APPENDIX H

GROUND-PENETRATING RADAR TECHNIQUES AND THREE-DIMENSIONAL COMPUTER MAPPING AT THE VALENCIA SITE (AZ BB:13:15 [ASM])

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INTRODUCTION

The American Southwest is a region with spectacular 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, archaeological remains are buried, often leaving no trace of prehistoric houses, storage pits, and other features hidden below the surface. This situation creates an enormous problem for archaeologists, land management officials, and developers who often must, by law, evaluate the impact of planned projects on archaeological sites. Archaeological excavations are expensive, and often, only small portions of a site slated for development can be uncovered. This leaves many buried features undetected and undocumented, and it is often impossible to obtain an understanding of site layout and organization. Increasingly, archaeologists and land managers are recognizing the need for preserving significant archaeological resources; however, preservation requires knowledge of what one is protecting. How this can be accomplished without damaging the resources has been an often insurmountable dilemma.

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.

At Valencia Vieja, an early component of the Valencia site (AZ BB:13:15 [ASM]), GPR was evaluated for its ability to locate a number of pithouses and associated features, some of which had already been identified in backhoe trench walls during Huckell's 1992 testing project (Huckell 1993) (Figure H.1). Many of the features known to exist were imaged using the methods described below, and other floors and features that were not encountered in the trenches were discovered by GPR mapping. The initial results of these investigations are presented by Conyers and Cameron (1998a, 1998b). In 1997 and 1998, large portions of Valencia Vieja were excavated in advance of the expansion of the nearby community college (Wallace 2003). One of the areas selected for large-scale excavation overlapped the area that had been GPR-mapped as part of this study. This provided an opportunity to evaluate the mapping data generated by ground-penetrating radar in comparison with excavation results.

HISTORY OF GROUND-PENETRATING RADAR IN ARCHAEOLOGY

Ground-penetrating radar was first used by archaeologists at Chaco Canyon, New Mexico, to locate walls covered by wind-blown sediment (Vickers et al. 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 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 et al. 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 (Conyers and Goodman 1997:149-194; Goodman 1996; Goodman and Nishimura 1993; Goodman et al. 1995; Goodman et al. 1994).

Many archaeologists who utilize GPR at their sites today are still primarily 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 Valencia Vieja.

GROUND-PENETRATING RADAR METHODS

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

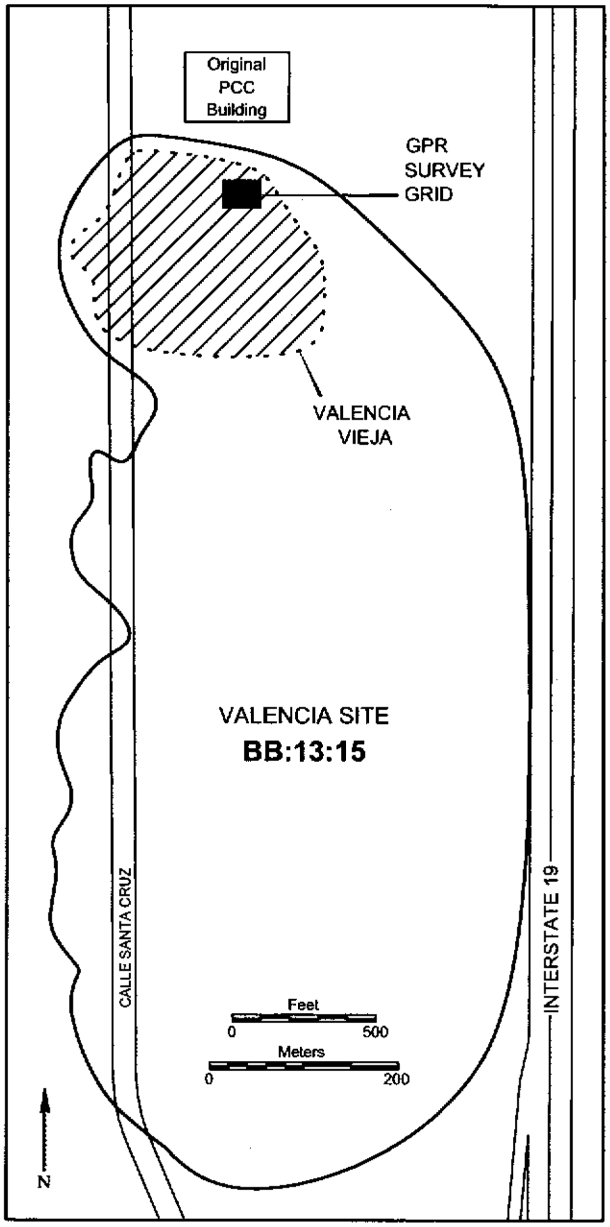

Figure H. 1. Map of the Valencia site (AZ BB:13:15 [ASM]), showing the Valencia Vieja locus and location of ground-penetrating radar survey grid.

each line. As radar energy moves through various materials, the velocity of the waves changes 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 changes and a portion of the radar energy reflects back to the surface and is recorded. The remaining energy continues 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 (Figure H.2). A typical 50-meter transect may collect 2,000 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 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 (Figure H.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, surface topography, and vegetation. Electrically conductive or highly magnetic materials will quickly dissipate radar energy and prevent its transmission to depth. Therefore, the best conditions for energy propagation are 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. Although these conditions are optimal, any low conductivity media will transmit radar energy, no matter what its moisture content (Conyers and Goodman 1997:44-54). Features that are buried too deeply may be 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 1,000 MHz. Low-frequency antennas (10-120 MHz) generate long wavelength radar energy that can penetrate up to 50 m in certain conditions, but are

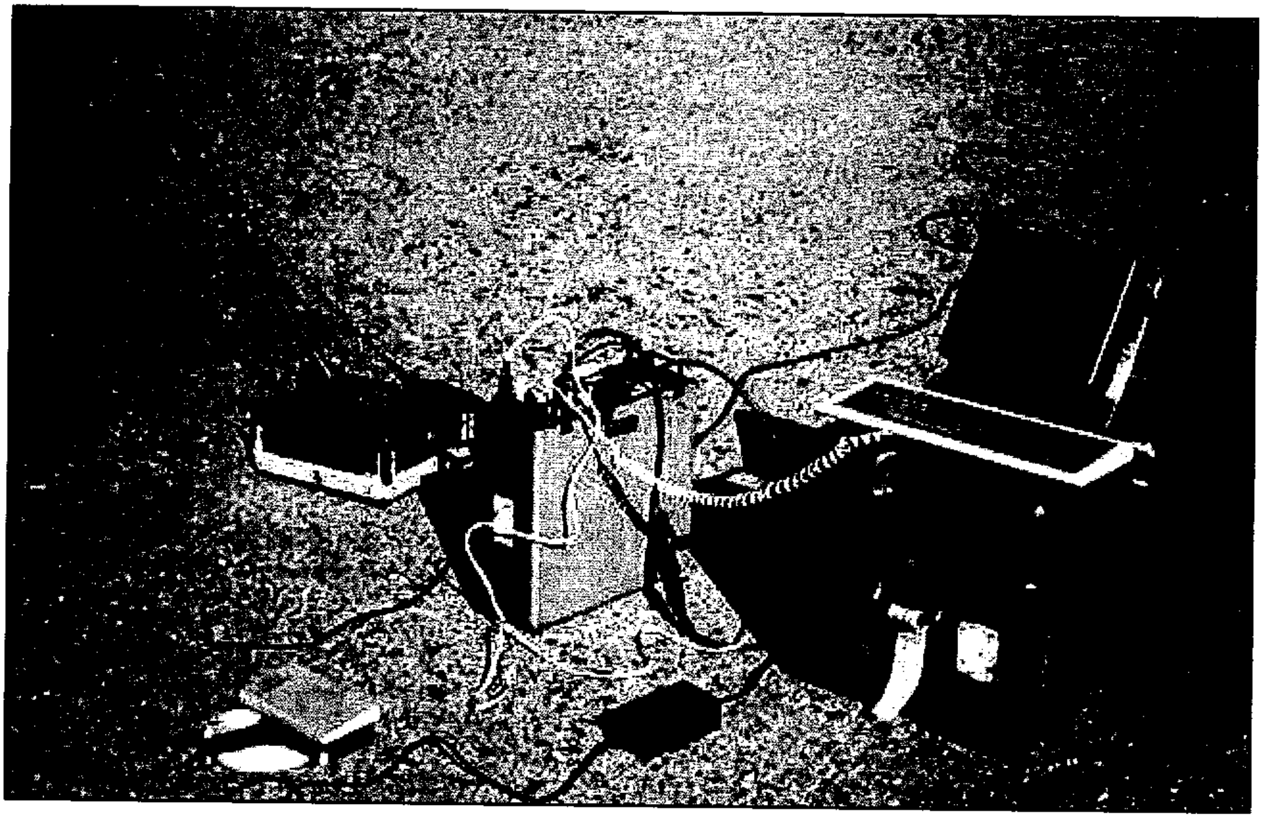

Figure H.2. The ground-penetrating radar system used in this study was a Geophysical Survey System SIR-10, with a 500-MHz antenna.

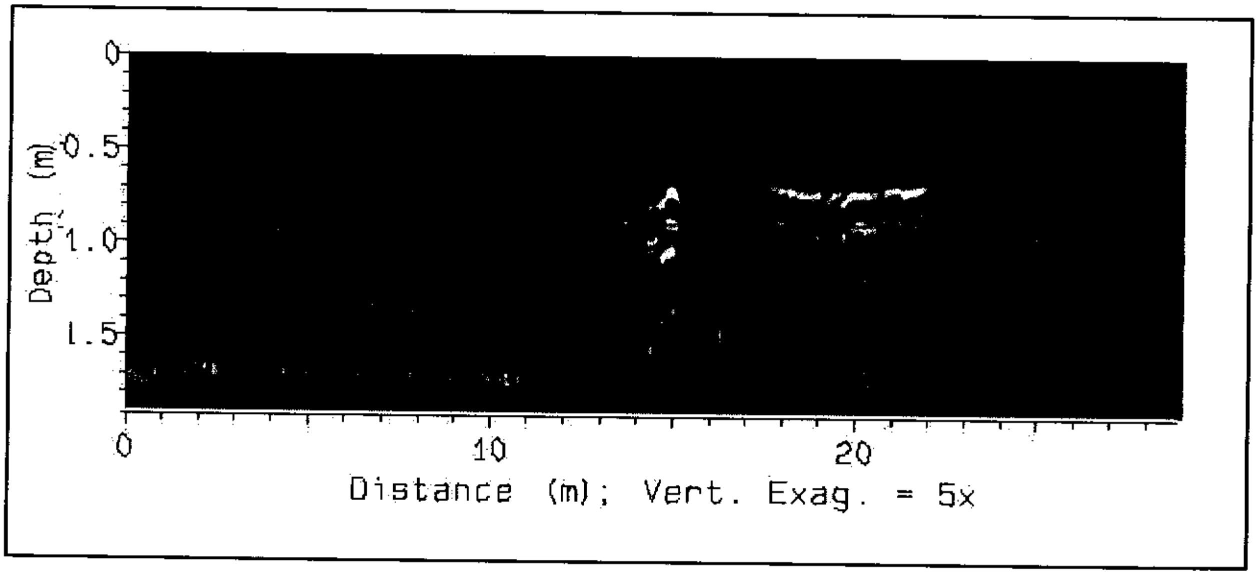

Figure H.3. Ground-penetrating radar profile of a pit structure at the Valencia Vieja site (AZ BB:13:15 [ASM]). (Vertical exaggeration 10:1.)

capable of resolving only very large buried features. In contrast, the maximum depth of penetration of a 900 MHz antenna is 1 m or less in typical materials, but its generated reflections can resolve features with a maximum dimension of only a few centimeters. A tradeoff, therefore, exists between depth of penetration and subsurface resolution. Archaeologists typically use antennas with frequencies between 100 and 1,000 MHz for the best resolution at depths ranging from 1-5 m.

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 important low-amplitude reflections, and computer processing techniques are used to enhance and define these more subtle features.

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 research questions being 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 computer-processed in all cases, to filter out background "noise" and enhance the clarity of reflections derived from important features and specific stratigraphic horizons. To create the maps generated in this report, an amplitude slice-map was used, which utilizes a computer processing technique that correlates and compares reflection amplitudes in all profiles within a grid (Conyers and Goodman 1997:149-195; Goodman 1996; Goodman et al. 1995). This processing method can do, in a few minutes, what is much too time consuming to do manually. Amplitude slice maps digitally compare, correlate, and map the relative amplitudes of GPR reflections within defined horizontal layers in the ground. A map of each slice contains the spatial distributions of amplitudes, which are the direct product of contrasts between buried materials at that depth. Therefore, those maps become analogous to a map of all significant changes in the ground within arbitrary excavation levels.

TESTING THE GPR METHOD AT VALENCIA VIEJA

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. For example, domestic architecture among the ancient Hohokam of southern Arizona, prior to the Classic period (prior to A.D. 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 of the feature. These structures are sometimes visible as depressions, but they often leave no surface indications.

The Valencia site is located within the southern city limits of Tucson, Arizona, and includes over 1 km of archaeological remains along the eastern bank of the Santa Cruz River (see Figure H.1). Excavations and surface collections have documented a long history of occupation in the area (Doelle 1985; Elson and Doelle 1986; Huckell 1993; Wallace 2003; this volume). The site received limited use during the Cienega phase (800 B.C. to A.D. 150). After an apparent hiatus, the Valencia Vieja locus was settled about A.D. 425, becoming a sedentary village by A.D. 500. Valencia Vieja was occupied until about A.D. 700 when that locus was abandoned and the village moved south about 0.5 km. That new locus expanded and later dispersed along 5 km of the river during the eleventh century.

Ground-penetrating radar tests were conducted in a portion of the Valencia Vieja locus that was soon to be subjected to disturbance by expansion of the campus of a community college (see Figure H.1). In 1992, archaeological test investigations 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, inclu-ding 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 backfilled.

Valencia Vieja 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 many times 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. The goal at Valencia was to conduct tests to determine if three-dimensional GPR imaging techniques could be used to provide better definition of these types of features.

In May 1997, a 29-m by 40-m GPR grid was established in the northern portion of Valencia Vieja. It was concentrated on what was later excavated as stripped Block 2 (see Wallace 2003), 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 Valencia Vieja in 1992, included both houses-in-pits and true pithouses (Huckell 1993; Lindeman 2003). Houses-in-pits consist of a shallow depression, with a brush superstructure built inside the depression. True pithouses were deeper, oval or rectangular pits, with postholes for the walls of a wooden superstructure built outside the pit. True pithouses often had massive amounts of adobe coating the walls and roofs; this was less apparent for houses-in-pits. Over half of the structures excavated in 1997-1998 at Valencia Vieja had burned, often firing the adobe used to coat the floors and superstructure (Lindeman 2003). Because true pithouses use the pit walls as the lower portion of the walls of the house, their pits often equate to the shape of the floor (sometimes pits are larger and partly filled to make the walls). Conversely, the pits excavated for houses-in-pits are often larger and more irregularly shaped than the structures built within them. The space between the built pit structure and the pit outline around it was then filled, sometimes with nearby trash or spoil dirt.

The Valencia Vieja pit structures ranged in area from 3.3 to 27.0 m^2 (mean = 11.1, standard deviation = 5.9). Dimensions ranged from 2.1 to 6.3 m in length (mean = 4.2, standard deviation = 1.0). Floors consisted of hard-packed earth, or earth covered with adobe plaster. After abandonment, the pits were filled with collapsed material from the structures' walls and roof, and then often intentionally filled with discarded refuse from nearby structures. They also gradually filled with aeolian sand, silt, and slope wash consisting of redeposited terrace sediments. Maps and descriptions of excavated features at Valencia Vieja are available in Lindeman (2003).

The ground surface of the GPR grid was covered with recent trash, consisting of metal objects and concrete that had been dumped on this portion of the site. Much of the trash was partially buried, indicating some 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 (see Figure H.2). 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 in a profile that were collected at the same time 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 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 urban areas. After the processing was complete, 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 (see Figure H.3) located between 60 and 100 cm depth. The compacted earth or adobe-plastered 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.

The amplitude slice-map processing technique (Conyers and Goodman 1997:149-194; Goodman et al. 1995) was first applied to the processed data set 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 Vieja site grid (Figure H.4), a 1.1-m search radius was used, meaning 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. 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 the backhoe did not usually 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 at that time.

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 H.3), were then plotted on the base map and compared to the location of the computer-generated amplitude anomalies (see Figure H.4). This comparison showed all 11 amplitude anomalies that corresponded to structures discovered in the backhoe trenches also corresponded 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.

Many of the computer-generated amplitude maps, and the reflections visible on profiles, project away from where they were encountered in the trenches. This is because the GPR maps are analyzing data in three-dimensions, while the features visible in the narrow backhoe trenches cannot be archaeologically mapped beyond the limits of the trench profile (although sometimes projections from trench data are possible).

Geophysical mapping at Valencia Vieja discovered a set of possible buried cultural features between testing phase backhoe trenches that were previously unknown. At least 10 GPR anomalies were identified as probable pit structures located between backhoe trenches that would not likely have been found without geophysical testing.

EXCAVATED RESULTS AND GPR DATA COMPARISONS

The 1997-1998 excavations at Valencia Vieja provided an opportunity to independently evaluate the correlation of GPR data to a typically excavated portion of an archaeological site. A large portion of the area mapped with ground-penetrating radar was excavated. Excavation techniques included initial scraping ("stripping") with a specially fitted backhoe bucket to expose soil stains that indicate the location of cultural fill within archaeological features. Cultural features were generally readily identified in this manner at Valencia Vieja, although some houses-in-pits that were unburned and had not filled with trash, were difficult to spot (Lindeman 2003). Extramural pits are more difficult to identify, as they are often filled with relatively sterile soil that differs little from the surrounding soil matrix. Therefore, only a subset of them are expected to be identified. Soil stains marking the locations of possible cultural features were mapped, and a series of structures and pits identified in the area that had been GPR mapped were excavated (see Figure H.4). Feature stains that were mapped, but left unexcavated are also shown in Figure H.4. Large oval or rectangular stains typically proved to be excellent signatures of pit structures at this site.

Figure H.4 correlates the GPR mapped data to the archaeological remains actually uncovered. Several observations concerning the utility and significance of the results are possible, focusing on the portion of stripped Block 3 that overlaps the GPR-mapped unit. For this discussion, pit structure Features 38 and 261 are combined, as they shared a single pit. Of the 11 structure pits identified in the GPR-mapped and excavated area (this includes stains that are probable structures), 6 were identified in GPR profiles, and 10 were identified as reflection amplitude anomalies. Ignoring GPR readings at the very edge of the excavated block due to difficulties in feature identification in this zone, there are one or two areas identified through GPR profiling where no archaeological features were identified in subsurface tests. For house-

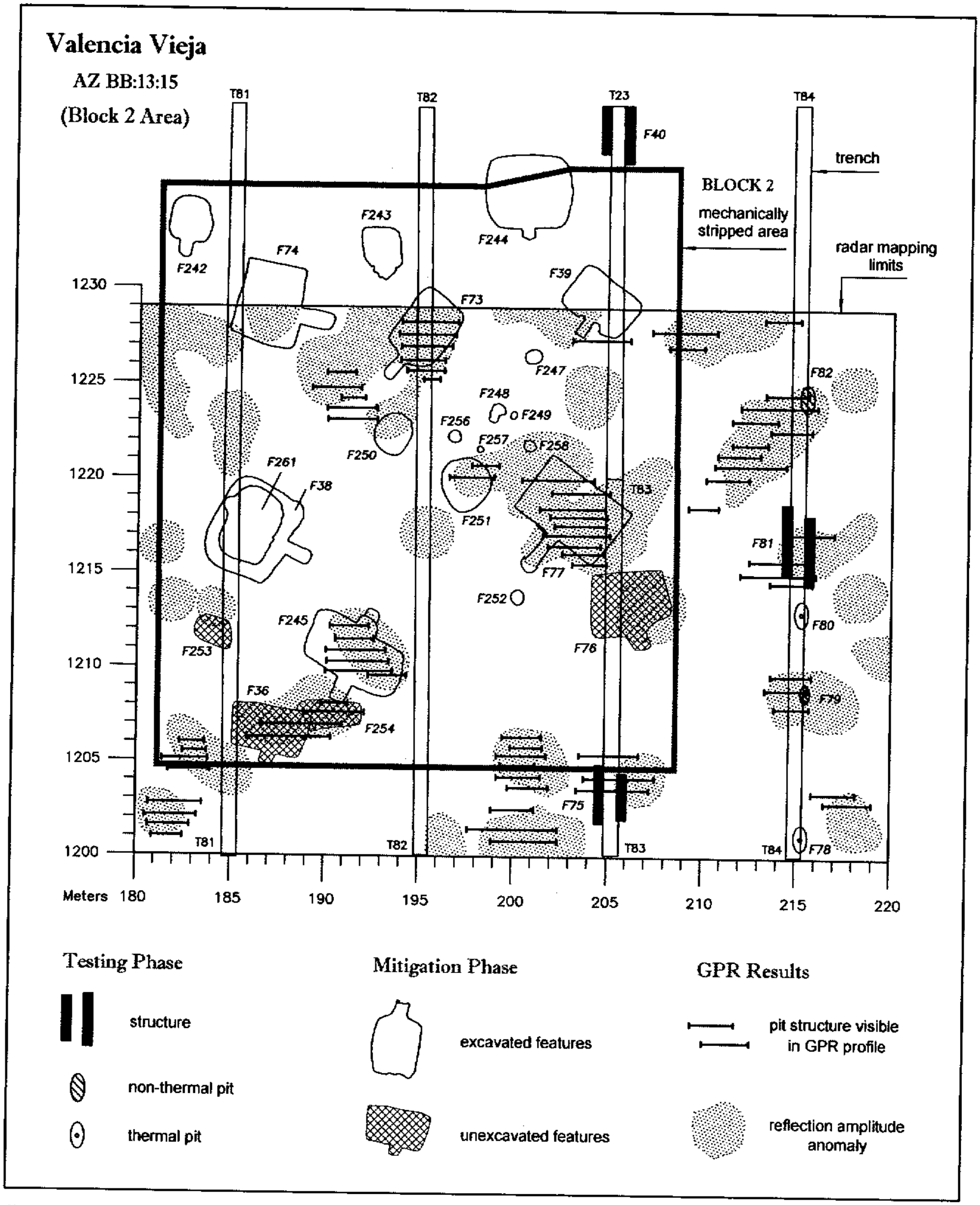

Figure H.4. Amplitude anomaly map and interpretation, Valencia site (AZ BB:13:15 [ASM]). (The distribution of high amplitude radar reflections in a slice from 50 to 100 cm below the surface are shown overlying the location of excavated and tested archaeological pit structures and extramural pits. Interpreted ground-penetrating radar profile pithouse locations are also plotted.

sized reflection amplitude anomalies, a relatively strong correlation with archaeologically identified structures is seen.

The only significant "miss" by the GPR mapping was Features 38 and 261, two houses-in-pits that shared the same pit and floor on the western side of the mapped area. The floor of this structure was moderately rodent disturbed. The stripped surface stain was substantially larger than the identified pit cut for these features, leading us to wonder if the excavated pit was very wide relative to its depth, with walls that sloped very gradually rather than being straight vertical cuts. Together, these factors may have resulted in poor GPR definition (due to a lack of contrast in materials) using the same techniques that had been applied to the other features.

In some cases, excavation results explain and confirm the GPR signatures. For example, the floor of true pithouse Feature 74 was extremely disturbed from tree roots and rodent burrowing, leaving only a few small patches of intact adobe. It was filled with thermally altered fractured rocks and trash. As expected, the GPR mapping did not produce a profile signature of the structure, but it successfully identified a less distinct reflection, marking its location. This is a clear sign that one cannot rely on GPR profile data alone, and it highlights the point that geophysical data should always be used in conjunction with more standard excavation techniques.

At the resolution of GPR mapping applied to Valencia Vieja, it is not expected that precise feature outlines will be identified, and limitations of the technique are expected to add some fuzziness to the results. The slight offsets of some anomalies relative to mapped features may be at least partly explained in this manner. In addition, the exceptional preservation of burned adobe from structure walls and roofs that often fill portions of the structures, are expected to confuse the identification of "floors" in GPR profile mapping–even though the features may be plainly visible as an anomaly.

Areas of GPR-mapped anomalies where no archaeological features were identified raise the question of which data are correct. This cannot be answered with the information at hand, but it is not a black-or-white issue. It is not certain that all archaeological features were identified in the vertical zone stripped, nor is it certain there were not additional features buried below the depth stripped to. It is also possible the GPR techniques used identified minor soil or moisture interfaces without archaeological meaning–leading to confusing GPR results in a few places.

CONCLUSIONS

Ground-penetrating radar mapping at the Valencia site highlights many of the problems that have plagued all types of geophysical archaeological mapping, and it 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 with Huckell's test excavations, 85 percent of the known features were visible by GPR. Additionally, at least 10 pit structures were visible by GPR that were not found in the trenches and would likely not have been discovered using traditional excavation methods. Comparison with subsequent excavation results demonstrated a strong correlation in general locations of buried archaeological pit structures with radar signatures, when both profile and amplitude anomaly data were considered.

The strong correlation of GPR-mapped pit structure locations and actual structures identified through excavations allows interpretation of GPR data outside the area excavated in 1997-1998. Most notably, there are strong indications of additional structure(s) south of the stripped block. The GPR "hit" adjacent to trench-identified Feature 75 may indicate an association with the courtyard group the early Feature 245 and Features 36 and 254 may have been part of. It also supports the existence of dense habitation from stripped Block 3 south to the edge of the site plaza. East of Block 3, GPR mapping identified a possible structure adjacent to Feature 39–one of the earliest structures excavated at the site (Wallace 2003). Is this structure related to Feature 39, or is it part of a separate courtyard group to the east?

In conclusion, ground-penetrating radar surveys can be of tremendous value for the rapid, nondestructive determination of the number and character of subsurface features at archaeological sites. Many parts of the Southwest have conditions 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 budgeted for.

Ground-penetrating radar also can have significant benefits for pure research projects. Few pure-research-funded archaeologists have the ability 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. This study also showed how important it is to carefully analyze GPR data after it has been collected, and it 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 paper 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 featuresacross a grid in ways impossible to do manually. Computer techniques can sometimes produce images of subtle features not visible to the human eye.

Specific application of GPR to individual sites requires an interplay between excavation data and GPR interpretation to maximize the discovery potential of GPR mapping. At Valencia Vieja, we learned that precise feature outlines were not visible in the radar maps at the level of resolution applied, but that general feature locations and floor preservation was identifiable. Some features will be missed, but that does not preclude the technique's utility in providing general patterns of feature distribution. Further, we suspect more refined results could be obtained if additional excavations focused on testing GPR signatures and "tuning" the results for further applications.

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 filtered and processed with amplitude slice-maps to delineate possible buried features. If there is any question as to the origin of the mapped reflections, as there was at Valencia Vieja, individual profiles across the features can be visually interpreted and compared to the amplitude slice-maps.

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

ACKNOWLEDGMENTS

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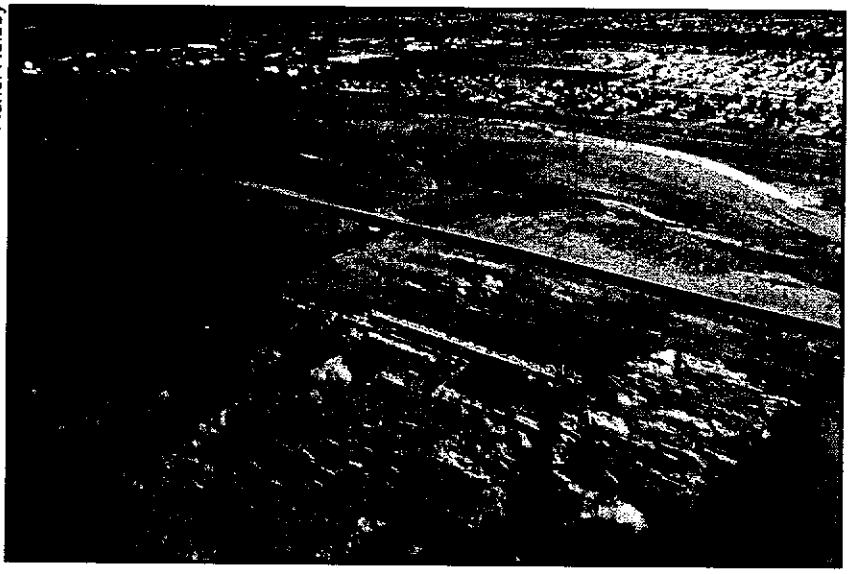
Archaeological Excavations at Valencia Vieja: Appendices and Supplemental Data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