# Ground-Penetrating Radar

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## 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 to discover and map buried archaeological features and associated geological units in ways not possible using traditional excavation field methods. It is the most precise 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 transmission of pulses of electromagnetic (radar) energy (generated at the ground surface by an antenna) that are transmitted into the ground as propagating waves and reflected off buried discontinuities. They travel back to the surface and are detected at a receiving antenna, digitized, and saved as a string of data. The distribution and orientation of subsurface waves produced by this reflection process are recorded in elapsed time of travel, amplitude, and frequency of the waves. When many hundreds or thousands of these reflections are viewed in two dimensional profiles, geological or archaeological units of importance can be identified and mapped. Besides the reflections from geological units (Conyers 2016), the reflections of cultural significance might be architectural components, living surfaces, use areas, and a variety of other associated cultural features. Two and three-dimensional maps and profiles of buried sites can then 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.

**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.

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 to answer a variety of geological and archaeological questions. When data are acquired in a closely spaced series of 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 *2016~~5~~*). 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).

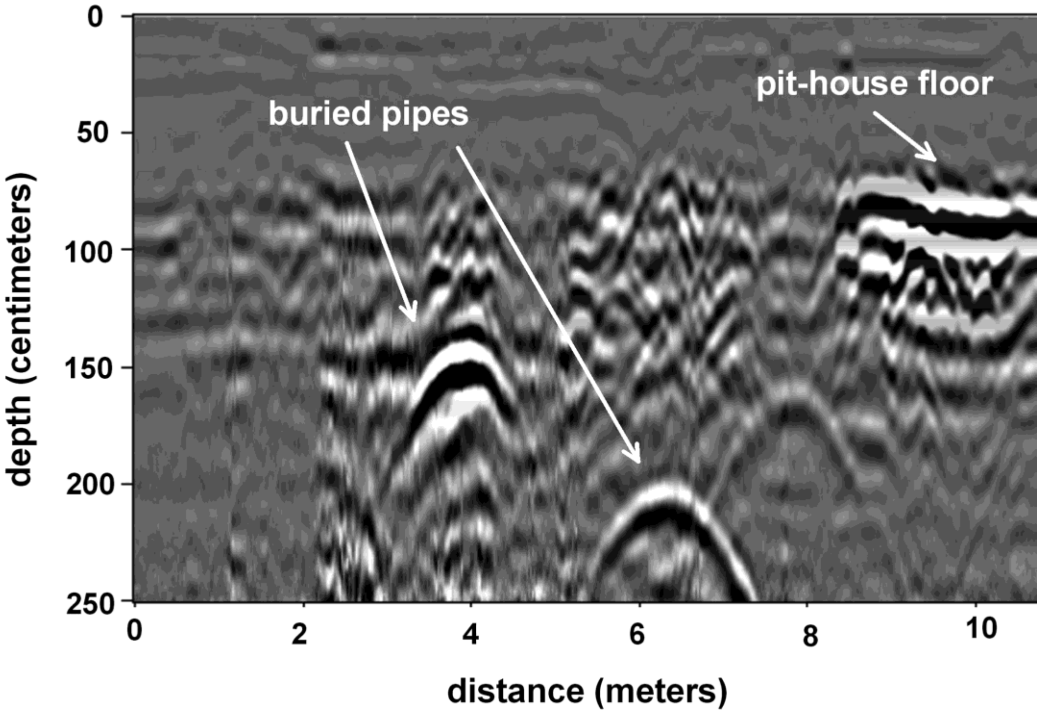


**Figure 2.** A reflection profile 11 m long displaying reflections to a depth of 250 cm. Two hyperbolic reflections from buried pipes are point source reflections, and a distinct planar reflection was produced from a buried house floor. This profile was collected in a water pipeline right-of-way near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

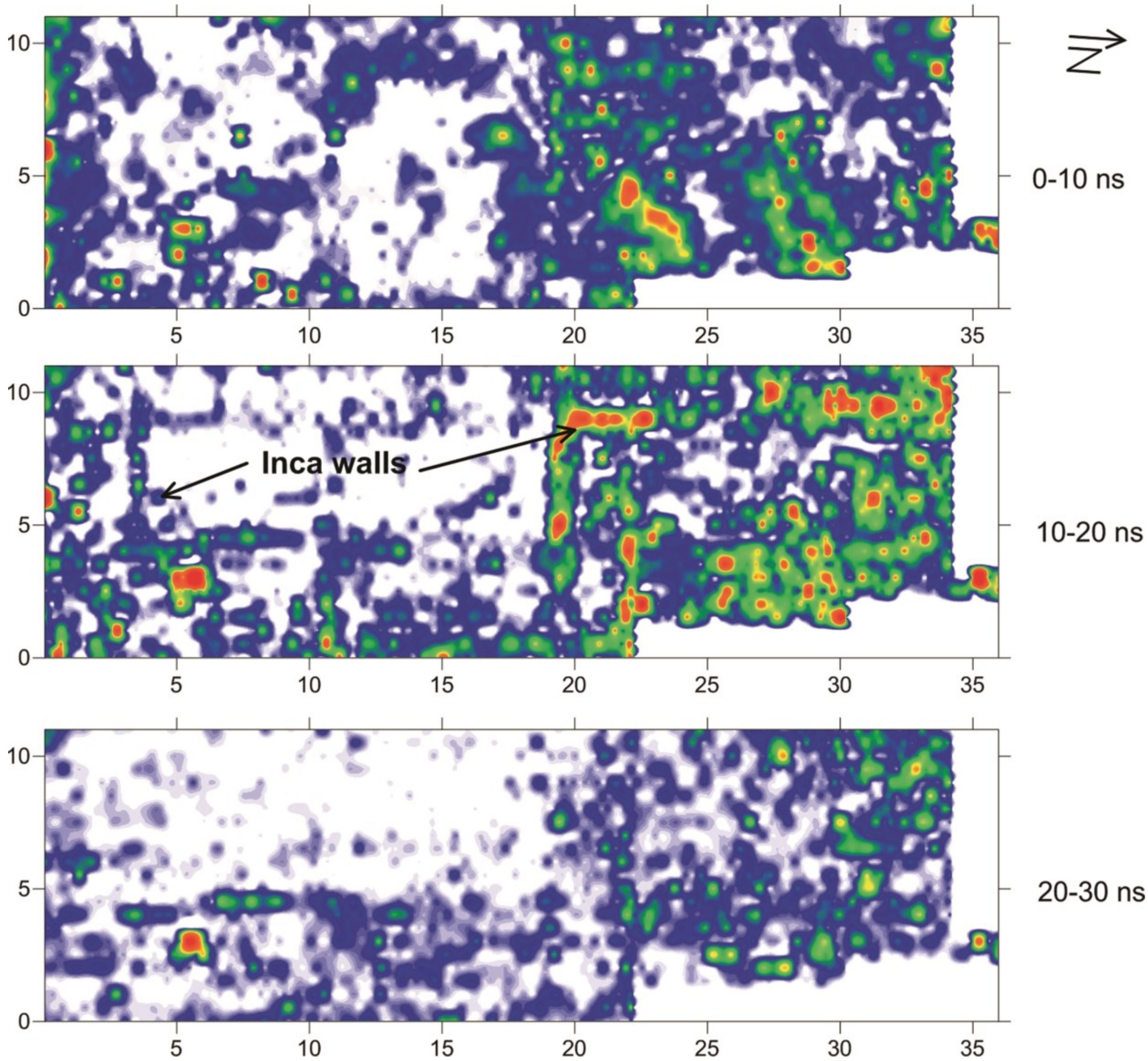


**Figure 3.** Amplitude slice-maps displayed in two-way radar travel time measured in nanoseconds (ns). Each 10 ns interval represents approximately 40 cm of depth. The horizontal slice representing 10–20 ns shows distinct high-amplitude walls, produced from buried Inca structures in highland Ecuador.

Ground-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 condition variables

The success of GPR surveys is 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 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 can resolve 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 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 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.

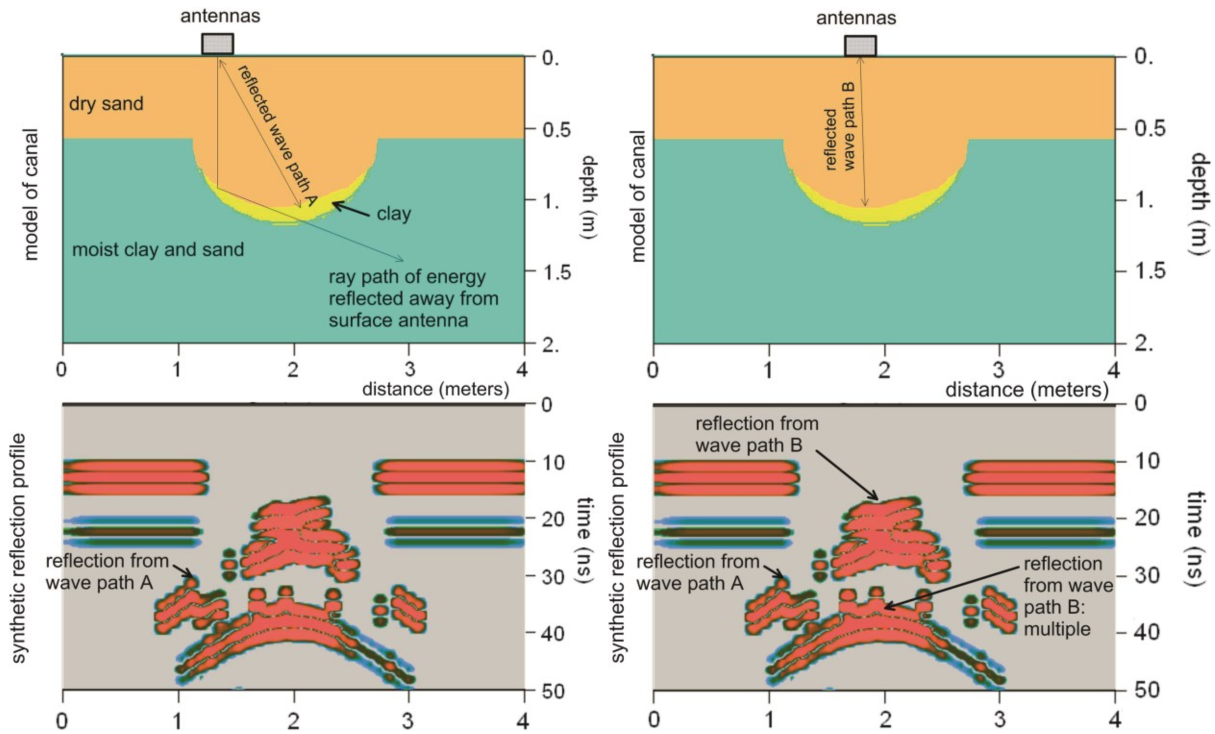


**Figure 4.** Computer-generated reflection model of a buried canal filled with a thin layer of clay illustrating how complex reflections can be recorded as energy is transmitted through the ground. On either side of the trench, the reflections are accurately recorded from the interface of the dry sand 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.

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 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.

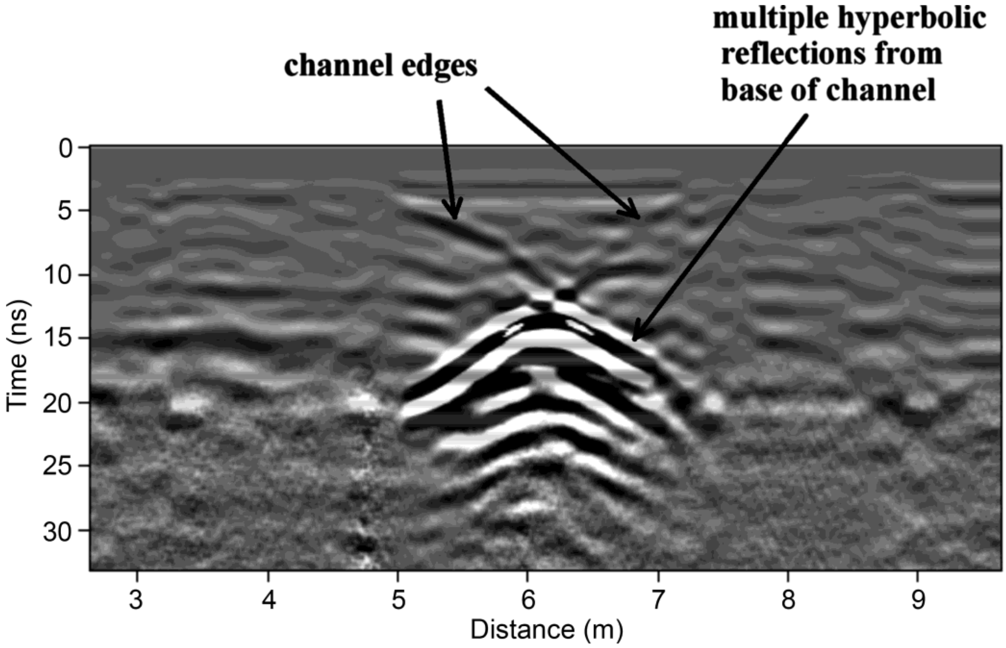


**Figure 5.** Reflection profile from a buried channel that demonstrates reflections similar to those modeled in Figure 4. The channel edges are very low amplitude, while a very high-amplitude series of hyperbolic reflections are recorded from the base of the channel, which are recorded as high amplitude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

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 is 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, 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. 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 often over large areas (Conyers and Leckebusch *2010*; Trinks et al. *2018*). 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 *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 to enhance them, and the features can be rotated and shaded until a desired image is produced.

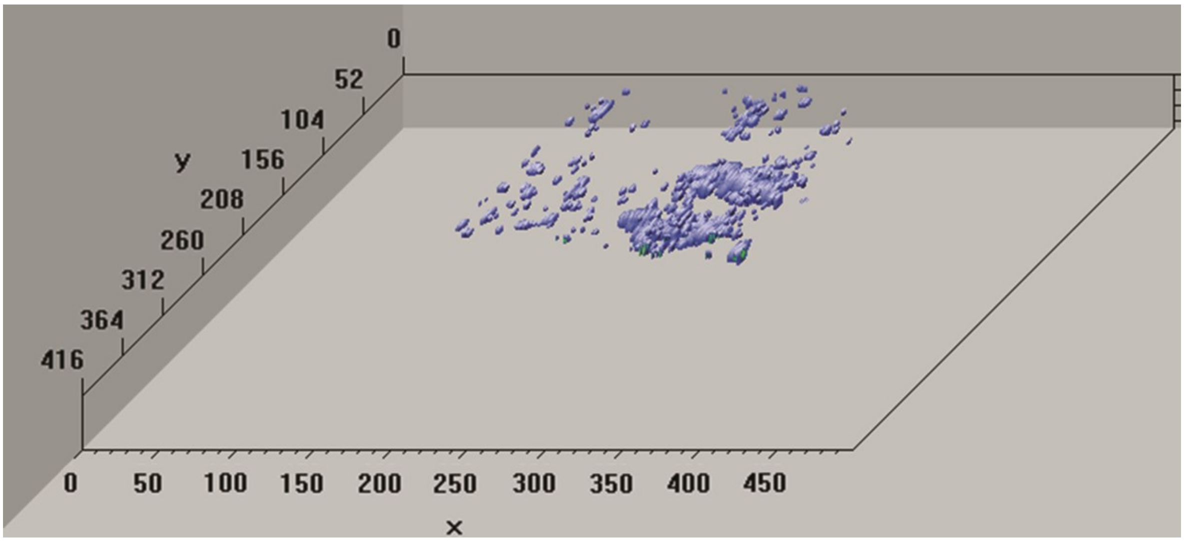


**Figure 6.** Isosurface image of a buried pit house floor and associated rocks in a three-dimensional block of reflections. These reflections are from a pit house buried in sand dunes near Port Orford, Oregon, USA.

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 to produce 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.

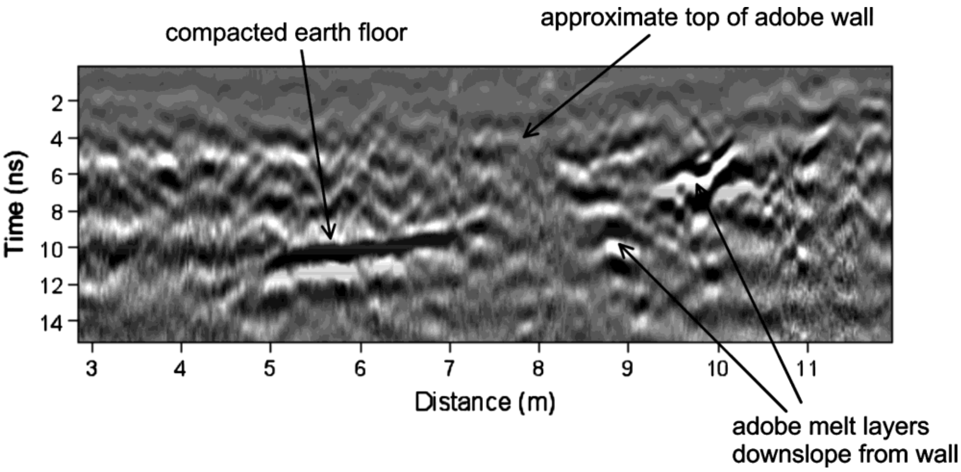


**Figure 7.** Reflection profile shows a distinct high-amplitude reflection from a compacted earth floor, with an associated vertical adobe wall which does not reflect radar energy. The wall is effectively invisible because it is composed of homogenous clay and sand, which contains no stratigraphic interfaces 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.

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 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.

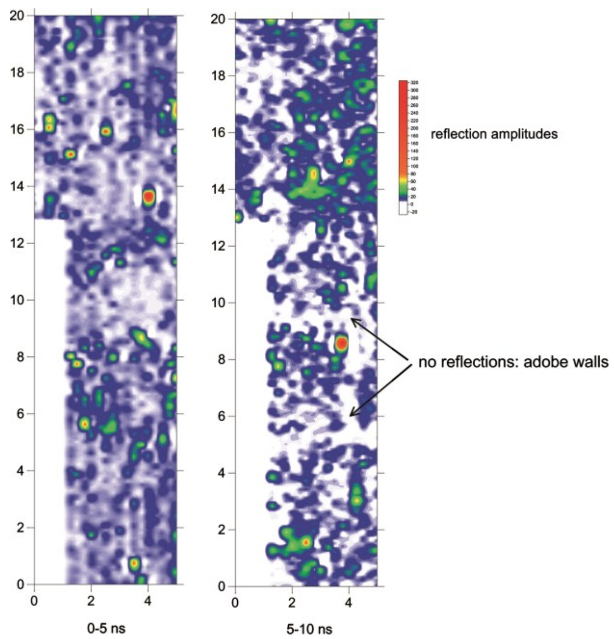


**Figure 8.** Amplitude slice-map of the adobe walls shown in Figure 7. The walls are shown in white as areas of no reflection, while random stones or layers of adobe melt adjacent to the walls produce high-amplitude reflections. These are Hohokam walls in Tucson, Arizona, USA.

As GPR is a three-dimensional technique, many important interfaces in the ground can be detected and then situated in space. Many practitioners use GPR solely to produce maps of reflection amplitudes in defined slices in the ground (Conyers et al. 2019), but with some thoughtful data interpretation, a variety of images of the ground can be produced if individual reflections are studied irrespective of depth. One example of this type of analysis is the imaging of a buried living surface (Figure 9) dating to about 8,720 $^{14}C$ years BP (Davis et al. 2014). Here a high amplitude radar reflection was produced using 270 MHz antennas at an interface between a buried soil horizon (and its adjacent fluvial channel) called the LU-6 level. This distinct radar reflection is visible over a large area, where excavations on both the east and west (Figure 10) have confirmed its depth. Those depths were then used to "tie" this known horizon directly to the GPR profiles (Conyers 2016).

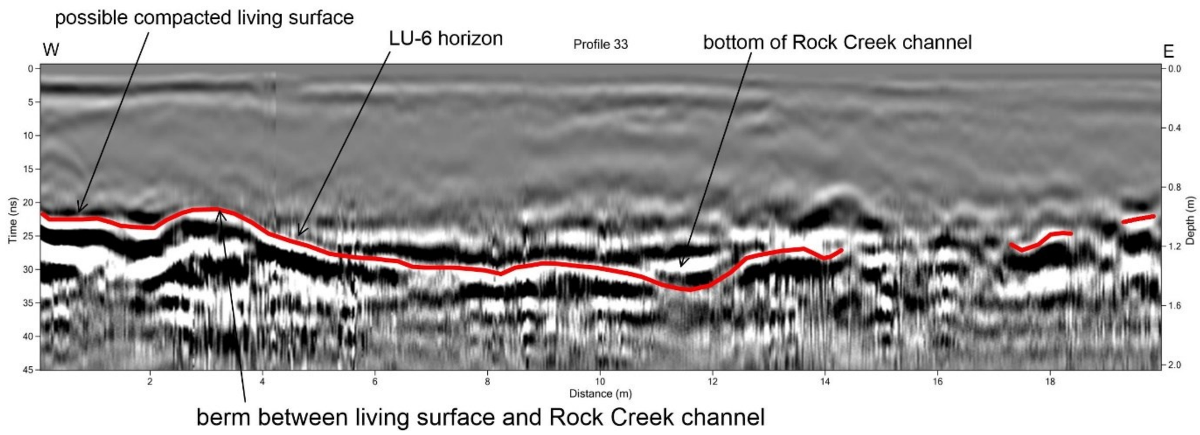


**Figure 9:** The "picking" of one interface in the ground along one reflection produces digital data of its depth, which can then be exported, along with similar data from adjacent profiles for image production. This is the LU-6 horizon from the Coopers Ferry Site in Idaho, USA, which shows this layer sloping into the bottom of a small fluvial channel to the east.

This type of GPR mapping "picks" a horizon, defined by either a positive or negative phase of the wave that was generated from the buried interface (Figure 9). This can be done automatically using a variety of software programs (or more laboriously manually), and the depths of the interface can be exported to other software for visual mapping. When this is done for many parallel profiles in a grid, a three-dimensional surface of the layer of interest can be produced.

At the Coopers Ferry site in Idaho, USA, where this was done, the surface of interest is a compacted soil unit, visible in excavations, where its density suggests it was compressed by foot-traffic in or around a dwelling or other use-surface (Figure 9). An analysis of many reflection profiles just to the east of the compacted surface indicates that there is a small rise (perhaps a constructed berm) on its eastern side. The layer then slopes downward to the east into what was a channel of either Rock Creek (now located to the west of the site), or one of its subsidiary channels.

The digital data derived from the "picking" of reflections generated from this buried horizon was then gridded and mapped across a large grid to produce a contour-map of the surface about 8,700 years ago (Figure 10). Other visualizations of this buried surface show this fluvial feature to the east of the excavations to be a meandering channel, with the compacted living surface located along the northwest corner of the grid in Area A, where excavations have exposed it. The berm to the west of this compacted surface visible in the reflection profiles then takes on a new significance, as it may have been a constructed barrier to keep an important use-area from periodically flooding.

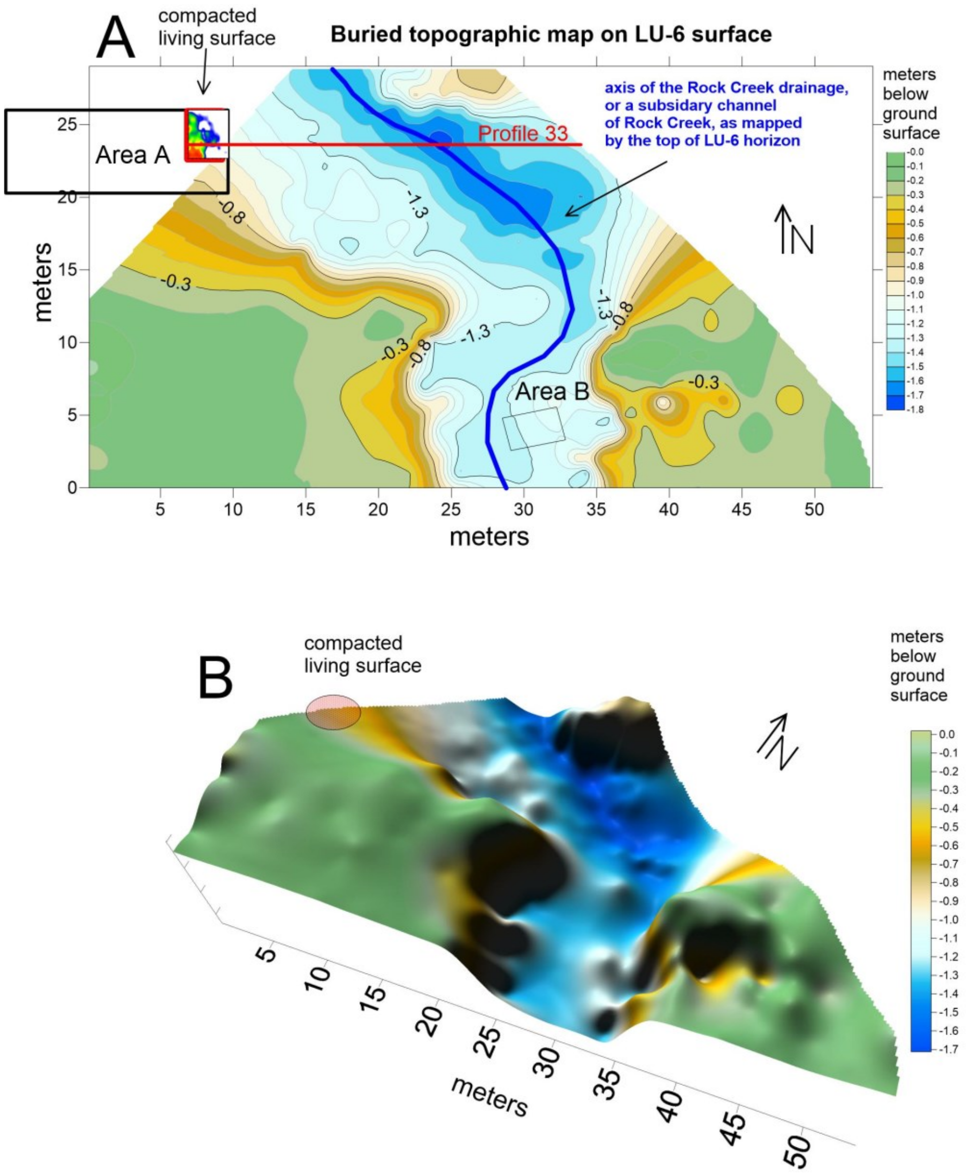


**Figure 10.** The LU-6 horizon, which is "picked" from reflection profiles shown in Figure 9, was the exported to software to produce contour and a three-dimensional image of the buried surface to the east of the excavations in Area A where it was exposed and studied.

A variation of this horizon "picking" method was used to study the three-dimensional surfaces of the ceiling and floor of a cave in the Atapuerca complex in Spain (Bermejo et al. 2020). At Atapuerca, there are many cave systems produced in limestone bedrock that contain abundant hominid and human remains spanning almost a million years of time. Over one of the cave systems, called the Elefante/Peluda caverns, the 270 MHz antennas were capable of transmitting radar waves to more than 6 meters in depth, and high amplitude radar waves were reflected from both the ceiling-air and the air-floor interfaces (Figure 11). The ceiling interface, which can be identified as a reversed polarity reflection, was generated when radar waves moved from the bedrock into the underlying void, where the velocity of the waves increased to the speed of light (Conyers 2012, 171).

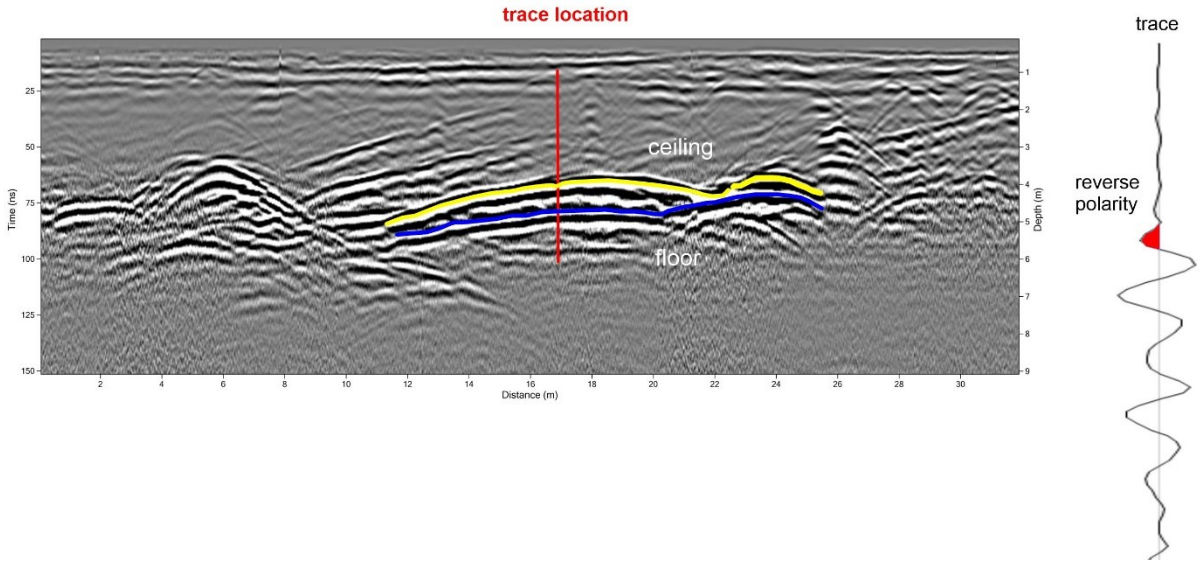


**Figure 11.** Interpretation of one GPR reflection profile from a cave in Spain showing the ceiling and floor interfaces that were "picked" and their depths exported as digital values. The ceiling in this profile was identified by the reverse polarity reflection (shown in one reflection trace on the right), produced as the radar waves increased velocity to the speed of light as they entered the cave void space.

In this situation, the floor and ceiling reflections were picked, once each could be identified in the individual reflection profiles. The ceiling reflection's depth below the ground surface could be quickly converted to depth in the ground, once the relative dielectric permittivity of the limestone bedrock was calculated (Conyers 2013, 107). The floor reflection, however, was "pulled up" in the reflection profiles due to the high velocity of the radar waves within the void space of the cave (Conyers 2012, 173). These reflection times were then adjusted downward to their correct depth below the ground surface, using the velocity of the speed of light within the cave void.

All digital data were then exported to a visualization program, with which the floor and ceiling layers can be viewed from various angles showing this cave in three-dimensions (Figure 12). These digital values of the ceiling and the cave when converted to depths can quickly be used to calculate the total volume of the void space within the cave. A variation of this method of GPR analysis could be readily applied to a variety of other ground conditions that do not contain voids, such as shell midden thicknesses or the thickness and distribution of other units of interest. In these cases, the top and bottom of the units can be "picked" and similar images and calculations performed using this method.

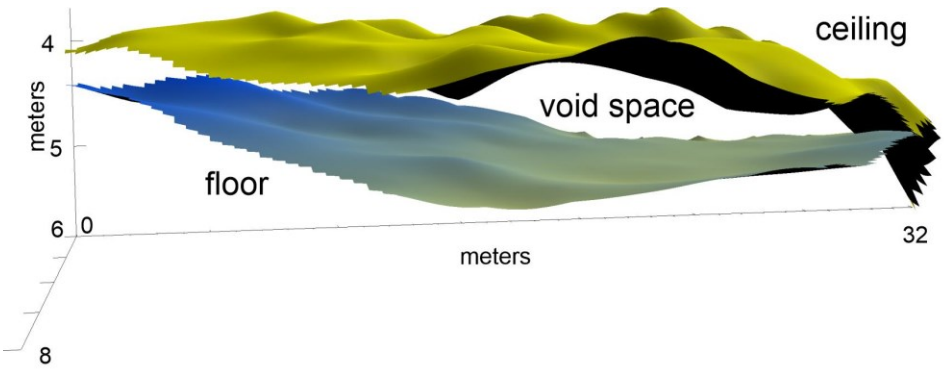


**Figure 12.** Exported depth values from the “picking” of the ceiling and floor reflections of the cave were adjusted for correct depth using velocity measurements and placed into a visualization program to produce images of a portion of the Elefante/Peluda cave system at Atapuerca, Spain.

# 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. Individual layers of significance can also be “picked” and mapped in three dimensions, producing important visualizations of buried landscapes or other buried features of interest. When these multiple datasets are interpreted archaeologically, they can serve as a powerful tool that can integrate archaeological sites into the overall geological context.

# Cross-References

Atapuerca, Spain
Coopers Ferry, Idaho

# Bibliography

*Bermejo L, Ortega AI, Parés JM, Campaña I, Bermúdez de Castro JM, Carbonell E, Conyers LB (2020) Karst features interpretation using ground-penetrating radar: a case study from the Sierra de Atapuerca, Spain. Geomorphology 367:107311

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

*Conyers LB (2012) Interpreting Ground-Penetrating Radar for Archaeology. Routledge, London

*Conyers LB (2013) Ground-Penetrating Radar for Archaeology, 3rd edn, Alta Mira Press, Lanham, MD

*Conyers LB (2016) Ground-Penetrating Radar for Geoarchaeology. Wiley & Sons, Hoboken, NJ

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

*Conyers LB, Sutton M-J, St Pierre E (2019) Dissecting and interpreting a three-dimensional ground-penetrating radar dataset: an example from northern Australia. Sensors 19(5):1239

*Davis LG, Nyers AJ, Willis SC (2014) Context, provenance and technology of a Western Stemmed Tradition artifact cache from the Cooper's Ferry Site, Idaho. American Antiquity 79(4):596–615

*Trinks I, Hinterleitner A, Neubauer W, Nau E, Löcker K, Wallner M, Gabler M, Filzwieser R, Wilding J, Schiel H, Jansa V, Schneidhofer P, Trausmuth T, Sandici V, Ruß D, Flöry S, Kainz J, Kucera M, Vonkilch A, Tencer T, Gustavsen L, Kristiansen M, Bye-Johansen L-M, Tonning C, Zitz T, Paasche K, Gansum T, Seren S (2018) Large-area high-resolution ground-penetrating radar measurements for archaeological prospection. Archaeological Prospection 25(3):171–195