ADVANCES IN GROUND-PENETRATING RADAR EXPLORATION IN SOUTHERN ARIZONA

Lawrence B. Conyers

ABSTRACT

Ground-penetrating radar mapping has the potential to discover and map many archaeological features in southern Arizona that are buried in a variety of geological settings. When earthen features are buried in sediment of a different composition, distinct reflections are generated and readily visible in reflection profiles and amplitude slice maps. Walls composed of adobe and buried in material of the same composition are more challenging, but can be identified by areas of no reflection or delineated by the more highly reflective nature of the flanking adobe melt layers. Earth ovens and floors are readily visible in profile and amplitude maps in most burial conditions, as they produce distinct horizontal reflections at the burned surfaces. Irrigation canals and agricultural fields can also be challenging to see with GPR when the canal fill is the same composition as the surrounding sediment. However, when the sediments of the canal channel fill and surrounding matrix are composed of different materials, they are readily visible but can produce "phantom" reflections due to the complex way that radar energy travels in the ground. When archaeological sites are buried by approximately a meter in fluvial sediments that are electrically conductive, no radar energy passes to below that depth and GPR is unsuitable for discovery and mapping. In conditions where burial occurred above active floodplains where aeolian sediments and slope wash is common, energy penetration is greater and cultural features buried up to about 2 m can be readily identified in GPR images. This greater penetration is due to less clay and moisture in the ground, which tends to attenuate radar energy at shallow depths.

The necessity for locating, mapping, and understanding buried cultural materials in southern Arizona has long been appreciated by archaeologists (Sternberg and McGill 1995). Earthen architecture quickly erodes after abandonment, is re-deposited as adobe melt, and is then often covered and obscured by aeolian or alluvial sediment. Cultural features that were constructed in active floodplains can also be quickly buried and preserved, and are largely invisible today on the ground surface. The archaeological community has historically relied on surface surveys to locate these types of sites by locating artifact scatters or by using random shovels tests or backhoe trenches.

These common discovery methods can be statistically inaccurate or destructive, in the case of trenching or shovel testing, or not viable at all if artifacts are buried by sediment and have not been brought to the surface by some post-depositional mechanism. Geophysical surveys can be a potential alternative to discover and then map buried cultural features of many types and their associated stratigraphy. The most commonly employed geophysical methods for the shallow subsurface are magnetics, electrical resistance, and ground-penetrating radar (GPR), all of which have the potential to identify buried cultural materials (Gaffney and Gater 2003; Campana and Piro, eds. 2009). None have been widely used in southern Arizona.

Ground-penetrating radar is the only near-surface geophysical method that produces a data set in three-dimensions and can therefore potentially map many deeply buried or stratigraphically complex archaeological sites in southern Arizona. The use of GPR in southern Arizona was first published by Sternberg and McGill (1995), with examples from Hohokam sites at Marana Mound, Los Morteros and Casa Grande, and the late Archaic period site of Milagro. These results demonstrated the method's usefulness using two-dimensional radar reflection profiles to identify a number of buried features, including floors, ovens, canals, and middens. Preliminary testing of amplitude analysis for mapping in three-dimensions was conducted at the Valencia Viejo site in Tucson (Conyers and Cameron 1998; Conyers and Wallace 2004). The testing demonstrated a new method for areally extensive mapping using GPR in southern Arizona. Recent advances in GPR data processing, including filtering and three-dimensional image production, now allow geophysical

Lawrence B. Conyers / Department of Anthropology, University of Denver / lconyers@du.edu

Journal of Arizona Archaeology 2012, Volume 2, Number 1: 80-91

Figure 1. A GSSI Inc. SIR-3000 system with an attached survey wheel for distance measurement. The 400 MHz antennas are positioned in the fiberglass box. Antennas that transmit radar waves into the ground are connected by a cable to the control box for immediate viewing and digital recording to disk.

archaeologists greater flexibility in their interpretation of radar reflections generated in the ground (Conyers 2004, 2010). As a result of these advances in software and the speed and flexibility of computer and GPR hardware, the GPR method was again tested in southern Arizona on stratigraphically complex and buried sites beginning in 2007.

At Marana Mound, north of Tucson on the lower piedmont of the Tortolita Mountains near the Santa Cruz River, earthen architecture buried by alluvial sand and silt was mapped in two and three-dimensions. University Indian Ruin in east Tucson presents a different burial medium for similar architecture, as it is high above any active fluvial or alluvial depositional center. The burial there was by thin deposits of aeolian sand and extensive erosion and re-deposition of the architectural features themselves. The Las Capas and Rillito Fan sites, both in the prehistorically active floodplain of the Santa Cruz River, provided tests of the method in this depositional environment where agricultural fields and irrigation canals were rapidly covered by fluvial sand and silt. Other sites along the Gila River floodplain near Casa Grande National Monument, where higher amounts of carbonate and salt was precipitated in the fluvial sediments, provided an example of GPR in a more electrically conductive medium, which tended to attenuate energy with depth and create somewhat lesser reflected wave definition.

These sites, while not inclusive, provided tests for many different types of cultural features and geological conditions common in southern Arizona. Variations in the type of equipment changed for each site, and the methods of data processing and interpretation were also modified for specific site conditions. The results of those tests for the discovery and mapping of those features are presented here.

THE GPR METHOD

Ground-penetrating radar is a near-surface geophysical technique that allows archaeologists to discover and map buried archaeological features in ways not possible with traditional field methods. The method consists of measuring the elapsed time between pulses of radar energy that are transmitted from a surface antenna, reflected from buried discontinuities, and then received back at the surface (Conyers 2004). Discontinuities that reflect radar energy can be changes in lithology, contacts between cultural features and surrounding matrix, or water saturation differences due to sediment property differences. When the distribution and amplitudes of those radar wave reflections can be related to certain aspects of archaeological sites, such as the presence of architecture, use areas, or other associated cultural features, high definition three-dimensional maps and images of buried archaeological remains can be produced. Ground-penetrating radar is a geophysical technique that is most effective at buried sites where artifacts and features of interest are located within 2 to 3 m of the surface, but has occasionally been used for more deeply buried deposits (Conyers 2004:49; Conyers 2009).

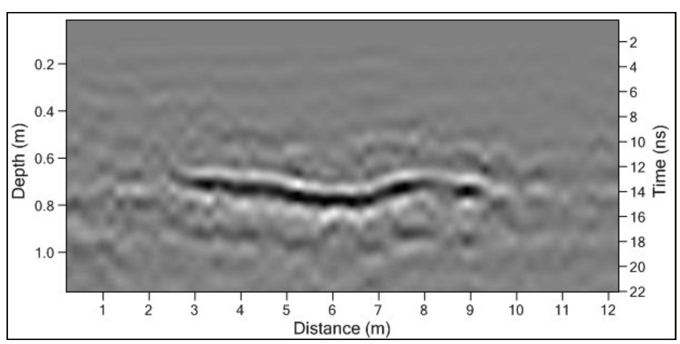

Figure 2. Reflection profile using the 400 MHz antennas at Compound Mound 1, Marana Mound site. A house floor is visible as high amplitude horizontal reflections at Compound 1, Marana Mound site. The floor at 14 nanoseconds (two way radar travel time) correlates to about 65 cm depth at this location.

A growing community of archaeologists has been incorporating GPR as a routine field procedure in many parts of the world (Conyers 2004; Gaffney and Gater 2003) and in a more limited way in southern Arizona (Conyers and Cameron 1998; Conyers and Wallace 2004; Sternberg and McGill 1995). Resulting GPR maps and images can act as primary data that can be used to guide the placement of excavations, define sensitive areas containing cultural remains to avoid, place archaeological sites within a broader environmental context, and study human interaction with, and adaptation to, ancient landscapes (Conyers 2009, 2010; Kvamme 2003).

As radar pulses are transmitted through various materials on their way to the buried target features, their velocity will change, depending on the physical and chemical properties of the material through which they are traveling (Conyers 2004:45). Each abrupt velocity change generates a reflected wave, which travels back to the surface to be recorded. Velocities of radar energy in the ground are important, because only the wave travel times are measured and not their actual depth in the ground. However, if velocity through the ground can be calculated, then distance (or depth in the ground) can be accurately estimated (Conyers 2004:99). Distance estimates can be used to produce useful three-dimensional reflection data to produce accurate images in space.

Most typically in archaeological projects, GPR radar antennas are moved along the ground in transects (Figure 1) and two-dimensional profiles of a large number of reflections at various depths are created. This process produces profiles that are images of subsurface stratigraphy and buried archaeological features along lines (Figure 2). When data are acquired in a closely-spaced series of transects within a grid, and reflections are correlated and processed, an accurate three-dimensional picture of buried features and associated stratigraphy can be constructed (Conyers 2004:148). This can be done visually by analyzing each profile, or with the aid of computer software that can create maps of many thousands of reflection amplitudes from all profiles within a grid that produces maps at various depths.

Ground-penetrating radar surveys allow for a relatively wide aerial coverage in a short period of time, with excellent subsurface resolution of both buried archaeological materials and associated geological stratigraphy. This three-dimensional resolution gives GPR an advantage over other near-surface methods with respect to buried archaeological feature resolution.

Different antenna frequencies are used for varying depth penetration and subsurface resolution (Conyers 2004:39). The higher the frequency waves are, the shallower the depth of energy penetration will be, but the greater the resolution of subsurface features will be also (and vice-versa for lower frequency antennas). In this study the 400 MHz antennas were capable of resolving features of approximately 20-30 cm in dimension and transmit energy to a maximum depth of 2.5 m. The 900 MHz antennas could resolve features approximately 5-10 cm in size, but were only capable of resolving those features to a maximum depth of 80 cm.

While the GPR method has wide applicability in many different sediment and soil types, the best energy penetration and subsurface resolution occurs when the ground is electrically resistive (Conyers 2004:33; Conyers and Connell 2007). In southern Arizona this type of ground is usually aeolian or alluvial sediment that has a low concentration of electrically conductive clay, carbonate, or salt. These environments are usually found above active floodplains, where running water or wind has winnowed out the clay in sediments and salt and carbonate precipitation is lower. Retained moisture in a sediment or soil that contains any of these electrically conductive constituents produces a material with a high cation-exchange capacity, which effectively attenuates radar energy (Conyers and Connell 2007). In even moderately electrically conductive ground, radar energy can be attenuated at a shallow depth regardless of the frequency of the antenna used for transmission (Conyers 2004). Those attenuating environments are mostly confined to floodplain environments in southern Arizona.

DATA PROCESSING AND INTERPRETATION

Raw GPR reflection data are a collection of many individual traces, spaced at varying intervals, along two-dimensional transects within a grid. Each reflection trace from one location on the ground contains a series of stacked waves received from certain depths in the ground that vary in amplitude depending on the amount and intensity of energy reflection that occurred at buried interfaces. When traces are stacked vertically and in sequence, standard two-dimensional profiles are created. These profiles show variations in amplitudes of reflected waves that vary along transects (see Figure 2). They can be viewed much like profiles along vertical faces of excavations. An analysis of the varying amplitudes in space can potentially show subsurface changes in stratigraphy and physical properties of cultural materials within the matrix of sediments and soils. The higher the compositional contrast in buried materials along a buried interface are, the greater the amplitude of the reflected wave generated at that contact. These contrasts are usually sediment grain size and porosity variations, which control the amount of retained water in the various media

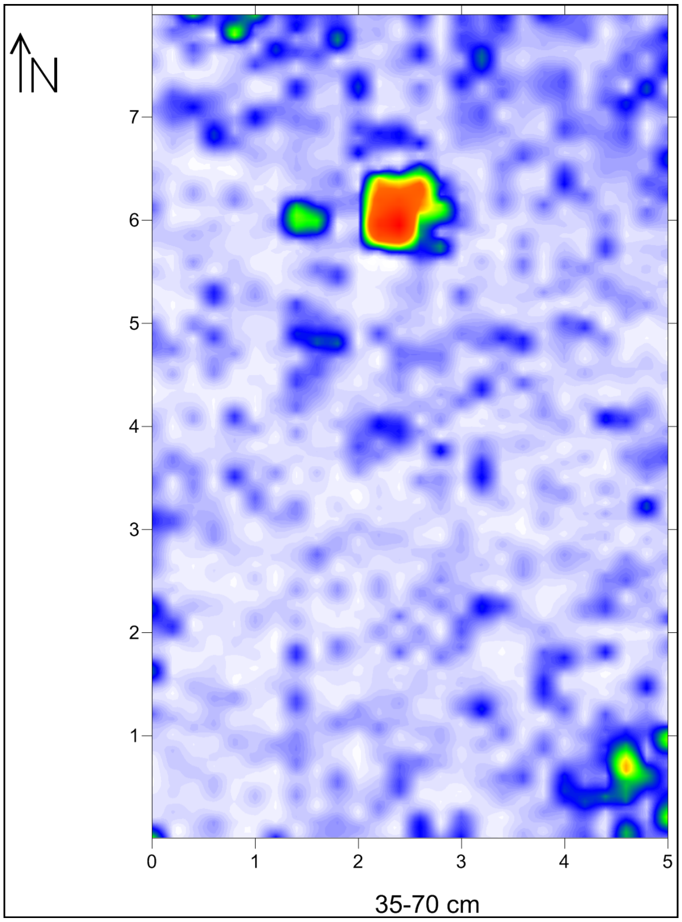

Figure 3. Amplitude slice-map of the base of an earth oven. The image was constructed using 21 parallel reflection profiles collected in this grid. This 5 x 8 m map shows the relative strength of reflections from 35-70 cm in the ground. Dark gray denotes areas of high amplitude and white and lighter gray homogeneous non-reflective ground.

(Conyers 2004:45). When viewed in profile, the higher amplitude reflections are the areas of black and brighter shades of white visible within a gray-scale image, while the areas of little to no reflection are neutral gray in color (see Figure 2). If amplitude changes can be related to important buried features and stratigraphy, the location of higher or lower amplitudes at specific depths can be used to reconstruct the location and nature of subsurface materials in three-dimensions. Areas of low amplitude waves usually indicate homogeneous materials, while those of high amplitude denote areas of high subsurface contrast, such as the contacts of archaeological features and the surrounding matrix.

The spatial location of amplitudes in a three-dimensional volume can help greatly in subsurface interpretation when slice-maps at specific depths in the ground are produced. Maps of this sort are generated by re-sampling all reflection amplitudes in all profiles within a grid and then averaging the amplitudes in slices of a given thickness. Reflection amplitudes are then gridded and interpolated to provide a uniform placement of radar reflection strengths throughout the mapped area (Conyers 2004:148). When viewed in map-form, each slice can portray in plan view the distribution of all reflected wave amplitudes at a desired depth, with slices analogous to maps of arbitrary excavation levels in archaeological excavations (Figure 3). In these maps, low amplitude variations within a slice denote little subsurface reflection and therefore the presence of homogeneous material, while high amplitudes indicate significant subsurface discontinuities, and, in many cases, detect the presence of buried features or very different compositions of sediment layers. Degrees of amplitude variation in each amplitude slice can be assigned arbitrary colors or shades of gray along a nominal scale.

GPR IN SOUTHERN ARIZONA

There are a variety of burial conditions in southern Arizona that cover and preserve cultural remains and that serve as excellent tests for GPR. Alluvial environments, such as along the Santa Cruz, Gila, and Rillito Rivers, often bury materials, sometimes to depths of many meters. At the Rillito Fan (Huckleberry 2009) and Las Capas (Nials 2008) sites, GPR was used to image Early Agricultural period irrigation canals and associated agricultural beds below approximately 1 m or less of silt and sand sedimentary cover. At Marana Mound the Classic period Hohokam features were covered with about 50-100 cm of alluvial silts and sands (Pearthree et al. 1992; Waters and Field 1986). At University Indian Ruin cultural features were covered with minor amounts of aeolian material, with most of the matrix surrounding cultural features consisting of adobe melt from what were once above-ground compacted earthen structures (McKittrick 1988). Each environmental condition required different GPR data collection and processing procedures.

A number of important cultural features were studied with GPR at these sites. Often, buried features that were smaller than approximately 20 cm in dimension were difficult to image with GPR, because they could not be readily differentiated from smaller natural sedimentary layers or rocks. In general, large irrigation canals 1 m in width, agricultural beds, and horizontal floors, when filled with certain types of sediments, were the most visible cultural deposits in both reflection profiles and amplitude slice-maps, because these features of interest differed in composition from the surrounding matrix. Architectural walls composed of the same material as the surrounding ground tended to be much more difficult to identify using GPR, as they are composed of homogeneous earth that is non-

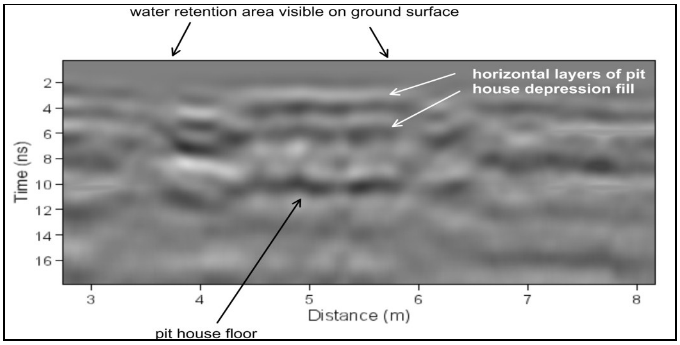

Figure 4. Reflection profile using the 400 MHz along the Gila River floodplain. The profile shows a subtle pit-house floor and overlying fill sediment reflections directly below a noticeable surface depression.

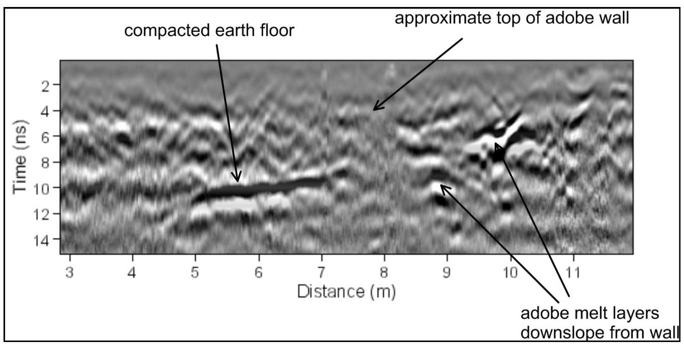

Figure 5. Reflection profile using the 900 MHz antennas of compacted earthen floors at University Indian Ruin. The profile shows compacted earthen floors that produce strong reflections and an associated wall that is non-reflective and therefore almost invisible. This profile is not corrected for topography. The ground slopes to the right of the image, which is why the adobe melt layers are located on that side of the wall.

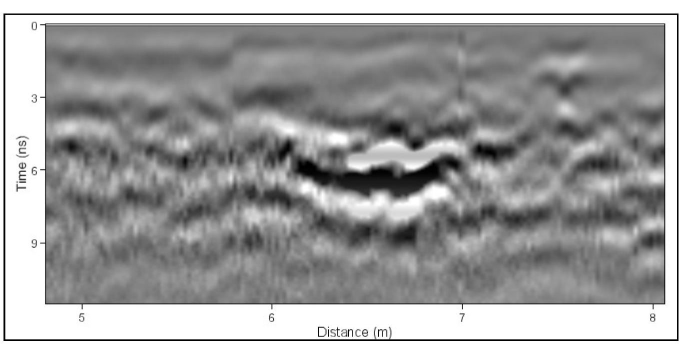

Figure 6. Reflection profile using the 900 MHz antennas across the base of an earth oven at University Indian Ruin.

reflective to radar waves. Earthen features of this sort are often bounded or buried by adobe melt layers consisting of almost the same composition, which produces little in the way of compositional differences that might reflect energy at their interface.

Floors and other horizontal features

Horizontal features, when buried by material that is different in composition, are readily visible in GPR profiles. At Marana Mound, features in Compound 1, Locus 2 (Fish et al. 1992) were covered by sediment deposited on the toe of alluvial fans that drain the Tortolita Mountains to the east. House floors of pit structures and above ground buildings are composed of primarily compacted earth, which is sometimes partially burned. These floors are readily visible as high amplitude horizontal reflections (see Figure 2).

In a flat area on the first terrace above the Gila River floodplain near Coolidge, a number of very subtle depressions, which tend to collect moisture in the winter, are visible on the surface. These features have not been excavated, but the buried floors are still visible in GPR profiles. Directly below the areas of surface water retention, horizontal layers directly below the ground surface are likely layers of sediment that filled pit house depressions (Figure 4). The pit house floor is visible at about 10 nanoseconds (approximately 60 cm depth) below the surface. The radar reflections are much less distinct here than at Marana Mound, because the ground contains much more precipitated salt and carbonate, which tends to attenuate radar energy in the ground. In this area radar waves rarely penetrate deeper than about 1 m because of the electrically conductive precipitates in the burial medium.

Compacted earth floors associated with walls are often visible in profiles, while the walls, composed of similar material, are non-reflective and therefore almost invisible (Figure 5). The floor in Figure 5 is horizontal, but it is somewhat distorted because the profile was collected on a sloping ground surface and not adjusted for topography. The wall, which was later excavated, is non-reflective because it is composed of homogeneous earth that contains no discontinuities that reflect radar waves. The down-slope adobe melt layers to the right of the wall, derived from the wall's erosion after abandonment, are readily visible as high amplitude reflective layers. Adobe melt layers, when they are interbedded with materials of a different composition such as thin layers of wind blown sand, readily reflect radar energy from the bed contacts.

Other horizontal cultural features, such as the bottoms of baking ovens, appear much like house floors in reflection profiles, but are smaller in dimension and tend to be bowl-shaped (Figure 6). The burned portion of the oven covered by natural fill is the interface that produced the high amplitude reflec-

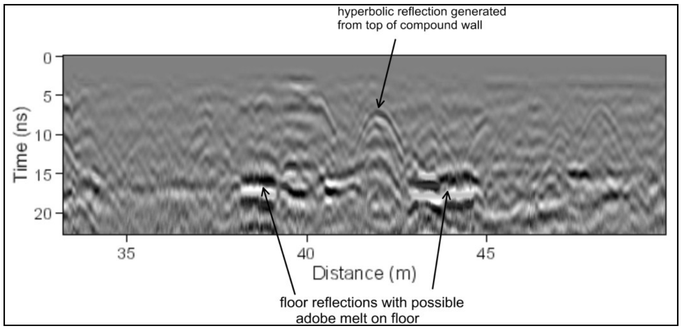

Figure 7. A 400 MHz reflection profile crossing the compound wall at Marana Mound site. The top of which is visible as a distinct hyperbolic reflection. Adjacent to the wall are horizontal reflections generated from floors or other flat cultural surfaces.

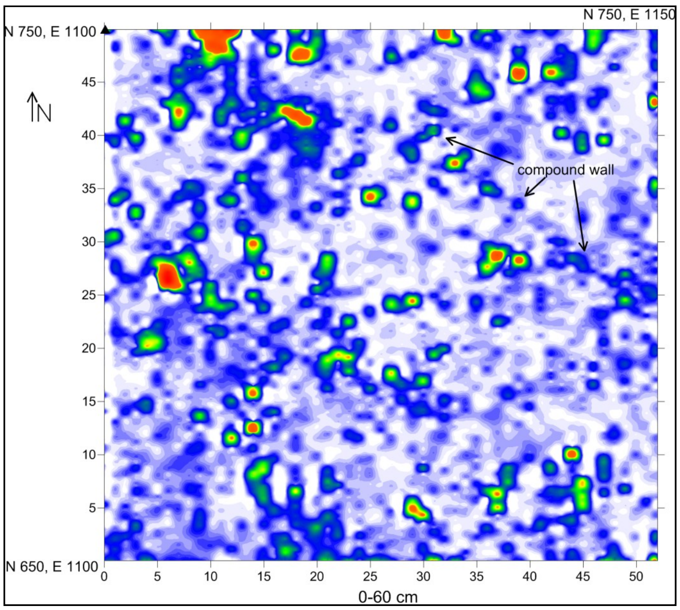

Figure 8. Amplitude map of reflections within the upper 60 cm. The map shows the location of the hyperbolic reflections from a partially eroded compound wall. Dark gray indicates areas of high amplitude reflection, while white and light gray are areas of little or no reflection.

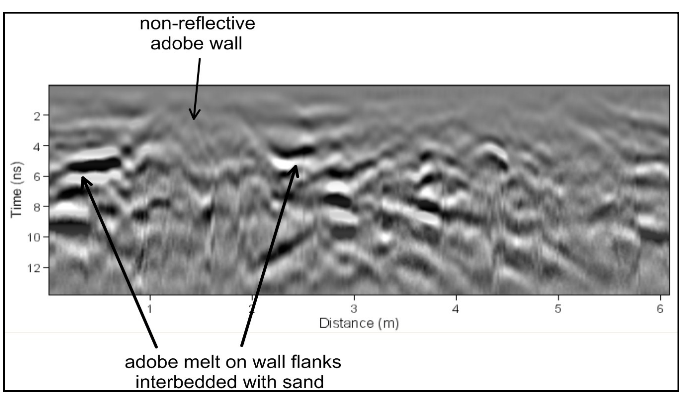

Figure 9. Reflection profile of 400 MHz reflections at University Indian Ruin. The map shows a non-reflective adobe wall bounded by interbedded sand and adobe melt layers that are highly reflective.

tion. While this feature was not excavated, the ground surface around it contains concentrations of ash and fire-cracked rock. Its dimensions, seen in both profile and map view, and its cuspate shape are all indicative of an earth oven, others of which have been excavated nearby. When many profiles in a grid over this oven were processed into amplitude slice-maps, the outline of the base of the oven can be viewed in horizontal map-view (see Figure 3).

Walls

Walls are one of the most challenging cultural features to visualize with GPR profiles and maps in southern Arizona. Many, if not most Hohokam walls tend to be composed of compacted and homogeneous earth that was locally obtained with some additional binding material of sand and gravel. These materials, which were mixed prior to construction, produce an architectural feature that is almost devoid of distinctly different compositional interfaces; therefore, the internal structures of walls have little ability to reflect radar waves traveling through them. In addition, the standing vertical portions of un-eroded walls are mostly oriented parallel to the direction of radar traveling into the ground from the surface antennas, and do not provide a surface from which to reflect energy. Walls therefore are not readily visible in profiles as reflections, but instead are distinguishable as areas of little or no reflection. They can often be identified by studying the placement of materials that were eroded and deposited on either side of them, not the walls themselves. Those adjacent features are usually adobe melt layers or layers of sediment deposited after abandonment.

When the partially intact walls are buried by sediment of a very different composition, their tops produce a distinct hyperbolic-shaped reflection (Figure 7), as the wall tops act as a point-source target (Conyers 2004:54). At Marana Mound, the bounding wall of Compound 1 is visible as a subtle hyperbola, bounded by highly reflective layers that are either floors or layers of adobe melt. When many profiles are processed into amplitude slice-maps, the compound wall that produced distinct point-source hyperbolas in many parallel reflection profiles within a grid can be mapped in distinct slices (Figure 8).

The non-reflective nature of typical Hohokam earthen walls has been observed in GPR data at a number of sites. Only when walls are preserved in special burial conditions, as seen at Marana Mound where they are buried by and in stratigraphic contact with sandy alluvial material, are hyperbolic reflections generated. At University Indian Ruin, very thick earthen walls are bounded by layers of adobe melt, and, while the walls are not visible as distinct reflections, the bounding melt layers, interbedded with aeolian sand,

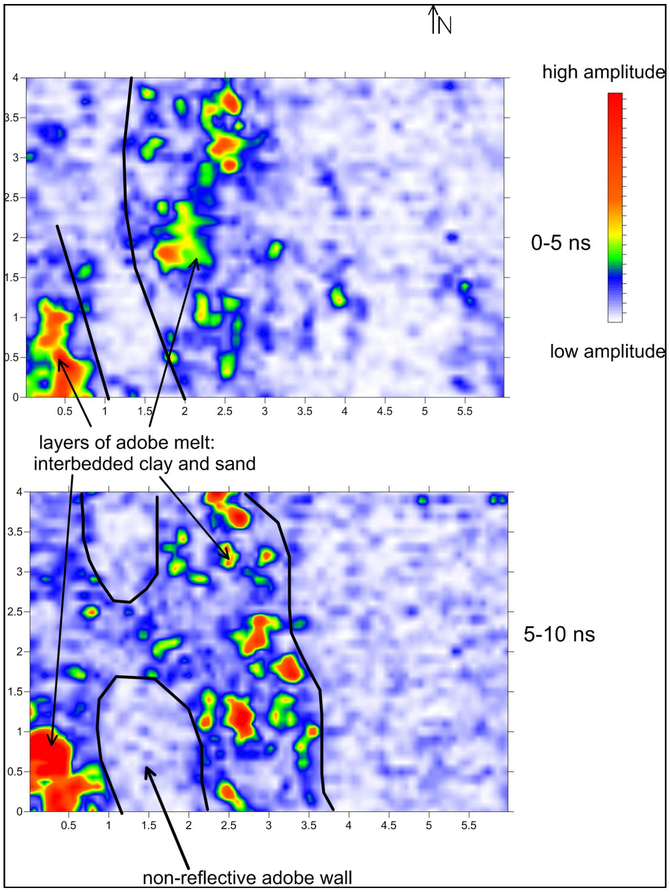

Figure 10. Amplitude maps showing areas of adobe melt that produce high amplitude reflections adjacent to a non-reflective adobe wall at University Indian Ruin.

produce distinct sub-horizontal layers (Figures 5 and 9).

In order to produce a map of the walls where no distinct wall hyperbolas were generated, amplitude slices are created to delineate the non-reflective areas. These non-reflective areas are the walls, and the high reflective areas bounding them are interbedded adobe melt and sand layers on the walls' flanks (Figure 10). In environments such as this, when the burial mechanism is erosion of the architectural features themselves, the addition of minor sediment to the melt layers can produce stratigraphic surfaces that generate high amplitude reflections. The walls produce almost no reflections, but are still visible as areas of no contrast in both profiles and in slice maps.

Canals and Agricultural Beds

Buried cultural features that are composed of sediment and soil that are covered by sediment of roughly the same composition are difficult for the human eye to see, even when exposed. They provide a challenging problem for geophysics in general. However, as GPR has the ability to produce images in three-dimensions, the method can be potentially successful. As a test of the GPR method, reflection data were collected at the Rillito Fan site near the confluence of the Rillito and Santa Cruz Rivers. At this site excavations along a pipeline corridor had discovered a number of Early Agricultural canal systems that transported water from the Rillito south and then west to the Santa Cruz floodplain, where agricultural fields were located (Huckleberry 2009). The tops of the canals were visible in backhoe trenches approximately 1.5 m below the present day ground surface. Excavations had removed between 80 and 100 cm of the overburden prior to the collection of the GPR data. The overburden sediment in this area is Rillito Creek alluvium, which consists of arkosic mineralogy and abundant muscovite grains. This clay-rich sediment is somewhat electrically conductive and little radar energy penetrated below 1.2 m. This high electrical conductivity precluded GPR testing of these features without the removal of some of the overburden sediment.

Two distinct canals at Rillito Fan are preserved just upstream from the confluence of the Rillito Creek and Santa Cruz River where this test was conducted. The canals had been filled with sandy sediment during floods, and portions had been constantly renovated, cleaned out, and re-constructed during their use life. The GPR reflection profiles that crossed the canals at right angles showed the edges of the canals as only faint reflections. The bulk of the sediment that filled the canals and the adjoining floodplain is composed of almost the same material; thus, there was little compositional discontinuity from which to reflect radar energy. The faint reflections that were produced from the canal edges were probably generated at boundaries that placed somewhat finer grained sediment or a thin clay drape next to the sand and silt through which the canal was excavated. Also, the edges of the canals slope at an angle such that radar energy that encounters them is reflected away from the surface antenna and not recorded. For this reason, only minimal reflection was recorded from canal edges. However, a very distinct series of reflections was produced at the very bottom of the canal, which generated what appears as stacked point-sources hyperbolas. This occurred where the base of the canals contain coarser sand fill, which directly lies on finer-grained floodplain deposits. The sediment discontinuity is therefore dramatic in these conditions, and the contact produced high amplitude reflections. Reflections at this interface were enhanced where the base of the canal is shaped like a bowl, which tends to focus radar. The energy recorded from this interface was high in amplitude.

The hyperbolic geometry of the reflections from the base of the channel is also distinctive. It is the product of the method with which radar energy is transmitted from the surface antenna and reflected from interfaces in complex ways. Radar waves propagate outward from antennas in a cone and spread with depth (Conyers 2004:62). The antennas recorded energy that reflected from the farthest edge of the canal prior to the surface antenna passing over it (Figure 11). That energy traveled to and from the antenna at an angle but was recorded as if the arrivals occurred from directly below the antenna's location. This phenomena produced a series of "phantom" reflections in the shape of a hyperbola as the antenna moved toward the canal and then away from it. Energy reflected from the canal's other side was recorded in the same way as the antennas passed away from the buried feature. Also, the canal's farthest edge dipped toward the surface antenna and therefore reflected much of the radar energy. The energy reflected from the interface traveled directly back to the surface antenna and produced the very high amplitude reflections visible in Figure 12.

When multiple canals are superimposed and interbedded with floodplain deposits, GPR reflection profiles can produce complex pictures of the stratigraphy. At the Rillito Fan site, in the adjacent floodplain, Channel III is associated with a clay layer that is interpreted as the ancient agricultural field or floodplain sediments (Figure 13). The clay layer produces a very distinct reflection, while its associated channel is visible but less distinct. The overlying Channel II, of a later age, is incised almost to the depth of the older floodplain layer and is readily visible in the GPR profile.

Similar canals were studied at the Las Capas site, along the eastern margin of the Santa Cruz River near the mouth of the Cañada del Oro. At this site the canals were indistinct in GPR profiles, because they were filled with almost the same sediment as the bounding floodplain material that they were incised into (Figure

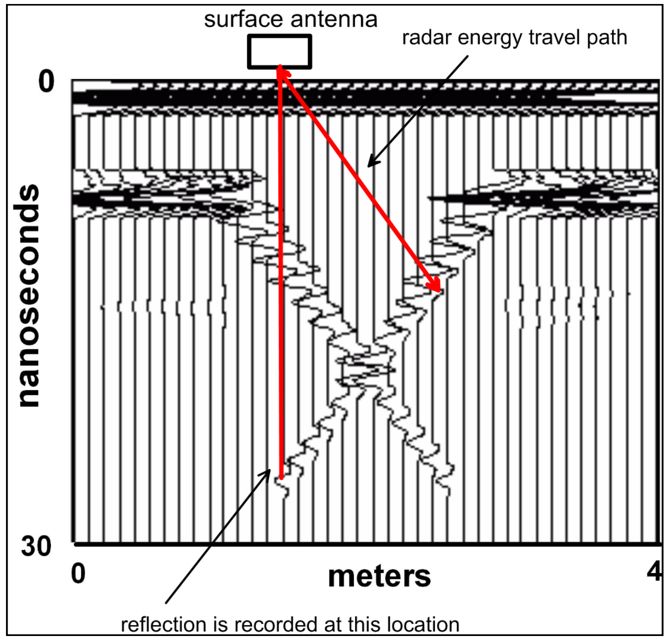

Figure 12. Model of a canal's reflections as an antenna is moved across it at a right angle. The actual edge of the canal is recorded directly below the antenna. In addition, "phantom" reflection hyperbola appear directly below the base of the canal. As energy is transmitted from the surface antenna in a cone, the farthest edge of the canal generates a reflection, which is recorded as if it were directly below the antenna.

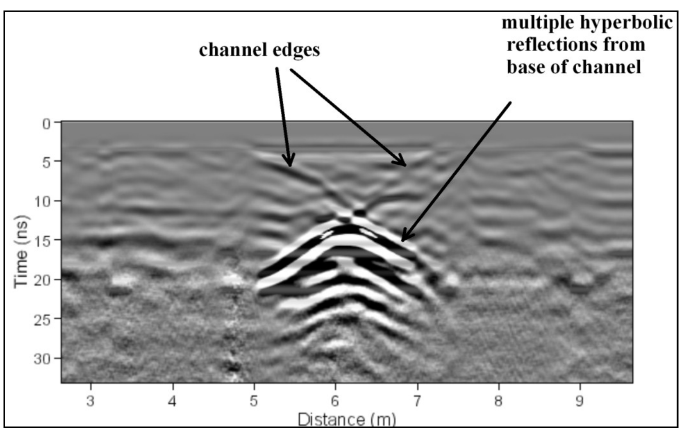

Figure 11. GPR reflection profile using 400 MHz energy crossing an Early Agricultural period irrigation canal at right angles at the Rillito Fan site. The channel edges are barely visible. However, distinct multiple point source hyperbolas were generated at the base of the canal where the bowl-shaped geometry of the bed boundary reflected almost all radar energy back to the surface.

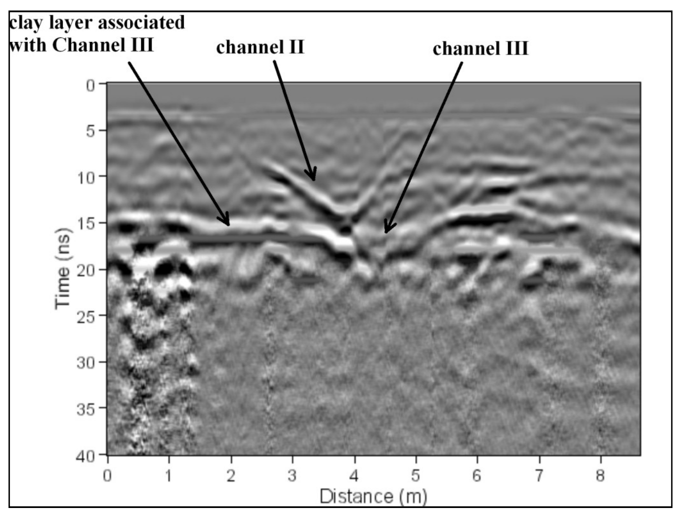

Figure 13. GPR reflection profile using the 400 MHz antennas at the Rillito Fan site. The profile shows two superimposed canals and an associated floodplain clay layer.

14). These canals were also wider with broader bases, and therefore did not focus radar energy like the narrower channels at Rillito Fan. While they are still visible, only low amplitude reflections were recorded.

Amplitude slice maps of irrigation canals constructed with many tightly spaced profiles collected in a grid can produce potentially misleading images of the channels and associated floodplain deposits. These horizontal amplitude maps that cross canals produce images of the differences in sediment types at bed boundaries. Therefore, they map the differences in sediment types that filled the canals, and not the canals themselves. In addition, the edges of the canals can often produce only very low amplitude reflections. It is usually only the sediment that is preserved in the bottoms of the canals that generates high amplitude reflections. The greatest lithologic change occurs at the base of the canals where the sand fill contrasts with the surrounding silt and clay. This contrast produces an interface that reflects radar energy. An amplitude slice map crossing two canals at Rillito Fan demonstrates this concept (Figure 15). At this site high amplitude reflections are generated only in places where sand was preserved in the channel. Associated clay and silt on the margins of the canal also produce high amplitude reflections. Portions of the channel, however, are totally invisible in the slice map, as the sediment that filled these features was the same composition as the surrounding material. Therefore, no distinct bed boundaries were present to reflect radar energy. A third channel at Rillito Fan was discovered with GPR and was originally interpreted as a previously unknown canal. Only after excavation was it found to be a natural channel produced during a prehistoric flood episode that eroded the irrigation canals (Huckleberry 2009). It was impossible to differentiate natural and constructed canals using GPR.

Early Agricultural period planting beds, which were extensively mapped at the Las Capas site, are challenging features for GPR, as they are very subtle and difficult to see even when exposed to view. As a test of GPR, a grid of reflection data was collected in an area that was scheduled for exposure by areally extensive excavations (Nials 2010). Using the 900 MHz antennas for higher resolution but shallower energy penetration, reflection data were acquired and an amplitude map was produced in the layer containing the agricultural beds at a depth of 20 cm. This map clearly shows changes in the soil layer due to creation of small catchment basins used for holding water. The square and rectangular beds are visible on GPR maps as amplitude features. These GPR readings may reflect prehistoric agricultural activities on the floodplain that involved the mixing of buried sandy sediments with surficial fine-grained sediments (Figure 16). These units would not be visible with GPR at this location without extensive removal of attenuating sediment prior to data collection.

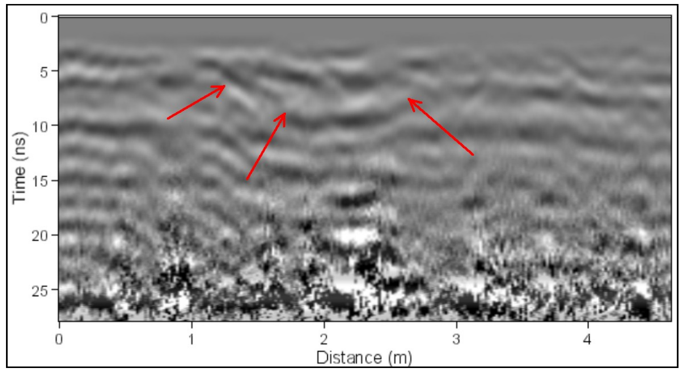

Figure 14. GPR reflection profile using 400 MHz energy crossing an Early Agricultural period irrigation canal at the Las Capas site. Reflections from this feature are much less distinct because the sediment that filled the canal is the same composition as the surrounding matrix. The similar composition produces only weak reflections. The channel is also wider at the base, which does not create a focusing boundary at its base to transmit radar energy back to the surface antenna.

CONCLUSIONS

A number of important archaeological features common in southern Arizona were successfully imaged using GPR technology. Horizontal floors of compacted earth or clay were the most readily visible in reflection profiles as distinct high amplitude reflections. When amplitude slice maps over large areas are constructed in layers that contain these floor reflections, the aerial extent of floor features can be mapped. Plaza surfaces and other intramural work areas, while not studied as part of this project, would likely be just as visible. In a similar way, earth ovens, which are smaller in extent, also produce high amplitude reflections visible in profile and horizontal amplitude maps. When these features are buried in sediment that contains salt or electrically conductive clay, which are common in desert environments, radar energy is attenuated during transmission and the features are less distinct or completely invisible if buried deeply enough. These sediments produce a medium that is not conducive to radar energy penetration, and all transmitted energy is attenuated close to the surface. In the Santa Cruz River floodplain, any features buried more than one meter in sediment are invisible due to this type of energy attenuation. The Gila River sediment appears to be even more electrically conductive due to greater amounts of carbonate and salt, and radar attenuation occurs at even shallower depths. With 400 MHz antennas, features located above the floodplain that are not covered by

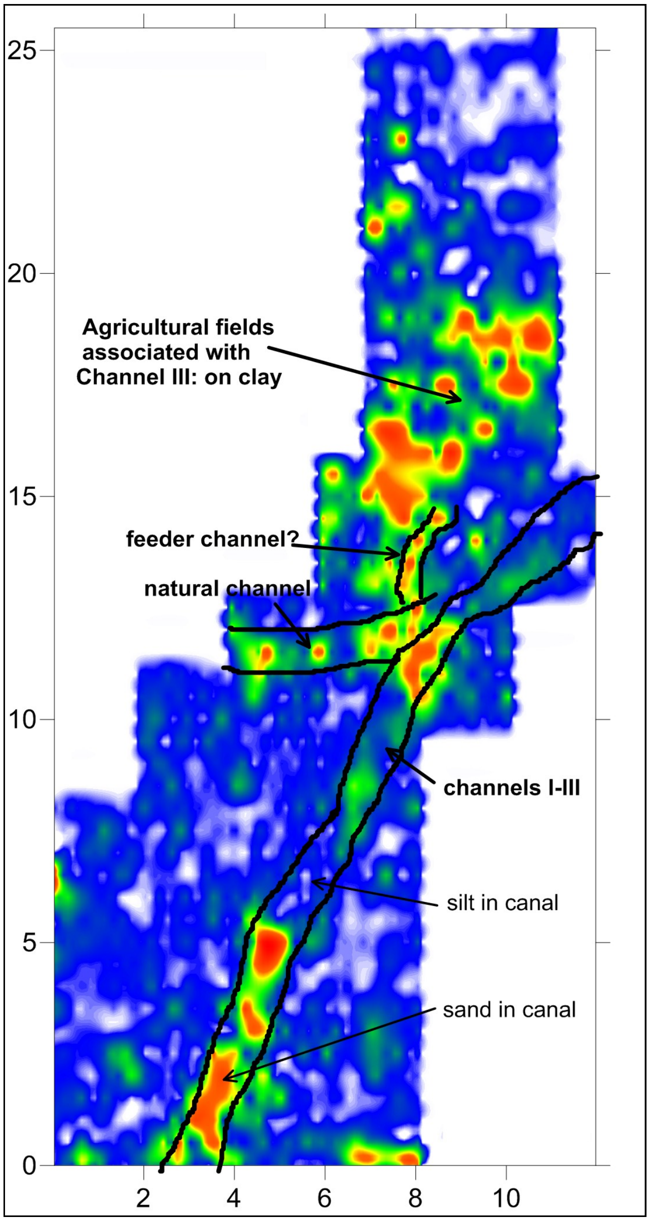

Figure 15. Amplitude slice map of a series of canals and associated agricultural beds at the Rillito Fan site. The map was produced from the 400 MHz reflection profiles. The channel margins that are visible in profile are drawn in black ,while the shades of gray are denote the strength of reflections. In the southern portion of the canal and a few other areas, sand fills the channel. This fill produces distinct reflections which are light gray. Elsewhere, the canal fill is the same composition as the surrounding sediment; therefore, only very weak or no reflections are produced (identified as white). These areas of the canals are indistinguishable from the surrounding floodplain sediment. A natural channel, produced during a flood, is also visible in a portion of the mapped area. The area north of the channels, originally interpreted as a feeder canal and agricultural fields, was mechanically stripped. No evidence of those features was found. The highly reflective areas were likely produced from interbedded floodplain sediments.

this attenuating fluvial sediment may be mapped with GPR to depths up to 2 m.

Standing walls constructed of earth produce few radar reflections and appear as areas of no reflection in profiles and amplitude slice maps. These walls were constructed of homogeneous clay and binding agents, and therefore produce a medium that is non-reflective and also attenuating to radar energy. Because these walls have usually been eroded over time and are bounded and buried by adobe melt and interbeds of sediment, radar reflections from these proximal units are distinct. The location of some walls can therefore be mapped by analyzing the layers that bound walls, which are those that produce the high amplitude reflections.

Agricultural canals and planting beds, which are buried in floodplain sediments, are potentially visible in GPR reflection profiles if they are not buried below the depth of radar energy attenuation. If buried below 1 m in the Santa Cruz and Gila River Valleys, overlying

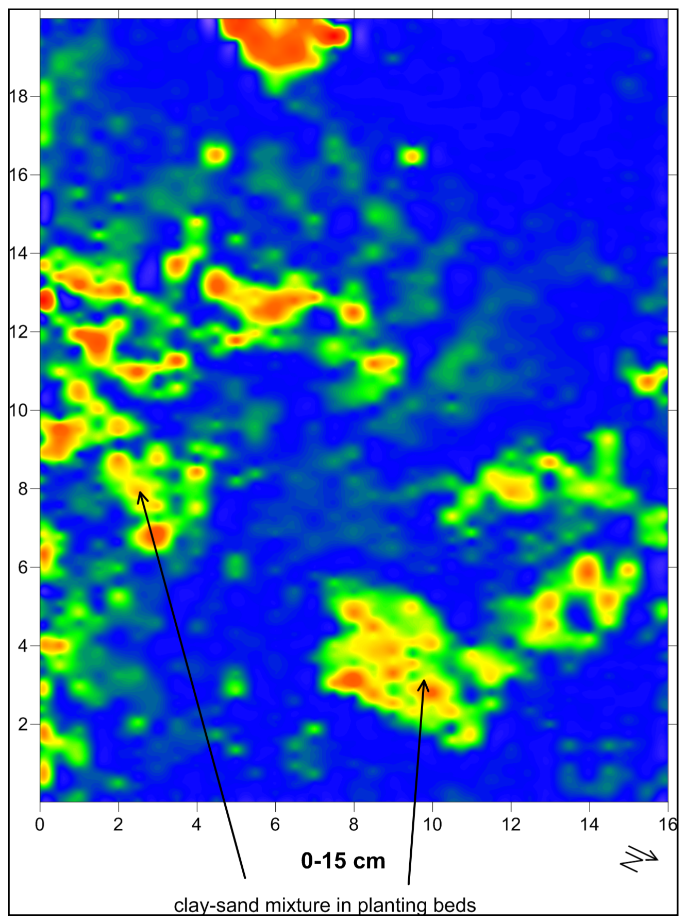

Figure 16. GPR amplitude map of planting beds at the Las Capas site. The map is composed of profiles collected with the 900 MHz antennas. The rectangular units contain an amalgamation of soil constituents within the small catchment basins, which are visible as high amplitude features.

sediment must be removed before GPR data collection. When sufficient energy is available for reflection from canals, they are readily visible in profile. Complex reflections can be produced from the channels as the sides of canals are often poor reflection surfaces; the sides slope away from the surface antennas and therefore scatter energy away from the surface. However, reflection will occur from the canal edges that are in front and behind the surface antennas when profiles are collected perpendicular to the canal orientations. This produces phantom reflections that appear in profiles below the actual location of the canals. These reflections can be confusing unless the nature of radar reflections in the ground is understood and taken into consideration. In addition, bases of some canals can often produce very high amplitude reflections if they are bowl-shaped and contain sediment fill that is compositionally different than the surrounding sediment. These surfaces are highly reflective and focus radar energy; they allow very high amplitude reflections to be transmitted back to the surface antennas and recorded. Subtle agricultural fields are also visible, such as the rectangular “waffle beds” at the Las Capas site. In all cases, soil and sediment distributions in canals and agricultural beds are highly variable and can potentially produce confusing amplitude slice maps. For instance, if canals are filled by both sandy and finer-grained sediment along their reaches, the amplitude maps will produce linear high amplitude features only when sand is bounded by silt and clay layers. When the canal fill is similar to the surrounding sediment, the amplitude maps will display areas of no reflection, because there is not enough variability in sediment to produce reflections.

Depending on the depth of burial, composition of the archaeological features, the surrounding burial material, and the geometry of these features, GPR can be of great value in discovering and mapping cultural resources in southern Arizona. While the method cannot be applied to all areas of interest, with considered and knowledgeable collection, processing, and interpretation, GPR has a wide range of applications in the area. A knowledge of not only the nature of buried archaeological features is important, but also the associated soil and sediment layers and their composition and chemistry. Software is now available that can readily be used to produce processed and filtered reflection profiles and amplitude slice maps to construct useful images of the subsurface.

Acknowledgements. Many thanks to Desert Archaeology, Northland Research and University of Arizona School of Anthropology, Gary Huckleberry and Paul and Suzanne Fish, Dave Ross, and Paul Swader for assistance in data collection. Many thanks to Gary Huckleberry for his comments, edits and suggestions, which improved this paper greatly.

REFERENCES CITED

Campana, Stefano, and Salvatore Piro (editors)
2009 *Seeing the Unseen-Geophysics and Landscape Archaeology.* CRC Press/Balkema: Taylor and Francis Group, London.

Conyers, Lawrence B.
2004 *Ground-penetrating Radar for Archaeology.* Altamira Press, Walnut Creek, California.
2009 Ground-penetrating Radar for Landscape Archaeology. In *Seeing the Unseen-Geophysics and Landscape Archaeology*, edited by Stefano Campana and Salvatore Piro, pp. 245-256, CRC Press/Balkema: Taylor and Francis Group, London.
2010 Ground-penetrating Radar for Anthropological Research. *Antiquity* 84:175-184.

Conyers, Lawrence B., and Henry D. Wallace
2004 Ground-penetrating Radar Techniques and Three-Dimensional Computer Mapping at the Valencia Site. In *Archaeological Excavations at Valencia Vieja*. Technical Report No. 2001-11, pp. 135-143, Desert Archaeology, Tucson, Arizona.

Conyers, Lawrence B., and Catherine M. Cameron
1998 Finding Buried Archaeological Features in the American Southwest: New Ground-penetrating Radar Techniques and Three-Dimensional Computer Mapping. *Journal of Field Archaeology* 25(4):417-430.

Conyers, Lawrence B., and Samuel Connell
2007 The Applicability of Using Ground-penetrating Radar to Discover and Map Buried Archaeological Sites in Hawaii. *Hawaiian Archaeology* 11:62-77.

Fish, Suzanne, Paul R. Fish, and John H. Madsen
1992 *The Marana Community in the Hohokam World.* Anthropological Papers of the University of Arizona, Number 56. University of Arizona Press, Tucson.

Gaffney, Chris, and John Gater
2003 *Revealing the Buried Past: Geophysics for Archaeologists.* Tempus, Stroud, Gloucestershire.

Huckleberry, Gary
2009 Prehistoric Canals within the Pima County Interconnect Project Corridor, Pima County, Arizona. Report submitted to Northland Research, Inc., Marana, Arizona.

Kvamme, Kenneth L.
2003 Geophysical Surveys as Landscape Archaeology. *American Antiquity* 63(3):435-457.

Pearthree, P. A., K. A. Dempsey, J. Onken, K. R. Vincent, and P. K. House
1992 Geomorphic Assessment of Flood-Prone Areas on the Southern Piedmont of the Tortolita Mountains, Pima County, Arizona. Arizona Geological Survey Open-File Report 91-11, Tucson.

McKittrick, M.
1988 Surficial Geologic Maps of the Tucson Metropolitan Area. Arizona Geological Survey Open-File Report 88-18, Tucson.

Nials, Fred

2010 Archaic Planting Beds at the Las Capas Site. Report submitted to Desert Archaeology, Tucson, Arizona.

2008 Geomorphology and Stratigraphy. In *Las Capas: Early Irrigation and Sedentism in a Southwestern Floodplain,* edited by J. Mabry, pp. 35-54. Anthropological Paper No. 28. Center for Desert Archaeology, Tucson, Arizona.

Sternberg, Ben K., and James W. McGill

1995 Archaeology Studies in Southern Arizona using Ground Penetrating Radar. *Journal of Applied Geophysics* 33:209-225.

Waters, Michael, and John J. Field

1986 Geomorphic Analysis of Hohokam Settlement Patterns on Alluvial Fans along the Western Flank of the Tortolita Mountains, Arizona. *Geoarchaeology: An International Journal* 1:329-345.