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Discovery, mapping and interpretation of buried cultural resources non-invasively with ground-penetrating radar

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Abstract

Ground-penetrating radar is an extremely useful tool for the mapping and interpretation of buried cultural remains within 2–3 metres of the surface, especially when the stratigraphy is complex. Standard reflection profiles can be processed to correct for depth and distance, and also filtered and processed to make cultural features visible. When many profiles are collected in closely spaced transects in a grid, reflections can be re-sampled and displayed in amplitude slice-maps, and isosurface renderings to make buried features visible. Sometimes, however, the abundance and complexity of subsurface reflections is so complex that each individual profile must be interpreted manually, which necessitates an understanding of radar wave propagation, reflection, refraction and attenuation in the ground. In order to differentiate reflections from cultural features this understanding of radar energy must be merged with an understanding of the chemistry of the ground, soil and geological stratigraphy, and how those variables affect radar reflections. When taken as a package of visualization tools, GPR can be used as an effective tool for interpreting aspects of history and culture at buried sites in ways not possible using traditional archaeological methods.

Keywords: ground-penetrating radar, cultural resources

(Some figures in this article are in colour only in the electronic version)

Introduction

Ground-penetrating radar (GPR) is a near-surface geophysical technique that allows scientists to discover and map buried cultural features in ways not possible using traditional field methods. It is the most widely used near-surface geophysical method to produce three-dimensional images and maps of the ground. The method consists of measuring the elapsed time between when pulses of radar energy are transmitted from a surface antenna, reflected from buried discontinuities, and then received back at the surface. When the distribution and orientation of those subsurface reflections can be related to aspects of buried cultural features such as the presence of buried architecture, human use areas or other associated remains, high definition three-dimensional maps and other images of buried sites can be produced. GPR is a near-surface geophysical technique that is most effective with buried sites where artefacts 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 GPR as a routine non-invasive field procedure (Conyers 2004a, Gaffney and Gater 2003). Their maps and images can act as primary data that can be used to guide the placement of excavations, define sensitive areas containing cultural remains to avoid, place archaeological sites within a broader environmental context and study human interaction with, and adaptation to, ancient landscapes (Conyers 2010, Conyers and Leckebusch 2010, Kvamme 2003).

Usually in archaeological GPR studies radar antennas are moved along the ground in transects and two-dimensional profiles of a large number of reflections at various depths

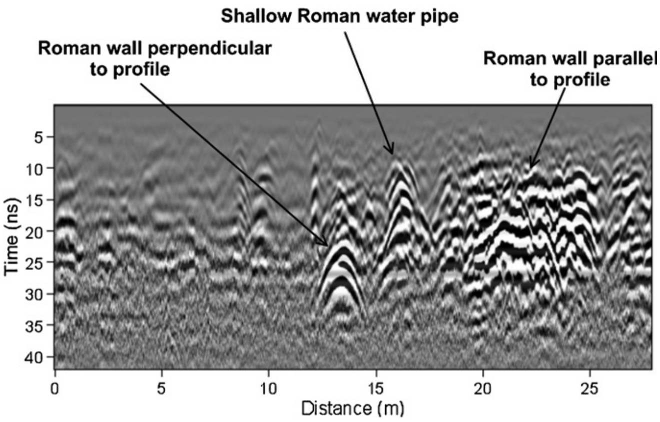

Figure 1. GPR reflection profile of Roman remains at Ashkelon, Israel. When profiles cross walls perpendicularly, point-source reflection profiles are produced, and when they parallel lines, the top of the wall produces a complex series of high amplitude planar and point-source reflections.

are created, producing profiles of subsurface stratigraphy and buried archaeological features along lines (figure 1). Many closely spaced two-dimensional profiles within a grid can then be processed to produce horizontal amplitude slice maps (figure 2) and isosurface renderings (figure 3) that produce images of reflections of certain amplitudes in three-dimensional space. Recently systems have been developed that can simultaneously transmit and receive from numerous antennas in an array, which are still in the developmental stage, but which have the potential of producing even more accurate three-dimensional images (Conyers and Leckebusch 2010, Leckebusch and Rychener 2007, Leckebusch *et al* 2008).

While three-dimensional images are often effective at producing interesting and useful images when buried, archaeological features produce distinct reflections within a somewhat homogeneous matrix (figures 2 and 3). However, when associated stratigraphy is complex, each of the individual reflection profiles must be analysed individually. Many GPR practitioners have recently tended to rely a great deal on slice maps and isosurface images, as they simplify the hundreds and thousands of reflections within many profiles into a few useful images. However, the individual reflection profiles often contain important information that can potentially be filtered out during the production of these slice maps and isosurfaces, and therefore the profiles need to be individually analysed also.

There are a number of software programs that are useful at making amplitude slice maps from numerous reflection profiles in a grid. All GPR hardware manufacturers have their own programs for this type of analysis, each produced for the needs of their customers. Some are very good for pipe and utility location, others for environmental and civil engineering applications, and others for a wider variety of applications. While the exact algorithms that are used in each are usually not available, the results of the product of each can be viewed visually. Three amplitude maps of the same horizontal slice in the ground using three different amplitude analysis programs

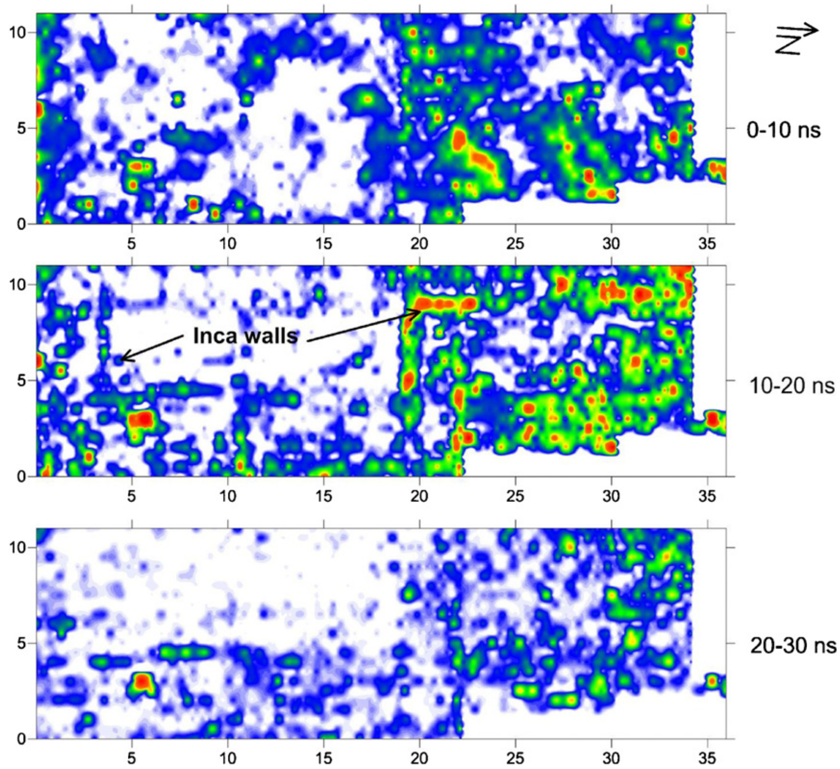

Figure 2. Many reflection profiles can be processed into horizontal slices, with the placement of reflection amplitudes coloured rainbow shades. This map of an Inca site from Ecuador shows the location of adobe and stone walls of a royal residence enclosure. Each slice is defined in two-way travel times in nanoseconds, which can be converted to depth when velocities are calculated.

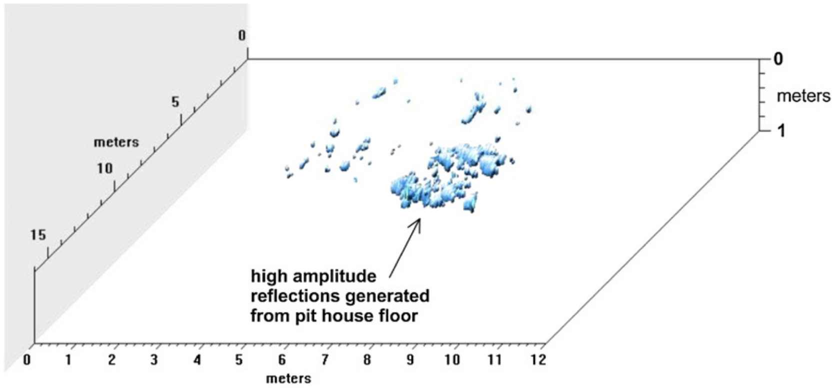

Figure 3. Isosurface image of the highest amplitude reflections from a pit-house floor preserved within sand dunes along the Oregon Coast, USA. Random stones, probably related to human activity that occurred in the dunes can be seen as small reflections scattered above and around the buried house floor.

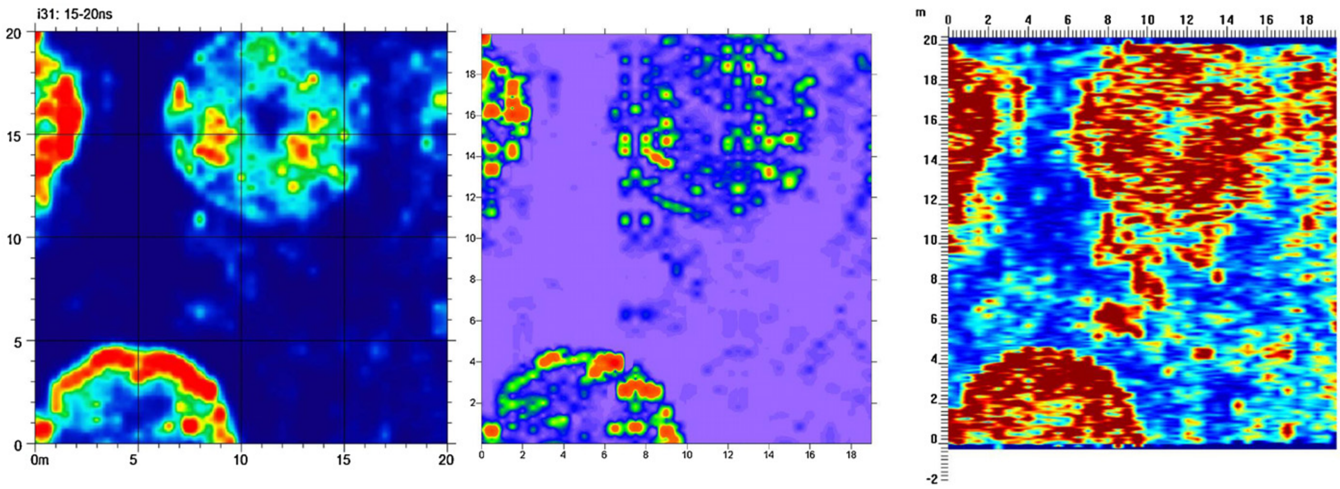

Figure 4. Comparison of amplitude slice images from three different software programs with different re-sampling algorithms. On the left is GPR slice (http://www.gpr-survey.com), the middle is GPR process (http://mysite.du.edu/~lconyer) and on the right is EKKO mapper (http://www.sensoft.ca). The features in the image are circular bases of historic brick kilns in Ohio (data courtesy of Jarrod Burks).

are shown in figure 4. The three buried features visible in the maps are the bases of historic kilns in Ohio, USA, which generate very high amplitude reflections. The image on the left is very useful for identifying the features as a whole, but tends to average reflections somewhat. The middle map produces an image of almost each and every brick within these features, but tends to produce less distinct overall maps. The map on the right is much less distinct in all respects and appears to have produced a map of features that are not found in the other images, for unknown reasons.

Very much the same type of variation in the visualizing software for reflection profiles is true for differing software manufacturers (figure 5). The most important aspect for generating images of these profiles is the ability to change the gains, filter out noise, adjust scales for depth (in time and distance) and produce distance measurements along the transect accurately. Often archaeologists tend to bypass basic interpretation of reflection profiles, as these images tend to be complex and sometimes difficult to interpret without a detailed understanding of what generates reflections in the ground. Accurate and useful profile interpretation ability only comes with experience and knowledge of not only of how radar energy moves, reflects, refracts and is attenuated in the ground but also the background in soil and sediment stratigraphy and the physical and chemical properties of the ground.

As an example of the differences in software images that are available, figure 5 shows a standard output and the same profile that has been processed in a way where the buried features are more visible. The upper image has had background noise removed, but the axes have not been modified and the reflections gained to make the features more visible and interpretable. In the lower profile the distinct hyperbolas, which are individual graves, are much more easily distinguishable as reflection hyperbolas. Shallow roots, which produce the less distinct hyperbolas, also become visible in the lower profile.

Complexities in the GPR method

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 (Conyers

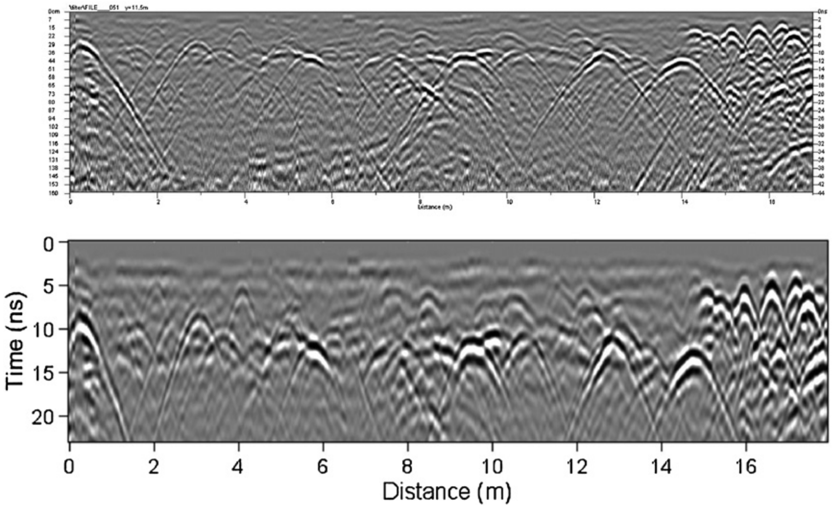

Figure 5. Comparison of reflection profiles produced from different software in a historic cemetery in Georgia, USA. The upper profile includes the complete time window and has background removed, but no re-gaining of the amplitudes. The lower profile has had reflections re-gained and then spatially averaged within a smaller time window to make the reflection hyperbolas from burials more visible. Shallow roots are also visible in the lower profile as low amplitude hyperbola reflections in the 5–6 ns time range.

2004a, p 28). While some studies suggest that GPR is only successful in areas where soils and underlying sediment are dry (Annan and Davis 1992), radar wave penetration will occur in any type of ground that is not highly electrically conductive (Conyers 2004b). Radar energy becomes both dispersed and attenuated as it radiates into the ground. When portions of the original transmitted waves are reflected back towards the surface they will suffer additional attenuation by the material through which they pass, before finally being recorded at the surface. Therefore to be detected as reflections, important subsurface interfaces must not only have sufficient electrical contrast at their boundary (which is what creates the reflections) but must also be located at a shallow enough depth where sufficient radar energy is still available for reflection. As radar energy is propagated to increasing depths the energy also becomes weaker as it spreads out over more surface area and is absorbed by the ground, making less available for reflection.

Post-acquisition frequency filtering and reflection amplification techniques can sometimes be applied to reflection data after acquisition that will enhance some very low amplitude reflections in order to make them more visible, but in all ground conditions all radar energy is lost at a certain depth and in certain materials. The depth of complete energy attenuation is often difficult to predict in advance of a survey, but can be readily determined once antennas are moved over the ground in a prospective area and the depth (as measured in two-way radar travel time) of coherent reflected waves is determined. While in some cases greater depth penetration can be obtained using lower frequency antennas, often all radar energy is attenuated at a certain depth no matter what frequency antenna is used (Conyers 2004a).

The complexity of radar travel paths in the ground is an additional variable that is sometimes difficult to predict in advance and also interpret in GPR reflection profiles once data are visible in amplitude slice maps and isosurface images.

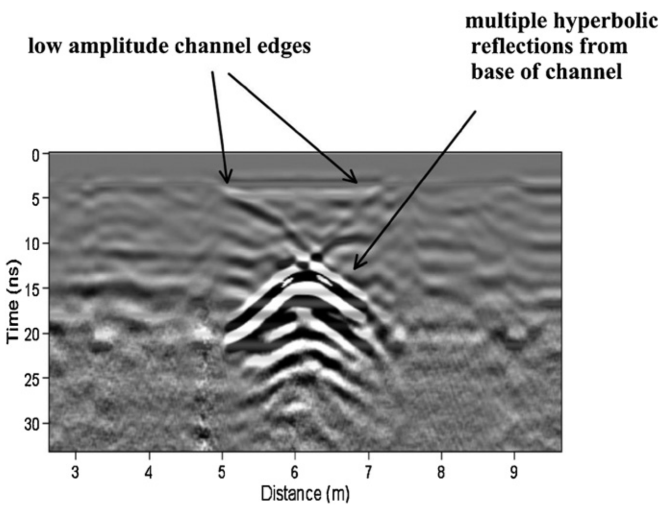

Figure 6. Reflection profile crossing a prehistoric irrigation canal in southern Arizona. The highest amplitude reflections are generated from the base of the canal, while the edges of the canal are lower amplitude reflections that are difficult to discern from the background.

Radar waves not only are transmitted in the ground in a conical pattern from the surface antenna, but will also be reflected and refracted in complex ways when interfaces of different thickness and orientation are encountered. An example of this complexity is a prehistoric irrigation canal's edges, which are only faintly visible in a reflection profile (figure 6). The highest amplitudes are generated from the base of the channel because a layer of mud was deposited there in a small 'bowl-shaped layer' which acted as a highly reflective focusing surface. This interface is displayed as a point-source radar reflector that generated a very distinct series of hyperbolic-shaped reflections. The edges of the channel itself produce only very faint reflections because sediment of similar chemical and physical properties occurs in the both the channel fill

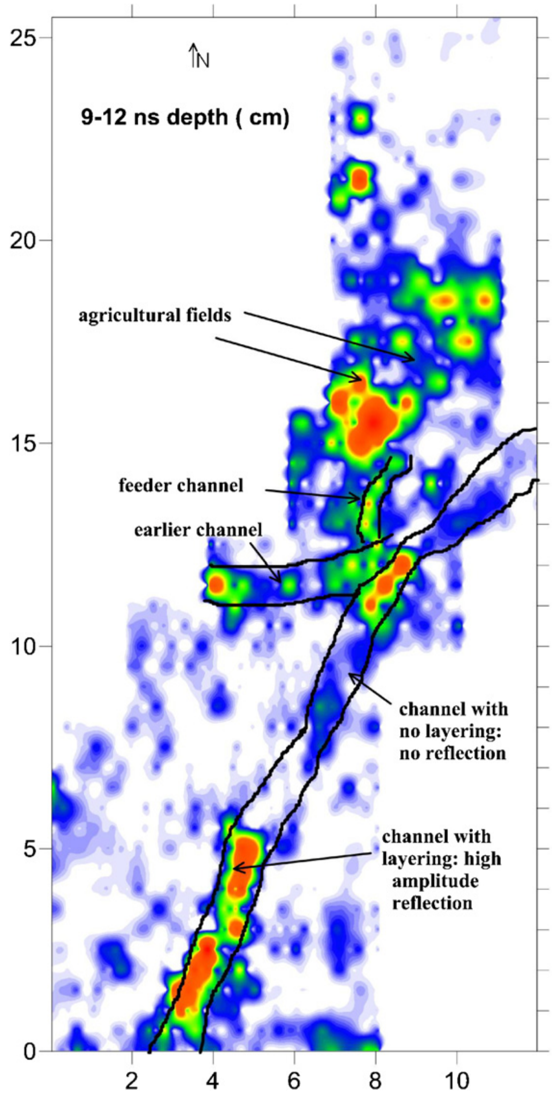

Figure 7. Amplitude slice map of prehistoric irrigation canals in southern Arizona, USA. Changes in the sediment types preserved in the base of the channels are producing changes in radar reflection amplitudes along the canals. Associated small feeder canals and agricultural fields are also visible.

and the adjacent material. In addition, the channel edges dip in a way such that much of the radar energy that strikes them is reflected away from the surface-receiving antenna and therefore not recorded. If many profiles in a grid were processed into amplitude slice maps the channel (that is the target of the GPR survey) would tend to be obscured by the high amplitude reflections that were produced from only the base of the channel. The high amplitude reflections visible in an amplitude slice map will mimic the location of the channel but they are recorded in the time window below the base of the channel itself. Also, as only the high amplitudes are usually mapped in slice maps, the image of the channel actually displays changes in the sediment types preserved in the base of the channel, not the channel itself (figure 7). An understanding of what has produced the reflections would therefore be necessary before an accurate interpretation of the amplitude maps is possible. The slice maps are still accurately mapping portions of the channels, but it is actually changes in the sediment types preserved in the base of the channel that are being displayed, and those are recorded below the actual depth (as recorded in time) of the canal.

As a way to help understand, or predict in advance, how radar energy will move in the ground and what types of reflections might be recorded, predictive models can be produced (figure 8). These models (Goodman 1994) take into account the electrical properties of the ground and archaeological features, as well as their orientation and radar frequency and transmission geometry in two dimensions. The resulting models can be extraordinarily helpful in interpretation, as they can generate images of what reflections would be produced from those features in the ground given those parameters, and a view of their orientation and recorded time. Those models can then be used as a guide to what equipment should be used and the collection parameters prior to going to the field and also for interpreting and processing reflection profiles after collection (figure 8). When this modelling procedure was conducted in Tunisia the ceiling and floor of an underground church can be seen as high amplitude reflections, while the vertical walls are modelled as invisible. The ceiling produces a very prominent reflection and is accurately located in space, while the model shows that the flat floor would produce an upward bowing reflection due to the 'pull up' created by faster velocities of waves travelling within the overlying void space. The reflection profiles collected in the field showed almost exactly what the model predicted (figure 8).

Processing and interpretation methods for complex sites

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 (Conyers 2004a, 2010). At the site of Petra in Jordan, much is known about the late Nabataean and Roman occupation of this impressive desert valley, the remains of which are located within 2 m of the ground surface (figure 9). There is also subtle and potentially important evidence of an earlier occupation of the valley prior to this time by people who originally lived in much more humble dwellings. These structures were likely razed and covered over during the first-century urbanization episode, which created a city layout that can be seen at or near the surface of Petra today (Conyers 2010). One site at Petra was tested with GPR to look at the deepest architectural remains below about 2 m depth (Conyers *et al* 2002). Reflection profiles within the grid show a very subtle sloping reflection that is correlative to an ancient living surface visible in nearby excavations. This reflection was hypothesized to have been generated from the living surface on the valley floor prior to the first-century urbanization construction episode.

In order to produce images of the buried surface and remaining features built on it, the amplitudes of all GPR reflections in all profiles within the grid were digitized, gridded

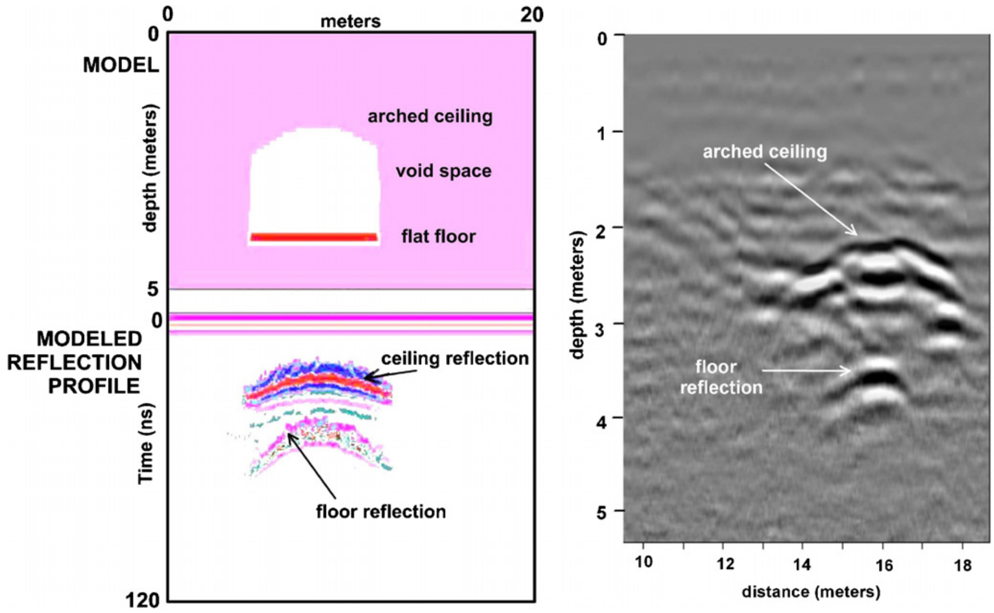

Figure 8. Synthetic reflection profile generation of an underground church in Tunisia (http://www.gpr-survey.com/gprsim.html). Only the ceiling, floor and walls of the church were simulated, producing reflections that accurately depicted the upward bowing ceiling, and a pronounced upward bowing floor. 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.

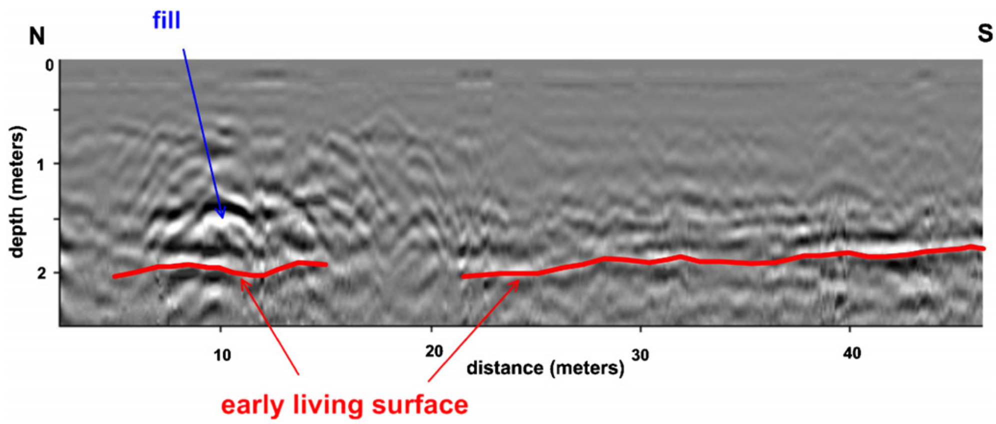

Figure 9. Reflection profile showing the subtle reflection surface with variable amplitudes under first-century fill.

and mapped in slices parallel to this sloping surface (figure 10). The highest amplitude reflections correspond to either standing architecture or architectural rubble on and directly above this buried surface. Areas with no significant reflection are open spaces or pathways between buildings on that pre-first-century surface. This type of GPR analysis produces horizon-specific maps showing the remains of simple buildings (Conyers 2010) and possible pathways between them. The pathways are identifiable as linear zones of no reflection, which led from the highlands to the south, towards the water drainage to the north (figure 10). The orientations of early buildings along these pathways show that they were built in various orientations and likely placed on land that was suitable for building at that time. This type of informal construction likely functioned only as part-time living quarters. Only later in the late first century BC when the Nabataeans had established control over trade routes from south Arabia to the eastern Mediterranean did social differentiation and monumental construction take place. The remains of these later more formal buildings (figure 10) from that construction period are in stark contrast to these earliest habitations. In the upper GPR slice the structures within what became a formal garden were invariably oriented to the cardinal directions, consistent with Hellenistic influenced building practices from later Nabataean times.

In deep and stratigraphically complex areas amplitude maps and isosurface images are of little value, as slices will often cross-cut reflections, or those reflections will clutter isosurfaces, creating distorted and inaccurate images. When this is the case, only manual interpretation of each individual reflection profile can produce accurate interpretations.

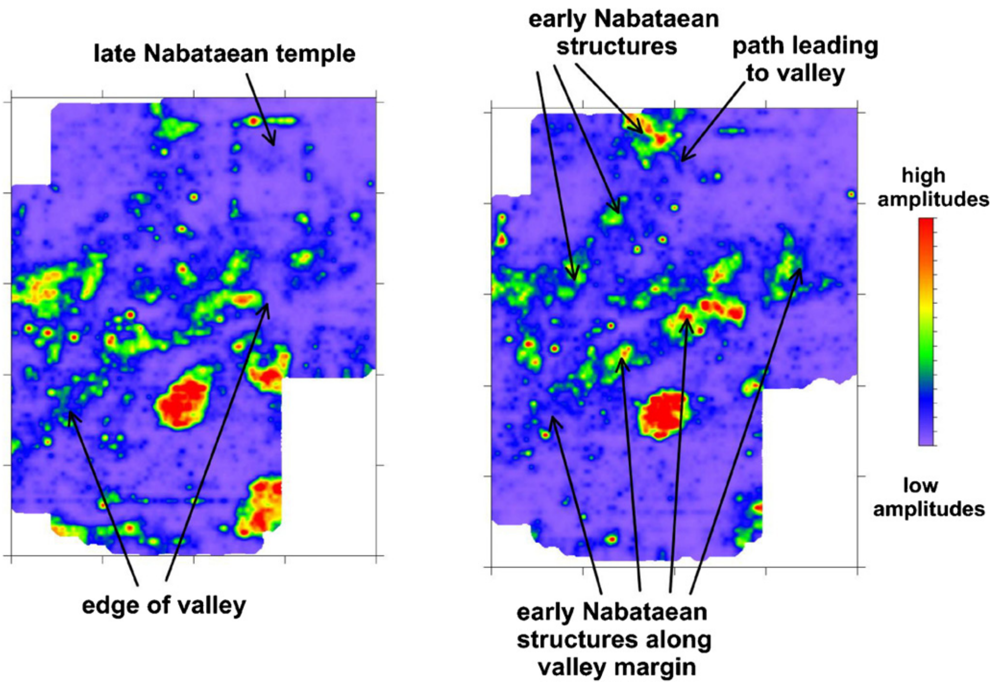

Figure 10. Example of an amplitude slice-map, showing columns and walls of a buried late-Nabataean temple at Petra, Jordan. The slice on the left is showing the buildings constructed on the fill after the first-century urbanization project. On the right (deeper slice) is the image of features built on the living surface prior to the filling episode.

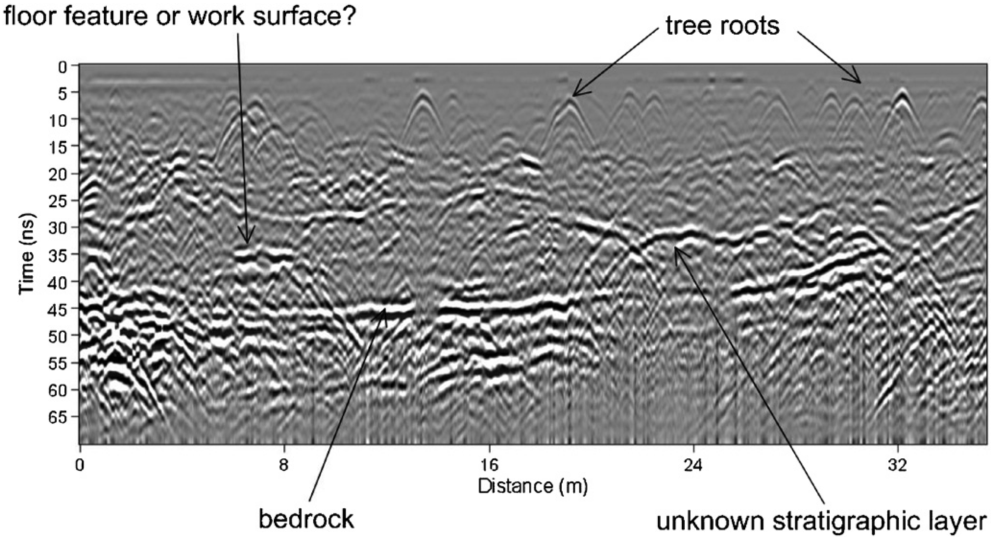

Figure 11. Reflection profile using the 400 MHz antennas in front of a rock shelter in Queensland, Australia. Bedrock and tree roots are visible as planar and hyperbolic reflections respectively. Probable cultural features, such as the distinct planar floor or work surface were also visible in individual profiles.

A large grid of reflection profiles was collected in front of a rock shelter in Queensland, Australia. The area mapped appears from its surface expression to be a small basin that would have collected not only naturally deposited sediment, but also remains of a very long human occupation, spanning as many as 30 000 years. Reflection profiles were quite complex, but a very high amplitude reflection from the sandstone bedrock was visible (figure 11). Core holes confirmed the origin of this reflection, and allowed for accurate time–depth conversions. Many shallow tree roots were visible in all profiles, and could be ignored during interpretation. The origin of other reflections above the bedrock is speculative, but is likely hard-packed floors or work surfaces (figure 11) in front of the rock shelter.

A map of the depth to bedrock in this small basin in front of the shelter was possible, but only after velocity analysis had converted all radar travel times to depth, and each individual profile was interpreted (figure 12). This image shows bedrock

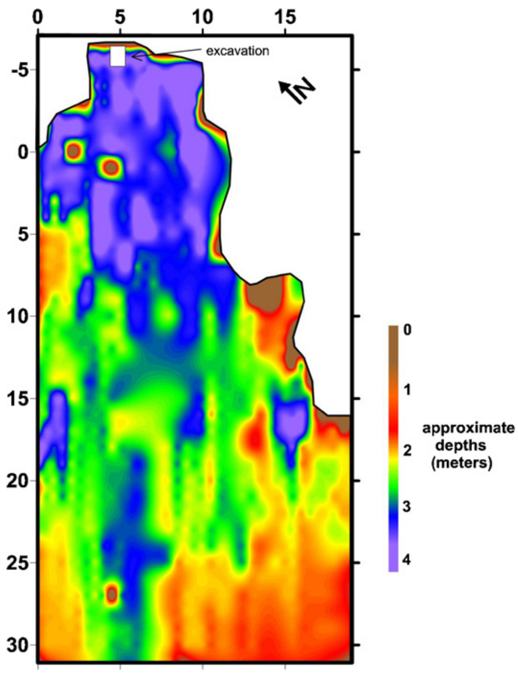

Figure 12. Depth to bedrock map at a rock shelter in Queensland, Australia, produced from interpreting individual reflection profiles in a large grid.

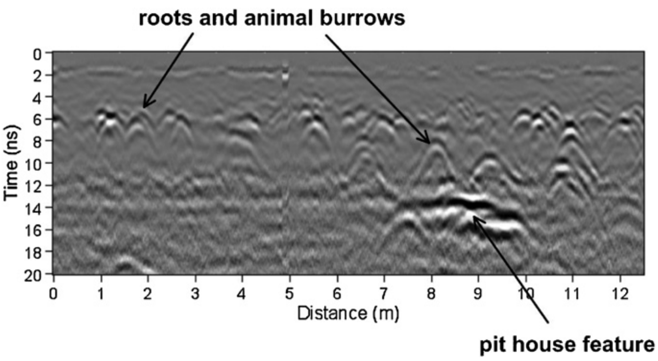

Figure 13. Reflection profile from the Oregon Coast, USA, showing hyperbolic reflections from roots and animal burrows, but also a high amplitude planar reflection from a pit house. Many profiles of this sort within a grid were used to create the isosurface image in figure 14.

protuberances and the edge of the basin, and small sub-basins that might contain sites of varying ages. In this case only a detailed analysis of each individual profile in the grid allowed for the production of this map of the small natural basin in front of the rock shelter.

When many closely spaced reflection profiles are collected in a grid the amount of information in every profile can be overwhelming in terms of mapping features in the ground in a timely fashion. When this is the case the amplitudes of reflected waves in all profiles in a grid can be visualized in an isosurface and certain amplitudes illustrated and shaded with artificial sunlight in order to produce images of buried features. Figure 13 shows reflection profiles collected using the 900 MHz antennas in transects spaced only 20 cm apart, each of which showed many reflections from roots and animal burrows. Within these complex reflections was a planar reflection that was produced from some features in a pit house. In any one profile this feature could be identified as cultural, but its actual shape in three dimensions was difficult to discern.

All reflection profiles within the grid were then sampled and only the high amplitude reflections were coloured and shaded to produce an isosurface image (figure 14). This image illustrates only the very high amplitudes and shows two edges of the pit feature that are composed of very different material from the matrix of the site. These appear to be ‘benches’ or work areas within the structure, which were not immediately visible in individual reflection profiles. The utility of producing these types of images from many profiles that record reflections in three-dimensional space is apparent.

There are times when the highest amplitude radar reflections are not the target of a GPR survey, but instead areas of no reflection are important. In southern Arizona the ancient Hohokam people, who inhabited the area from about AD 200 to 1400, constructed many buildings from compacted adobe. The mud used to construct the adobe walls was usually quarried very near where the buildings were constructed, and therefore there is often little if any chemical or physical difference between the architectural features and the surrounding ground. As a result, walls bounded by undisturbed sediments and soil have no lithological changes that would reflect radar waves. At best, walls are visible as areas of no reflection at all because the adobe mixture used to construct them were homogenized during their construction. In addition the adobe often contains a high amount of clay. When moist this material can attenuate radar energy that is transmitted through it, creating areas of no reflection when visible in GPR reflection profiles (figure 15).

As these adobe walls deteriorated and were eroded over time the mud tended to ‘melt’ adjacent to the walls during rainstorms. Between melting episodes wind-blown sand and silt were deposited, which produced interbedded layers of adobe melt and coarser sediment adjacent to the lower portion of the walls that remained standing. The melt-sediment layers produce sedimentary layers that are capable of reflecting high amplitude radar energy. These layers adjacent to the walls produced high amplitude sloping reflections, which are visible in profiles (figure 15). In this case areas of no reflection bounded by high amplitude reflections indicate the presence of adobe walls, with the areas of no reflection being the actual walls of interest.

When many GPR reflection profiles are sliced and viewed in horizontal slices the high and low amplitudes are visible and can be used to map the location of the walls (figure 16). In this case the areas of high amplitude contain the remains of walls that have eroded over time, and the areas of no reflection are the intact walls themselves.

GPR technology to test ideas about the human past

An important re-direction in the use of geophysics for archaeology is the GPR method’s ability to test cultural models

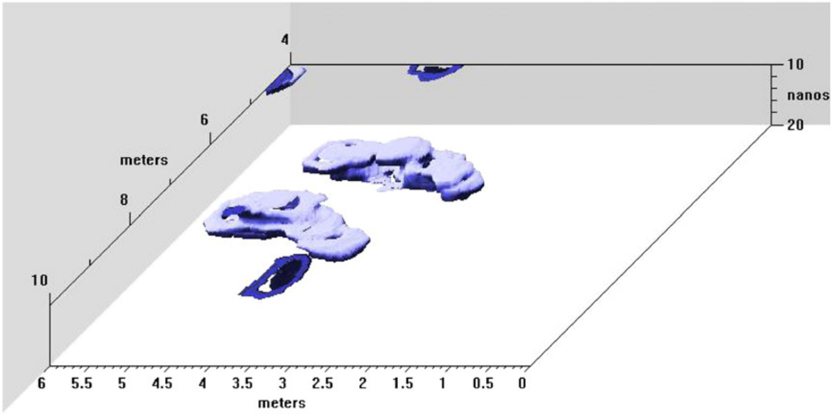

Figure 14. Isosurface image of benches or work areas within a pit house on the Oregon Coast, USA. In this image only the highest amplitudes of the reflections were used to create the image.

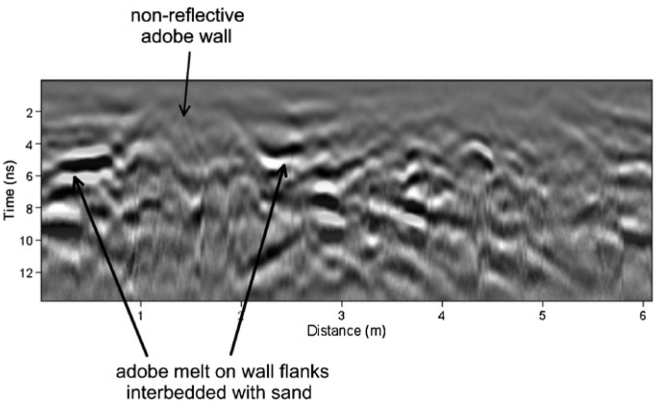

Figure 15. Reflection profile that crosses an adobe wall of compacted mud. The wall is non-reflective because it is composed of homogenized clay-rich material, which has no boundaries that would reflect radar energy. Its composition also attenuates energy, producing areas of no reflection.

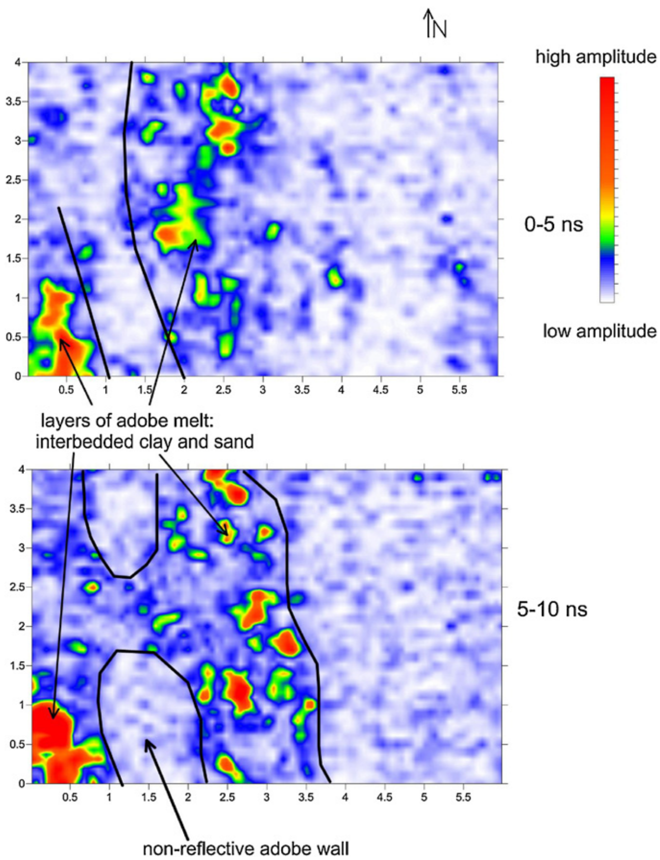

Figure 16. Amplitude slice map that shows adobe walls as areas of no reflection, bounded by layers of eroded adobe from the walls, interbedded by wind blown sand. The eroded areas are highly reflective as these interfaces produce a good deal of radar energy reflection.

about the human past. Most archaeological geophysics is still focused on its application of finding buried objects or features that can later be excavated using traditional archaeological methods. The GPR processing and image production methods illustrated here are becoming routine and most practitioners can now produce accurate three-dimensional images of the ground. If they are correctly interpreted, GPR images can now be used to test hypotheses about human activity such as social organization and 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 2010, Conyers and Osburn 2006). In this way 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 is often curtailed due to preservation issues.

Conclusions

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 for landscape analysis. Using high-definition two-dimensional reflection profiles, three-dimensional maps of amplitude changes can define physical and chemical changes in the ground that are related to the cultural materials of importance. When these data and maps are used to test ideas about human activities of all sorts, they offer a powerful and time-efficient way to study ancient human behaviour, social organization and other important archaeological concepts.

In the processing of GPR reflection data, maps and images must be generated and then integrated with information about sediments, soils and the geometry and composition of buried cultural features in order to make accurate interpretations about what is preserved in the ground. This can be done by placing these cultural data from excavations within horizontal amplitude maps that produce images of only certain amplitudes within a three-dimensional volume of radar reflections, which might be high amplitudes from important buried features, but also could be areas of no reflection at all. In some cases only a detailed analysis of reflection profiles can differentiate natural geological layers from cultural features, especially when the ground contains an abundance of reflections. In all cases, the results of GPR reflection images must be identified and mapped spatially in the ground. When multiple images that are both two and three dimensional in view are interpreted, they can provide a powerful tool for the integration of archaeological sites within what are often complex ground conditions.

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