energy frequency. Lower-frequency antennas (10–120 MHz) that generate long-wavelength radar energy can penetrate up to 50 m in certain conditions, but are capable of resolving only very large subsurface features. For example, dry sand and gravel, or unweathered volcanic ash and pumice are media that allow radar transmission to depths approaching 8–10 m, when lower-frequency antennas are used. In contrast the maximum depth of penetration of a 900-MHz antenna is about 1 m or less in typical soils, but its generated reflections can resolve features down to a few centimeters in diameter. A trade-off therefore exists between depth of penetration and subsurface resolution. These factors are highly variable, depending on many site-specific factors such as overburden composition and porosity, and the amount of moisture retained in the soil.

4. GPR DATA INTERPRETATION

Standard two-dimensional images can be used for most basic data interpretation, but analysis can be tedious if many profiles are included in the database. In addition, the origins of each reflection in each profile must sometimes be defined before accurate and meaningful subsurface maps can be produced. Often detailed image definition comes only with a good deal of interpretive experience, because the primary goal of most GPR surveys is to identify the

size, shape, depth, and location of buried remains and related stratigraphy. The most straightforward way to identify the size, shape, depth, and location of buried materials is by first identifying their produced reflections and then correlating them within and between adjoining two-dimensional reflection profiles. A more sophisticated method of GPR processing is amplitude slice-mapping, which creates maps of amplitude differences of reflected waves in discreet horizontal slices within a grid. The result can be a series of maps that illustrate the three-dimensional location of reflection anomalies derived from a computer analysis of the two-dimensional profiles (Figure 2). This method of data processing can only be accomplished with a computer using GPR data that are collected and stored digitally.

Three-dimensional amplitude maps are possible with GPR data because all reflection data collected by GPR is nothing more than a collection of many individual traces along two-dimensional transects within a grid. Each of those reflection traces contains a series of waves that vary in amplitude depending on the amount and intensity of energy reflection that occurred at buried interfaces. An analysis of the spatial distribution of the amplitudes of reflected waves is important because it is an indicator of potentially meaningful subsurface changes in lithology or other physical properties. If amplitude changes can be related to important buried features and stratigraphy, then location of those changes can be used to reconstruct the subsurface in three-dimensions. Areas of low-amplitude waves usually indicate uniform matrix material or soils, while those of high amplitude denote areas of high subsurface contrast such as buried archaeological features, voids, or important stratigraphic changes. In order to be interpreted, amplitude differences must

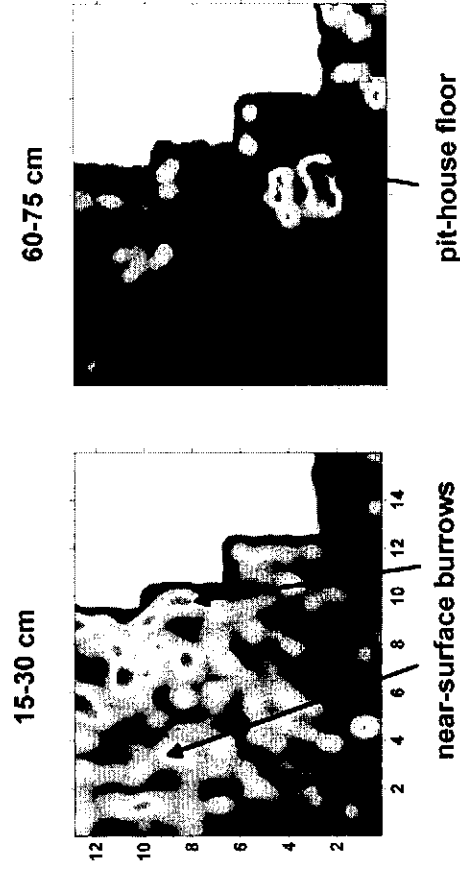


Figure 2. Amplitude slice-maps at two levels, showing in plan view rodent burrows near the surface and in the deeper slice the pit-house floor shown in one profile in Figure 1.

be analyzed in slices that examine only changes within specific depths in the ground. Each horizontal amplitude slice consists of the spatial distribution of all reflected-wave amplitudes, which are indicative of changes in sediments, soils and buried materials.

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. To compute horizontal time-slices the computer compares amplitude variations within traces that were recorded within a defined time window. When this computation is done both positive and negative amplitudes of reflections are compared to the norm of all amplitudes within that window. No differentiation is usually made between positive or negative amplitudes in these analyses; only the magnitude of amplitude deviation from the norm. Low amplitude variations within any one slice denote little subsurface reflection and therefore indicate the presence of fairly homogeneous material. High amplitudes indicate significant subsurface discontinuities, in many cases detecting the presence of buried features. An abrupt change between an area of low and high amplitude can be very significant and may indicate the presence of a major buried interface between two media. Degrees of amplitude variation in each time-slice can be assigned arbitrary colors or shades of gray along a nominal scale. Usually there are no specific amplitude units assigned to these color or tonal changes.

The unique ability of GPR systems to collect reflection data in a three-dimensional package lends itself to the production of a number of other three-dimensional images not possible using other methods (Conyers, 2004a; Conyers et al., 2002a; Goodman et al., 1998; Goodman et al., 2004; Leckebusch, 2000, 2003). If reflection data are collected in a grid of closely spaced transects, and there are many reflection traces gathered along each transect, reflection amplitudes can be accurately placed in three-dimensions and then rendered using a number of visual display programs. In this way GPR data from archaeological sites become analogous to many other imaging techniques used in other disciplines, which rely on energy sources such as seismic waves and magnetic resonance. In medical imaging complex three-dimensional techniques can produce images of certain amplitudes derived from these waves to display internal body parts, or even electrical impulses in the brain as a function of different stimuli. In archaeology, radar reflections can be used in the same way, but instead produce images of buried archaeological features.

Using GPR data buried features can be rendered into isosurfaces, meaning that the interfaces producing the reflections are placed in three-dimensions and a pattern or color is assigned to specific amplitudes in order for them to be visible (Conyers et al., 2002a; Goodman et al., 2004; Leckebusch, 2003). In programs that produce these types of images certain amplitudes (usually the

highest ones) can be patterned or colored while others are made transparent. Computer-generated light sources, to simulate rays of the sun, can then be used to shade and shadow the rendered features in order to enhance them, and the features can be rotated and shaded until a desired product results.

5. EXAMPLES OF GPR MAPS AND IMAGES

Often in complexly layered sites, where more deeply buried horizons contain materials of greater age, horizontal GPR amplitude maps can illustrate dramatic cultural changes over time. In this way the deeper slices will show older building activities, while the shallow slices show more recent ones. This difference was demonstrated at an historical-period site in Albany, New York, USA, where fire-insurance maps of the city were available showing the location of buildings present on town lots at specific time periods, going back to the year 1857. These maps showed dramatic building, demolition, and redevelopment episodes over a period of only 150 years. All buried materials from each construction episode are now located under a paved parking lot. The amplitude slice-maps were constructed in 25-cm-depth slices (after radar travel times were corrected for velocity), and images of the buried architectural features visible in the GPR amplitude maps were compared to the historical lot maps (Figure 3). The slice from 50–75 cm depth shows building foundations whose location compared almost exactly to domestic structures and a large kiln that were present in 1890. In progressively deeper slices, those 1890 buildings were still visible, but deeper foundations from older structures were also visible in the slice in the 150–175 cm depth (Figure 3). When the locations of those features were compared to the oldest maps from 1857, no correlation was found to any mapped structures. The deeper slices were therefore producing images of buildings that were present prior to the construction of any extant maps of the city. These very old building remains are awaiting excavation and their age and function remain unknown. The shallower slices and their structural remains correlated almost perfectly with the most recent fire-insurance maps.

In this example from historical New York the horizontal amplitude slice-maps can be a way not only to map building locations over time, but also, when integrated with enough other information such as historical maps and artifacts from excavations, determine their function as well. The changing make-up of neighborhoods can potentially be determined using these GPR amplitude maps, each of which is from a specific time period, if the sequential amplitude slices are roughly comparable to time periods. In this way GPR images can be much more than just a tool for finding and mapping buried features; they can also be a database from which to study social change and a wealth of other historic and anthropological questions.

Often reflection profiles can be difficult to interpret, even after filtering,

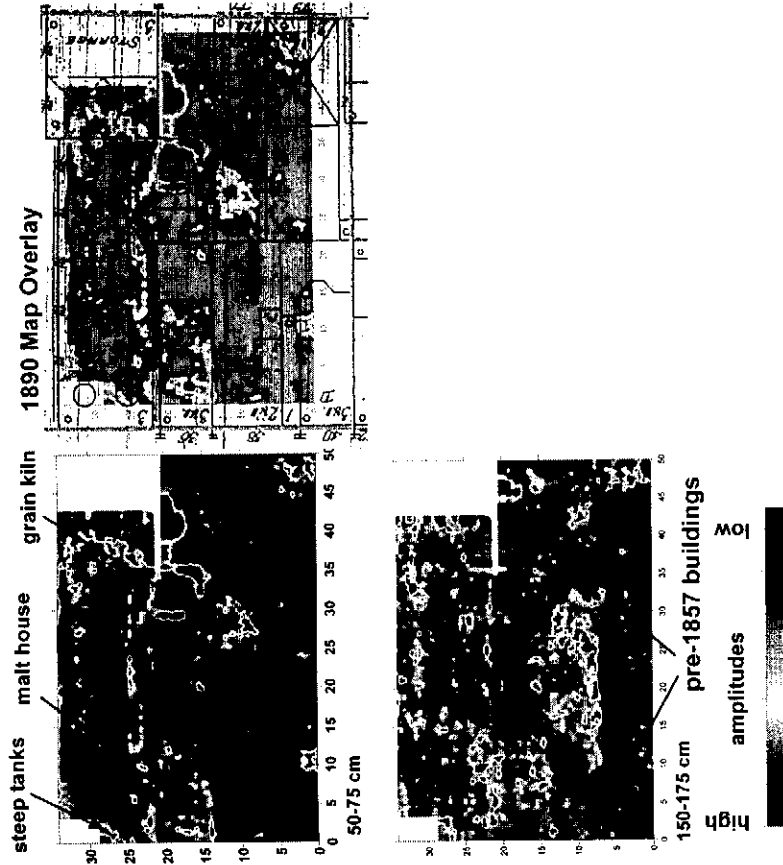


Figure 3. Amplitude slice-maps of an historical-period site in Albany, New York, preserved under a parking lot. The two slices illustrate very different preserved architecture at different depths. When the shallow slice from 50–75 cm is compared to the 1890 fire insurance maps, there is good correlation with what was known. The deeper slice shows smaller buildings from pre-1857.

differing vertical and horizontal exaggeration. There is often a temptation when one looks at particularly “noisy” reflection profiles such as the one in Figure 4 to give up and call the survey a failure as there are no amplitude changes readily visible in it. The profile in Figure 4 was collected with 900-MHz antennas in a boggy area in the California Sierra Nevada Mountains, USA. The goal was to map recently deposited sedimentary units in the hope of defining fluvial, marsh, and floodplain sediments that might have been present in the mid-19th century. Historical records indicated that the ill-fated Donner party, a wagon train that was immigrating to California and attempting to cross the mountains in November of 1846, camped near a creek in the study area and were stranded there all winter. Many eyewitness accounts reported that the survivors found themselves in a bog in the spring of 1847 when

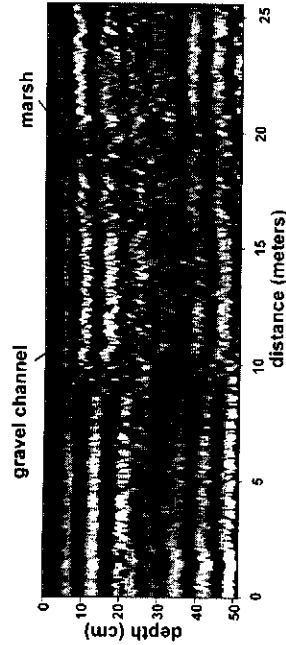


Figure 4. Reflection profile across a marsh which contains a small gravel channel. Reflection character is the only way to differentiate these lithological differences.

because the environment has changed a great deal, and is now on the edge of a reservoir that was flooded in the 1960s. It was hoped that an analysis of the environment as it existed during the time of the Donner Party encampment might yield clues to where the winter campsite was located, as it was known that there was a small creek nearby in the early winter, and the area became a bog in the spring. The GPR method was used because it had the ability to map in three-dimensions and, even though almost all the prospective area is today wet and boggy, because similar environments with an abundance of peat beds had proven excellent areas for GPR mapping in Scotland (Clarke et al., 1999).

The reflections in the 900-MHz profiles that crossed the present-day bog proved to be noisy and discontinuous, and few good reflections were visible that could be readily interpreted (Figure 4). There are, however, changes in the reflection character along profiles, with some areas containing few good reflections and others that appeared to contain many very small hyperbolic reflections, especially within the upper 20 cm of the reflection profiles. As little interpretation could be done using the individual profiles, it was decided to study the amplitude changes spatially within all the profiles in a grid to determine if there were any patterns to the distribution of these reflections either spatially or with depth.

When the amplitudes in all the profiles in the grid were studied in slice-maps, one sinuous area of higher-amplitude reflections was visible from the 10–20 cm slice (Figure 5). After further study of the reflection profiles in two-dimensions, it was hypothesized that the anomalously high amplitude area probably corresponds to the presence of many small gravel clasts deposited in a creek, each of which generated the small reflection hyperbolas at that depth. Auger holes were then dug on either side of the high amplitude feature, and within it (Figure 5). A study of the sediments recovered from them showed that holes 1 and 3 consisted of silt and peat, with abundant charcoal, while the sediment in hole 2 was mostly sand and gravel and contained very little peat. This subsurface information confirms that the sinuous anomaly in the 10–20 cm slice was likely a small sand- and gravel-filled creek. The areas

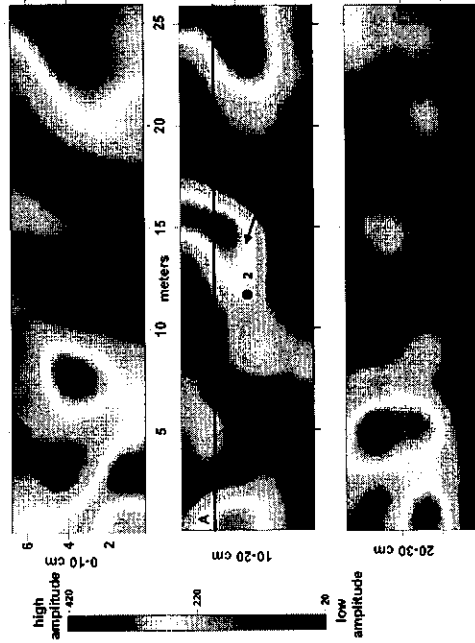


Figure 5. Amplitude slice-maps across the marsh and small channel seen in Figure 4. The sinuous channel (A) is readily visible in the middle slice and was confirmed in auger hole 2, while adjoining marsh sediment was recovered in holes 1 and 3.

adjacent to it, which are much lower in reflection amplitude, are areas where marsh and floodplain sediments were deposited.

Although remains of the Donner Party camp were not found in this immediate area, the study was successful in defining the shallow creek with adjacent marshy floodplain deposits, which can be used as a guide for further subsurface testing in a search for artifacts. Most importantly, this study illustrates how even reflection data that are difficult to interpret in two-dimensional profiles can produce useful data when studied in amplitude slices. When data of this type are then incorporated with standard archaeological and historical information, large areas of ground can be studied quickly and excavation efforts can be concentrated in the most prospective locations.

Often GPR amplitude slice-maps are capable of producing images that are not only almost invisible in reflection profiles, as shown in the example above, but the buried features that produced the reflection anomalies are also almost invisible to the human eye even when uncovered in excavations. A GPR survey was conducted in an orchard, where surface plowing had destroyed any indication of buried features likely to exist below. The area surveyed was the site of an early homestead in the mid-1800s in Denver, Colorado, USA, which was converted to a stage-wagon stop and finally reverted to a family farm in the 20th century. There were historical documents indicating that a number of buildings had been located somewhere in the orchard area, but their exact locations were unknown. The area had also been subjected to a number of floods, which buried any possible remaining features below more than a meter of sediment.

A grid of 400-MHz GPR reflection data was collected in the orchard, and slice-maps were constructed every 20 cm in the ground, after radar travel times were converted to depth (Figure 6). At the 75–100 cm depth a distinct linear feature was discovered, and in the deeper slices, another linear feature crossing it at an angle. Modern utility maps show plastic water lines cutting through the orchard, which generated the linear reflection anomalies. More interesting, however, was a 4-meter-square amplitude feature in the 75–100 cm depth, which was not correlative to any of the historical buildings that had been mapped in the area. This feature was hypothesized to be a buried building floor, because of its perfectly square geometry. Auger holes were dug both inside and outside the square feature, and no discernible difference could be seen in the two sediment samples from the depth indicated in the amplitude slice-map. Thinking that perhaps velocities, which had been estimated from hyperbola fitting of point source hyperbolas generated from the pipes, were

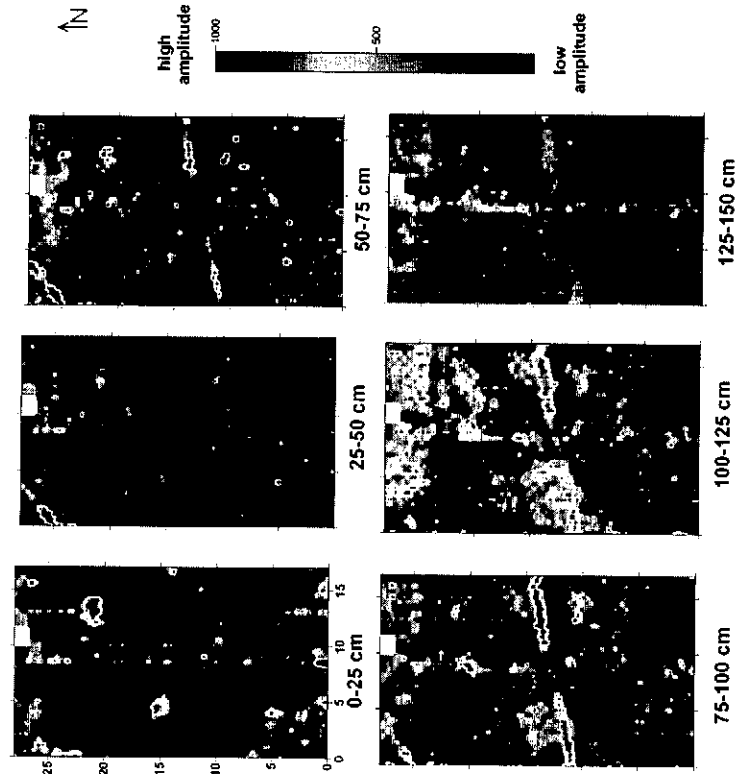


Figure 6. Amplitude slice-maps of GPR collected in an orchard. An irrigation pipe is visible as (A). The square feature (B) was excavated and found to be a very thin sand layer that was at one time associated with the floor of an historical-period building.

incorrect, a test excavation was placed directly on top of one of the pipes to uncover it in order to confirm the depth to a known object. The pipe was found at exactly the depth shown in the GPR maps, raising the confidence level of the velocity analyses and the slice-maps depths. A more careful analysis of the soil and sediment stratigraphy in the excavations adjacent to and just below the pipe was then made. A layer 2 cm thick that was just a little sandier than layers above and below was found within the square GPR feature. When excavations were extended outward, this sandy layer was found to be overlain by broken pieces of flat sandstone, which were probably used as pavers in the floor of a small house or shed.

It appears that there was a small building in the orchard at one time, whose floor was paved with sand and then covered with flat flagstone. When the building was abandoned, the usable sandstone pieces were probably salvaged for use elsewhere, and the remaining sandy sub-floor was covered by sediment during floods, and by the build-up of soil. All that remains of the house today is the very subtle sand layer. The feature is so subtle that normal excavation methods would have likely overlooked it, as it would have been interpreted as just another sandy layer in the orchard's sediment and soil package. Even once the feature had been discovered in excavations, it could still not be seen in GPR reflection profiles without using a good deal of imagination. Only subtle changes in radar reflection amplitudes, processed as amplitude slice-maps, were capable of finding and mapping this feature, which was only distinguishable by its distinctive square shape.

At the site of Petra, Jordan, Roman and Byzantine structures are buried in wind-blown sand (Conyers et al., 2002). Walls, floors, and standing columns are often visible in reflection profiles as distinct hyperbolic reflections. Amplitude slice-maps can be used to map the reflections from these architectural features in plan view, which is the usual way of imaging three-dimensional GPR reflections. Isosurfaces can also be created from these reflection data that reveal an image of the buried architecture in a very different way (Figure 7). In this rendering, the shallowest slices were not included, as they contained many small point source reflections from shallow rock rubble. The very deepest slices were also not included, as the data from that depth tended to be "noisier," and resulted in high amplitude streaking in the rendered images (Conyers et al., 2002). These reflection data were ideal for rendering because most of the reflections collected in the grid were generated from buried architecture, and the surrounding wind-blown sand matrix generated almost no reflections of any amplitude. Once the rendering was constructed on the computer it could also be rotated or tilted in a number of different orientations in a video display (Conyers et al., 2002).

Often in stratigraphically complex areas, reflections from geological layers can obscure and potentially clutter amplitude maps with reflections from non-cultural horizons. When this clutter occurs detailed analysis of reflections and the layers that produced them is necessary. Along the Pacific Coast near

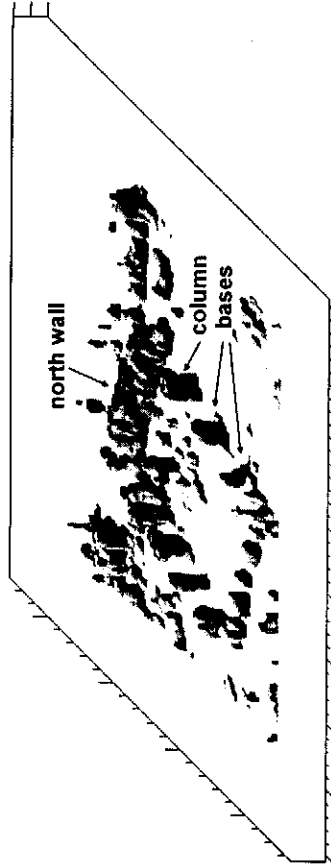


Figure 7. Rendering of high amplitude reflections from a buried Byzantine building at Petra, Jordan. Buried column bases and a distinct north wall are visible.

Port Orford, Oregon, USA, a buried pit-house village is preserved in stabilized coastal dunes. The dunes contain many large cross-bedded units of sand and silt, each of which produces distinct GPR reflections (Figure 8). A 400-MHz antenna was used in this area, which was capable of defining each of the major dune horizons as sloping reflections, with the pit-house floors as horizontal reflections (Figure 8). A reflection profile parallel to an erosional bank that exposed many of these geological units as well as one exposed pit-house floor, was used to determine the origin of reflections. When the GPR reflections profile was compared to the photograph of the natural and cultural layers, the origins of reflections were easily determined. A series of horizontal amplitude maps was then constructed that filtered out the steeply dipping beds (those produced from the sand-dune stratigraphy), and mapped only the horizontal reflections from the pit-house floors (Figure 2). Those floors could then be

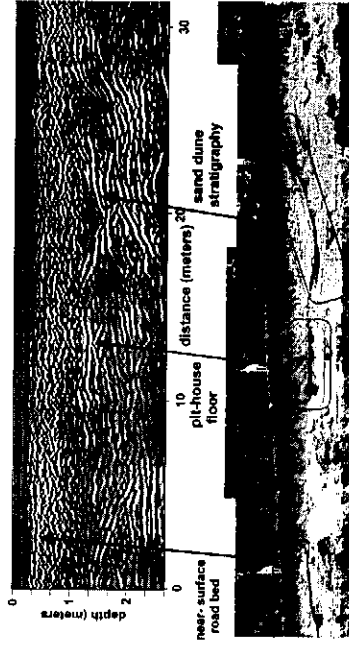


Figure 8. GPR reflection profile collected parallel to an erosional cutbank where a pit-house floor and complex sand dune stratigraphy are visible. These features are also visible in the reflection profile.

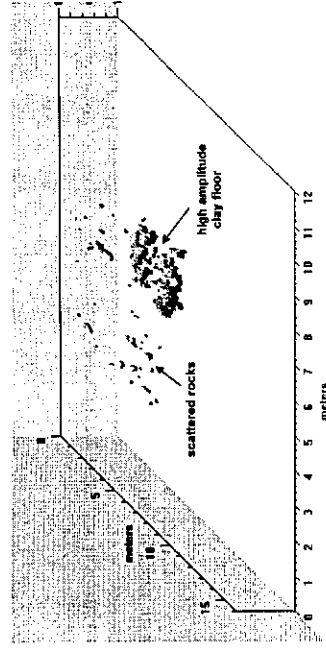


Figure 9. An amplitude isosurface of the pit-house floor visible in the amplitude slice-map in Figure 2.

discriminated from the surrounding sand matrix by filtering out the lower amplitudes, leaving only the high amplitudes from the compacted clay floors. When this was done, the remaining high-amplitude reflections were rendered in three-dimensions to produce an image of the buried floor, revealing two "benches" of compacted clay, separated by a less-compacted area, which might be a separate work area or partially disturbed floor surface (Figure 9).

6. CONCLUSION

Ground-penetrating radar has the unique ability of near-surface geophysical methods to produce three-dimensional maps and images of buried architecture and other associated cultural and natural features. By using high-definition, two-dimensional reflection profiles, researchers can generate three-dimensional maps of amplitude changes that can define physical and chemical changes in the ground that are related to buried materials of importance. Often it is how the physical and chemical changes in various buried materials affect the retention and distribution of water in the ground that is of highest importance. Subtle changes in the amplitude of radar reflection can often be related to the presence or absence of cultural materials, thereby producing maps of changes that would be difficult to see in normal excavation trenches or through other subsurface evaluation techniques.

In the processing of GPR reflection data, maps and images must be generated so that buried cultural materials of interest can be visualized and interpreted. This result can be accomplished by using horizontal amplitude maps, sliced in layers or three-dimensional isosurfaces, which produce images of only certain amplitudes within a three-dimensional volume of reflections. In all cases, the results of these amplitude images must be differentiated from the surrounding geological layers.

REFERENCES

- Bevan, Bruce and Kenyon, Jeffrey, 1975, Ground-penetrating radar for historical archaeology. *MASCA Newsletter* 11(2):2-7.
- Clarke, M. Ciara, Utsi, Erica and Utsi, Vincent, 1999, Ground-penetrating radar investigations at North Ballachulish, Moss, Scotland. *Archaeological Prospection* 6:107-121.
- Conyers, Lawrence B., 1995, The use of ground-penetrating radar to map the buried structures and landscape of the Ceren site, El Salvador. *Geoarchaeology* 10(4):275-299.
- Conyers, Lawrence B., 2004a, *Ground-penetrating Radar for Archaeology*. AltaMira Press, Walnut Creek, California.
- Conyers, Lawrence B., 2004b, Moisture and soil differences as related to the spatial accuracy of amplitude maps at two archaeological test sites. In *Proceedings of the Tenth International Conference on Ground Penetrating Radar: June 21-24, Delft, The Netherlands*, edited by Evert Slois, Alex Yaravoy and Jan Rheberger, pp. 435-438. Delft University of Technology, The Netherlands Institute of Electrical and Electronic Engineers, Inc., Piscataway, NJ.
- Conyers, Lawrence B., and Cameron, Catherine M., 1998, Finding buried archaeological features in the American Southwest: New ground-penetrating radar techniques and three-dimensional computer mapping. *Journal of Field Archaeology* 25(4):417-430.
- Conyers, Lawrence B., and Goodman, Dean, 1997, *Ground-penetrating Radar: An Introduction for Archaeologists*. AltaMira Press, Walnut Creek, California.
- Conyers, Lawrence B., and Lucius, Jeffrey E., 1996, Velocity analysis in archaeological ground-penetrating radar studies. *Archaeological Prospection* 3:312-333.
- Conyers, Lawrence B., and Spetzler, Harinut, 2002, Geophysical Exploration at Ceren. In *Before the Volcano Erupted*, edited by Payson Sheets, pp. 24-32. University of Texas Press, Austin.
- Conyers, Lawrence B., Ermenwein, Eileen G., and Bedal, Leigh-Ann, 2002, Ground-penetrating radar (GPR) mapping as a method for planning excavation strategies, Petra, Jordan. E-tiquity Number 1, <http://e-tiquity.saa.org/%7Eetiquity/tit1el.html>
- Gaffney, Chris and Gater, John, 2003, *Revealing the Buried Past: Geophysics for Archaeologists*. Tempus, Stroud, Gloucestershire.
- Goodman, D. and Nishimura, Y., 1993, A ground-radar view of Japanese burial mounds. *Antiquity* 67:349-354.
- Goodman, Dean, Nishimura, Yashushi, Hongo, Hitomichi and Maasaki, Okita, 1998, GPR Amplitude rendering in archaeology. In *Proceedings of the Seventh International Conference on Ground-penetrating Radar, May 27-30, 1998. University of Kansas, Lawrence, Kansas, USA*, pp. 91-92. Radar Systems and Remote Sensing Laboratory, University of Kansas.
- Goodman, Dean, and Piro, Salvatore, Nishimura, Yasushi, Patterson, Helen, and Gaffney, Vince, 2004, Discovery of a 1st century AD Roman amphitheatre and other structures at the Forum Novum by GPR. *Journal of Environmental and Engineering Geophysics* 9:35-42.
- Kvamme Kenneth L., 2003, Geophysical surveys as landscape archaeology. *American Antiquity* 63(3): 435-457.
- Leckebusch, J., 2000, Two and three-dimensional ground-penetrating radar surveys across a medieval choir: a case study in archaeology. *Archaeological Prospection* 7:189-200.
- Leckebusch, J., 2003, Ground-penetrating radar: A modern three-dimensional prospection method. *Archaeological Prospection* 10:213-240.
- Neubauer, W., Eder-Hinterleitner, A., Seren, S. and Melichar, P., 2002, Georadar in the Roman civil town Carnuntum, Austria: An approach for archaeological interpretation of GPR data. *Archaeological Prospection* 9:135-156.
- Vaughan, C.J., 1986, Ground-penetrating radar surveys used in archaeological investigations. *Geophysics* 51(3):595-604.