7

Interpretation of GPR Data

When GPR data were first applied to archaeology in the 1970s, most interpretations were made by viewing raw reflection profiles and searching for "anomalies" that might have been produced by reflections from buried archaeological features (Bevan 1977; Sheets et al. 1985). Often reflection profiles were printed out and analyzed on paper as they were collected in the field or viewed and interpreted on a video monitor. These interpretation methods were at best crude and inaccurate, but they were about all that could be done with analog reflection data that were not stored on some kind of digital medium for later processing.

Unfortunately, this kind of interpretation is still practiced by many GPR users, but usually only when data are being acquired in the field and are immediately viewable on the computer screen as they are collected. Most GPR users that still employ these kinds of "on-the-fly" interpretations are aware of the pitfalls that can be encountered when trying to make interpretations in this manner. All should now be aware that field records should be processed to remove noise, scales must be corrected in either the vertical or horizontal directions, and picking out anomalies on the screen that may or not have any meaning to the questions being asked (assuming they can be recognized!) is fraught with problems.

With the advent of digital data filtering and sophisticated data processing, in the late 1980s, profiles could finally be interpreted in a more refined and scientific manner than was previously possible (Conyers 1995; Goodman 1994). However, until the advent of three-dimensional amplitude analyses in the mid-1990s, most GPR data interpretation consisted of analyzing reflections in profiles that "looked like" buried features of interest and correlating them to other reflections in adjoining profiles in a method that has been termed "wiggle picking" by some interpreters. Using this technique, buried features can still often be identified, their depth determined, and their spatial placement within a grid mapped, but the process is laborious and has many problems. Using the visual interpretation method, interpreters are often unsure which reflections were generated from features of interest and which might have been produced from geological "background," and therefore the origin of many mapped anomalies are often little more than educated guesses. Unfortunately, this kind of data interpretation is still practiced for some GPR studies as many practitioners have not applied many of the more sophisticated interpretation methods discussed here, such as synthetic modeling, amplitude time slicing, and three-dimensional rendering. But even when these more sophisticated interpretation methods are applied, it is almost always necessary to still use some kind of "wiggle picking" analysis. This is usually done so that the maps and images being produced can be correlated with features identified in profiles and that are of archaeological interest. All GPR studies should therefore include some components of two-dimensional reflection profile analysis, modeling, and three-dimensional mapping, as discussed in this chapter.

SYNTHETIC GPR MODELS

Synthetic modeling of two-dimensional reflection profiles using a computer was developed in an attempt to model buried objects, stratigraphy, and important reflection surfaces (Goodman 1994). Modeling can provide the interpreter with an idea of what real-world GPR reflection data "should look like" and will allow more accurate interpretation of GPR reflection profiles once they are processed (Conyers and Goodman 1997; Goodman 1994; Goodman and Nishimura 1993). It can also allow the interpreter to construct a model of known stratigraphy and archaeological features prior to going to the field in order to determine if a GPR survey will be capable of delineating the buried materials of interest. Once models are constructed on the computer, they can be quickly modified for different-frequency antennas to determine the optimum equipment to take to the field for the depth necessary to resolve the features of interest. After GPR data have been acquired and are processed into reflection profiles, models can then be readjusted to more accurately represent known field conditions as a guide in interpretation. When used in this way, they are a great benefit in making interpretations, especially in determining the origins of reflections visible in GPR profiles.

Computer-simulated radar profiles are generated by tracing the theoretical paths of radar waves during transmission through various media with specific relative dielectric permittivities, electrical conductivities, and magnetic permeabilities. All possible reflections from modeled interfaces in the ground are taken into account (Goodman 1994). The two-dimensional geometry of the subsurface stratigraphy and archaeological features are programmed into the model to generate as close to a real-life case as possible.

As is often the case, two-dimensional reflection profiles can look significantly different from how the buried structures would appear in cross section if viewed in the wall of a trench. Most important, they are not at all like those most of us are used to seeing from other more common computer-enhanced images such as those from X rays or computer tomography (CT) scans in medical technology. Once synthetic models are studied and the generation of reflections can be compared to the modeled archaeological features, they can also be an excellent learning tool to help understand how radar energy is propagating and reflecting in the ground.

Synthetic models of important components of an archaeological site can only be produced if some prior information about subsurface conditions is available. The electrical and magnetic characteristics of sediment and soil conditions must often be estimated as well as the geometry of overburden units and the composition of the buried archaeological features of interest. These data are then put into the computer in a two-dimensional model that is a simplification of a vertical slice through the ground. The computer will use this information to predict reflectivity coefficients (equation 3.2) encountered at various interfaces, energy attenuation with depth and within each unit, the velocity of radar energy in different layers, and the amplitude of reflections received back at the surface (Goodman 1994). After the model is generated, resulting reflections are plotted in two dimensions in the same fashion as standard GPR reflection profiles, and its horizontal and vertical scales can be adjusted, just as with real reflection profiles. After analysis of any model, input parameters can then be changed and the simulation rerun until a reasonable match between the real and synthetic reflection profiles is obtained. This iterative process of parameter input and comparison to real-world data is referred to as *forward modeling* in geophysical prospecting (Powers and Olhoeft 1994, 1995; Zeng et al. 1995) and is a powerful interpretation tool.

Creating a Synthetic Computer Model

To generate a synthetic reflection profile, large numbers of potential radar wave paths through the two-dimensional model are calculated on a computer, which approximate the paths that radar waves would take in the ground. This type of two-dimensional modeling is well known in seismic processing and is often referred to as *ray tracing* in geophysical terminology (Cai and McMechan 1994; Goodman 1994; Leckenbusch and Peikert 2001). Unlike seismic modeling, GPR models must also take into account the conical-shaped transmission patterns of the surface transmitting antennas (Goodman 1994). Ray path models in GPR are based on algorithms that take into account a number of complex equations concerning conductive-dissipative electromagnetic propagation theory (Jackson 1977).

Some possible wave paths that must be considered when creating a synthetic computer reflection profile are shown for the example in figure 7.1. These, and many other possible ray paths similar to them, must be programmed into the computer to generate an accurate model of what radar energy will do in the ground. In the figure 7.1 example, there are four different media in which radar waves can travel through and be reflected from: air, unit 1, unit 2, and unit 3. A synthetic reflection profile that would be produced for this simple four-layer model would therefore need to take into account waves that are reflected off each subsurface interface, but also ray paths that are partially reflected off some interfaces and partially transmitted and refracted across others. At least six separate ray travel and reflection pathways would have to be incorporated into the model (see figure 7.1). In this simple example of possible wave paths, some of the radar waves will reflect off the interface between units 1 and 2 and will be recorded back at the surface antenna. Others will be transmitted through this interface and refracted, only to be reflected off the interface between unit 2 and unit 3. In the real world, only a portion of the energy from each energy pulse would be reflected and refracted at each boundary, but for simplicity the model is set so that each radar ray has one distinct path. For instance, one wave will be reflected off the interface between units 1 and 2, traveling directly back to the surface where it is recorded at the receiving antenna. Another wave travels the same path, but instead of being recorded at the receiving antenna it is rereflected back into the ground from the air–unit 1 interface. The wave paths of these multiple reflections will then travel back into the ground to be rereflected back to the surface at the same interface. A similar ray path with multiple reflections is also simulated at the interface between unit 2 and unit 3. There will also be ray paths simulated that take what are called "dogleg" paths, traveling in complicated multiple reflection paths off of all the modeled interfaces prior to finally arriving back at the surface. These, and other paths within the cone of illumination of the transmitting antenna, are simulated on the computer many thousands of times to arrive at a composite for all the reflected waves that arrive back at the surface antenna. The computer then moves the antenna along the modeled ground surface, and the process is repeated for many surface antenna locations along the programmed transect. The computer predicts the time at which the modeled waves return to the receiving antenna on the surface and records their resulting amplitudes.

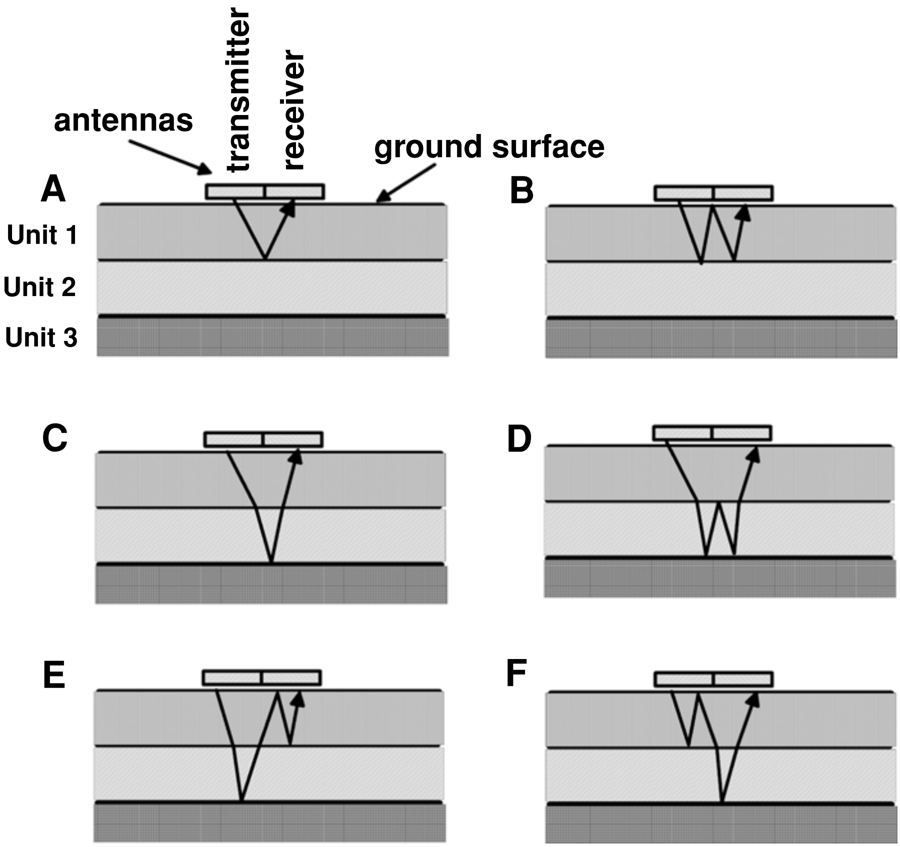

FIGURE 7.1
Possible Ray Paths in Stratified Material. To model potential radar reflections in the ground, many radar wave pathways must be considered. The simplest path is from the surface antenna to a buried interface and back to the surface antenna (A). Multiple reflections occur in (B). Energy can also be refracted and then reflected (C) or any combination of reflection and refraction (D, E, F).

To compute the synthetic profile, all the modeled waves that are returned to the receiving antenna from each of the many hundreds of paths are totaled at each antenna location over the profile. The time at which each is received and the resulting amplitudes are also recorded, and the simulated reflection traces are plotted in a standard two-dimensional profile. The number of reflections or transmissions that occurred at each interface can be adjusted by the modeler. Using the RDP and electrical conductivity data that are input for each simulated stratigraphic unit, the computer calculates the reflection coefficients at each interface and the amount of radar energy that is reflected or transmitted. Attenuation along the path of each modeled wave is also computed from the relative dielectric permittivity and electrical conductivity estimates that are programmed into the computer program. In the real world, there are an infinite number of possible wave travel paths and resulting amplitudes, but if the model is constructed without too much complexity, large numbers of possible ray paths will generate a coherent and usable synthetic model (Conyers and Goodman 1997; Goodman 1994).

Details about the electromagnetic theory involved and the mathematical description of all steps in the model is given in Goodman (1994). In real field conditions, numerous out-of-plane reflections must also be taken into account (Carcione 1996; Grasmueck 1996; Leckebusch 2003). Much more complicated three-dimensional modeling techniques have recently been developed for seismic reflection data used in petroleum exploration, which are just starting to be applied to GPR studies (Lehmann et al. 2000).

Synthetic Modeling Applications

In areas where buried features have considerable geometric variation within a short distance, GPR reflection profiles and the models of these buried features can be very complex. An example of a synthetic reflection profile for a buried V-shaped trench with steep sides and two different subsurface layers is shown in figure 7.2. The model predicts that some radar waves will have a single reflection off the subsurface interface. Others will have multiple reflections in the ground from within the trench, and these are also taken into account. The direct reflected waves (those with only one reflection off the interface) show the outline of the trench, with less amplitude on its edges due to ray scattering that occurs from its sloping sides. Because the antenna will “see” the far wall of the trench before encountering it, due to the conical transmission pattern from the surface antenna, reflections from the trench side will be recorded (in measured time) at a depth greater than the actual trench bottom. The same is true as the antenna moves

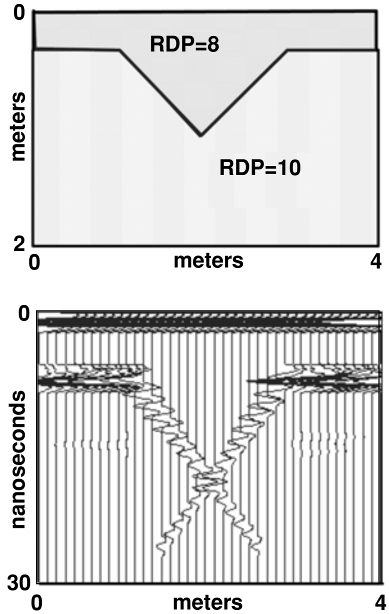

FIGURE 7.2
A V-Trench Synthetic Model. A synthetic model where radar wave paths travel to and from a V-shaped trench. Waves are reflected multiple times within the trench, before energy reaches the receiving antenna. The result in this model shows a "bow tie" pattern in the modeled reflection profile.

away from the trench and reflections are received from its opposite side. The net result of these reflections, as the antennas are moved along the ground surface, causes what is referred to as a "bow tie" effect when the model is viewed in profile. Other multiple reflection features are also created as radar waves are reflected three or more times within the trench but are recorded as very low-amplitude waves due to progressive energy attenuation during transmission through the ground.

In the V-trench case (figure 7.2), if the synthetic model were not constructed and analyzed, the reflections beneath a trench of this sort might be mistaken for a point source hyperbola derived from something possibly buried in the bottom of the trench, or perhaps some other type of buried feature below the trench. The model, however, demonstrates that these reflections in the profile are the result of multiple reflections from inside the trench and do not represent a "real" feature. When similar trenches are seen in real reflection profiles at a site (such as the one in figure 7.3), they can be easily identified in profiles because the model has simulated and predicted their shape in advance.

A model that illustrates how layered materials of varying thickness, with differing RDP, produce reflections is shown in figure 7.4. In this model, the flat interface between units 2 and 3 represents a buried living surface and is the archaeological interface of interest. The complexity in this model arises from the differences in RDP and thickness changes in the two overlying units.

In figure 7.4, the thick section of material with a high RDP in unit will slow the radar energy as it travels vertically from the ground surface, to the interface of interest, and back to the ground surface. The thinner section of this high-RDP material in the middle of the model illustrates how radar energy will travel from the ground surface to the interface of interest, and then back to the ground surface in a shorter amount of time than at the edges because it is traveling for less distance in lower-velocity material. The resulting reflections generated from the interface of interest at the top of unit 3, when plotted in two-way travel time, will therefore be distorted due to these velocity and thickness differences in the overlying unit. Under the area where a thinner section of low-velocity material

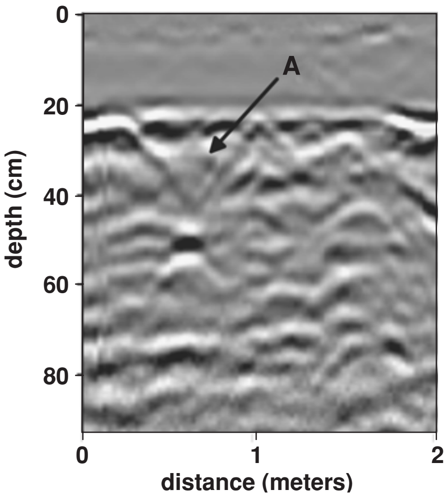

FIGURE 7.3
A V-Trench Discovered in a Reflection Profile. This V-shaped trench generated a classic bow tie reflection (A) like that modeled in figure 7.2. This profile was collected in a highly disturbed historic mining area near Blackhawk, Colorado.

(higher RDP) is modeled, the lower interface will appear to bow upward. This upward and downward bowing of the lower interface, caused only by differences in the velocity and thickness of the overlying material, creates the illusion of an undulating surface of the interface between units 2 and 3, referred to as a *velocity pull-up* in one area and a *pull-down* in the other.

A velocity pull-up similar to the model in figure 7.4 would also be noticeable in the field below a large buried void space. The increase in radar wave velocity as waves are traveling within the void would create an artificial upward bowing of reflections that were generated from materials below it. A pull-down could also occur where localized conditions create a decrease in radar wave velocity, possibly due to abrupt stratigraphic or archaeological change laterally along a feature or a possible change in overlying soil conditions. A fluctuating water table, or changes in the water saturation of buried units located above the water table, can also slow radar waves and distort underlying reflections due to localized variations in velocity. This phenomenon was noticed in a sand dune area where a pipe, which was known to be horizontal, appeared in a reflection profile

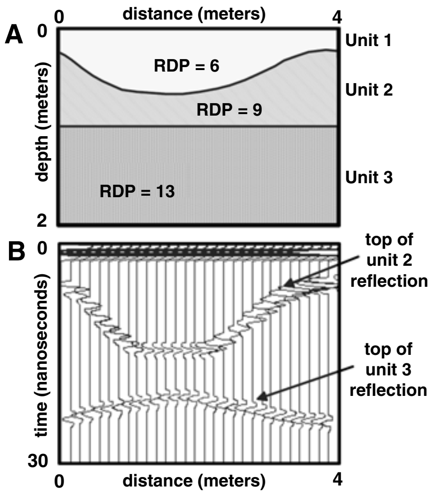

FIGURE 7.4
A Three-Layer Velocity Model. Three layers of material are modeled with a high RDP unit (unit 2) sandwiched between units 1 and 3 are shown in A. Radar energy travels for a shorter distance through the lower-velocity material of unit 2 in the middle of the model, creating a velocity "pull-up" of the reflection at the top of unit 3 and "pull-downs" on either side.

to undulate (figure 7.5). Its pull up and pull down is only a function of differences in RDP in the overlying sand dune beds, much like demonstrated in the model in figure 7.4.

The model in figure 7.4 and the undulating pipe, which is actually horizontal (figure 7.5), demonstrate one of many pitfalls that interpreters of GPR data can encounter when there are large changes in velocity within the ground overlying buried materials of interest. In addition to these problems, because of complex refraction and transmission within subsurface layers, radar energy may not be transmitted at all through some types of materials because of total energy attenuation or complete reflection. These "unilluminated" regions that occur below these types of materials are also referred to as *shadow zones* (Goodman 1994). They are areas where no reflections occur even though features that could potentially reflect energy are present. Often these and many other "non-intuitive" reflection and transmission scenarios would not be recognized without first generating synthetic models of real-world conditions and studying their outcomes.

Synthetic Models Compared to GPR Profiles

When a relatively simple reflection profile of a buried pit house was processed and analyzed, its floor and possible subfloor features were immediately visible (figure 7.6). The house floor was then cored to confirm its presence and also to evaluate the properties of its compacted and partially baked floor and the sedi-

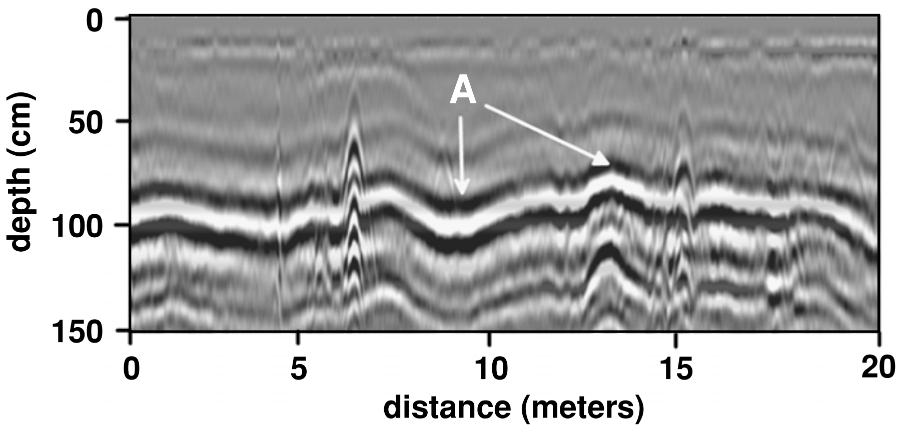

FIGURE 7.5
Vertical Distortion Due to Near-Surface Velocity Differences. A horizontal pipe appears to undulate because of velocity changes in the overlying sand dune beds. At points marked (A), there are both pull-ups and pull-downs.

ment covering it (Conyers and Cameron 1998). Upon further analyses of each profile crossing the floor feature, additional subtle features were visible on or below the floor, whose origin was unknown. One of the most distinct was what appeared to be a break in the floor surface that was hypothesized to be an entrance to a subfloor cistern, which is common in pit houses in the area of the American Southwest where these features were found (figure 7.6).

A synthetic model was constructed of the floor with a subfloor storage cistern, to determine if this type of cultural feature could be producing what was seen in the reflection profile (figure 7.7). Information obtained from the core was used to determine sediment properties used in the model. The synthetic model indicated that a cistern of the sort modeled would probably not be visible in reflection profiles, except for perhaps a very subtle reflection at its base. Its sides would probably be invisible because of their vertical faces, and all reflections below the highly reflective floor would also be very weak, as most of the radar energy would be reflected back to the surface producing a shadow below it. The model supports the presence of a possible subfloor feature in the real reflection profile as it shows a

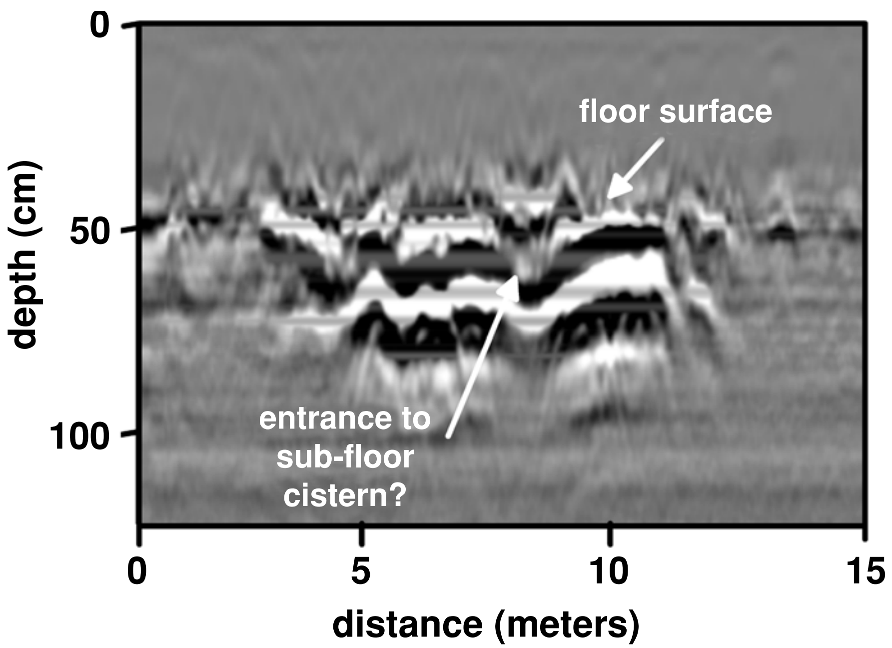

FIGURE 7.6
A Pit House Floor with Possible Subfloor Feature. The gap in the floor reflection may be the entrance to a subfloor cistern, which is not otherwise visible.

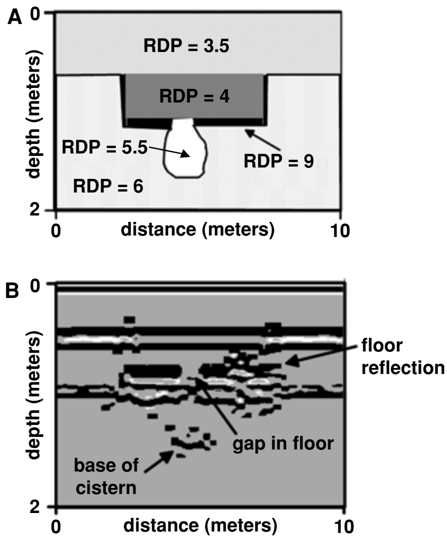

FIGURE 7.7
Synthetic Model of a Pit House Floor. This model indicates that the vertical walls of the subfloor cistern would not be visible in a reflection profile because little energy is reflected from them. The base of the large storage cistern is barely visible, as most of the radar energy is reflected back to the ground surface from the floor, producing a shadow below. The only clue to the subfloor feature is a gap in the floor reflection, similar to what was visible in the reflection profile in figure 7.6.

break in the horizontal floor reflection, which is just like that visible in the actual reflection profile crossing the buried floor (figure 7.6). Without some confirmation from the synthetic model, a feature as subtle as this would probably go unnoticed by most interpreters.

INTERPRETING AND MAPPING MANY GPR REFLECTION PROFILES IN A GRID

In areas where well-defined GPR reflections are recorded in profiles, detailed subsurface mapping of the location of buried surfaces and archaeological features (if they can be identified) is possible. Prior to making these kinds of maps, the genesis of the reflections must be understood so that the maps being constructed are meaningful, by visual interpretation, analysis of two-dimensional synthetic models, or both. Once the reflections in profiles are differentiated and the origin of important are defined, they can be manually, or with the aid of a computer, correlated from profile to profile within a grid and between grids in an area. If velocity and surface topographic corrections have been made, accurate depth maps that define buried topography, or anthropogenic modifications to that landscape, can then be constructed (Conyers 1995; Conyers and Goodman 1997: 137; Imai et al. 1987; Milligan and Atkin 1993).

Manual profile interpretation of this sort can be very time-consuming and always relies on interpretive experience. The origin of reflections and their importance to the questions at hand must also be determined in advance or a great deal of energy might go into identifying and interpreting reflections that may not answer any archaeological questions. For this reason, velocity analysis, correlation of reflections to known materials in excavations, and two-dimensional modeling (or all the above) should be performed in advance of any manual profile interpretation.

Example of Buried Landscape Reconstruction from Interpreting Reflection Profiles

A standard manual GPR correlation and paleotopographic mapping technique was used to define and then map a buried sixth-century living surface at the Ceren Site in El Salvador (Conyers 1995). At this site, the ancient living surface is now covered by between 2 and 6 meters of volcanic tephra, which preserves the ancient landscape, architecture, and artifacts (Sheets 1992). The buried surface was initially defined in GPR reflection profiles using both velocity analysis and synthetic computer modeling (Conyers and Goodman 1997). This important reflection that correlates to the buried living surface was then correlated within all reflection profiles, and its subsurface attitude was manually mapped.

The top of the buried living surface is the most important interface to map with GPR at this site because it was the ground surface that was built on, farmed, and modified prior to burial by volcanic ash (Conyers 1995). During interpretation, each profile in the grid was first processed to remove background noise, adjusted for surface topographic changes when necessary, and frequency filtered. Velocity analyses including direct-wave studies and laboratory measurements of sediment samples were conducted to arrive at RDPs for each unit (Conyers and Lucius 1996). Two-dimensional models were produced for many of the architectural features that were known to have been constructed on the living surface so that they could be identified in profiles (Conyers 1995). Velocity information was then used to correct radar travel times to depth, and the final two-dimensional profiles were printed on paper for visual analysis. The reflection generated at the buried living surface could be identified through a long and laborious process of stratigraphic correlations within and between all reflection profiles. This was done by hand-coloring both the buried living surface reflection and all structures built on it on each paper profile. The elevations of all identified reflections were then measured with hand calipers every meter along more than 12,800 linear meters of paper reflection profiles.

Distinctive point source reflections with apexes above the clay floors of buried structures were visible in some profiles. It is probable that these point source reflections are the record of reflections that occurred from the tops or sides of standing columns or walls, as predicted in previously constructed two-dimensional synthetic models. These hyperbolic reflections and also some distinct reflections from horizontal clay floors were used to map all visible buried structures (figure 7.8).

This manual interpretation process took about two months, as the critical reflections in each profile had to be visually correlated profile by profile throughout nine different adjoining and sometimes overlapping GPR grids and "tied" at each perpendicular transect intersection to assure consistency. Subsurface elevations along each profile were then plotted on a grid map and contoured both by hand and using a computer mapping program to reveal the three-dimensional topography of the buried living surface (plate 1). The final maps were produced from more than 475 reflection profiles covering a surface area of more than 4 hectares. This time-consuming interpretation process ultimately produced good subsurface maps that were an accurate guide for the placement of archaeological excavations that could test features of interest.

The topographic, stratigraphic, and archaeological complexity at this site necessitated this type of manual data interpretation, which, if it were conducted elsewhere, would have to be budgeted for, in both time and money. Although some computer-processing programs claim to be able to automatically correlate reflections from profile to profile within grids, the stratigraphic complexity usually encountered at most archaeological sites makes this type of "automatic" interpretation tenuous at best. When clients or archaeological colleagues hear how time-consuming this type of GPR data processing can become, they are usually either totally enthralled with the amazing detail that can result or discouraged to think about what it might cost in time and money to reach a viable conclusion.

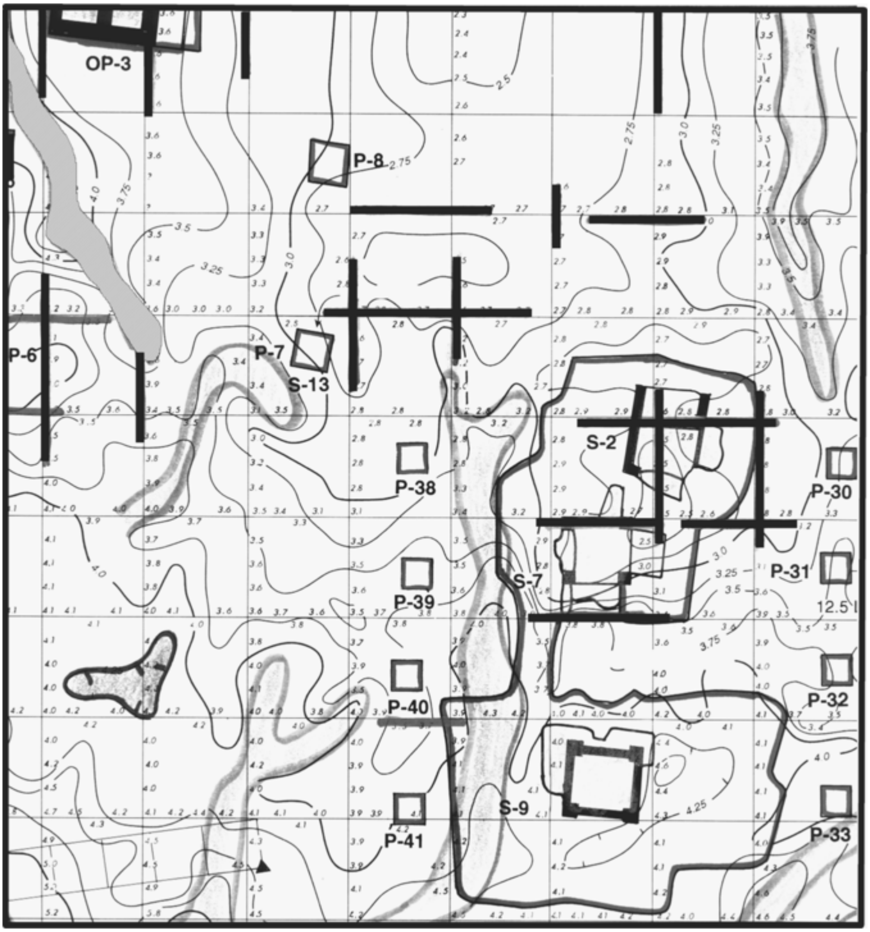

FIGURE 7.8
Hand Mapping of Reflection Profiles in a Grid. Many reflection profiles in a grid were manually interpreted, and those of importance were noted to produce a map of the buried landscape and cultural features built on it. This subsurface map of a portion of the Ceren site in El Salvador shows many water channels and house platforms.

In contrast to the above laborious processing method, a more recent GPR survey at a very complex buried site at Petra in Jordan covering an area of more than 80 × 50 meters was acquired in two days and produced a data set that generated usable and important results in about two additional days of data processing, using the amplitude analyses techniques discussed later in this chapter (Conyers et al. 2002). The reflection data at Petra, however, are so complex and potentially interesting that they still deserve months of manual interpretation in order to derive all the information that is contained in them. It is doubtful this will ever occur. This typical scenario of "GPR data overload" can be both a blessing and a curse, depending on the processing and interpretation time that can be budgeted for, the questions that need to be answered, and the resources available. Sometimes difficult decisions must be made as to how much information can or must be gathered from each grid of GPR data collected. Often only a small fraction of the subsurface information that GPR data can potentially yield is extracted from each survey, leaving many hundreds of CDs and other storage media filled with potentially important data just waiting for hypotheses to be generated and tested, time for interpretation, and usually funds to pay for it. When time is not available for the type of manual profile analysis conducted at the Ceren site, some combination of manual and visual processing can still be combined with the amplitude analysis techniques discussed here in order to produce very usable and accurate maps and images, which can often be produced and interpreted in a matter of hours.

AMPLITUDE ANALYSIS IN SLICE MAPS

The primary goal of most GPR surveys in archaeology is to identify the size, shape, depth, and location of buried cultural remains. The most straightforward way to accomplish this is by identifying important reflections, correlating them within two-dimensional reflection profiles as discussed earlier, and then mapping them, but this can be very time-consuming and sometimes inaccurate. A more sophisticated type of GPR data manipulation is amplitude slice map analysis that creates maps of reflected wave amplitude differences both spatially and with depth in a grid (Conyers and Goodman 1997; Goodman 1996; Goodman et al. 1998). The result can be a series of maps that illustrate in three dimensions the location of reflection anomalies, derived from a computer analysis of many two-dimensional profiles. What is being mapped in this method are the amplitudes of reflected waves (and their recorded depth in the ground), which are proxy measurements of the differences in materials at buried interfaces that reflect the radar energy. This method of data processing can only be accomplished by a computer using GPR reflection data that are stored digitally.

Raw reflection data collected in most GPR studies are nothing more than a collection of many hundreds of thousands of individual reflection traces along two-dimensional transects within a grid. Each of those reflection traces contains a series of waves that vary in amplitude depending on the intensity of energy reflection that occurred at buried interfaces. When these traces are plotted sequentially in standard two-dimensional profiles, the specific amplitudes within individual waves that contain important reflection information are usually difficult to visualize, and interpretation can be arduous. Also, in the past when raw; unprocessed GPR reflection profiles had no discernible reflections or recognizable anomalies of any sort, the survey was usually declared a failure, and little if any further interpretation was conducted. Only with the advent of more powerful computers and sophisticated software programs in the mid-1990s that could manipulate large sets of digital data was important subsurface information in the form of amplitude changes at various depths within a grid extracted from tens or sometimes hundreds of individual profiles possible. This method can produce three-dimensional packages of amplitudes, which can be analyzed in bulk, quickly producing maps and images of important high (or sometimes low) amplitudes that were generated from buried archaeological or related geological features of interest (plate 2).

An analysis of the spatial distribution of the amplitudes of reflected waves is important because it is an indicator of subsurface changes in lithology or other physical properties of buried materials. The greater the amplitude of a reflected wave, the greater difference in physical and chemical properties of materials at a buried interface reflecting that radar energy. Areas of low-amplitude reflections usually indicate uniform matrix material or soils, while those of higher amplitude denote areas of high subsurface contrast such as buried archaeological features, voids, or important stratigraphic changes. In order to be correctly interpreted, amplitude differences must often be analyzed in horizontal slices that examine only changes within specific layers in the ground.

Each amplitude slice of a certain thickness is comparable to an arbitrary archaeological excavation level, except using GPR data each level consists of a spatial representation of reflected wave amplitudes instead of sediment, soil, or feature changes and associated artifacts. In plate 2, stone foundations of buried buildings, which contrast with a wind-blown sand matrix, produce high amplitudes, which are readily apparent in amplitude slice maps. This example, from the Petra site, in Jordan (Conyers et al. 2002) had excellent velocity contrasts at the interfaces between the architectural stone and the surrounding sand, producing very high-amplitude reflections at their interfaces, which could be easily interpreted.

When spectacular GPR maps, such as those shown in plate 2, are used as an example of what GPR can do there is always the hope that similar data processing and image production at less definitive sites will produce similar results. Often this is not the case. Although amplitude slicing will produce excellent maps in some cases, or marginally usable maps in others, using only this technique for interpretation is usually not enough. It is a mistake to produce only generic slice maps in the hope that what one is searching for will immediately appear in the resulting images. Slice maps cannot be made automatically, like having photographs developed, but must be constructed thoughtfully and adjusted for various site parameters such as depth of interest, dimension and orientation of buried features, and the nature of the surrounding matrix. Their production therefore requires some prior knowledge of site conditions and often a detailed analysis of individual reflection profiles that have been used to produce the maps, all of which have hopefully been processed and filtered in some way to improve reflection data quality. Raw reflection data should also never be given to someone to slice who is not familiar with their collection, as they will have limited knowledge about site conditions and may therefore not be able to determine the correct slicing parameters or be able to interpret the results.

The most powerful way to utilize amplitude slice maps is to first view and interpret individual reflection profiles in two dimensions to "get a feel" for the types of reflections present and their depth in the ground. Velocity analysis using hyperbola fitting can be done at this time, if velocities are not already known, so that the depth of visible reflections in the ground can be determined. Slice maps can then be constructed of the number and thickness necessary to produce maps of the reflections that were generated from buried features or stratigraphic layers of interest. Once they are constructed, such as those in plate 2, for many horizontal or subhorizontal slices in the ground, reflection profiles can then be viewed again and reinterpreted to more precisely define the origin of amplitude features seen in the maps. In this way, the orientation, thickness, and relative amplitudes of anomalies are readily interpretable in three dimensions using both slice mapping and two-dimensional profile interpretation.

Amplitude slices are usually made in equal time intervals, with each slice representing an approximate thickness of buried material in the ground. They are always constructed in radar travel times, which can later be converted to depth if velocity analysis has been performed. Viewing amplitude changes in a series of horizontal time slices in the ground is therefore analogous to studying geological and archaeological changes of equal depth layers (Conyers et al. 2002; Goodman et al. 1995; Malagodi et al. 1996; Milligan and Atkin 1993). When amplitude anomalies in each slice are then correlated to known archaeological features and stratigraphic changes that might be available for study in nearby excavations, extremely accurate three-dimensional maps of a site, broken down into levels, can be constructed. In addition, a grid of GPR reflection data may be sliced very thinly and viewed as a video, with slices projected sequentially on a computer screen as layers are “uncovered” from the ground surface to some depth in the ground (Conyers et al. 2002; Grasmueck et al. 2004). The precise location of all reflections in the ground, if processed into many sequential slices, can also be analyzed as a three-dimensional “cube” of data and certain amplitudes rendered to produce realistic images of the subsurface as three-dimensional objects called *isosurfaces* (Conyers et al. 2002; Goodman et al. 1998; Heinz and Aigner 2003; Leckebusch 2003; Leckebusch and Peikert 2001), which will be discussed in more detail later.

Amplitude anomaly maps need not be constructed horizontally or even in equal time intervals. They can vary in thickness and orientation, depending on the archaeological and geological questions being posed. Surface topography and the subsurface orientation of features and stratigraphy of a site may sometimes necessitate the construction of slices that are neither uniform in thickness nor horizontal. They can also be construed to follow one distinct horizon (Conyers and Goodman 1997). This can easily be done on the computer when reflection data are in a digital format.

To compute horizontal amplitude slices the computer programs must compare amplitude variations within reflection traces that were recorded within a defined time window from all profiles in a grid (Conyers and Goodman 1997: 153). Usually computer programs that perform this task will ask for the amount of spatial correlation and interpolation desired for each grid, consisting of many reflection profiles. This process interpolates amplitudes of reflected waves along profiles and between them, producing a grid of data for each slice that can then be mapped. When this is done, both positive and negative amplitudes of reflections are compared to the mean within each slice. Usually no differentiation is made between positive or negative amplitudes, only the magnitude of amplitude deviation from the average. Low-amplitude variations within any one slice denote little subsurface reflection at that level and location and therefore indicate the presence of fairly homogeneous material. High amplitudes indicate the presence of significant subsurface discontinuities, in many cases buried features, as they are produced by reflection at the interfaces between highly contrasting material types. Degrees of amplitude variation in each slice are then assigned arbitrary colors or shades of gray along an ordinal scale, which can be varied to enhance higher, middle range, or lower-amplitude areas at each slice in the ground. Usually there are no specific amplitude units assigned to these color or tonal changes, as "natural" amplitudes are usually preadjusted prior to collection or modified after data are gathered by range gaining or other data processing steps. A crude form of amplitude adjustment, similar to range gaining, can also be performed after the maps are made by altering the range of values that are assigned different colors or shades of gray in each slice map. This will effectively enhance some amplitude values, while suppressing others, to make some features more or less visible to the human eye.

It must be remembered that because most subsurface layers are not perfectly horizontal, and most stratigraphic units vary in thickness laterally, some horizontal time slices may not be comparing reflection amplitudes within the same soil or sediment units in the ground (Beres et al. 1999). For instance, if the programmed amplitude slices cross stratigraphic boundaries of units that are dipping in the ground, there will be an amplitude anomaly registered where the slice crosses the stratigraphic boundary (plate 3). The resulting amplitude map derived from this slicing geometry would therefore be illustrating subsurface changes that are the product of the slicing method and the geologic changes across slices, and not the presence of the types of buried archaeological features that are the target (plate 4). When this occurs, amplitude slice maps can be potentially very misleading and are not illustrating either meaningful geological or archaeological changes. Some interpreters have attempted to characterize the shapes and sizes of anomalies produced by slices that cross-cut geological layers of different sorts, with little success (Beres et al. 1999).

Topographic and cross-cutting complications can often be adjusted for if the orientation and thickness of the subsurface layers are known, which can usually be determined by interpreting processed reflection profiles before slicing. The slicing problem illustrated in plates 3 and 4, where amplitude slices cross stratigraphic boundaries, demonstrates how multiple interpretation techniques including slice mapping and profile interpretation should always be employed in an iterative fashion.

The spacing of profiles and the amount of interpolation between profiles during slice map construction will often determine the resolution of the resulting reflection amplitudes when plotted in map form (Neubauer et al. 2002). If too much interpolation over a large search area is used, amplitude maps will tend to become blurred and feature definition decreases (plate 5). In contrast, a very small search radius and therefore little spatial interpolation can sometimes create a very "noisy" or "busy" amplitude map, and features may remain hidden in the clutter, if the reflections derived from features of interest are not distinct enough from those generated by the surrounding matrix.

A great deal of thought must also go into data processing of individual reflection profiles prior to slicing. Often reflection hyperbolas must be migrated and reflection data filtered before the amplitude slicing step. Then slicing parameters must be chosen including slice thickness, orientation, interpolation radius, and gridding method. Some slicing parameters might generate very accurate and usable maps, while others generate outcomes that may be totally uninterpretable, depending on the data quality, orientation of features in the ground, and stratigraphic complexity. With both experience and experimentation, the infinite number of potential processing parameters can be reduced to a few that have been found to work in certain conditions.

Often many different slicing methods must be attempted and studied before a usable map is obtained. In addition, each grid of GPR data collected during different field projects, each with different equipment and acquisition settings, will always necessitate different types of amplitude analyses using different slicing parameters. This tends to make GPR data collection, processing, and interpretation complicated, but exciting and rewarding, too, as each can potentially yield different results depending on the processing techniques. When this occurs, it is important to determine whether the maps are illustrating what is really present in the ground, or whether one is creating anomalies that are a function only of the slicing techniques used. This can only be done by going back and viewing the individual reflection profiles and visually correlating the reflections visible there to those plotted in the amplitude maps.

Amplitude Slice Maps on Level Ground

When the ground surface and underlying units are horizontal, or nearly so, amplitude time slices that are constructed parallel to the ground surface will usually follow stratigraphic and soil layers and therefore not cut across bed boundaries. It is only when the slices cross bedding planes that anomalous amplitude regions are produced, as illustrated in plates 3 and 4. As long as bedding units are parallel and there are no cross-cutting relationships between units, such as cut and fill channels or intrusive anthropogenic features, each horizontal slice will produce images of archaeological features that are relatively older with depth. Amplitude time slices can then be representative of relative age, as deeper slices will show features that were constructed prior to those visible in shallower slices.

At a historic site in Albany, New York, maps of the city were available showing the location of buildings present on town lots, going back to the year 1857. Amplitude slice maps were then constructed in 25-centimeter depth slices (after velocity analysis was performed), and images of the buried features visible in the GPR maps were compared to the historic lot maps (plate 6). The slice from 50- to 75-centimeter depth shows the building foundations whose location compared almost exactly to domestic structures and a large kiln that were present in 1890. In progressively deeper slices, those 1890 buildings were still visible, but deeper foundations from older structures were also visible in the slice in the 150- to 175-centimeter depth (plate 6). When the locations of those features were compared to the oldest historic maps from 1857, no correlation was found to any mapped structures. The deeper slices were therefore producing images of buildings that were present prior to the construction of any maps of the city. They are awaiting excavation, and their age and function remain unknown.

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

Amplitude Slices on Uneven Ground

When the ground surface changes a good deal over a grid, it is important to collect elevations within that grid so that profiles, and amplitude time slices, can be adjusted for topography. This is especially important when stratigraphic boundaries do not parallel the ground surface but may follow some other orientation. For instance, if a small burial mound was constructed by piling up horizontal soil in layers, amplitude time slices that were produced parallel to the present ground surface would cross many of those bed boundaries, creating anomalous amplitude values that would be meaningless in the resulting maps.

To test this concept, two series of amplitude time slices were constructed at a geophysical archaeology test site in Illinois (Isaacson et al. 1999). At this site, two burial crypts were constructed in 1998 to simulate human burials (even including pig carcasses to simulate human remains). A mound was then constructed of roughly horizontal layers of soil over the crypt. Reflection profiles were collected using 400-megahertz antennas in 25-centimeter spaced transects over the mound. The easiest way to produce amplitude slice maps of this feature is to construct each slice parallel to the ground surface, but by doing so, the slices cross-cut many of the boundaries between horizontal soil layers in the mound (figure 7.9). The resulting 25-centimeter thick amplitude slices constructed in this way produced a series of concentric high amplitude areas in many of the slices, with each high-amplitude ring in the maps denoting the location where those slices crossed the horizontal bedding boundaries (plate 5). Those slices that are not corrected for topography are therefore illustrating amplitudes that have no validity to what is buried below the surface and are the function of incorrect slicing geometry.

When data from the same grid is sliced horizontally after topographic corrections, each amplitude time slice is parallel to the bedding surfaces created by

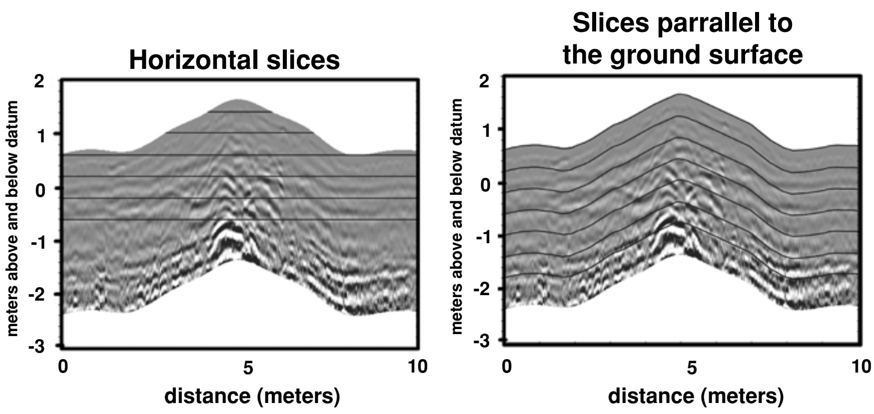

FIGURE 7.9
Slicing Choices in Topographically Complex Areas. This reflection profile over a mound with significant topographic relief can be sliced horizontally or in slices parallel to the ground surface. The slices parallel to the ground surface cross bedding boundaries and produce anomalous reflection readings in slice maps. When profiles are adjusted for topography and then sliced horizontally, each slice is parallel to the horizontal bed boundaries, producing a more realistic series of slice map images, which are shown in plate 7.

the mounding up of soil over the crypts. The slices do not therefore cross horizontal soil units, and no anomalous amplitude readings are created (plate 7). The deeper slices cross the crypts themselves, and high amplitude anomalies are produced in the exact location of the void spaces and crypt edges within the mound.

To create the topographically adjusted slices, the mound had to be topographically surveyed with a transit, with each survey point used to adjust reflection profiles for surface elevation changes. This can be a laborious process, but necessary, if detailed and accurate maps are to be produced. Some GPR systems are in development that will automatically collect surface elevations as well as horizontal locations in a grid using Global Positioning System (GPS) technology, which will allow immediate data corrections of this sort.

Subtle Feature Discovery with Amplitude Mapping

Often reflection profiles can be difficult to interpret, even after filtering, postacquisition processing, and the production of many profile views with differing vertical and horizontal exaggeration. There is often a temptation when one looks at reflection profiles such as the one in figure 7.10 to give up and call the survey a failure as no amplitude changes are readily visible in it. The profile in figure 7.10 was collected with 900-megahertz antennas in a boggy area in the California Sierra Nevada Mountains. The goal was to map recently deposited sedimentary units in the hope of defining fluvial, marsh, and floodplain sediments that might have been present in the mid–nineteenth century. Historic records indicated that the ill-fated Donner party, a wagon train that was immigrating to California and attempting to cross the mountains in November 1846, camped near a creek in the study area and were stranded there all winter. Many eyewitness accounts reported that the survivors found themselves in a bog in the spring of 1847 when the snow melted. Finding the remains of that camp today is complicated because the environment has changed a great deal, and it is now on the edge of a reservoir that was flooded in the 1960s. It was hoped that an analysis of the historic environment as it existed during the time of the Donner party encampment might yield clues to where the winter campsite was located, as it was known there was a small creek nearby in the early winter, and the area became a bog in the spring. The GPR method was considered because even though almost all the prospective area is today wet and boggy, similar environments with an abundance of peat beds had proven excellent areas for GPR mapping in Scotland (Clarke et al. 1999; Leopold and Volkel 2003).

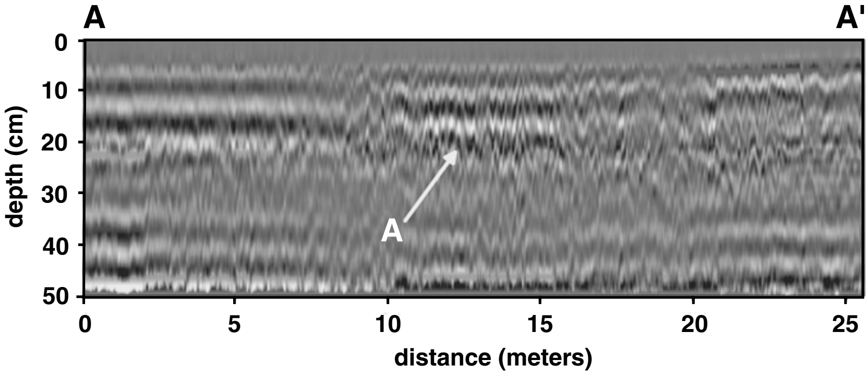

FIGURE 7.10
Reflection Profile with No Distinctive Reflections. This profile was collected in a shallow wetland area near Truckee, California. Little variation is apparent in the reflections, but some changes in amplitude are noticeable as an area of small reflection hyperbolas (A). This profile (A-A′) is located on the amplitude slice map in plate 8.

The reflections in the 900-megahertz profiles that crossed the present-day bog proved to be noisy and discontinuous, and few good reflections were visible that could be readily interpreted (figure 7.10). There are, however, changes in the reflection character along profiles, with some areas containing few good reflections and others that appear to contain many very small hyperbolic reflections, especially within the upper 20 centimeters of the reflection profiles. As little interpretation could be done using the individual profiles, it was decided to study the amplitude changes spatially within all the profiles in the grid to determine if there were any patterns to the distribution of these reflections either spatially or with depth.

When the amplitudes in all the profiles in the grid were studied in slice maps, one sinuous area of higher-amplitude reflections was visible in the 10- to 20-centimeter slice (plate 8). After further study of the reflection profiles in two dimensions, it was hypothesized that the anomalously high-amplitude area corresponded to the presence of many small gravel clasts in a creek, each of which generated the small reflection hyperbolas at that depth. Auger holes were then dug on either side of the high-amplitude feature and within it (plate 8). A study of the sediments recovered from them showed that holes 1 and 3 consisted of silt and peat, with abundant charcoal, while the sediment in hole 2 was mostly sand and gravel and contained very little peat. This subsurface information confirms that the sinuous anomaly in the 10- to 20-centimeter slice represents a small sand- and gravel-filled creek channel. The areas adjacent to it, which are much lower in reflection amplitude, are areas where marsh and floodplain sediments were deposited.

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

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

A grid of 400-megahertz GPR reflection data was collected in the orchard, and horizontal amplitude slice maps were constructed every 25 centimeters in the ground, after radar travel times were converted to depth (plate 9). At the 75- to 100-centimeter depth, a distinct linear feature was discovered, and in the deeper slices, another linear feature crossing it at an angle. Modern utility maps show plastic water lines cutting through the orchard, which generated linear reflection anomalies. More interesting, however, was a 4-meter square high amplitude feature in the 75- to 100-centimeter depth, which was not correlative to any of the historic buildings that had been mapped in the vicinity. This feature was hypothesized to be a buried building floor, if for no other reason, than its perfectly square geometry.

Auger holes were dug both inside and outside the square feature, and no discernible difference could be seen in the two sediment and soil samples from the depth indicated in the amplitude slice map. Thinking that perhaps velocities, which had been estimated from hyperbola fitting of point source hyperbolas generated from the pipes, were incorrect, researchers placed a test excavation directly on top of one of the pipes to uncover it in order to confirm depth to a known object. The pipe was found at exactly the depth shown in the GPR maps, raising the confidence level of the velocity analyses and the resulting amplitude slice map depths. A more careful analysis of the soil and sediment stratigraphy in the excavations adjacent to and just below the pipe was then made. A 2-centimeter thick layer that was just a little sandier than layers above and below was found within the square GPR feature. When excavations were extended outward, this sandy layer was found to be overlain by broken pieces of flat sandstone, which were probably used as pavers in the floor of a small house or shed.

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

Amplitude Maps to Search for Vertical Features and Graves

Most often GPR mapping in archaeology is used to produce images of planar features such as buried house floors, important stratigraphic interfaces that are subhorizontal, or distinct geometric orientations of point source reflections, such as buried wall tops or stone circles. Vertical interfaces that might be found in grave shafts or other similar features are often more difficult to map, as most radar energy propagating into the ground from surface antennas is traveling parallel to the boundaries of interest, and little reflection therefore results. Vertical shafts that lead to tombs, however, are visible when amplitudes are mapped in slices, as noticeable reflection changes between the material that fills the shafts and that surrounding it. In Japan, shafts leading to burial tombs were visible as high-amplitude reflections in numerous slices stacked on top of each other

(Conyers and Goodman 1997: 184). Historic and prehistoric graves are also often visible in the same fashion (Bevan 1991; Davenport 2001a, 2001b; Davis et al. 2000; Nobes 1999; Strongman 1992).

In a historic cemetery in Colorado, many graves could be located by amplitude changes in a number of horizontal slices (plate 10), although these changes were difficult to identify in individual profiles (figure 7.11). In this case, the graves were found by analyzing the lowest amplitudes, as the grave shafts were filled with homogenized back fill material. This occurred because during their excavation, the natural stratigraphy in the ground was destroyed, producing fewer high-amplitude reflections in the refilled shafts than the surrounding intact units.

If graves are excavated into sediment that is layered, the layers outside the grave shaft will retain their natural stratigraphy, while the material placed back into the grave will be homogenized, producing a distinctive disruption in layering (figure 7.11). Sometimes these truncation features are visible in amplitude slicemaps, but often profiles must be processed and analyzed individually, and the location of these features hand-plotted on maps as they are identified in each reflection profile. Any human remains preserved within them will probably not be visible, as they may not contrast enough with the surrounding material.

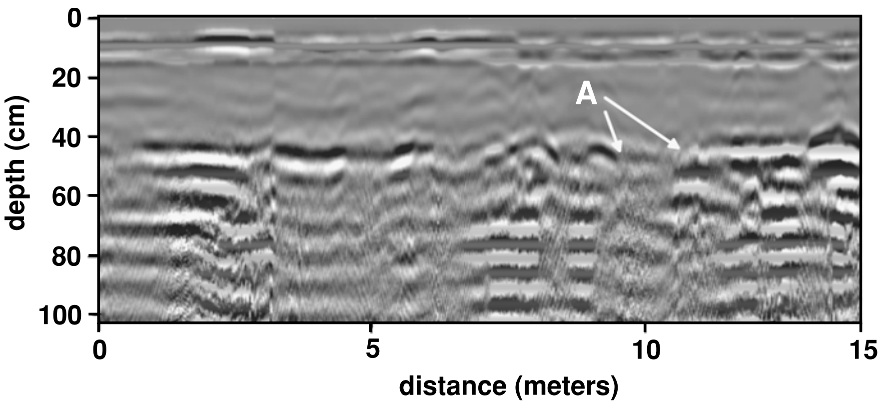

FIGURE 7.11
Stratigraphic Truncation in a Cemetery. This reflection profile was collected in an historic cemetery near Boulder, Colorado, where only the vertical shaft is visible as an area of low amplitude. Truncations of the stratigraphy by the vertical shaft are visible at locations (A).

When graves contain coffins that have not collapsed and retain some void space, they are readily visible in profile as distinctive reflection hyperbolas (figure 7.12). The hyperbolic reflections are often high in amplitude, and if the hyperbola axes are migrated back to their sources, very distinct images of graveyards can be made, with various coffin sizes and depths of burials differentiated. Often reflection profiles and amplitude slice maps in these cemeteries are distinct enough to determine the difference between adult and child burials by the size of the coffins and depth of burial. Whether coffins were lined with metal can also be determined by whether they have the distinctive multiple reflections common for buried metal.

Production of Rendered Images

The unique ability of GPR systems to collect reflection data in a three-dimensional package lends itself to the production of a number of other three-dimensional images not possible using other methods (Conyers et al. 2002; Goodman et al 1998, 2004; Heinz and Aigner 2003; Leckebusch 2000, 2003). If reflection data are collected in a grid of closely spaced transects, and if there are many reflection traces gathered along each transect, reflection amplitudes can be accurately placed in three dimensions and then rendered using a number of visual display programs. In this way, GPR data from archaeological sites become analogous to many other imaging techniques used in other disciplines, which

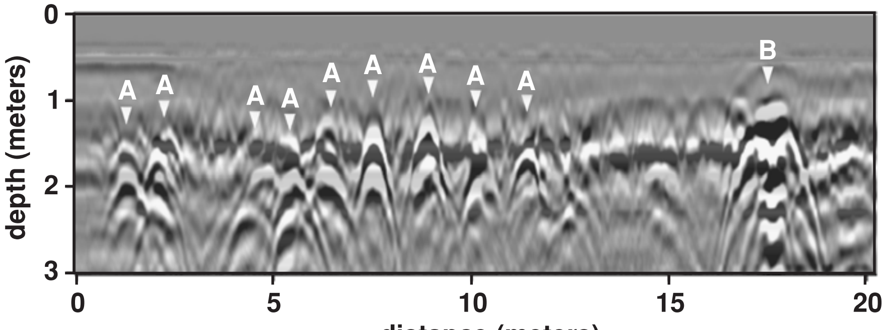

FIGURE 7.12
Graves with Distinct Reflection Hyperbolas. Each casket (A) is visible as a distinct reflection hyperbola, probably generated from void spaces within. A very large casket, composed of or lined with metal, is visible at location B. Reflection data were collected at the Military Cemetery at Fort Vancouver, Washington.

rely on energy sources such as sonic waves and magnetic resonance. In medical imaging complex, three-dimensional techniques can produce images of certain amplitudes derived from these energy sources to display internal body parts, or even electrical impulses in the brain as a function of different stimuli. In archaeology, radar reflections can be used in the same way but instead produce images of buried cultural features.

Using GPR data, buried features or interfaces can be rendered into isosurfaces, meaning that the interfaces producing the reflections are placed in three dimensions, and a pattern or color is assigned to specific amplitudes in order for them to be visible (Heinz and Aigner 2003; Leckebusch 2003). In programs that produce these types of images, certain amplitudes (usually the highest ones) can be patterned or colored while others are made transparent. Computer generated light sources, to simulate rays of the sun, can then be used to shade and shadow the rendered features in order to enhance them, and the features can be rotated and shaded until a desired product is produced.

These types of images have been denigrated by some as "too flashy," "without any practical value," or more like high-tech video games than archaeological geophysics. Humans, however, are visual animals, and we can often comprehend three-dimensional images much easier than reflections in profiles or standard amplitude slice maps. One of the goals of archaeological geophysics should be to "see into the ground," and what better way than to make an image of the ground that is representative of what a site would look like if totally excavated? Three-dimensional renderings can often be the most readily comprehensible of all GPR images for this purpose, especially for the nongeophysically initiated.

To produce rendered images with GPR profiles, all reflection profiles in a grid must first be processed and filtered to produce the "cleanest" final product possible. Background noise and interfering frequencies must be removed and important amplitudes from features to be rendered range gained to enhance their visibility. Hyperbolic reflections should also be migrated back to their origins. Many slice maps must then be produced in very thin time intervals, in order to produce layers of digital data in closely spaced parallel planes. If these slices are constructed too thinly, reflection waveforms can sometimes be dissected into many small meaningless packages, and the resulting amplitude values may contain only a part of each wave reflected, and not the wave as a whole. For instance, if there is a 20-nanosecond window over which reflection data were collected, and each reflected wave in the ground has a wavelength of about 2 nanoseconds (about average for a 400-megahertz antenna), then the most slices that should be

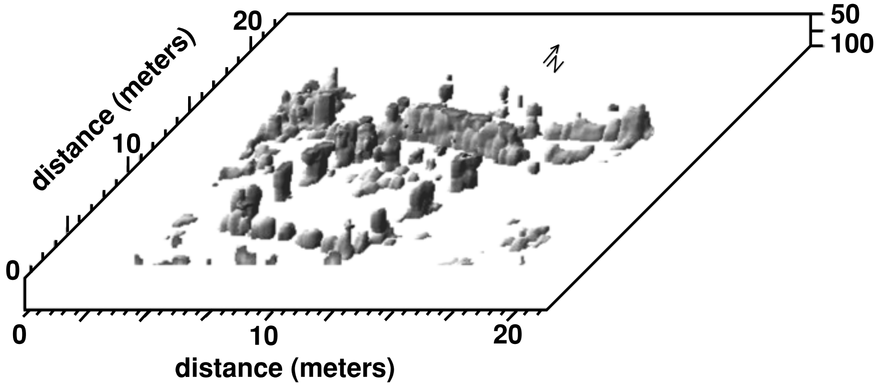

FIGURE 7.13
Three-Dimensional Rendered Surface. This is a three-dimensional rendering of the buried building at Petra, Jordan, shown in the slice maps in plate 2. The highest-amplitude reflections are rendered in their three-dimensional location, and artificial light is projected to make the features more visible.

generated (and not dissect the waves into many pieces to obtain amplitudes) would be 10. For this reason, a running average may be preferable for creating a large three-dimensional database for rendering, where a 20-nanosecond window of reflections is dissected into 40 horizontal slices, each 3 nanoseconds in thickness, but overlapping the adjoining slices by a nanosecond or two. There would be some averaging of the amplitude data in this method, but a greater likelihood that complete waveforms will be averaged in each slice, and then made visible by rendering. Grasmueck et al. (2004), however, have shown that in some contexts very thin slices with no overlap can still produce good images.

When the buried structure from Petra in plate 2 was sliced thinly in this fashion, and only the highest amplitudes were rendered into an isosurface, a very distinct image of a buried building was constructed (figure 7.13). In this rendering, the shallowest slices were not included, as they contained many small point source reflections from shallow rock rubble. The very deepest slices were also not included, as the data from that depth tended to be noisy and resulted in high-amplitude streaking in the rendered images (Conyers et al. 2002). These reflection data were ideal for rendering because most of the reflections collected in the grid were generated from buried architecture, and the surrounding wind-blown sand matrix generated almost no reflections of any amplitude. Once the rendering was constructed on the computer, it could also be rotated or tilted in a number of different orientations in a video display (Conyers et al. 2002).