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Analysis and interpretation of GPR datasets for integrated archaeological mapping

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ABSTRACT

An integrated approach to ground-penetrating radar interpretation should include not only the standard amplitude slice maps and isosurface renderings but also an analysis of individual reflection traces and adjusted and processed reflection profiles. Only when all those basic datasets are interpreted can the plethora of reflection features at various depths and locations within a grid be understood, especially in complex geological and archaeological settings. Topographically adjusted profiles can provide important clues to changes in reflectivity along a transect, indicating why certain amplitude features are visible (or not) in slice maps. An integration of excavation and outcrop data with reflection profiles can often indicate what features are producing high-amplitude reflections and which are yielding no reflection at all. Even individual reflection traces can be studied for polarity changes, which can help in identifying the types of buried materials that are producing reflections. All these datasets, some of which are often overlooked, must be integrated during interpretation, especially in complicated ground conditions.

INTRODUCTION TO INTEGRATED GPR DATA PROCESSING

The use of ground-penetrating radar (GPR) for archaeological mapping and interpretation has evolved from a purely exploratory technique using an interpretation of two-dimensional reflection profiles to one that now commonly uses three-dimensional mapping and computer-generated visualization programs to study much larger areas of the subsurface (Conyers 2013; Goodman and Piro 2013). These now-standard visualization techniques produce amplitude slice maps from two-dimensional reflection profiles and generate isosurface renderings from those complex three-dimensional datasets (Linford 2014) and recently from three-dimensional data collected using multi-antenna arrays that generate "real" three-dimensional output (Conyers and Leckebusch 2010; Novo *et al.* 2008; Trinks *et al*. 2010), including animations of large complex datasets. The use of multiple arrays also allows for three-dimensional migration of complex reflections, producing a much more "crisp" and accurate three-dimensional set of images (Sala and Linford 2012). All of these new collection and processing techniques are the product of robust and easily accessible hardware and software advances that can collect and process very large datasets quickly and efficiently. Many recent GPR adherents have joined the shallow geophysics community as GPR collection systems have become common, more intuitive to operate during data acquisition, and with efficient data transfer to powerful computers for processing and analysis. This is a very positive development as the three-dimensional power of the GPR method is being appreciated and applied to many fields, including archaeology (Conyers 2012).

Here I present a critique and reminder to those who use standard processing method for GPR, as many recent adherents have been ignoring the basic GPR reflection data in their interpretation. I propose that an integrated analysis is necessary using both the now-standard three-dimensional images with the basic data (reflection traces and profiles) from which these images are produced. When all GPR data are analyzed holistically, a better understanding of the often-complex three-dimensional output can be made. Examples are presented to show how standard software steps that slice datasets to produce three-dimensional maps can sometimes produce misleading and erroneous interpretations. Topographic corrections prior to slice mapping can often alleviate some of these amplitude sampling problems, but in complexly layered ground, only a manual interpretation of reflection profiles will produce accurate conclusions. Sometimes, buried features of interest do not reflect radar energy at all, and therefore, a completely different interpretation that searches for low or absent reflection amplitudes is necessary. Often, only a detailed analysis of individual reflection traces can determine what types of materials in the ground are producing reflections of interest, with an example presented of reflected wave polarity showing differences in radar velocity in the ground as a function of physical and chemical properties along reflection interfaces.

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GPR SOFTWARE PROCESSING STEPS LEADING TO COMMON IMAGES

Software program manuals and other publications on GPR data processing typically advance a series of recommended computer processing steps that users should proceed through in order to reach the "final products", which are usually amplitude maps and isosurface renderings (Annan 2009; Cassidy 2009; Goodman and Piro 2013). These recommended processing stages usually include, but are not limited to: range gain, band-pass filtering, frequency filtering, spectral whitening, background removal, migration, Hilbert transformation, deconvolution, smoothing, stacking, and, finally, resampling of the processed digital data to produce the final images. While each of these steps can often be necessary, and often important (Conyers 2013), automatically applying any or all of these data processing steps within a stream of processing tasks can often produce a final product difficult to interpret (Conyers 2012). This can occur as the GPR data have often been drastically modified along a processing pathway in ways not always appreciated or understood by many GPR interpreters. While many of these data processing tools are useful and sometimes necessary, only when a GPR user integrates the basic "raw" reflections visible in traces and profiles can producing an intuitive and integrated final interpretation be realized.

The usual final products of GPR mapping involve the presentation of amplitude images that are the product of a computer analysis of thousands or even hundreds of thousands of reflection "anomalies". Often, in archaeological analysis, the abundance of radar reflections, which are not necessarily the focus of a GPR survey, is recorded and displayed from bedding contacts, velocity changes, and other variations in the ground that are not the goal of a survey (Conyers 2012). This occurs because data processing software is "dumb", in which it only generated maps from user instructions within menus where input processing parameters are selected, often without understanding complex conditions in the ground or how these processing steps resample, process, grid, and display the final products.

In the GPR method, individual traces (Fig. 1) are used to produce reflection profiles, which are then resampled to generate amplitude slice maps. Each of those processing steps produces important images that must be understood, integrated, and then individually analyzed in conjunction during interpretation. When the nature of the ground is understood and geological and archaeological reflection features are then defined and understood in three dimensions, data can be resampled and processed to produce a meaningful final product, in this case, the amplitude slice maps and isosurface rendering images.

In the example in Fig. 1, the images produced in the slice maps and isosurface rendering have been generated from the traces and reflection profiles in an informed series of steps. When it was determined from multiple reflection profile analysis that the archaeological feature of interest (in this case, a pit structure floor with adjacent living benches) was recorded between 40 cm and 75 cm in

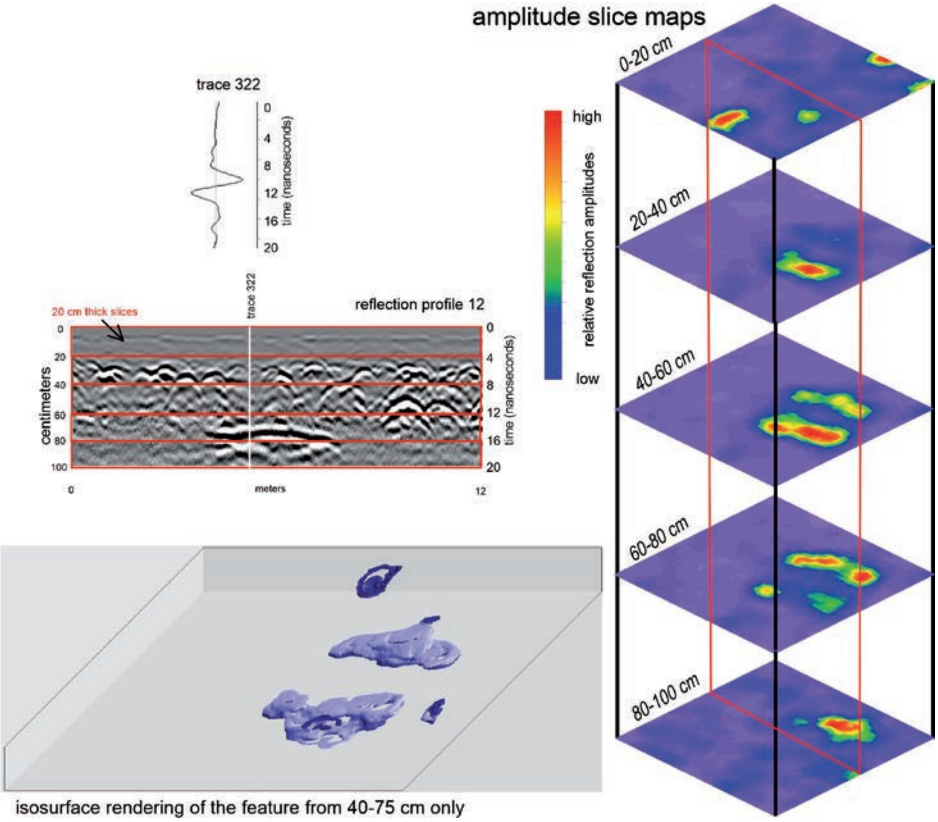

FIGURE 1
Standard GPR processing steps used to produce images from the basic data, which are reflections traces and profiles.

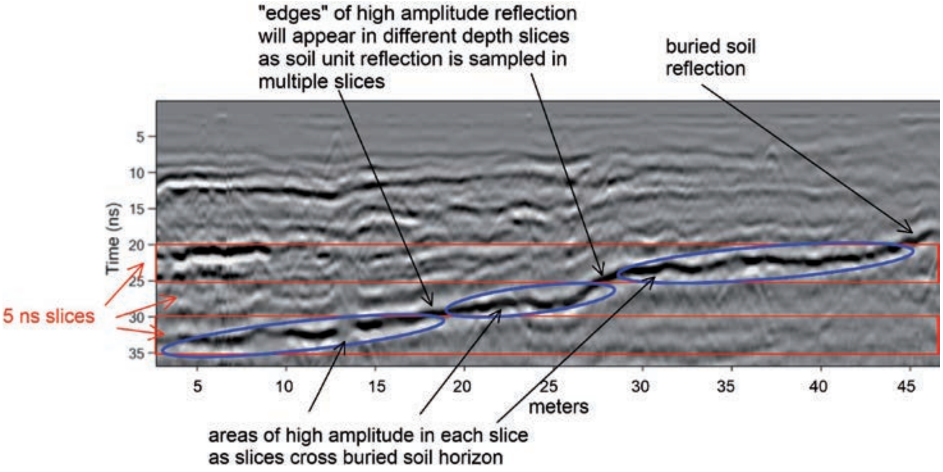

FIGURE 2
Reflection profile showing one high-amplitude reflection generated from a buried soil, which is sampled during amplitude slicing steps in slices of 5 ns each.

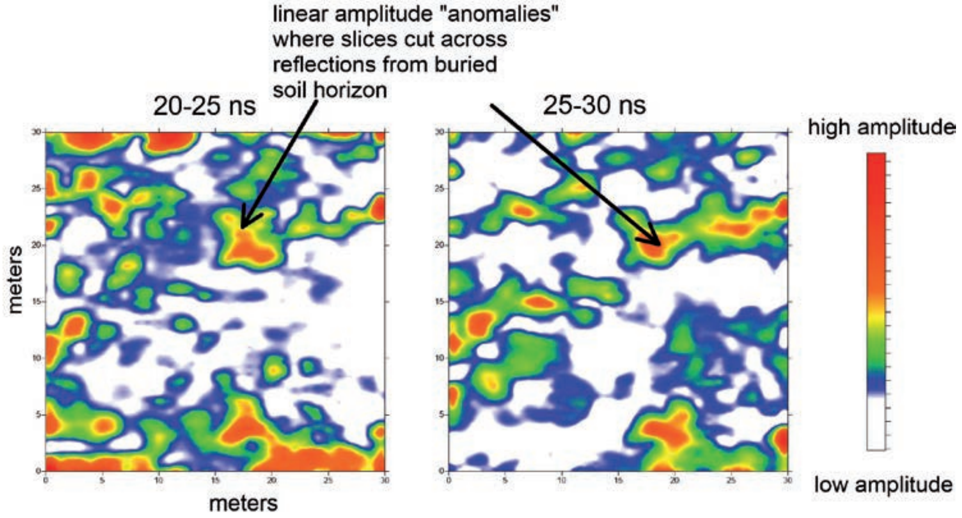

FIGURE 3
Results of amplitude slice mapping from 61 reflection profiles in a grid that include the buried soil shown in the profile in Fig. 2. Depth slices have plotted what appear in the images to be aerially discrete linear reflections, but are really only the reflections from one dipping horizon sampled in multiple slices.

the surveyed area, the slice images from only those depths were then produced and used for a final archaeological interpretation. The shallow reflections from the ground surface to about 40-cm depth are not included in the final isosurface image as they illustrate only small reflection hyperbolas from shallow stones. Informed data processing in this case was possible because an analysis of the traces and reflection profiles was done prior to generating the three-dimensional images. If reflections in all the profiles within this grid had been processed in a “batch” without understanding the complexity that produced reflections in the ground, many slices would have been generated that would have illustrated shallow stones that are not part of the archaeological feature of interest.

EXAMPLES OF RADAR REFLECTION COMPLEXITY THAT GENERATED ERRONEOUS IMAGES

If amplitude slicing software is programmed to generate relative reflection intensity within certain time windows, the computer processing steps will sample all reflection traces and then plot every reflection amplitude from those commands irrespective of the ground conditions. For instance, even in simple geological conditions, resampling of reflection profiles in amplitude slicing methods will generate “anomalies” at varying depths from one horizon if it is resampled within different slices in the ground (Fig. 2). In the example in Fig. 2, each depth that is sliced contains only a portion of the one horizon’s reflection, making it appear that individual “anomalies” are present at discrete depths (Fig. 3). If the geological materials in the ground were even more complexly bedded, the computer sampling methods will display a reflection from one continuous horizon as if it were a series of aerially restricted “anomalies” at various depths.

If the layers in the ground are even more complex than the example in Fig. 2, most GPR processing software used to generate three-dimensional images will generate extraordinarily busy “anomaly” maps that are mostly irrelevant to the final interpretation. Any archaeological features that produce reflections within complexly layered ground will be effectively hidden within the final images. The risk in this simple example of layered ground lies with users who rapidly progress through a series of data processing steps to reach the final product without understanding the basic reflection information from which the images are produced. Only an integrated analysis of the individual GPR reflection profiles, from which the final product is produced, will allow a user to understand what has produced the final product.

Basic questions about GPR and what is being imaged in the ground must be asked during data processing. The most basic question is: what has produced the reflection? This can often only be determined from viewing reflections in profiles and understanding what produces radar reflections (Conyers 2012). Were the radar reflections generated from aerially restricted point sources such as individual stones? Did laterally extensive bedding planes produce the reflections? From what depths (as measured in either two-way travel time or velocity-corrected depths) are these reflections recorded? Should an interpretation concentrate only on specific areas of the grid, or depths in the ground, where reflections were generated from the archaeological materials of interest? What depths generate no reflections or very low-amplitude reflections, and might the materials in the ground that generated those reflections be the archaeological targets? Did water retention in parts of the survey area cause velocity differences that make it appear that horizontal units of archaeological features are deeper or shallower in datasets? What amplitudes or wave polarities are indicative of the features of interest? These are just a few of the common questions that must be asked and answered prior to producing what are usually looked at as the “final products” of GPR surveys, which are slice maps and isosurface renderings.

FIGURE 4

Collecting 400-MHz GPR reflection profiles in coastal sand dunes to produce images of the buried middle-Paleolithic soil horizon, visible just to the left of the GPR antennas in this photo.

EXAMPLES OF GPR INTERPRETATION FROM COMMON GPR DATASETS SHOWING HOW MULTIPLE DATASETS MUST BE INTEGRATED AND INTERPRETED IN A COMBINED WAY

In a study, to map a middle Paleolithic soil zone buried beneath coastal sand dunes in Portugal (Fig. 4), reflection profiles were collected that display the radar reflection from the horizon of interest as it became progressively buried in sand. Reflection profiles viewed in un-processed displays show the reflection horizon as a distinctively high-amplitude planar surface, which becomes readily visible in profiles with basic amplitude gaining (Fig. 5). This profile is quite difficult to interpret in this basic two-dimensional format because of the undulating ground surface and the recording of the reflections from the horizon at various depths.

While the middle-Paleolithic horizon is very distinctive in this profile (Fig. 5), any amplitude mapping of many profiles of this sort collected within a grid without taking into account the complex topographic variations would be foolhardy as slices would cut across the buried soil unit of interest. Even horizon slicing (Conyers 2012), where resampling of amplitudes to display the spatial variation of those values along one specific reflection surface would still produce anomalous amplitude maps, as the soil unit of interest producing these radar reflections loses amplitude between 22 m and 28 m. While that loss in amplitude might be denoting a physical or chemical change in this buried unit, when this profile is viewed after topographic adjustment, it is immediately visible that the lowest amplitude is directly under the area where overburden sediment is the thickest (Fig. 6). An analysis of that added material at the top of the coastal sand dune shows the surface layer to be a soil composed of sandy clay with some organic matter. It likely retains moisture, producing a localized higher electrical conductivity area that attenuates radar energy directly below it and produces a low-amplitude reflection from the buried soil unit at depth. That variation in amplitude is only a function of radar energy strength moving through the ground and not changes in the soil itself. If detailed analysis of the individual profiles had not been done prior to amplitude analysis, an erroneous final interpretation would have resulted. In this example, any processing and image production beyond basic background removal and topographic adjustment of individual reflection profiles would likely generate invalid and misleading results.

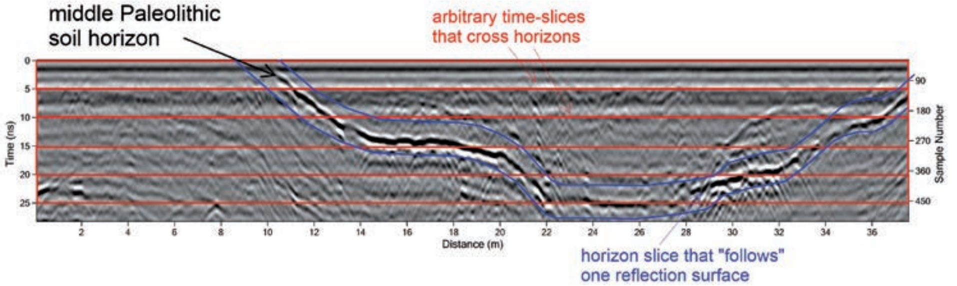

FIGURE 5

Unprocessed GPR reflection profile showing horizontal slices crossing the soil reflection and a horizon slice that samples only the amplitudes produced from reflections generated by the middle Paleolithic soil layer.

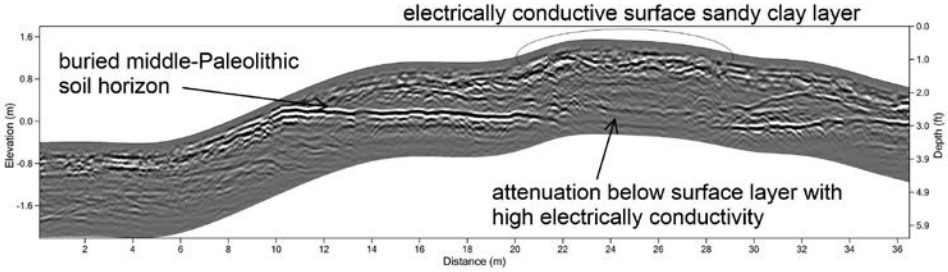

FIGURE 6
Topographically adjusted reflection profile shown in Fig. 5 that illustrates the change in the amplitude of the reflections from the middle-Paleolithic soil horizon is due to electrically conductive surface soils.

FIGURE 7
Adobe mud walls from southern Arizona. On the left is a wall visible as a colour and composition change surrounded by "adobe melt". On the right is a double wall of a house exposed during excavations.

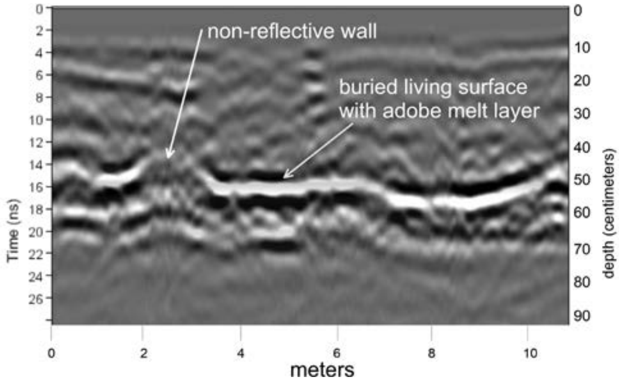

FIGURE 8
Reflection profile perpendicular to an adobe wall that is non-reflective, with adjacent "adobe melt" layers deposited on a buried living surface that are highly reflective.

Almost always, GPR users are taught to create amplitude maps (Fig. 1) and then interpret the spatial distribution and depth of the high-amplitude reflections (Conyers 2013). This basic interpretation makes sense in many ground conditions as reflections are created at interfaces of differing materials in the ground that have dissimilar physical and chemical properties and, therefore, water retention and distribution (Conyers 2012). It is often these interfaces between archaeological materials and the surrounding sediments and soils that produce the high-amplitude reflections. However, this is sometimes not the case, and only an integration of reflection profiles, surface outcrops, and then a correlation of that analysis with amplitude slice maps will produce accurate interpretations.

In southern Arizona, the archaeological features of interest constructed by the ancient Hohokam people are homogeneous clay walls and floors constructed with what is called adobe (Conyers 2011). They are sometimes visible on the ground surface as distinct linear features that vary in colour and composition from the surrounding matrix (Fig. 7, left). When excavated, these mud walls are sometimes visible as "double walls" where original houses were rebuilt and added on to over time (Fig. 7, right).

Buried walls of this sort are not reflective to radar waves, as they were produced by mixing clay and other fine-grained materials with water to produce what are termed "puddled adobe" features with no interior bedding planes or other interfaces from with to reflect energy. Any vertical interfaces between the walls and surrounding materials or in double walls are also not reflective as radar waves transmitted from the surface move parallel to these vertical boundaries, or if radar waves intersect the interfaces, they are reflected away from the surface recording antenna and not recorded. In reflection profiles, vertical clay features of this sort appear as areas of no reflection (Fig. 8), and unless an interpreter pays attention to areas of no reflection in profiles, these features will often go unnoticed.

When houses made out of adobe were abandoned, the surrounding living surface was periodically covered by layers of clay as rainfall "melted" the standing walls and that material was deposited on the ground surface adjacent to the walls. Over time, these periodically deposited clay layers became interbedded with wind-blown sand producing planar sediment units of very different composition that reflect radar waves with high amplitudes. It is units of this sort adjacent to the walls that are most visible in reflection profiles.

Once the reflective nature of the buried features of interest is known from analyzing profiles, those interpretations can be integrated with standard amplitude slice maps (Fig. 9). Standard amplitude maps show that it is the non-reflective areas that are

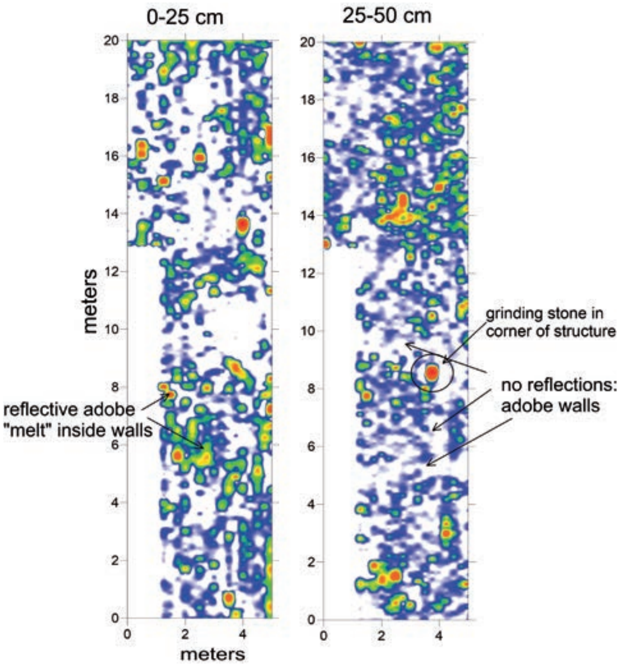

FIGURE 9
Amplitude maps of a structure composed of adobe walls, which are not reflective. High-amplitude adobe “melt” is preserved within the walls, which is the product of post-abandonment deposition.

denoting the buried walls. Often, those very subtle non-reflective regions would not be immediately recognizable to the human eye without first integrating profile interpretations with amplitude maps. As an interesting sidenote, one high-amplitude reflection in the 25 cm–50-cm-depth slice went un-interpreted during interpretation as only the non-reflective features were delineated (Fig. 9). That small high-amplitude reflection turned out to have been generated by an important grinding stone that was placed upside down in the corner of this building, perhaps as an offering when the roof and upper walls were burned during a termination ritual.

In this example an integration of outcrop and excavation data with reflection profiles demonstrates how the features of interest are non-reflective. When those areas of non-reflection are viewed in horizontal amplitude slices, it is the subtle no-reflection zones that are showing the location of the buried house walls.

The basic dataset from which all GPR products are produced is reflection traces. Most of the time, in standard GPR, data processing and interpretation traces are immediately stacked along antenna transect lines to produce reflection profiles (Fig. 1) and rarely are they analyzed individually for most GPR projects, which is perfectly acceptable. However, there can often be important information included in those individual traces that can help with an interpretation of the physical properties of materials in the ground that are producing reflections.

When oscillating radar waves encounter buried interfaces and the waves change velocity, reflection will occur (Conyers 2013). Usually, as radar energy moves deeper into the ground, moisture retention increases and radar travel velocity will decrease. When radar energy is reflected from a buried interface where the wave velocity decreases, the polarity of the reflected wave will be the same as the direct-wave generated from the transmitting antenna (Fig. 10). This is the normal case in most ground conditions, and therefore, most reflections are recorded as normally polarized sine waves. However, if a drastic *increase* in velocity occurs at a boundary, such as a void space where propagating radar waves increase again to the speed of light, a reflection will be generated that is visible in traces as a reversed polarity sine wave (Damiata *et al.* 2013; Daniels *et al.* 2003). Theoretically, similar wave polarity changes will occur if there is any drastic increase in velocity along an interface even if it is not a void space, but these conditions in the ground are rare. With the search for graves or other buried objects that contain voids, an analysis of the polarity of waves recorded in individual reflection traces is an important interpretive tool for understanding buried materials. Usually, amplitude slice maps do not plot the polarity of waves, only their amplitude, and therefore, an analysis of individual traces is necessary.

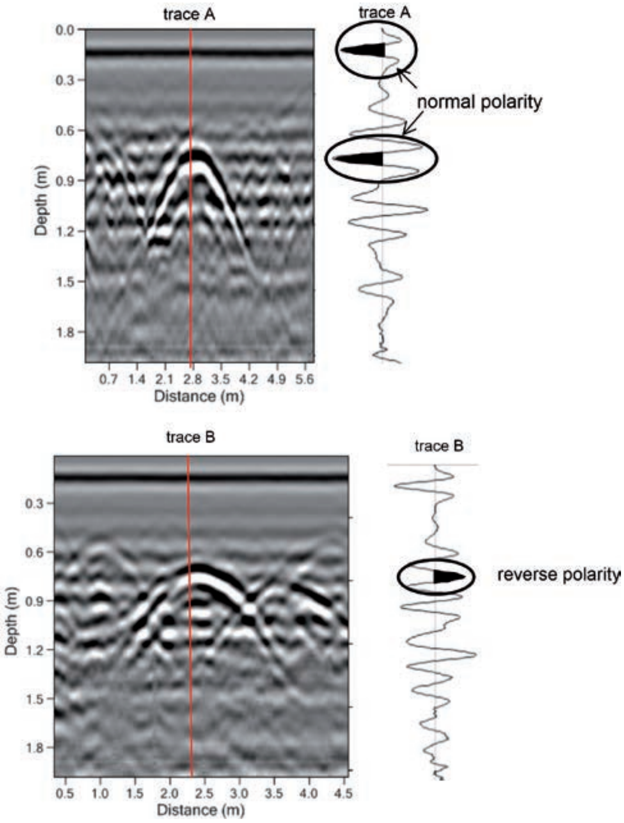

FIGURE 10
Comparison of reflection traces from waves reflected from two graves. In burials that retain void spaces within caskets, reflections are reversed polarity (trace B). The usual case for most buried materials produces reflections that are normal polarity (trace A).

CONCLUSION

While amplitude slice maps and isosurface renderings have revolutionized the way GPR data are presented, an accurate interpretation of those images often necessitates integration with more standard data analysis derived from reflection profiles and individual traces. The complexity of stratigraphic interfaces in the ground and changes in topography and surface materials can produce amplitude "anomalies" in the ground that are a function of the way data are resampled during processing. Only when profiles can be adjusted for these common variations will the amplitude images be interpretable. While the common GPR processing steps move through a series of computing steps to the final products, users should often step back to the raw data as they are the simplest images of reflections in order to interpret the slice maps and isosurfaces. While some may consider this integrative interpretation method "old fashioned", as profile and trace analysis was the way most GPR reflections were processed prior to the now-common amplitude images, an understanding of intuitively generated reflection profiles and traces can produce important clues during interpretation tasks.

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