## GROUND-PENETRATING RADAR

Lawrence B. Conyers
Department of Anthropology, University of Denver, Denver, CO, USA

### Synonyms

Georadar; Ground-probing radar

### Definitions

*Amplitude*: The intensity or strength of a recorded electromagnetic wave.

*Attenuation*: The dissipation of electromagnetic energy due to the spreading of energy in the ground and the conductivity of earth materials.

*Noise*: Any recorded energy from a source that is not the object of study.

*Point target*: A spatially restricted object in the ground that usually produces a hyperbolic-shaped reflection.

*Pulse*: A very short duration electrical charge placed on an antenna in order to produce an electromagnetic wave that propagates outward.

*Range-gain*: A data processing step that increases the amplitudes of waves recorded in the ground so that they are visible in two-dimensional reflection profiles.

*Reflection hyperbola*: The reflection produced by a buried point source.

*Stacking*: The averaging of recorded waves in sequential traces to produce one composite trace as a way to even out surface disturbances, ground clutter, or noise.

*Time window*: The two-way travel time within which radar waves are recorded, measured in nanoseconds (ns).

*Trace*: A series of waves recorded at one spot on the ground surface.

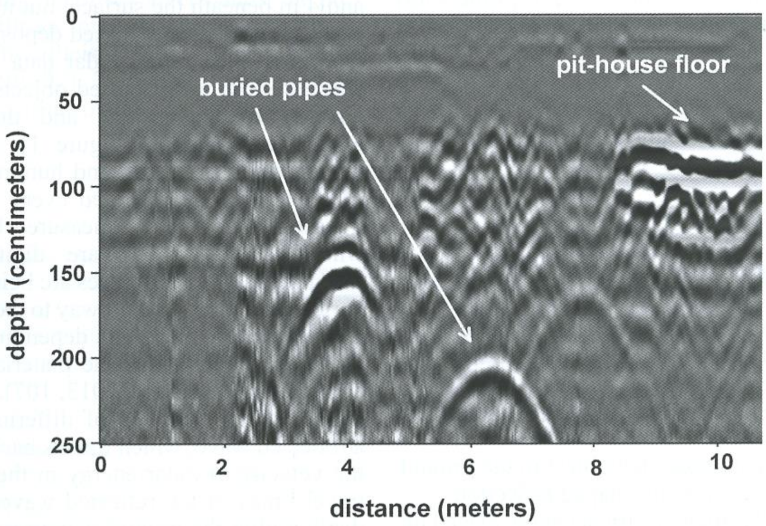
### Introduction

Ground-penetrating radar is a near-surface geophysical technique that is employed in order to discover and map buried archaeological features and associated geological units in ways not possible using traditional excavation field methods. It is the best near-surface geophysical method that characterizes the three-dimensional arrangement of subsurface geological units and associated archaeological features. The method consists of measuring the elapsed time between the emission of pulses of electromagnetic (radar) energy (generated at the ground surface by an antenna), transmitted to some depth as propagating waves, reflected off buried discontinuities, and then received back at the surface by a receiving antenna. The distribution and orientation of such subsurface reflections of geological or archaeological importance are then identified and mapped. When aspects of those radar reflections are related to buried features of archaeological sites – such as the presence of architecture, living surfaces, use areas, or other associated cultural features – high-definition three-dimensional maps and images of buried sites can be produced. Ground-penetrating radar is a geophysical technique that is most effective at buried sites where artifacts and features of interest are located between 20 cm and 4 m beneath the surface, but it has occasionally been used for more deeply buried deposits.

Ground-penetrating radar data are acquired by radar waves reflecting off buried objects, features, or bedding contacts in the ground and then detected back at a receiving antenna (Figure 1). Antennas are usually moved along transects, and hundreds or even thousands of reflections are recorded every meter. Distance along transects is commonly measured by an attached survey wheel, as reflections are digitized and saved on a computer. As radar pulses are being transmitted through various materials on their way to the buried target features, their velocity will change depending on the physical and chemical properties of the material through which they are traveling (Conyers, 2013, 107). Each distinct velocity change at an interface of differing materials generates a reflected wave, which travels back to the surface. When the velocity of radar energy in the ground is calculated, travel times of the reflected waves can be converted to depth within the ground (Conyers, 2013, 28), producing a three-dimensional dataset.

Most typically in archaeological GPR, surface radar antennas are moved along the ground in linear transects, and two-dimensional profiles of a large number of reflections at various depths are created, producing profiles of subsurface stratigraphy and buried archaeological features along parallel and sometimes perpendicular lines like long cross sections through the ground (Figure 2). However, depending on surface complexity and vegetation cover, reflection profiles can be oriented in any direction and length in order to answer a variety of geological and archaeological questions. When data are acquired in a closely spaced series of

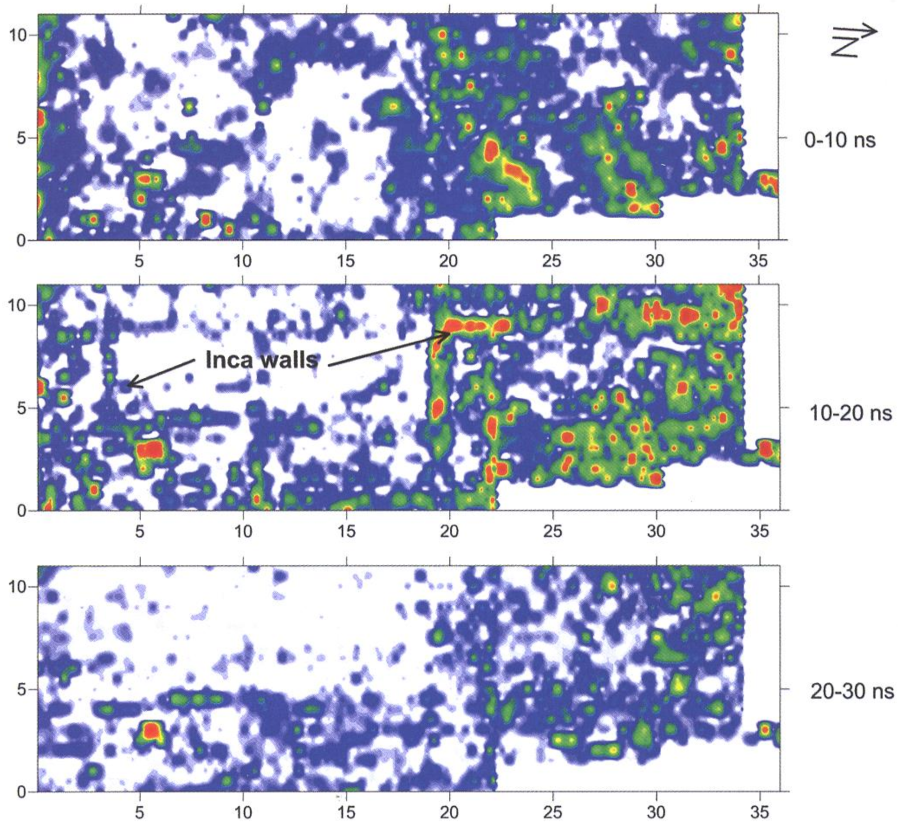
**Ground-Penetrating Radar, Figure 1** GPR equipment including 400 MHz transmission and reception antennas in the fiberglass box, attached survey wheel for distance measurement, and the radar control unit and computer attached to the operator's back. This is a Geophysical Survey Systems SIR-3000 system.




**Ground-Penetrating Radar, Figure 2** A reflection profile 11 m long displaying reflections to a depth of 250 cm. Two hyperbolic reflections from buried pipes are point source reflections, and a distinct planar reflection was produced from a buried house floor. This profile was collected in a water pipeline right-of-way near Alamogordo, New Mexico, USA.

transects within a grid, and reflections are correlated across transects and processed, three-dimensional maps and other images of buried features and associated stratigraphy can be constructed (Conyers, 2012, 25; Conyers, 2013, 69; see also Conyers, 2015). These images and maps are produced with the aid of computer software that can create maps using many thousands of reflection amplitudes from all profiles within a grid at various depths (Figure 3).

Ground-penetrating radar surveys allow for a relatively wide coverage of surface area in a short period of time, with grids of 50 × 50 m composed of as many as 100 profiles collected in a few hours. Often, the GPR method is used for detailed three-dimensional analysis of smaller grids within more extensively surveyed areas that are mapped using other geophysical methods, such as magnetometry and earth resistance that can be used later to produce scaled two-dimensional maps.




**Ground-Penetrating Radar, Figure 3** Amplitude slice-maps displayed in two-way radar travel time measured in nanoseconds (ns). Each 10 ns interval represents approximately 40 cm of depth. The horizontal slice representing 10–20 ns shows distinct high-amplitude walls, produced from buried Inca structures in highland Ecuador.

## Ground condition variables

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, 2013, 24). Radar wave penetration, and the ability to transmit energy through the ground and reflect energy back to the surface, is often enhanced in a dry environment, but dry ground is not necessarily a prerequisite. Some GPR surveys have been quite successful even in very wet environments as long as the medium through which the radar energy passes is not electrically conductive (Conyers, 2004). The mineralogy of materials in the ground is also important, especially clay type and content. Sediments that contain electrically resistive clay minerals such as kaolinite are excellent at allowing the transmission of radar waves, while bentonite, montmorillonite, and other electrically conductive clays are generally poor. Fresh water is an excellent medium for GPR, so radar energy transmission and energy can travel to great depths in lakes and through glacial ice. But when water comes in contact with electrically conductive minerals, an attenuating environment is created that destroys radar energy rapidly, conducting away the transmitted energy. Salty or brackish water will not allow radar energy transmission, and therefore, the method cannot be used in environments of this sort.

## Transmission, reflection, and recording of radar waves

The transmission of high frequency radar waves into the earth begins at the surface, with waves moving at the speed of light, then decreasing in velocity as they propagate into the ground. The elapsed time between transmission, reflection off buried discontinuities, and reception back at a surface radar antenna is then measured. Radar energy is generated at a transmitting antenna that is placed on, or near, the ground surface, and waves are generated which propagate downward into the ground where some of those waves are refracted at some interfaces and others reflected back to the surface. The discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, lithologic changes, differences in bulk density at stratigraphic interfaces, and, most importantly, water content variations, which are affected by all these variables (Conyers, 2012, 37; Conyers, 2013, 26). Any change in the velocity of propagating radar waves caused by changes in these ground conditions will generate a reflection. High-amplitude reflected waves are therefore often generated at the interfaces of archaeological features and the surrounding soil or sediment and at the contacts between geological units that vary in composition, density, and porosity, all of which affect the water saturation and therefore the velocity of transmitted radar energy. Void spaces, which may be encountered in burials, tombs, or tunnels, will also generate significant radar reflections due to a significant change in radar wave velocity, as propagating energy increases back to the speed of light in air.

The depth to which radar energy can penetrate and the amount of definition that can be expected from reflections generated at buried surfaces is partially controlled by the frequency of the radar energy transmitted. Radar energy frequency is dependent on the type of antenna used, as the antenna controls both the wavelength of the propagating wave and the amount of attenuation of the waves in the ground. Standard GPR antennas used in geoarchaeology propagate radar energy that varies in bandwidth between 10 and 1,200 megahertz (MHz). Antennas usually come in standard frequencies, with each antenna having one center frequency, but actually producing radar energy that ranges around that center by about one octave (one half and two times the center frequency). In general, low-frequency waves can propagate deeper into the ground, but they yield less subsurface resolution. For instance, 200 MHz antennas can potentially transmit energy to 4 or 5 m depth, but they are capable of resolving features or stratigraphy of only about a meter or so in dimension or thickness. In contrast, a 900 MHz antenna can resolve features as small as a few centimeters, but it is capable of energy transmission to only about a meter under most ground conditions. In electrically conductive ground, all radar energy is usually attenuated at very shallow depths, no matter what its frequency.

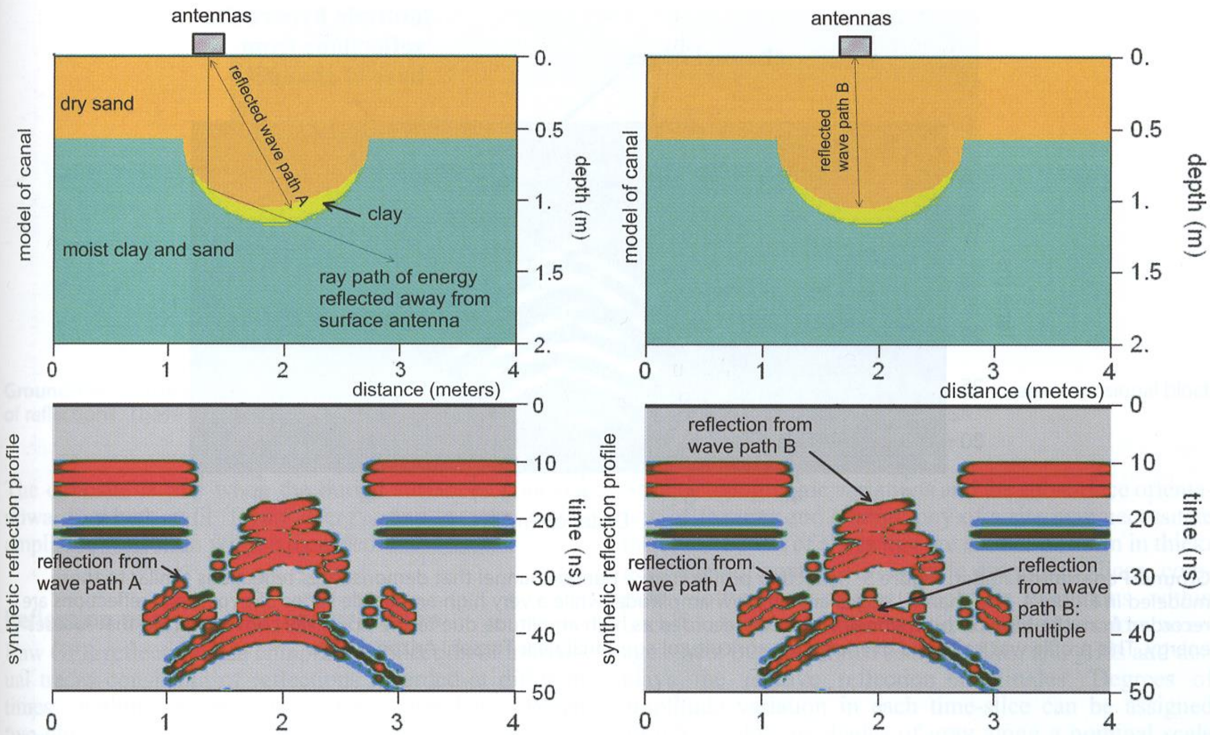
The two-way travel time, amplitude, and wavelength of the reflected radar waves produced by buried interfaces are recorded at the surface antennas, amplified, processed, and recorded for immediate viewing and later post-acquisition processing and display. Many reflections are recorded from various depths in the ground, with one series of waves at one location termed a reflection trace. Reflections are recorded within preset time windows, measured in nanoseconds of two-way travel time. During usual data acquisition procedures, two-dimensional profiles are created as the radar pulse transmission, reflection, and recording process is repeated many times a second and at programmed distances along transects as the antennas are pulled along the ground surface. Individual traces are then collected and placed in sequential order to produce profiles that represent vertical "slices" through the ground (Figure 2). Distance along each line is recorded for accurate placement of all reflection traces within a surveyed grid; this can be done using a survey wheel, GPS, or manual distance marks ticked off along tape measures.

Radar energy becomes both dispersed and attenuated as waves move into the ground after emerging from surface antennas. Energy that is reflected back toward the surface then will suffer additional attenuation by the material through which it passes, 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 but also must 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 signal becomes weaker as it spreads out over a greater volume of the subsurface and is absorbed by the ground, making less energy available for reflection. For every site, the maximum depth of penetration will vary with the geological conditions and the equipment being used. Post-acquisition data filtering and other data amplification techniques (termed range-gaining) can sometimes be applied to reflection data after acquisition that will enhance some very low-amplitude reflections in order to make them more visible.

## Other variables affecting GPR

Radar waves transmitted from standard commercial antennas radiate energy into the ground in an elliptical cone with the apex of the cone at the center of the transmitting antenna (Conyers, 2013, 67). This elliptical cone of transmission forms because the electrical field produced by the antenna is generated parallel to its long axis and therefore usually radiates into the ground perpendicular to the direction of antenna movement along the ground surface. The radiation pattern is generated from a horizontal electric dipole to which elements called shields are sometimes added that effectively reduce upward radiation. Some antennas, especially those in the low-frequency range from 10 to 200 MHz or so, are often not well shielded, or not shielded at all, and will therefore radiate radar energy in all directions. Lower frequency antennas also transmit energy that spreads out more as it leaves the antenna and moves into the ground. Unshielded antennas can generate reflections from a nearby person pulling the radar antenna, or from any other objects nearby, such as trees or buildings. Discrimination of individual buried features can then become more difficult, but anomalous reflections can sometimes be filtered out later during data processing.

Radar energy that is reflected off a buried subsurface interface that slopes away from a surface transmitting antenna will be reflected away from the receiving antenna and will not be recorded (Figure 4). A buried surface of this sort would be visible only if additional traverses were

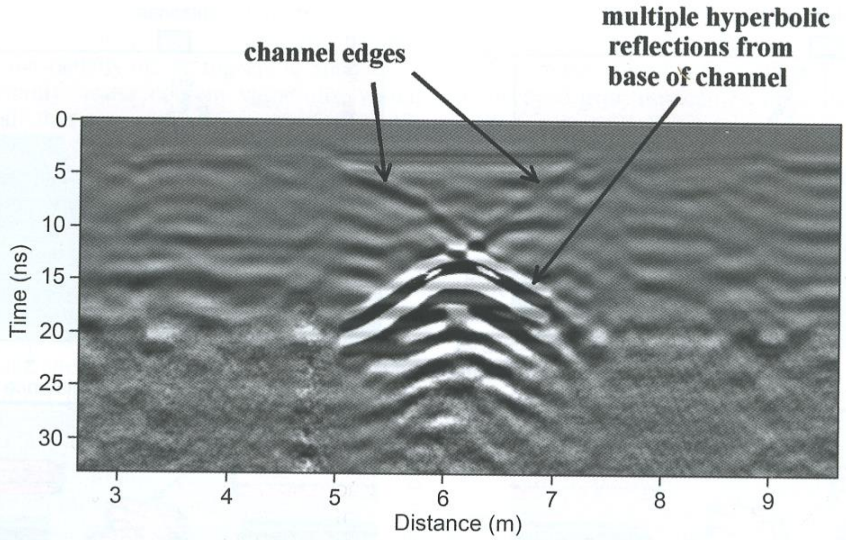



**Ground-Penetrating Radar, Figure 4** Computer-generated reflection model of a buried canal filled with a thin layer of clay illustrating how complex reflections can be recorded as energy is transmitted through the ground. On either side of the trench, the reflections are accurately recorded from the interface of the dry sand and the underlying moist clay and sand layer. However, when the antennas are over the trench but not over its center (*left side*), radar waves transmitted directly down intersect the clay layer and reflect away from the surface antenna, so their direct return is not recorded. Energy also is transmitted in front (and behind) the antennas, and thus, the waves that emerge from the antenna and move along path A are recorded as if they were reflected below the canal due to their longer travel times. As the antennas are moved forward and into the center of the canal, the actual location of the bottom of the canal reflection is recorded correctly from energy moving along path B. The same cycle and recording are repeated many thousands of times, creating this complex series of reflections in the synthetic reflection profile. Only the channel's base is recorded correctly in space with the other interface indications created by reflections that travel along other, longer wave paths.

collected at an orientation that would allow reflected energy to travel back to the surface recording antenna. For this reason, it is always important to acquire lines of reflection data within a closely spaced surface grid and sometimes in transects perpendicular to each other.

Small buried objects that reflect radar energy are termed point targets (Figure 2), while broader more extensive units such as stratigraphic and soil horizons or large, flat archaeological features such as floors are termed planar targets. Point targets can be walls, tunnels, voids, artifacts, or other nonplanar objects that often possess little of their own surface area with which to reflect radar energy. If they are too small, they will be totally invisible if lower frequency energy is transmitted into the ground. However, if high frequency energy is transmitted, many reflections will be generated from many small point targets, and this potentially crowded return of reflections can be described as clutter, if they are not the targets of the survey. In all cases, buried features need to be larger than the clutter to be visible, and they are generally not visible unless they are larger than about 40 % of the wavelength of the propagating energy (Conyers, 2013, 72).

Point source reflections often occur in the shape of hyperbolas (Figures 2 and 5). This reflection shape is produced because, as described above, most GPR antennas produce a transmitted radar beam that propagates downward from the surface in a conical pattern, radiating outward as energy travels to depth. Radar waves will therefore be reflected from buried point sources that are not located directly below the transmitting antenna but are still within the "beam" of propagating waves. The travel paths of oblique radar waves to and from the ground surface to point sources in front and back of the antenna are longer (as measured in radar travel time), but the reflections generated are recorded as if they were directly below but just deeper in the ground. As the surface




**Ground-Penetrating Radar, Figure 5** Reflection profile from a buried channel that demonstrates reflections similar to those modeled in Figure 4. The channel edges are very low amplitude, while a very high-amplitude series of hyperbolic reflections are recorded from the base of the channel, which are recorded as high amplitude due to the upwardly convex surface that focuses energy. This profile was collected over an early agricultural age canal near Tucson, Arizona, USA.

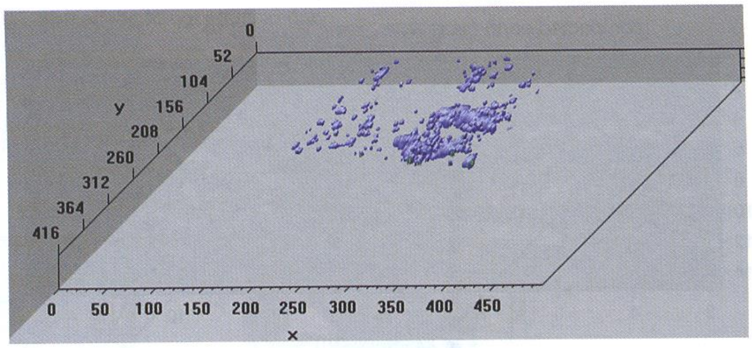
antenna moves closer to a buried point source, the receiving antenna will continue to record reflections from the buried point source prior to arriving directly on top of it and continue to record reflections from it moving away. A reflection hyperbola is then generated with only the apex of the reflection denoting the actual location of the object in the ground, with the arms of the hyperbola creating a record of reflections that traveled the increasingly oblique wave paths. In some cases, only half of a hyperbola may be recorded, if just the corner or edge of a planar feature is causing a discrete reflection, such as the edge of a buried house floor or platform. The shape of such hyperbolas can also be used to calculate radar travel velocity in the ground since their shape is a function of the velocity of radar energy as it moves in the ground (Conyers, 2013, 113). Hyperbola analysis to obtain velocities is therefore an extremely efficient and accurate way to convert radar travel times to depth in the ground.

Radar waves travel through the ground in complex ways, spreading out with depth, refracting, reflecting, and attenuating, as energy encounters differing materials in various orientations. This can sometimes lead to the recording of reflections that have not always traveled directly from the surface antenna to some buried reflection surface and back to the antenna. Radar energy can often reflect multiple times from various layers or even from the ground surface or the antenna itself, leading to reflections that are not indicative of the buried features of interest. To minimize the amount of reflection data that are recorded from the sides of a two-dimensional transect, the long axes of the transmitting antennas are usually aligned perpendicular to the profile direction. However, if there are buried elongated features parallel to the direction of antenna travel (and therefore parallel to the electromagnetic field generated by the antenna), only a small portion of the radar energy will be reflected back to the surface, so these features are likely to remain invisible.

Most GPR antennas produce radar energy in frequencies lying within the same frequency spectrum as those used in television, FM radio, and portable communication devices, and therefore, background noise will also be recorded along with reflections that come from within the ground. This noise can sometimes be removed during data collection or during post-acquisition processing where some frequencies can be enhanced and others filtered out.

When antennas move over uneven ground and clumps of vegetation, transmitted radar energy couples with the ground in various ways and can move into the ground in various orientations, producing anomalous recorded amplitude reflections. For this reason, it is preferable to move antennas in transects lying as flat as possible and at the same distance from the ground, in order to reduce coupling change anomalies.

Reflection from a buried interface that contains ridges or troughs, or any other irregular features, can focus or scatter radar energy, depending on the surface's orientation and the location of the antennas on the ground surface. If a reflective surface is convex upward, energy will tend to be reflected away from the receiving antenna, and only a low-amplitude reflection will be recorded.




**Ground-Penetrating Radar, Figure 6** Isosurface image of a buried pit house floor and associated rocks in a three-dimensional block of reflections. These reflections are from a pit house buried in sand dunes near Port Orford, Oregon, USA.

The opposite is true when the buried surface is concave upward, which will focus energy, and a very high-amplitude reflection will be recorded.

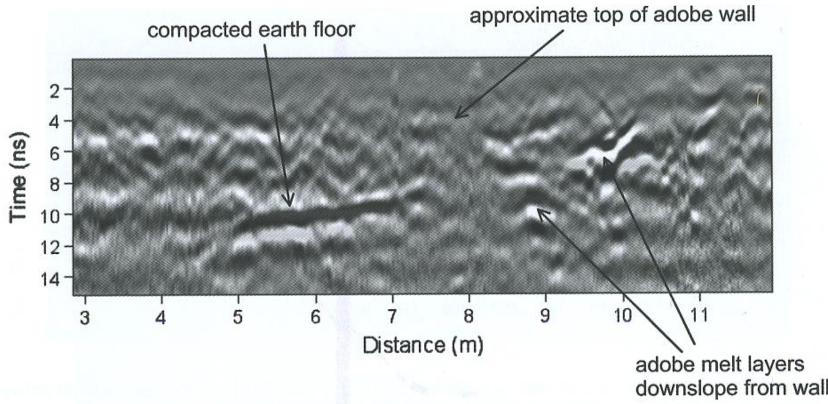
## Reflection analysis and interpretation

Raw GPR reflection data comprise a collection of individual traces consisting of reflections recorded at different times within a recording time window. When two-dimensional profiles are collected, these traces are spaced at various distances along transects, which can be displayed as profiles. New systems are being developed that can send and receive multiple radar pulses within complex three-dimensional grids that can potentially produce very precise three-dimensional images, but these systems have not yet been perfected (Conyers and Leckebusch, 2010). Each reflection trace contains a series of waves that vary in amplitude depending on the amount and intensity of energy reflection that occurs at buried interfaces. When these traces are plotted sequentially in standard two-dimensional profiles, amplitudes created from buried interfaces often denote layers of importance, with the strength of the reflections indicating the differences in composition between buried materials.

Each profile can be interpreted individually, after which buried features of interest are often immediately visible. When many tens or hundreds of profiles are collected forming a grid, this method of interpretation can often be laborious, so it is efficient to use computer software to produce maps and other images of the relative amplitudes of reflections in slice-maps (Figure 2) or to produce three-dimensional isosurfaces (Figure 6). In these images, areas of low-amplitude reflected waves indicate little or no reflection and therefore uniform materials, while high-amplitude reflections denote buried interfaces between highly contrasting materials, which could be stratigraphic interfaces or buried archaeological features. Amplitude slices need not be constructed horizontally or even in equal time intervals. They can also vary in thickness and orientation, depending on the questions asked. Surface topographic variations and the subsurface orientation of features and stratigraphy of a site may necessitate the construction of slices that are neither uniform in thickness nor horizontal. To compute amplitude slices, computer software compares amplitude variations within traces that were recorded within a defined window, averages them over a defined search radius, and grids and displays the relative reflection amplitudes. Degrees of amplitude variation in each time-slice can be assigned arbitrary colors or shades of gray along a nominal scale in map view or placed in a three-dimensional block and assigned colors or patterns so that reflections are visible (Conyers et al., 2002; Leckebusch, 2003; Goodman et al., 2004; Conyers, 2013, 187). In isosurface images, computer-generated light sources that 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 image is produced.

Both high and low amplitudes can denote buried features of interest, and only an understanding of the nature of the geological or archaeological features in the test area will allow for accurate interpretations. Compacted floors will often retain moisture and produce distinct planar high-amplitude reflections (Figure 7), while adjacent earthen walls of homogeneous material will remain invisible because there are no buried surfaces to reflect energy. The vertical contact between the wall and the adjacent material will also not reflect waves because transmitted radar energy passes by that interface at too low an angle without producing any reflections. Other stratigraphic features adjacent to the otherwise invisible walls might be visible, but they could be difficult to interpret without knowing something of the buried architectural context or understanding the types and composition of archaeological or geological features common in the area.

Amplitude slice-maps in areas of earthen architecture must be evaluated by locating areas showing no reflections, which denote the location of important features (Figure 8). This demonstrates how important it is to define whether the features of interest are highly reflective or




**Ground-Penetrating Radar, Figure 7** Reflection profile shows a distinct high-amplitude reflection from a compacted earth floor, with an associated vertical adobe wall which does not reflect radar energy. The wall is effectively invisible because it is composed of homogenous clay and sand, which contains no stratigraphic interfaces to reflect energy. The wall edges also do not reflect energy, as they are vertical and do not provide an interface that can reflect waves transmitted from the surface antenna. This profile was collected over Hohokam architecture in Tucson, Arizona, USA.

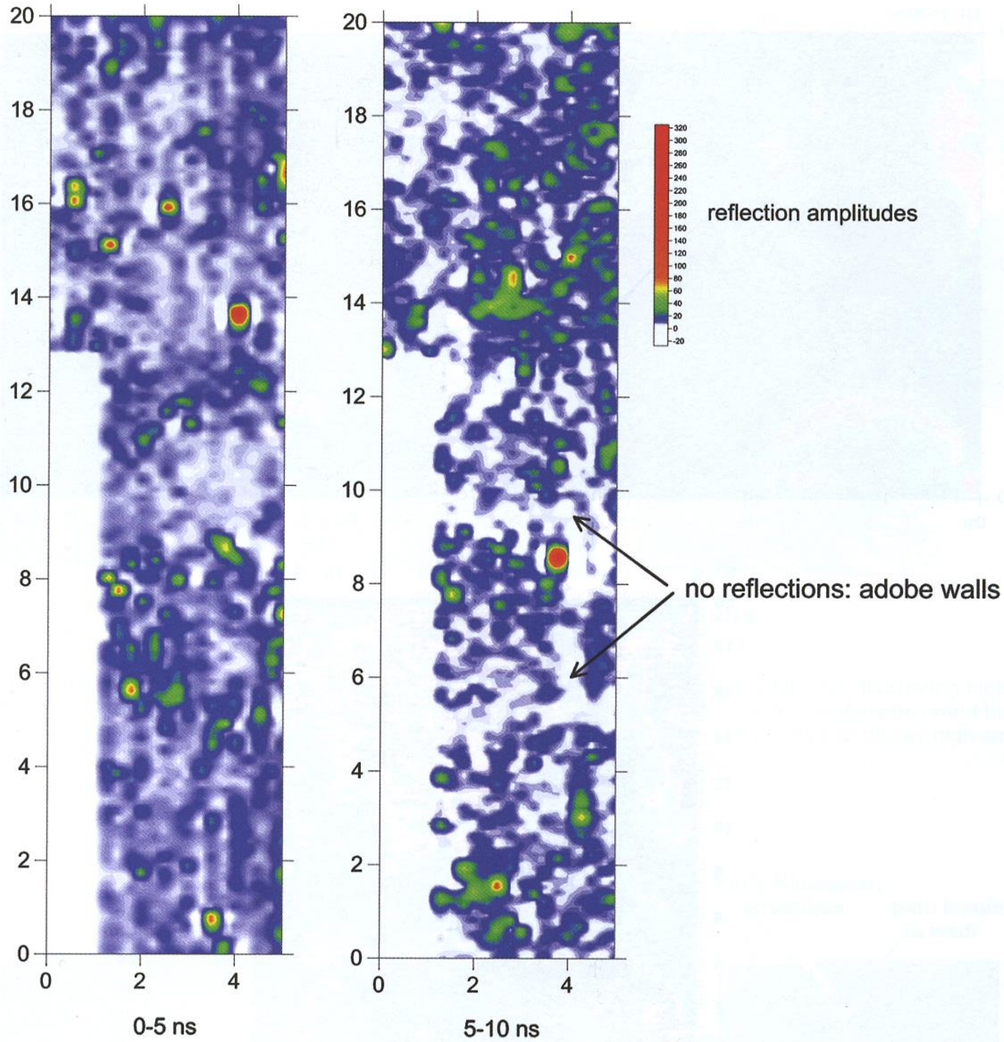
perhaps not reflective at all. There has always been a bias in GPR toward analyzing and mapping only the strongest reflections recorded; however, low- or no-amplitude areas may also be important, depending on the type of materials buried in the ground.

Various computer programs are available that use different algorithms for producing amplitude maps, all of which can be modified by the user depending on the types of questions being asked. Some programs tend to average reflections, producing more general maps, while others produce images of almost every reflection in the ground, which tend to be more exact but also highly complex. Other programs were developed for certain commercial applications, such as pipe location or other geotechnical uses, and are less useful for archaeological feature mapping and identification (Figure 9).

## Using GPR for archaeological interpretation

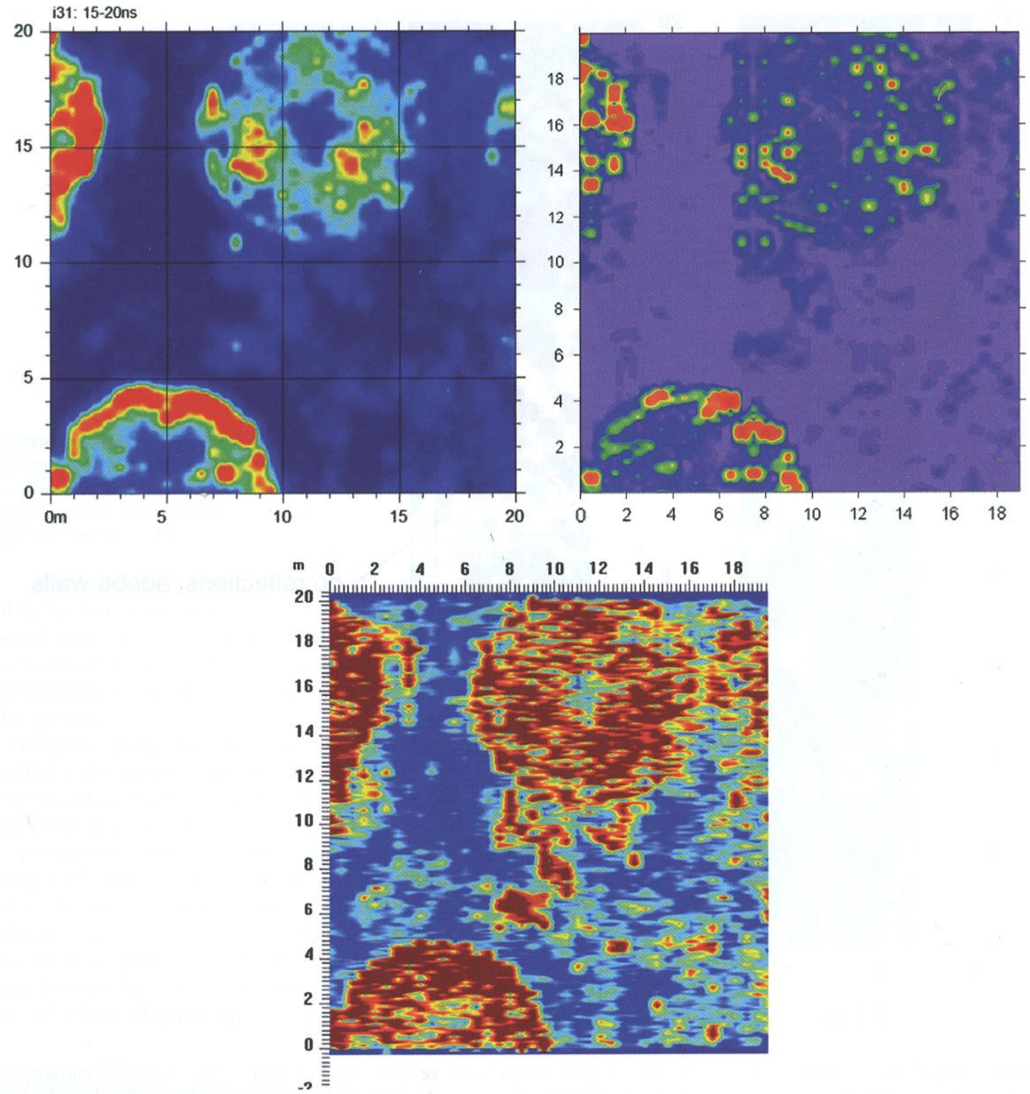
Archaeological geophysics has historically been used as a method for discovering buried archaeological remains and less often as a dataset for interpreting aspects of human history and testing anthropological hypotheses relating to culture. However, GPR, with its three-dimensional mapping ability, can, and should, be used to test ideas about humans in ways that are similar to standard archaeological methods (Conyers, 2010; Conyers and Leckebusch, 2010). If architecture, site organization, or any other aspects of human construction or modification of the buried landscape can be indicative of behavior, then GPR mapping can be of great benefit (Conyers, 2009). The GPR method can be an especially powerful tool when combined with standard archaeological excavations, especially when the geophysical images are used as a guide to the placement of subsurface tests. In this way, limited excavation and the exposure and study of important archaeological features and associated geological layers can be made, and information about those buried features can be projected in three-dimensions over a wide area.

An example of this type of GPR analysis is the testing of extensive surface features in southeastern Utah, USA, where a number of circular depressions were visible on the surface associated with scattered pottery that suggested there might be great kivas below. During the interval when the pottery recovered at the surface was made (about AD 900–1150), this general area in the southwestern USA was dominated by one political and economic entity centered about 200 km away at Chaco Canyon, New Mexico (Conyers and Osburn, 2006; Conyers, 2010; Conyers, 2012, 183). At Chaco Canyon and elsewhere in the American Southwest, great kivas of this age were architectural structures used to indicate strong political and economic ties to Chaco. In order to test the hypothesis that the area of presumed great kivas in Utah was connected in some way with Chaco Canyon, GPR data were collected on five of the large surface depressions. GPR maps at sites 1 through 3 (Figure 10) showed that there were kivas buried below the surface; they were not "great" kivas, however, but instead small, circular kiva structures consistent with a low population density farming community that was perhaps aware of Chaco Canyon, but not connected in the ways that had been hypothesized. Two of the sites tested with GPR contained no architecture whatever and are likely remnants of modern water reservoirs. In this case, GPR was the only method, barring extensive excavations, that could have discovered and mapped the presence and function of these buried architectural remains.



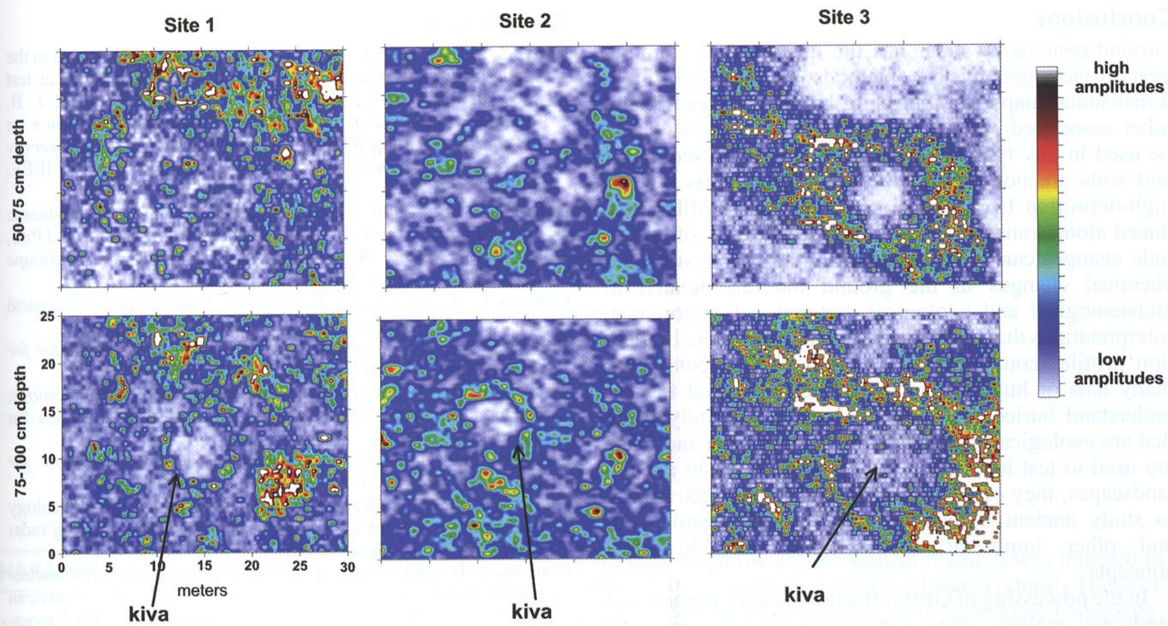

**Ground-Penetrating Radar, Figure 8** Amplitude slice-map of the adobe walls shown in Figure 7. The walls are shown in white as areas of no reflection, while random stones or layers of adobe melt adjacent to the walls produce high-amplitude reflections. These are Hohokam walls in Tucson, Arizona, USA.

In the Middle East, much is known about the late Nabataeans, desert traders who constructed monumental architecture in the vicinity of Petra, Jordan, and other areas along trade routes between Arabia and the Mediterranean coast (Conyers, 2010; Conyers, 2012, 187). In an attempt to understand the habitation of the Petra area prior to the construction of monumental architecture beginning in the first few centuries BC, GPR data were collected in an area called the Lower Market (Conyers et al., 2002). While the near-surface remains were easily mapped with GPR (Figure 11a), the deeper reflections were more complex and necessitated buried topographic adjustment to sloping stratigraphy. It was apparent by studying the reflection profiles that this area had been at one time on the edge of a wadi (small valley), which had been artificially filled and leveled prior to construction of temples and other structures in late Nabataean time. All GPR profiles were then interpreted to find the reflection corresponding to the buried living surface prior to filling, and amplitudes were mapped on that surface alone (Figure 11b, c). Those mapped reflection features showed that simple structures had been built bounding pathways leading to the valley bottom along with remains of other buildings along the upper edge of the valley; these

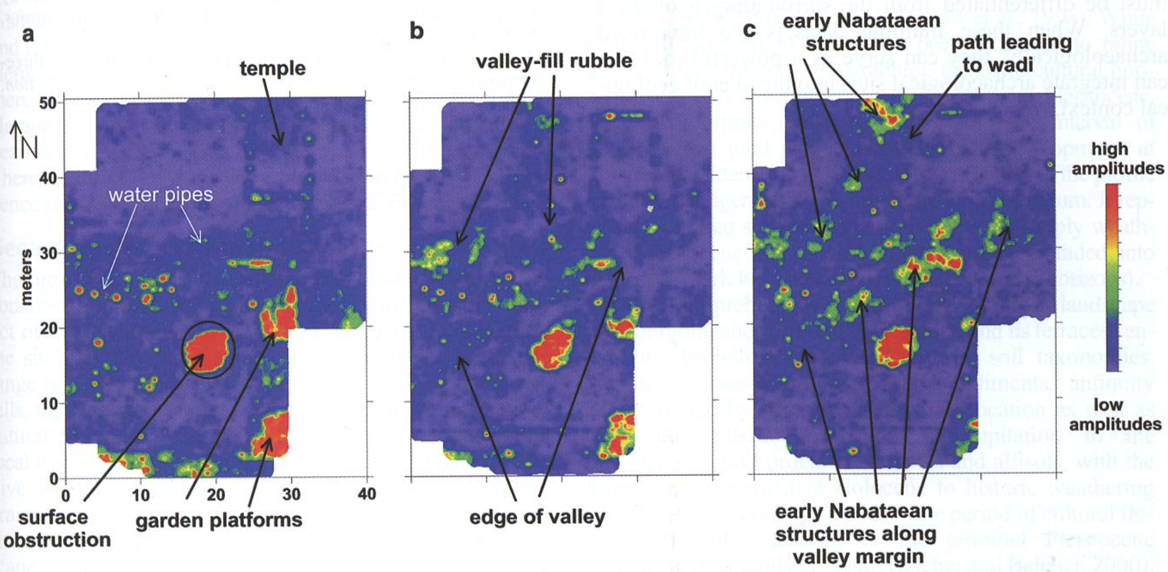



**Ground-Penetrating Radar, Figure 9** Amplitude slice-maps of one layer from 15 to 20 ns constructed using three different software programs. Each uses different resampling and gridding algorithms, which create very different images of the same features. At this site, in Ohio, USA, there are three buried kiln floors. On the left is an averaged horizontal slice showing the general features, in the middle a very exact slice showing every reflection, and on the right a slice produced by a program used to map mostly buried pipes and other linear features.

structures were then covered during the filling and leveling process. Excavations along the north edge of the GPR grid confirmed that those structures were of early Nabataean age, a time when the valley was in the early stages of habitation by people who would later become the famous builders and wealthy traders of Petra. The GPR mapping showed that the ancestors of the Nabataeans of Petra lived in simple structures aligned with the natural topographic features of the valley and that these structures were later abandoned as the wealth from control of trade with Arabia increased and the site became commercially connected to the complex cultures of the Mediterranean (Conyers, 2010). Only the three-dimensional mapping capabilities of GPR that produced accurate images of this stratigraphically complex site could have yielded this interpretation of the early history of Petra without laborious and expensive excavation.




**Ground-Penetrating Radar, Figure 10** Amplitude slice-maps of three sites in southeastern Utah, USA, illustrating high-amplitude circular kiva walls and other associated features. The interiors of these structures are filled with homogeneous wind-blown sand, which is non-reflective. At site 3, the kiva was constructed into bedrock, and therefore, both slices also display high-amplitude reflections from bedrock features.




**Ground-Penetrating Radar, Figure 11** Amplitude slice-maps need not be horizontal but can be constructed to follow stratigraphic horizons which are not level with the ground surface. Map (**a**) shows architectural features in a horizontal slice between 50 and 100 cm of the surface. Maps (**b**) and (**c**) are subhorizontal slices and display features built on an ancient living surface, which slopes to the north. These are early Nabataean in age, from Petra, Jordan.

## Conclusions

Ground-penetrating radar has the unique ability among near-surface geophysical methods to produce three-dimensional maps and images of buried architecture and other associated cultural and geological features. It can be used in any type of ground as long as the sediments and soils are not highly electrically conductive. Using high-definition two-dimensional reflection profiles produced along transects, three-dimensional maps of amplitude changes can be assembled that define physical and chemical changes in the ground that are related to archaeological and geological materials of importance. Interpretations that use individual two-dimensional reflection profiles combined into images of grids containing many tens or hundreds of profiles can be used to help understand buried archaeological sites, especially those that are geologically complex. When these data and maps are used to test ideas about human adaptation to ancient landscapes, they offer a powerful and time-effective way to study ancient human behavior, social organization, and other important archaeological and historical concepts.

In the processing of GPR reflection data for purposes of landscape analysis, maps and images must be generated and integrated with information obtained from other archaeological and geological data in order to provide age and context for the mapped sites. This can be done by inserting cultural data derived from excavations within amplitude maps that use only certain amplitudes within a three-dimensional volume of radar reflections. In all cases, the results of these amplitude images must be differentiated from the surrounding geological layers. When these multiple datasets are interpreted archaeologically, they can serve as a powerful tool that can integrate archaeological sites into the overall geological context.

## Bibliography


Conyers, L. B., 2004. Moisture and soil differences as related to the spatial accuracy of amplitude maps at two archaeological test sites. In Slob, E. C., Yarovoy, A. G., and Rhebergen, J. B. (eds.), *Proceedings of the Tenth International Conference on Ground Penetrating Radar, June 21–24, 2004, Delft University of Technology, Delft, The Netherlands*. Piscataway: IEEE, pp. 435–438.

Conyers, L. B., 2009. Ground-penetrating radar for landscape archaeology: method and applications. In Campana, S., and Piro, S. (eds.), *Seeing the Unseen: Geophysics and Landscape Archaeology*. Leiden: CRC Press/Balkema, pp. 245–255.

Conyers, L. B., 2010. Ground-penetrating radar for anthropological research. *Antiquity*, **84**(323), 175–184.

Conyers, L. B., 2012. *Interpreting Ground-Penetrating Radar for Archaeology*. Walnut Creek: Left Coast Press.

Conyers, L. B., 2013. *Ground-Penetrating Radar for Archaeology*, 3rd edn. Lanham: Altamira Press. Geophysical Methods for Archaeology, Vol. 4.

Conyers, L. B., 2015. *Ground-Penetrating Radar for Geoarchaeology*. Oxford: Wiley.

Conyers, L. B., and Leckebusch, J., 2010. Geophysical archaeology research agendas for the future: some ground-penetrating radar examples. *Archaeological Prospection*, **17**(2), 117–123.

Conyers, L. B., and Osburn, T., 2006. GPR mapping to test anthropological hypotheses: a study from Comb Wash, Utah, American Southwest. In Daniel, J. J. (ed.), *Proceedings of the 11th International Conference on Ground-Penetrating Radar, June 19–22, 2006, Ohio State University, Columbus, Ohio*. Piscataway: IEEE, pp. 1–8.

Conyers, L. B., Ernenwein, E. G., and Bedal, L.-A., 2002. Ground-penetrating radar discovery at Petra, Jordan. *Antiquity*, **76**(292), 339–340.

Goodman, D., Piro, S., Nishimura, Y., Patterson, H., and Gaffney, V., 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.

Leckebusch, J., 2003. Ground-penetrating radar: a modern three-dimensional prospection method. *Archaeological Prospection*, **10**(4), 213–240.