Ground-penetrating Radar Techniques and Three-dimensional Computer Mapping in the American Southwest

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New techniques of ground-penetrating radar (GPR) acquisition and computer processing were tested at archaeological sites in the American Southwest and found to be highly effective in producing images of buried archaeological features. These new methods, especially amplitude slice-maps, were combined with more standard data processing and interpretation techniques and tested at sites with little or no surface expression. In southern Arizona, numerous pit structures buried in terrace alluvium were discovered and mapped. In the Four Corners region, a Chaco period great kiva and other pit structures and features were mapped by GPR and later confirmed through excavation. At some sites, GPR surveys did not successfully identify buried archaeological features. These failed surveys highlight both geological and methodological problems including soil conditions, surface disturbance, and equipment calibration that may be avoided or ameliorated in future GPR surveys.

Introduction

The American Southwest is a region with abundant archaeological remains that are under constant threat from development activities including roads, pipelines, electrical transmission lines, and new housing projects. In much of the Southwest (FIG. 1), archaeological remains are buried, often leaving no trace of prehistoric houses, storage pits, and other features that are hidden below the surface. This situation creates an enormous problem for developers who often must, by law, evaluate the impact of planned projects on archaeological sites. Archaeologists who are contracted to determine whether archaeological sites are present in an area slated for development must usually make their assessment based only on surface remains, or sometimes limited subsurface excavation. This leaves many buried features undetected and hidden sites may be destroyed before their presence can be detected. A similar problem exists for research archaeologists who must interpret sites based on only a small excavated sample, especially at large sites, where an understanding of site layout and organization is limited.

Ground-penetrating radar (GPR) offers a rapid and inexpensive method for identifying subsurface archaeological features without excavation. Although the technique has been used for archaeological exploration and mapping since the 1970s, recent advances in GPR equipment and the computer processing of geophysical data have revolutionized its effectiveness. Until a few years ago, GPR was used simply to identify subsurface "anomalies" that may or may not represent archaeological features. Today, computer mapping techniques have been developed that produce sharp three-dimensional images of subsurface features over large areas. Geophysical maps have become not only a tool for discovering buried archaeological materials, but also a key part of archaeological data recovery and a powerful research tool.

Previous researchers have reported on the effectiveness of GPR in the Southwest in some preliminary geophysical surveys (e.g., Sternberg and McGill 1995; Vickers and Dolphin 1975). We suspected that new GPR equipment and especially some recently developed computer processing techniques would be able to build on these studies and

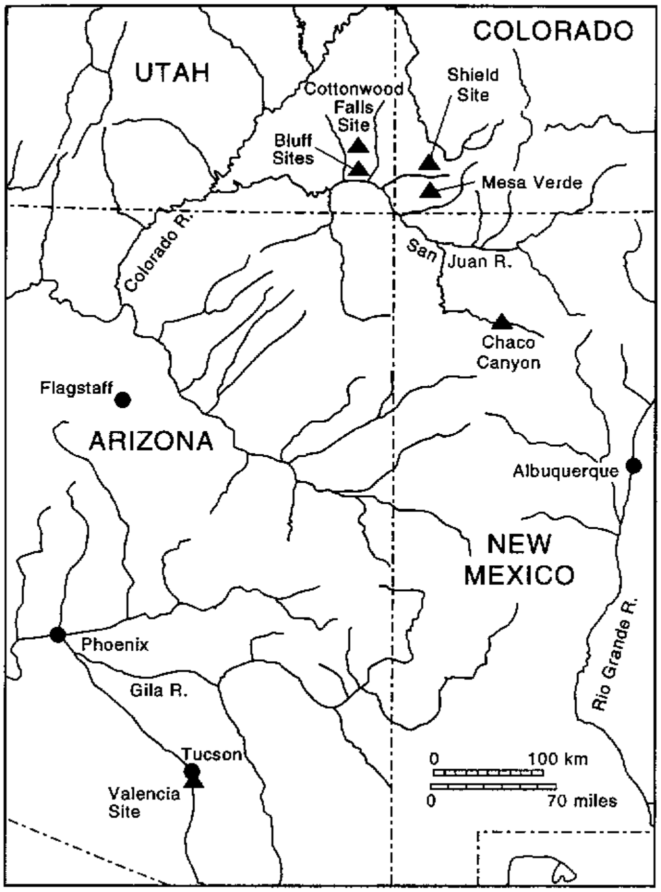


Figure 1. The American Southwest, showing archaeological sites where GPR surveys were conducted. The Bluff Great House, Southwest Bluff and Vaughan sites are located in the town of Bluff, Utah.

expand archaeologists' ability to use this powerful subsurface mapping tool.

Seven archaeological sites were chosen for GPR testing, three of which had been excavated before GPR data were collected, or were excavated immediately afterward so that the accuracy of images could be evaluated. We discovered that the GPR method is extremely valuable for locating and mapping buried archaeological remains at Southwestern sites. At three of the seven sites that were tested, excavations confirmed that GPR images accurately replicated the buried features. Certain geological and climatic conditions and equipment calibration errors, however, inhibited the collection of effective data for a variety of reasons at four of the other sites. We found that one critical factor to survey success is a knowledge of local geologic and climatic conditions prior to conducting the survey. When these conditions are known in advance, equipment can be correctly adjusted prior to collecting data and appropriate processing and interpretation techniques used later. This article reports on the results of this testing program and evaluates the methods employed.

Ground Penetrating Radar Use in Archaeology

Ground-penetrating radar was first used by archaeologists at Chaco Canyon, New Mexico (FIG. 1), to discover the location of walls covered by wind-blown sediment (Vickers, Dolphin, and Johnson 1976). These and other early GPR surveys used analog equipment that recorded unprocessed radar reflections on magnetic tape or printed them on paper. Archaeologists usually had to search paper records looking for "anomalies" that might represent radar reflections from buried features. This method was used successfully throughout the 1970s and 1980s to discover features as diverse as barn walls, underground storage cellars (Bevan and Kenyon 1975; Kenyon 1977), tunnels (Fischer, Follin, and Ulriksen 1980), Maya house platforms (Sheets et al. 1985), and house foundations and graves (Vaughan 1986).

In the mid-1980s digital GPR systems, which had the capability of storing, filtering, and processing large amounts of data with the use of computers became more common, producing high quality reflection profiles (Annan and Davis 1992). Large digital databases from many transects could be processed simultaneously within a grid, creating three-dimensional maps of sites (Goodman and Nishimura 1993; Goodman et al. 1994; Goodman 1996; Goodman, Nishimura, and Rogers 1995; Conyers and Goodman 1997: 149–194).

Today many archaeologists who employ GPR at their sites are still mainly concerned with identifying buried anomalies in individual transects that might represent features of interest. Although this type of GPR application is valuable because buried features can be immediately identified and excavated (or avoided), the technology now exists to process large amounts of digital data quickly and efficiently, producing large site maps in three dimensions, sometimes while still in the field. Some of these new techniques were used at the sites discussed in this paper and allowed us to study site layout and organization without extensive excavation.

Ground-penetrating Radar Methods

New techniques of GPR evaluated in this study allow for wide areal coverage in a short period of time, with excellent subsurface resolution. Some GPR surveys have been able to resolve stratigraphy and other features at depths in excess of 40 m, but more typically are used for mapping to depths between a few tens of centimeters and five meters.

Ground-penetrating radar data are acquired by transmitting pulses of radar energy into the ground from a surface antenna, reflecting the energy off buried objects, features, or bedding contacts and then detecting the reflected waves back at the ground surface with a receiving antenna. When collecting radar reflection data, surface radar antennas are moved along the ground in transects within a surveyed grid and a large number of subsurface reflections are collected along each line. As radar energy moves through various materials, the velocity of the waves will change depending on the physical and chemical properties of the material through which they are traveling (Conyers and Goodman 1997: 31–40). The greater the contrast in electrical (and to some extent magnetic) properties between two materials at an interface, the stronger the reflected signal (Conyers and Goodman 1997: 33–34). When travel times of energy pulses are measured, and their velocity through the ground is known, distance (or depth in the ground) can be accurately measured (Conyers and Lucius 1996). Each time a radar pulse traverses a material with a different composition or water saturation, the velocity will change and a portion of the radar energy will reflect back to the surface and be recorded. The remaining energy will continue to pass into the ground to be further reflected, until it finally dissipates with depth.

The GPR system used in this study was a Geophysical Survey System Inc. (GSSI) Subsurface Interface Radar-10 (SIR-10) that employed antennas housed in a fiberglass sled (FIG. 2). Radar energy is transmitted to and from the radar control system and computer by a cable. Other GPR systems are self-contained and connections between antennas and the computer are made with fiber optic cables (Conyers and Goodman 1997: 57–67).

A typical 50 m transect may collect 2000 or more individual reflection traces, which are a series of waves recorded from subsurface reflections at one location. Arrivals of reflected waves are measured in the time it takes a pulse to travel from the transmitting antenna, to the reflection surface, and back to the receiving antenna. These travel times

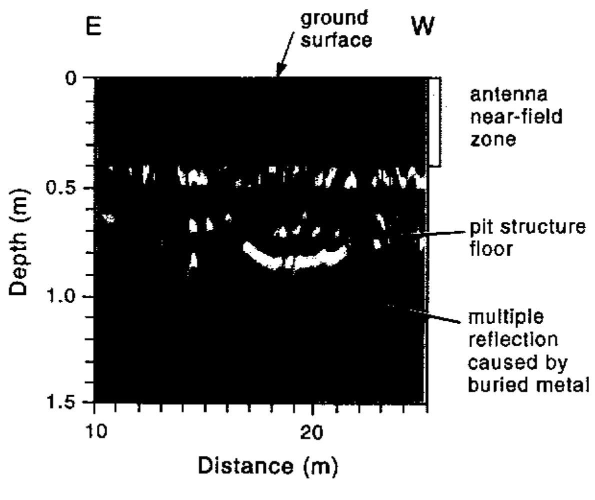
Figure 2. Collecting GPR data with 300 MHz antennas at the Bluff Great House site, Utah. Radar energy is transmitted from the base station (under umbrella on the right) to the antennas. The reflected data from below the surface is re-transmitted back to the base station in the same cable where it is recorded and can be viewed on a computer screen.

can be converted to depth if the velocity of the material through which they pass is known. Data are stored digitally on a computer and can be processed immediately, or after a survey is completed. When all the reflection traces collected in one transect are plotted horizontally, a two-dimensional profile of subsurface stratigraphy and archaeological features is produced (FIG. 3). Reflection profiles from many transects within a grid are then processed and correlated to produce an accurate three-dimensional picture of subsurface horizons and features.

The success of GPR surveys in archaeology is largely dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, and surface topography and vegetation. Electrically conductive or highly magnetic materials will quickly dissipate radar energy and prevent its transmission to depth. The best conditions for energy propagation are therefore dry sediments and soil, especially those without an abundance of clay. These sediments and soils are common in the Southwest, which is why the technique is so effective there. While these conditions are optimal, any low conductivity media will transmit radar energy, no matter what its moisture content (Conyers and Goodman 1997: 44–54). Deeply buried features may lie below the depth of maximum radar propagation and cannot be resolved. Heavily vegetated surface conditions, or a very uneven ground surface, can also negatively influence GPR surveys, making the transport of surface antennas difficult or impossible.

The depth to which radar energy can penetrate, and the amount of resolution that can be expected in the subsurface, is partially controlled by the frequency (and therefore the wavelength) of the radar energy transmitted (Conyers and Goodman 1997: 40–52). Standard GPR antennas propagate radar energy that varies in frequency from about 10 megahertz (MHz) to 1000 MHz. Low frequency antennas (10–120 MHz) generate long wavelength radar energy that can penetrate up to 50 m in certain conditions, but are capable of resolving only very large buried features. In contrast, the maximum depth of penetration of a 900 MHz antenna is about one meter or less in typical materials, but its generated reflections can resolve features with a maximum dimension of a few centimeters. A trade off therefore exists between depth of penetration and subsurface resolution. Archaeologists typically use antennas with frequencies between 100 and 500 MHz for the best resolution at depths ranging from one to five meters.

Figure 3. Ground-penetrating radar profile of a pit structure, Valencia site, Arizona. Vertical exaggeration 10:1.



The ability to "see" radar reflections on profiles is related to the amount of energy reflected and therefore the amplitude of the reflected waves. In many cases the human eye may not be able to discern some important low-amplitude reflections and therefore computer processing techniques must be used to enhance and define these more subtle features.

Reflection of radar energy from a buried surface that is not horizontal can either focus or scatter radar energy, depending on its orientation and the location of the antenna on the ground surface. If a buried planar surface is slanted away from the surface antenna or it is convex upward, radar energy will be reflected away from the receiving antenna and no reflection, or only a very low amplitude reflection, will be recorded (Conyers and Goodman 1997: 53–55). The opposite is true when the buried surface is tipped toward the antenna or is concave upward. Reflected energy in this case will be focused, and a very visible high amplitude reflection will be recorded.

Another limitation involves the creation of a "near-field zone." Energy radiated from a surface antenna generates an electromagnetic field immediately around the surface antenna (Balanis 1989; Engheta, Papas, and Elachi 1982). Within this zone "coupling" of the radar energy to the ground occurs and few, if any, reflections are produced. This phenomenon, called the near-surface zone of interference (Fisher, McMeechan, and Annan 1992) or the near-field zone (Conyers and Goodman 1997: 55–56), creates a layer just below the ground surface where little data are recorded (FIG. 3).

Once GPR data have been acquired in the field and recorded digitally on a computer, there is a wide range of data processing and interpretation techniques available to enhance and "clean up" the signal. Depending on the archaeological questions to be asked and the quality of the radar reflection data acquired, these processing techniques can be varied and modified to meet specific needs. In this study digital reflection data were in all cases computer-processed to filter out background noise and enhance the clarity of reflections derived from important features and specific stratigraphic horizons. For some sites, individual profiles were printed on paper, visually interpreted, and important reflections were correlated from line to line. For others, the amplitude slice-map technique was used. This method uses a newly-developed computer processing technique that correlates and compares reflection amplitudes in all profiles within a grid (Conyers and Goodman 1997: 149–195; Goodman 1996; Goodman, Nishimura, and Rogers 1995). This processing method can do in a few minutes what is much too time consuming to do manually. Both interpretation techniques were used at some sites in order to make accurate subsurface GPR maps.

Testing the GPR Method in the Southwest

Ground-penetrating radar techniques are especially useful in the Southwest because, for certain regions most archaeological features are deeply buried and are only recognizable as surface scatters of artifacts or, occasionally, a shallow depression. For example, domestic architecture among the ancient Hohokam of southern Arizona, prior to the Classic period (prior to A.C. 1100), consisted of shallow, ephemeral pit structures. These structures are rarely visible on the ground surface and can only be observed in profile after trenches have been excavated, which sometimes destroys some or all of the feature. In the northern Southwest, domestic architecture consisted of deep pit structures, constructed until about A.C. 700. Even after the development of above-ground structures, pit houses and other semi-subterranean structures (called kivas or great kivas) continued to be used for ritual and domestic purposes. Sometimes these structures are visible as depressions, but often they leave no surface indications.

We tested the effectiveness of the GPR technique at six archaeological sites in the northern Southwest and one in the southern Southwest. We used different data-processing techniques at each of these sites depending on geological conditions, the expected depth of archaeological features, and their size and assumed construction. Three of the seven sites yielded superior results, which are described below. Results from the remaining four, although producing few significant radar reflections, did provide important information about geological, climatic, and surface conditions that can influence optimal GPR results. From all tested sites, we learned a great deal about the use of GPR equipment most appropriate for different site conditions and, most importantly, how to customize the processing and imaging techniques in order to maximize results for the conditions encountered.

Valencia Site

The Valencia site is located within the southern city limits of Tucson, Arizona, and includes almost 5 km of archaeological remains along the east bank of the Santa Cruz River (FIG. 1). The site, part of the Tucson Basin Hohokam culture, was inhabited from as early as A.C. 600 to about 1300. The site is one of only two "ballcourt communities" (Wilcox 1991) remaining in this region (ballcourts were oval depressions used for ritual or community activities and may have been a version of the ritual ball game common throughout Mesoamerica).

Ground-penetrating radar tests were conducted in a portion of the Valencia site that will soon be subject to disturbance by expansion of the campus of a community college. In 1992, archaeological investigations conducted in advance of an earlier phase of campus development identified three loci associated with the prehistoric Valencia community (Huckell 1993). Initial assessment and testing of the loci included surface artifact collection, extensive backhoe trenching, and hand-dug test excavation units to look for specific archaeological features identified in backhoe trenches, which included pit structures and other extramural features. Backhoe trenches were typically 20 m long and spaced at 10 m and 20 m intervals across the portions of the site to be evaluated. Each trench was cut to a depth of at least 1.25 m, well below the level of prehistoric occupation. The backhoe trenches were later filled with the same material that had been removed.

The Valencia site provided an ideal opportunity to test the effectiveness of the GPR method because radar reflection data could be evaluated against the location of pit structures already identified in backhoe trenches. It was hoped that GPR might provide an alternative to the standard use of backhoe trenches to find archaeological features in the southern Southwest. Backhoe trenching is time consuming, costly, and destructive. Previous GPR studies nearby by Sternberg and McGill (1995) reported that Hohokam canals, trash pits, floors, and walls could be imaged in two-dimensional profiles. We wanted to conduct tests at the Valencia site to determine if recently developed three-dimensional imaging techniques could be used to provide better definition of these type of features.

In May, 1997, a 29 × 40 m GPR grid was established in the northern portion of Locus 2 of the Valencia site, in an area where four backhoe trenches had encountered 14 pit structures and a number of other extramural features in 1992 (Huckell 1993). The test area was located on the second river terrace above the Santa Cruz River. Undisturbed terrace sediments, observed in nearby gullies consisted of fluvial and alluvial channels containing poorly sorted clasts, with grain sizes ranging from fine silt to small cobbles, all highly cemented with caliche. This knowledge of the geological matrix and site burial conditions was critical in the interpretation of the GPR data.

The prehistoric pit structures excavated at Locus 2 in 1992 included both "houses in pits" and "pit houses" (Huckell 1993). Houses in pits consist of a shallow depression with a brush superstructure built inside the depression. Pit houses were deeper, oval pits with post holes for a wooden superstructure built outside the pit. The Locus 2 pit structures ranged from less than three to more than 6 m in maximum dimension. Floors consisted of hard packed earth or earth covered with clay plaster. After abandonment the pits gradually filled with aeolian sand and silt, and slope wash consisting of redeposited terrace sediments.

The ground surface of the GPR grid was covered with recent trash consisting of metal objects and concrete. Much of the trash was partially buried, indicating intense recent surface disturbance. Numerous small trees, bushes, and cacti, all containing thorns, also made GPR surveying difficult. Fifty-nine transects, spaced 50 cm apart, were collected using dual 500 MHz frequency antennas as transmitter and receiver (FIG. 4). Data collection was completed in approximately three hours. As individual lines were being surveyed, the unprocessed vertical GPR sections appeared on the computer screen and could be visually interpreted. No subsurface features were visible in the field and the initial results were very discouraging.

After returning from the field all lines were computer processed to remove background noise, which typically obscures GPR profiles with horizontal bands. This can be easily accomplished on the computer by arithmetically averaging all amplitudes that were collected at the same time in a profile and then subtracting the resulting wave from all reflection traces in the line. This process effectively removes all horizontal reflections and leaves only those non-horizontal (presumably geological or archaeological) reflections.

A second data filtering technique removed all recorded frequencies above 800 MHz and below 100 MHz in order to remove extraneous data that could have been caused by noise within the GPR system, FM radio transmission, cellular phone calls, and other noise common within the city. After this processing was finished each individual profile was printed on paper and radar travel times were converted to depth using approximate velocity conversions for caliche rich sandy gravel in southern Arizona (Sternberg and McGill 1995).

Continuous floors of pit structures were visible in profiles as high amplitude reflections (FIG. 3) located between 60 and 100 cm depth. The compacted earth or plaster floors, which are slightly concave upward focus the reflected energy and are immediately visible in the profiles. Small discontinuous reflections, produced from individual cobbles in the terrace gravels, were common throughout the profiles, but could be easily distinguished from the laterally extensive pit structure floors.

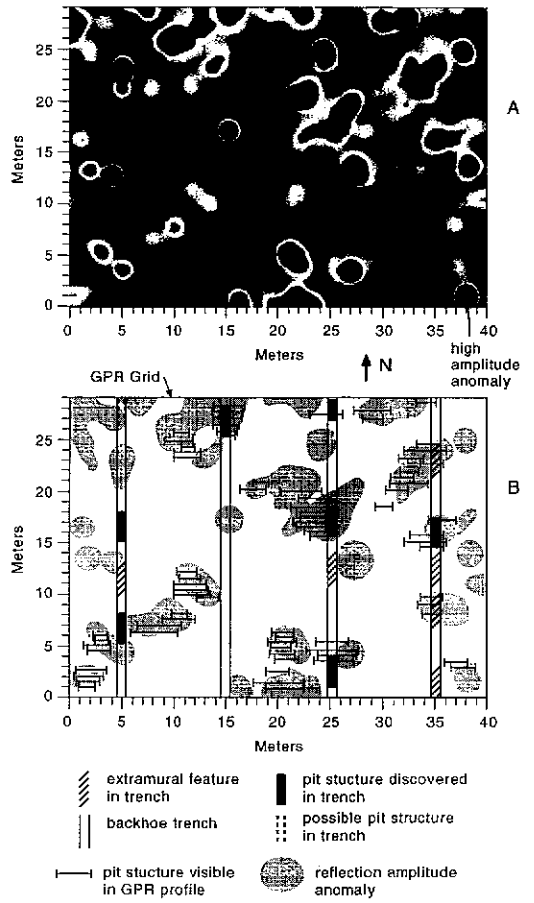


Figure 4. Amplitude anomaly map and interpretation, Valencia site, Arizona. Map A is the spatial distribution of high amplitude radar reflections in a slice from 50 to 100 cm below the surface. Map B is an overlay of these amplitude anomalies and the location of the pit structures visible in individual profiles. These are compared to the features that were visible in backhoe trenches.

The amplitude slice-map processing technique (Conyers and Goodman 1997: 149–194; Goodman, Nishimura, and Rogers 1995) was first applied to the processed data set in order to identify all significant high amplitude reflections between 50 and 100 cm depth within the grid. This is the depth at which the pit structure floors and other features were typically encountered in the backhoe trenches. This GPR processing method defined all significant reflections and mapped the spatial distribution of the reflected wave amplitudes within the defined slice. A resulting amplitude slice in the ground then becomes comparable to a map of an arbitrary excavation level in standard archaeological excavations, except the GPR map consists of a collection of reflected wave amplitudes instead of exposed archaeological features, sediments, soils, and artifacts.

Amplitude slice-maps are produced by comparing the relative amplitudes of the reflected radar waves that were recorded at certain depths and interpolating, gridding, and contouring them throughout the grid. The computer must compare many thousands of amplitude variations within all the profiles in a survey. The amount of interpolation between profiles and within lines dictates the resolution of the resulting anomalies when plotted in map form. In the Valencia site grid (FIG. 4) a 1.1 m search radius was used, meaning that the computer searched, compared, and interpolated amplitudes in a 1.1 m radius around each point in each line within the total grid.

When plotted in map form, low amplitudes in one area denote little subsurface reflection and therefore the presence of a fairly homogeneous material at the depth being analyzed. The clustering of high amplitudes in an area indicates significant and extensive subsurface reflection surfaces, in many cases detecting the presence and spatial distribution of pit structure floors.

Degrees of amplitude variation in the defined slice at Valencia were assigned arbitrary shades of gray along a nominal scale (FIG. 4). The presence of high-amplitude anomalies produced within the defined slice was then compared to the location of archaeological features discovered earlier in the backhoe trenches. Using this method 11 of the 14 known features were identified, although some were offset away from the test trenches because in most cases the backhoe did not encounter the middle of each feature. Numerous other amplitude anomalies were mapped between trenches that could be archaeological features, but could not be confirmed by the excavation data.

In order to understand what the computer was mapping as amplitude anomalies, all 59 individual transects in the grid were printed as vertical sections on paper. Potential pit structures that were visible as high-amplitude reflections at the same depth as the slice (similar to the floor imaged in Figure 3) were then plotted on the base map and compared to the location of the computer-generated amplitude anomalies (FIG. 4). This comparison showed that all 11 amplitude anomalies that correspond to structures discovered in the backhoe trenches also correspond to horizontal high-amplitude reflections visible in profiles. Other computer-generated amplitude anomalies not produced by reflections from archaeological features were probably caused by reflections from recent debris or geological variations in the sediment. Only one feature that was discovered in the backhoe trenches was not visible in the computer-generated amplitude maps or as a visible reflection in the profiles. In this case there may not have been enough velocity contrast between the feature and the surrounding matrix to produce a significant reflection, or the feature may have been partially destroyed during the earlier backhoe trenching.

Many of the computer-generated amplitude maps, and the reflections visible on profiles, project away from where they were encountered in the trenches. This situation occurs because the GPR maps are analyzing data in three-dimensions while the features visible in the narrow backhoe trenches are difficult to map spatially because only a small portion of the structure is visible in the trench.

The benefits of geophysical mapping at Valencia are even more important when considering the discovery of buried features that are visible using GPR but were not found in the backhoe trenches. At least 10 probable pit structures were discovered between the trenches that would not likely have been found without geophysical testing. Considering the amount of damage that trenching causes, the benefits of GPR mapping are significant.

Ground-penetrating radar mapping at the Valencia site highlights many of the problems that have plagued all types of geophysical archaeological mapping, and offers some possible solutions. The initial results obtained in the field were very discouraging because the data were extremely "noisy" and reflections were non-coherent. Only when the digital data were filtered and processed were reflections derived from the archaeological features identifiable. When the processed data were interpreted by computer using the amplitude slice-map technique, many more anomalies were produced than could be accounted for by the archaeological features known to exist. In this case a reliance on only computer interpretation would have produced a very misleading site map. To solve that problem, and to understand what the computer-generated map was producing, each individual line had to be manually interpreted and each mapped feature judged individually. When a comparison of the final computer and manually produced GPR maps were compared to the excavations, 85% of the known features were visible by GPR and their orientations in the ground were precisely mapped. In addition, at least 10 additional pit structures were visible by GPR that were not found in the trenches and would likely not have been discovered using traditional excavation methods.

Southwest Bluff Site

The Southwest Bluff site is located in the small town of Bluff in SE Utah (FIG. 1), an archaeologically rich area about 150 km west of Mesa Verde National Park. Prehistoric occupation of the area extends (discontinuously) from the

Paleoindian period through the end of the 13th century A.C., when large portions of the Four Corners area were abandoned. The Southwest Bluff site is located on the first river terrace above the San Juan River on a flat, sandy area with little vegetation. Local archaeologists had noticed surface scatters of ceramics and chipped stone here, as well as very low relief depressions that might be pit structures, possibly dating to the Basketmaker or early Pueblo periods (A.C. 700–1000).

Although no previous archaeological excavations had taken place at the Southwest Bluff site, the dry sandy substrate and the potential for buried archaeological features made it a suitable candidate for GPR tests. In June, 1996, a 30 × 50 m grid was established in an open area where abundant surface ceramics were visible. Prior to conducting GPR tests, the local stratigraphy was observed in a nearby excavation for a house foundation. The subsurface sediment consisted of friable, slightly calcareous cross-laminated fluvial sand and silt. The GPR equipment was first calibrated in this excavation by pounding a metal bar into the excavation wall, passing the radar antennas over the ground surface above the bar and measuring the elapsed time radar waves took to travel from the ground surface to the bar and back to the surface. These direct measurements yield both time and distance (depth) and allow for an approximation of the average radar velocity within the sediment (Conyers and Lucius 1996).

The GPR survey was conducted using 500 MHz antennas in transects spaced one meter apart. Because of surface obstructions, not all lines were the same length so the resulting grid was not perfectly rectangular. The ground was extremely dry when the survey was conducted, as the area had received no significant precipitation since minor winter snow storms many months earlier.

During GPR surveying unprocessed reflection profiles were viewed on the computer screen as they were collected. Portions of transects in the SW portion of the grid produced a distinctive horizontal reflection that appeared to be a pit structure floor, roughly circular in extent. Most significantly, it was not located in the area where the local archaeologists had noticed surface depressions.

All GPR data were computer processed to remove background noise and high and low frequencies, similar to data manipulation at the Valencia site. Radar travel times were converted to depth using the velocity data obtained from the nearby house excavation. The data were then processed using the amplitude slice-map technique to show amplitude anomalies from 80–100 cm in depth. The western portion of the resulting map is shown in Figure 5. The orientation of the high-amplitude anomaly shows a roughly circular floor outline, with a possible antechamber projecting to the north. A small portion of a similar anomaly was discovered at the same depth in the westernmost portion of the grid but continued under a large thorn bush and was not completely surveyed.

To test the origin of this high-amplitude horizontal anomaly, eight auger holes were drilled in and around the possible pit structure floor (FIG. 5). Three auger holes (holes 2, 3, and 6) penetrated aeolian sand that contained scattered ceramics and abundant charcoal and fire-cracked rock from near the surface to just above the floor of the probable pit structure. This sedimentary unit is probably wind-blown material that filled the pit structure soon after abandonment. Directly on the floor was burned adobe that may be roof fall. One small bone pendant and fragments of one broken piece of pottery were brought up in the auger tests from directly on the floor. The pottery sherds date to the Pueblo II period (A.C. 900–1150). The apparent pit structure floor was discovered in these three holes at almost the exact depth and location predicted in the amplitude slice-maps. Auger holes drilled away from the GPR anomaly (FIG. 5) encountered only a thin layer of aeolian sand with scattered broken ceramics, sitting directly on calcareous sand (probably a weak caliche horizon in fluvial sand), similar to the sediments visible in the nearby house excavation where the velocity tests were performed.

Ground-penetrating radar testing at the Southwest Bluff site clearly revealed a pit structure with a small antechamber. Similar pit structures are common in the northern Southwest, especially during Basketmaker III period and later (Cordell 1997: 233–238). The extent of the artifact scatter and one additional untested anomaly in the GPR maps suggest that there may be other pit structures nearby. Because subsurface conditions were ideal (dry sandy material), the archaeological features could be immediately imaged and their subsurface extent delineated while still in the field. The nearby velocity tests allowed for accurate conversions of radar travel times to distance, and the actual depth of the features could be measured.

The importance of local climatic conditions to GPR collection were vividly illustrated when the Southwest Bluff site was re-surveyed in October, 1997. The same GPR system was used to test whether the pit structure could be imaged after a heavy rain. In late September more than two inches of rain fell during the passing of a tropical storm. The night before the re-survey was conducted, about 1 cm of rain fell, making puddles on the surface. Data from this survey were processed in the same way as the earlier survey, but the pit structure floor was not visible. Instead the amplitude slice-map consisted of many high-amplitude reflections at different depths, which were probably generated by pockets of water differentially retained in sediments

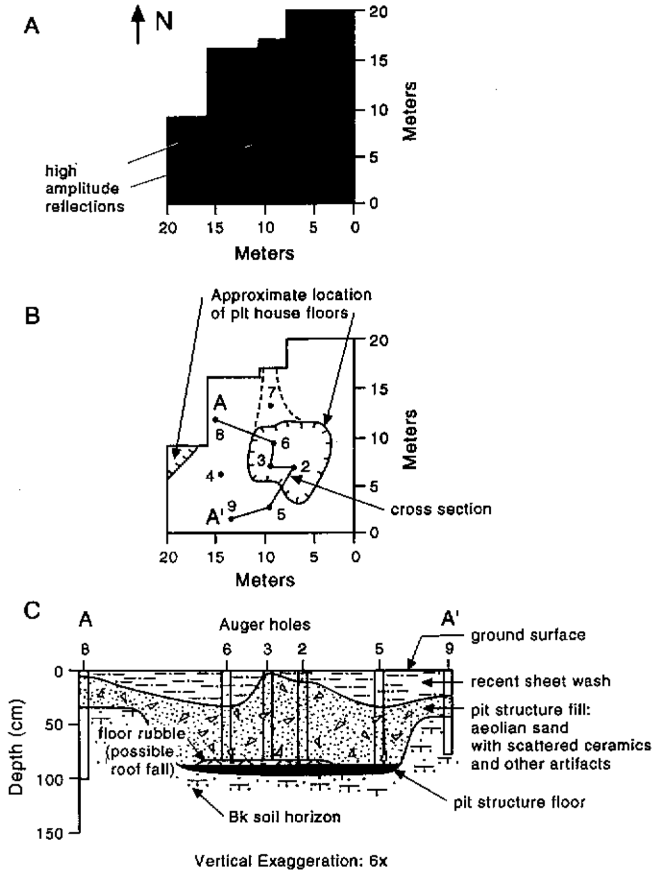


Figure 5. Southwest Bluff site maps and cross section. Map A is the spatial distribution of high amplitude reflections in the slice from 80 to 110 cm below the surface. The auger holes and cross-section location, with the outline of the pit structure floor are shown in B. The cross-section (C) shows the location of the pit structure floor and pit fill.

with varying compositions or pooled above impermeable layers. If the original survey had been conducted in similar conditions, the pit structure would not have been discovered.

Bluff Great House

The Bluff Great House site is located in Bluff, Utah (FIG. 1), on a high Pleistocene-age terrace north of the San Juan River about 1.5 km NE of Southwest Bluff site. It is part of a huge Chacoan regional system that covered much of the northern Southwest between A.C. 900 and 1150, centered in Chaco Canyon to the SE. The Bluff Great House, which is typical of other Chacoan sites, includes the great house itself, a two-storied structure with massive walls, a nearby great kiva, a "berm" (a low mound of earth and trash that surrounds and defines the Great House), and a prehistoric road that bisects the site, possibly connecting it to Chaco Canyon (personal communication, Steve Lekson, 1998). Each of these features is characteristic of other Chacoan Great House sites. Great kivas, like the one at Bluff, were large, deep, probably roofed, subterranean structures that were used for religious ceremonies and other community activities.

Beginning in 1995, the University of Colorado (CU) has conducted excavations at the Bluff Great House as part of an anthropological field school sponsored by CU's Department of Anthropology and University Museum. Planned excavations of the great kiva offered a unique opportunity to test the utility of the GPR technique on this type of structure. Great kivas are not only found at Chaco-era sites but are common throughout the northern Southwest from about A.C. 500–1300. We hoped that GPR would prove an effective technique for distinguishing great kivas from other large circular depressions common in the area, such as historic stock tanks. At the Bluff great kiva, it was also hoped that excavation of this feature could be limited, and targeted, by learning as much as possible in advance from GPR surveying.

Prior to excavation, the Bluff great kiva was evident only as a depression, 17 m in diameter and about 1 m deep. In order to test the nature of the sediment outside the kiva a 5 × 1 m backhoe trench was excavated to a depth of 1.5 m just west of the great kiva depression (FIG. 6). In the base of the trench calcium carbonate-encrusted fluvial terrace gravels of Pleistocene age lay directly on reddish-brown Mesozoic age Summerville Formation sandstone and siltstone bedrock. Above the terrace gravels was a highly disturbed layer of gravels, clasts of Summerville Formation, pieces of charcoal, and scattered broken ceramics. This disturbed layer is interpreted to be material that was excavated during the prehistoric construction of the kiva and dumped down the slope to the west.

A 40 × 30 m grid was set up over the feature and GPR surveys were conducted using both 300 and 500 MHz antennas in transects spaced 1 m apart. Individual lines were processed in the same way as the data from the Valencia and Southwest Bluff sites. The 500 MHz frequency data was found to have the best subsurface resolution, with almost the same depth of resolution (about two m maximum) as the 300 MHz data. It is usually thought that lower frequency antennas will project energy to greater depths, but if electrically conductive materials are encountered, all radar energy will be attenuated no matter what the frequency (Lucius and Powers 1997; Sternberg and McGill 1995). For this reason the 500 MHz data, which had the best subsurface resolution, was used in place of the 300 MHz.

The great kiva was identified in GPR reflection profiles

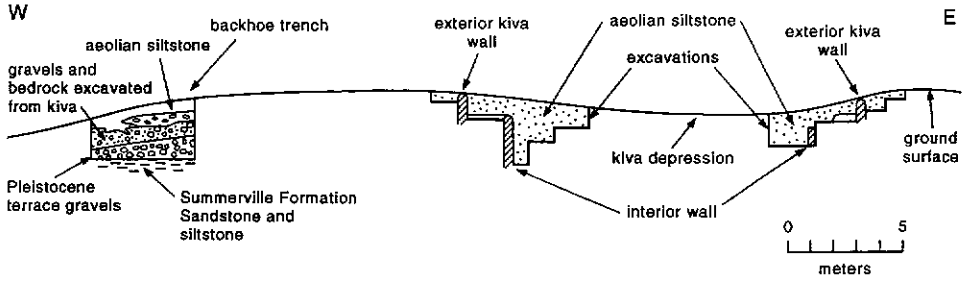


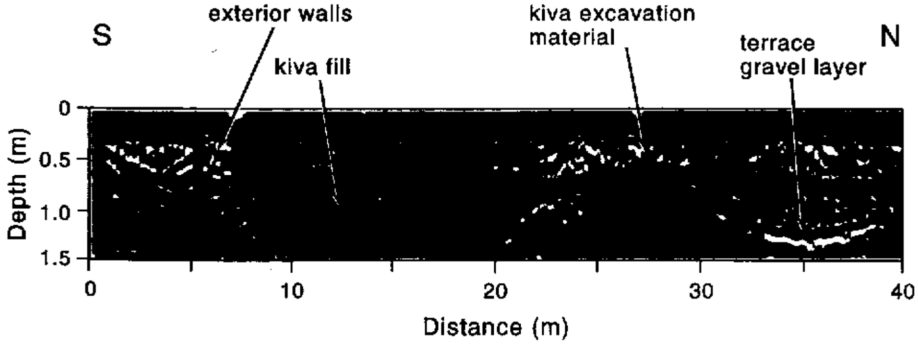
Figure 6. Cross section of the Bluff Great House site great kiva and the test trench to the west showing the stratigraphy and archaeological features visible in GPR maps.

by a distinctive difference between sediments inside and those outside the depression (FIG. 7). The interior portion of the kiva was visible in all 500 MHz profiles as an area of low amplitude reflections, indicating homogeneous fill material. Outside the depression discontinuous high amplitude reflections were visible, which appeared to have been produced by reflections from small point sources, possibly gravel and cobble clasts that were excavated from the kiva and then dumped around its perimeter. More continuous and deeper reflections outside the kiva were produced from undisturbed terrace gravel layers lying on Summerville Formation bedrock (FIG. 7).

Individual GPR lines were instructive, but contained so many discontinuous and complex reflections that visual interpretation was difficult. The amplitude slice-map method was therefore employed in order to allow the computer to make sense out of the complex records. All radar travel times were converted to depth using average velocity measurements from metal bar tests (similar to those conducted at the Southwest Bluff site) that were conducted in the backhoe trench to the west (FIG. 6). Amplitudes derived from the GPR reflection data were then processed into six horizontal slices, each approximately 25 cm thick. The three most illustrative slices are shown in Figure 8. In the slice from 50–75 cm an exterior standing wall of the kiva is visible. It is discontinuous, probably due to differential wall fall after the structure was abandoned. In the slice from 1.0–1.25 m the high amplitude reflections generated from the material removed during the prehistoric excavation of the depression are visible to the north and NW of the kiva. In this slice, and the one below it, the computer mapped a "squarish" feature within the exterior walls that is all but invisible in individual profiles. It was possible to image this feature in the amplitude slices because the computer is capable of quantitatively analyzing low amplitude reflections that the human eye misses and can compare them to other even lower amplitudes from nearby reflection traces. This interior feature was predicted to be a standing wall, but was puzzling because the kiva then would have two concentric walls, not one as expected.

Excavations in the great kiva consisted of deep trenches on the east and west margins of the depression, extending to a maximum depth of 3 m. A shallow exterior wall constructed of sandstone masonry was uncovered in both trenches (although it had been largely eroded in the eastern trench as predicted by the GPR map). The standing portions of the wall were in the exact location indicated by the GPR maps. About 2 m inside this wall another deeper wall was uncovered, coinciding with the "squarish" feature seen in the GPR maps (FIG. 8). Contrary to expectations, but as

Figure 7. Two-dimensional GPR profile of the Bluff Great House site great kiva. Vertical exaggeration 5:1.



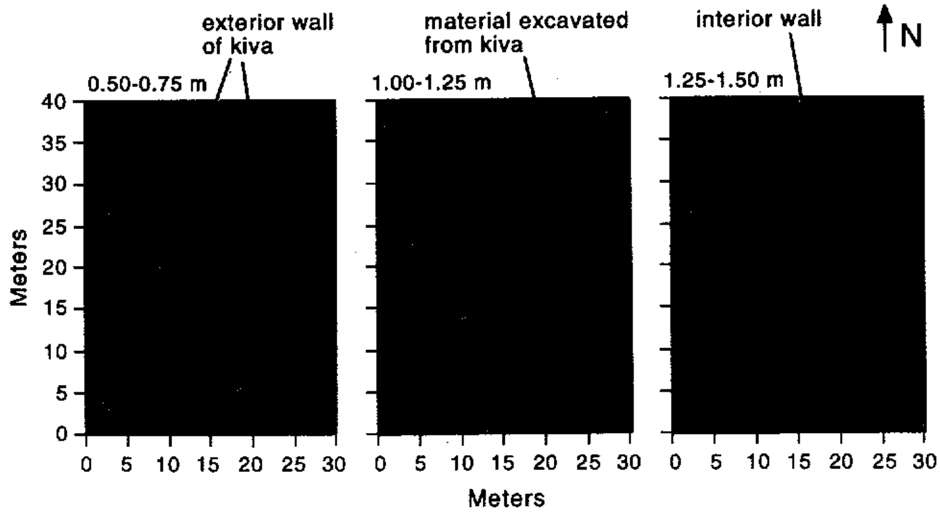


Figure 8. Amplitude slice-maps of processed 500 MHz GPR data from the Bluff Great House site great kiva. Each slice is analogous to an arbitrary excavation level, except the GPR maps show relative radar reflection amplitudes from buried features instead of the features themselves.

predicted by GPR mapping, the great kiva did indeed have two concentric walls. Although the exact nature of these two walls remains to be confirmed through further excavations, it appears that the shallow exterior wall may represent a series of antechambers surrounding the great kiva, while the interior wall defined the perimeter of the main chamber. Such antechambers are not common, but are known from other Chacoan great kivas in SE Utah (Winston Hurst, personal communication, 1997).

At the Bluff Great House site, unlike the Southwest Bluff site, individual GPR lines depicted a great deal of stratigraphic and archaeological complexity that was difficult to interpret visually. The amplitude slice-map method proved an ideal tool with which to define, quantify, and finally simplify the many thousands of complicated reflections that were recorded in the reflection profiles. Using this method "hidden" features became visible and the interior walls could be accurately mapped at their correct depth in the ground.

Other GPR Surveys

Ground-penetrating radar was tested at four other archaeological sites in the northern Southwest using the same methods that had been successful at the sites discussed above. At these sites GPR did not record subsurface features for a variety of reasons: geological or surface conditions thwarted use of GPR, the GPR equipment was inaccurately calibrated, or there was a lack of subsurface features to be imaged. These tests, although unsuccessful, illustrate some of the challenges and limitations of the GPR method and should be useful to others applying GPR in similar conditions.

At the Cottonwood Falls Great House, another Chacoan site located about 45 km north of Bluff (FIG. 1), heavy vegetation and shallow, disturbed archaeological features were a significant problem. At Cottonwood Falls, segments of a prehistoric road are visible (Hurst, Severance, and Davidson 1993) and provided an opportunity to test the GPR method on these linear, but obscure features. Chacoan roads are typically evident only as faint linear swales and excavations of these features have shown hard-packed surfaces that are flat in cross-section. Curbs have been recorded on some segments of the roads (Kincade 1983).

A 15 × 25 m GPR grid was established across a road segment and surveyed with 500 MHz antennas, with transects perpendicular to the road. Because of dense piñon pine, juniper, and sage vegetation, transport of the antennas over the ground was extremely difficult. The data were processed using the amplitude slice-map method in the hope that subtle soil compaction features or possibly constructed curbs or a pavement would be visible. Unfortunately in this area GPR was much better at delineating tree roots than buried features. Each tree was visible, probably because of moisture retention and soil differences around their roots. If the road is present in the subsurface its remaining features are too subtle to be differentiated from tree roots or other natural objects.

Extensive surface disturbance inhibited the use of GPR at an important Pueblo I site just a few hundred meters east of the Bluff Great House (FIG. 1). This site was excavated in the 1930s and is the type site for a local ceramic type called Bluff Black-on-red (Hargrave 1936). Unfortunately the ground surface in this area is highly disturbed, having been bulldozed and used as a trash area for many decades. Soils are composed of sandy clay and much of the fill around what little archaeology remains is composed of reworked Summerville Formation siltstone and claystone. Some indications of subsurface features are visible including alignments of stones that may be standing walls and subtle depressions. The area was tested by GPR to see whether any subsurface features such as storage pits or possibly room floors remain after the disturbance.

A 35 × 18 m grid of 500 MHz GPR data was acquired and processed using the amplitude slice-map method. No amplitude anomalies were discovered that correspond to the features visible on the surface. Each profile was visually analyzed and few coherent reflections were recorded. The high clay content of the sediments and soils in this area appears to have attenuated radar energy as it passed through the ground and the high degree of recent disturbance has probably jumbled the remaining features, making GPR mapping difficult or impossible.

Lack of clearly defined subsurface archaeological features may explain the unsuccessful GPR survey at the Vaughan site, located within the city limits of Bluff, Utah (FIG. 1). This site is located in an empty lot, just below the high river terrace on which the Bluff Great House rests. The area was chosen for GPR testing because local archaeologists noted abundant fire-cracked rock, broken pottery, and charcoal stains on the ground surface.

A 50 × 13 m grid of 500 MHz data was acquired to test for subsurface features. Data quality was good and a number of interesting reflections were recorded. The data were processed using the amplitude slice-map technique and few linear features that may represent buried walls or circular areas that could be pit structure floors were visible. The good reflections that were recorded may have been made by buried archaeological features, but could just as likely have been produced by geological variations. Because no pronounced features resembling the archaeology typical for this area were discovered, the area was not tested by excavation.

At the Shield site (FIG. 1), 18 km NW of Cortez, Colorado (about 120 km east of Bluff), surface disturbance and equipment problems rendered GPR tests ineffective. The Shield site is a large Pueblo II village located in an area that has been intensively farmed recently (and most likely prehistorically) because of its rich soils with good water-holding capacity. The site had been looted and bulldozed to level the ground. Crow Canyon Archaeological Center, located in Cortez, was planning to excavate this site and wished to use GPR to assess the condition of subsurface archaeological features. Little information was available about potential archaeological features and their possible depth of burial at the site and subsurface testing was prohibited by the landowner.

A 50 × 50 m grid was surveyed in a prospective area and unfortunately the computer was programmed to record reflections from between 3–5 m in the ground, which was too deep to record reflections from the archaeological features of interest. The resulting data were unusable because most of the radar energy was attenuated close to the surface and little was available for reflection at the depth recorded. In this case a better understanding of the depth and nature of features imaged might have yielded usable data. Work at this site demonstrates that knowledge of site conditions prior to conducting a GPR site survey is extremely important.

Conclusions

Ground-penetrating radar surveys can be of considerable value for the rapid, nondestructive determination of the number and character of subsurface features at archaeological sites. Many parts of the Southwest have conditions that are ideal for the use of GPR, including dry sandy soils and deeply buried sites. The GPR technique has important implications for both cultural resource managers and research archaeologists. The Southwest is experiencing explosive population growth and development. If GPR is used in advance of development projects, archaeological features can be assessed and often avoided, resulting in an enormous savings of time, money, and damage to archaeological deposits. Even where sites cannot be avoided, by learning the full extent of subsurface features, more appropriate excavation sampling can be developed and contract archaeologists will not be surprised by more extensive remains than they had anticipated.

Ground-penetrating radar also can have significant benefits for archaeological research projects. Few research archaeologists have the funding to excavate more than a tiny fraction of most sites and they must interpret prehistoric cultures and behaviors based on limited knowledge of site size, layout, and feature characteristics. The GPR mapping method can be used to identify the number, size, and character of buried features yielding a far more complete picture of a site than would be possible using excavation alone. Furthermore, where features are known to exist, as at the Bluff Great House, GPR surveys conducted prior to excavation can delineate the location and approximate depth of features of interest. Excavation strategies can then be formulated to efficiently test only targeted features, preserving others.

Our study revealed a number of factors that are important for successful GPR studies, especially a knowledge of local geologic and climatic conditions. We found that it is extremely important to assess the nature of soil and sediment matrices, as well as the nature of possible archaeological features prior to GPR surveys. Clay floors or stone walls that are buried in sandy or silty sediments (conditions like those at the Southwest Bluff site) produce highly visible reflections that are easy to interpret. Where the matrix was clay, radar energy was often attenuated and did not penetrate far enough into the ground to reach the target features. Saturated sediments, especially those recently wetted, also create confusing radar reflections due to reflection from pockets of ground water, as we learned during our second test at the Southwest Bluff site after a heavy rain. Where sites have been disturbed by looting, bulldozing, or other activities, GPR created a confused subsurface picture that was difficult to interpret.

Our study showed how important it is to carefully analyze GPR data after it has been collected, and confirmed the effectiveness of computer processing and imaging techniques. Many GPR surveys rely only on visual interpretation of unprocessed "noisy" reflection profiles, which have led some archaeologists to dismiss GPR as a limited or even worthless technique. The techniques described in this article allow GPR data to be filtered and processed to remove noise from extraneous sources and enhance important reflections. In many cases, careful data processing can mean the difference between success and failure.

Computer imaging techniques can produce maps of the subsurface that are easily interpreted by even the geophysically uninitiated. If specific amplitudes of reflections at measured depths are analyzed spatially, images of features in three dimensions can be made, sometimes while still in the field. These amplitude slice-maps can be created quickly and efficiently to compare, interpolate, grid, and map buried features across a grid in ways impossible to do manually. Computer techniques can sometimes produce images of subtle features that are not visible to the eye and are therefore invisible by means other than GPR, as was demonstrated at the Bluff Great House site.

Ground-penetrating radar surveys can be performed quickly and relatively cheaply, and fairly large tracts of ground can be covered. Surveys can be conducted in areas where features are suspected to exist and large data sets can be first filtered and then processed with amplitude slice-maps to delineate possible buried features, as at the Southwest Bluff site. If there is any question as to the origin of the mapped reflections, as there was at the Valencia site, individual profiles across these features should be visually interpreted and compared to the amplitude slice-maps.

The use of GPR for archaeological mapping was found to be extremely valuable in the Southwest where environmental conditions are frequently excellent for radar propagation and reflection. Although we found some limitations in the use of the technique under certain conditions, GPR technology, both data collection and processing, is evolving rapidly. We believe GPR will eventually become an essential tool for both the management and study of archaeological sites throughout the world.

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