Seeing the Unseen – Campana & Piro (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-44721-8

Ground-penetrating radar for landscape archaeology: Method and applications

L.B. Conyers
Department of Anthropology, University of Denver, Colorado, USA

ABSTRACT: Ground-penetrating radar mapping allows for a three-dimensional analysis of archaeological features within the context of landscape studies. The method's ability to measure the intensity of radar reflections from as deep as 5 meters in the ground can produce images and maps of buried features not visible on the surface. A study was conducted in the desert of the American Southwest to study the buried remains of ceremonial architecture within one valley in southern Utah. In this area large circular depressions on the ground were thought to be the remains of ceremonial buildings called kivas, indicating a connection of the people that lived there to a powerful and influential city to the south called Chaco. The ground-penetrating radar analysis of these features, however, showed them to be small family-sized kivas with associated roomblocks, which does not support these people's strong connection to the city to the south. When these buildings were mapped and then placed within the river valley, it was determined that each was likely the product of a single family or extended family, who probably lived by subsistence agriculture. This study shows the applicability of using three-dimensional GPR analysis to place the built-environment within its landscape in order to test ideas about and explain social factors and connections that were in place during prehistoric times.

1 INTRODUCTION

Ground-penetrating radar is a near-surface geophysical technique that allows archaeologists to discover and map buried archaeological features for landscape analysis in ways not possible using traditional field methods. The method consists of measuring the elapsed time between when pulses of radar energy are transmitted from a surface antenna, reflected from buried discontinuities, and then received back at the surface. When the distribution and orientation of those subsurface 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 with buried sites where artifacts and features of interest are located within 2–3 meters of the surface, but has occasionally been used for more deeply buried deposits. A growing community of archaeologists has been incorporating ground-penetrating radar (GPR) as a routine field procedure for landscape analysis (Conyers 2004a; Conyers and Goodman 1997; Gaffney and Gater 2003). Their maps and images act as primary data that can be used to guide the placement of excavations, define sensitive areas containing cultural remains to avoid and place archaeological sites within a broader environmental context and study human interaction with, and adaptation to, ancient landscapes (Kvamme 2003). Ground-penetrating radar data are acquired by reflecting distinct pulses of radar energy from a surface antenna, reflecting them off buried objects, features or bedding contacts in the ground, and detected those reflections back at a receiving antenna. As radar pulses are being transmitted through various materials on their way to the buried target feature, their velocity will change, depending on the physical and chemical properties of the material through which they are traveling (Conyers 2004a: 45). Each velocity change generates a reflected wave, which travel back to the surface. The velocity of radar energy in the

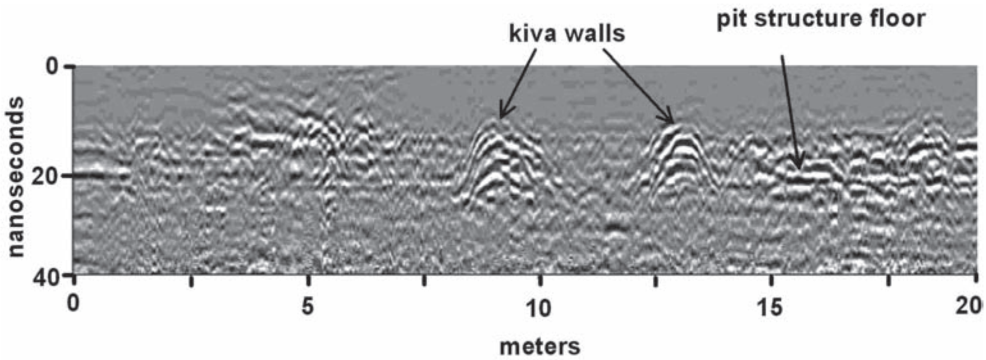


Figure 1. GPR reflection profile showing kiva walls and the floor of a pit structure from the Comb Wash area, southeastern Utah, USA.

ground is also important because when the travel times of the energy pulses are measured and their velocity through the ground is known, distance (or depth in the ground) can be accurately measured (Conyers 2004a: 99), producing a three-dimensional data set. Most typically in archaeological GPR radar antennas are moved along the ground in transects and two-dimensional profiles of a large number of reflections at various depths are created, producing profiles of subsurface stratigraphy and buried archaeological features along lines (Fig. 1).

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 2004a: 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 in a grid. 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 is what gives GPR an advantage over other near-surface methods with respect to buried archaeological feature resolution. Authors of papers to proceedings have to type these in a form suitable for direct photographic reproduction by the publisher. In order to ensure uniform style throughout the volume, all the papers have to be prepared strictly according to the instructions set below. A laser printer should be used to print the text. The publisher will reduce the camera-ready copy to 75% and print it in black only. For the convenience of the authors template files for MS Word 6.0 (and higher) are provided.

2 THE GPR METHOD

The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography and vegetation (Conyers 2004a: 28). It is not a geophysical method that can be immediately applied to any geographic or archaeological setting, although with thoughtful modifications in acquisition and data processing methodology, GPR can be adapted to many differing site conditions. In the past it has usually been assumed by most GPR practitioners that the method would only be successful in areas where soils and underlying sediment are dry (Annan and Davis 1992). Although radar wave penetration, and the ability to reflect energy back to the surface, is often enhanced in a dry environment, recent work has demonstrated that dryness is not necessarily a prerequisite for GPR surveys and even very wet environments are suitable, as long as the medium is not electrically conductive (Conyers 2004b).

The GPR method involves the transmission of high frequency electromagnetic radio (radar) pulses into the earth and measuring the time elapsed between transmission, reflection off a buried discontinuity and reception back at a surface radar antenna. A pulse of radar energy is generated on a dipole transmitting antenna that is placed on, or near, the ground surface. The resulting wave of electromagnetic energy propagates downward into the ground where some energy can be reflected back to the surface at discontinuities. The discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, lithologic changes, differences in bulk density at stratigraphic interfaces and most important water content variations. Reflection can also occur at interfaces between anomalous archaeological features and the surrounding soil or sediment. Void spaces in the ground, which may be encountered in burials, tombs, or tunnels will also generate significant radar reflections due to a significant change in radar wave velocity.

The depth to which radar energy can penetrate and the amount of definition that can be expected in the subsurface is partially controlled by the frequency of the radar energy transmitted. Radar energy frequency controls both the wavelength of the propagating wave and the amount of weakening, or attenuation, of the waves in the ground. Standard GPR antennas used in archaeology propagate radar energy that varies in band width from about 10 megahertz (MHz) to 1200 MHz. Antennas usually come in standard frequencies, with each antenna having one center-frequency, but actually producing radar energy that ranges around that center by about two octaves (one half and two times the center frequency).

The most efficient method in subsurface GPR mapping is to establish a grid across a survey area prior to acquiring data. Usually rectangular grids are established with a transect spacing of one meter or less. Rectangular grids produce data that are easier to process and interpret. Other shapes of grid acquisition patterns may be necessary because of surface topography or other obstructions. Data from non-rectilinear surveys is just as useful as those acquired in rectangular shaped grids, although more field time may be necessary in surveying, and reflection data must be manipulated differently during computer processing and interpretation for reflection amplitude analysis.

The two-way travel time and the amplitude and wavelength of the reflected radar waves derived from the pulses are amplified, processed and recorded for immediate viewing and later post-acquisition processing and display. During field data acquisition the radar transmission process is repeated many times a second as the antennas are pulled along the ground surface in transects. Distance along each line is recorded for accurate placement of all reflections within a surveyed grid. In this fashion two-dimensional profiles, which approximate vertical “slices” through the earth, are created along each grid line (Fig. 1).

Radar energy becomes both dispersed and attenuated as it radiates into the ground. When portions of the original transmitted signal are reflected back toward the surface they will suffer additional attenuation by the material through which they pass, before finally being recorded at the surface. Therefore to be detected as reflections, important subsurface interfaces must not only have sufficient electrical contrast at their boundary but also must be located at a shallow enough depth where sufficient radar energy is still available for reflection. As radar energy is propagated to increasing depths, and the signal becomes weaker as it spreads out over more surface area and absorbed by the ground, making less available for reflection. For every site the maximum depth of resolution will vary with the geologic conditions and the equipment being used. Post-acquisition data filtering and other data amplification techniques (termed range-gaining) can sometimes be applied to reflection data after acquisition that will enhance some very low amplitude reflections in order to make them more visible.

Many ground-penetrating radar novices envision the propagating radar pattern as a narrow “pencil” shaped beam that is focused directly down from the antenna. In fact, GPR waves radiated from standard commercial antennas radiate energy into the ground in an elliptical cone with the apex of the cone at the center of the transmitting antenna (Conyers 2004a: 62). This elliptical cone of transmission occurs because the electrical field produced by the antenna is generated parallel to its long axis and is therefore usually radiating into the ground perpendicular to the direction of antenna movement along the ground surface. The radiation pattern is generated from a horizontal electric dipole antenna to which elements are sometimes added that effectively reduce upward radiation, called shields. Sometimes the only shielding mechanism is a radar absorbing surface placed above the antenna to neutralize upward radiating energy. Because of cost and portability considerations (size and weight), the use of more complex radar antennas that might be able to focus energy more efficiently into the ground in a more narrow beam has to date been limited in archaeology.

Some antennas, especially those in the low frequency range from 10 to 100 MHz, are often not shielded and will therefore radiate radar energy in all directions. Using unshielded antennas can generate reflections from a nearby person pulling the radar antenna, or from any other objects nearby such as trees or buildings. Discrimination of individual targets, especially those of interest in the subsurface, can be difficult if these types of antennas are used. However, if the unwanted reflections generated from unshielded antennas can be identified, they can be easily filtered-out later. If reflections are recorded from randomly located trees, surface obstructions, or people moving about randomly near the antenna, they are more difficult to discriminate from important subsurface reflections and interpretation of the data is much more difficult.

One of the most important variables in GPR surveys is the selection of antennas with the correct operating frequency for the depth necessary and the resolution of the features of interest (Conyers 2004a: 64). Proper antenna frequency selection can in most cases make the difference between success and failure in a GPR survey and must be planned for in advance. In general the greater the necessary depth of investigation, the lower the antenna frequency should be used. But lower frequency antennas are much larger, heavier and more difficult to transport to and within the field than high frequency antennas. For instance a 100 MHz antenna is about 2 meters long. It is not only difficult to transport to and from the field, but must usually be moved along transect lines using some form of wheeled vehicle or sled. In contrast, antennas greater than 400 MHz are usually 50 centimeters or smaller in maximum dimension, weigh very little, and can easily fit into a suitcase.

Low frequency antennas (10–120 MHz) generate long wave-length radar energy that can penetrate up to 50 meters in certain conditions, but are capable of resolving only very large subsurface features. In pure ice, antennas of this frequency have been known to transmit radar energy many kilometers. In contrast the maximum depth of penetration of a 900 MHz antenna is about one meter or less in typical soils, but its generated reflections can resolve features down to a few centimeters in dimension (Conyers 2004a: 47). A trade-off therefore exists between depth of penetration and subsurface resolution. The depth of penetration and the subsurface resolution is actually highly variable, depending on many site-specific factors such as overburden composition, porosity and the amount of retained moisture. If large amounts of electrically-conductive clay, are present, then attenuation of the radar energy with depth will occur very rapidly, irrespective of radar energy frequency. Attenuation can also occur if sediment or soils are saturated with salty water, especially sea water.

The ability to resolve buried features is mostly determined by frequency and therefore the wavelengths of the radar energy being transmitted into the ground. The wavelength necessary for resolution varies depending on whether a three-dimensional object or an undulating surface is being investigated. For GPR to resolve three-dimensional objects, reflections from at least two surfaces, usually a top and bottom interface, need to be distinct. Resolution of a single buried planar surface, however, needs only one distinct reflection and therefore wavelength is not as important in its resolution.

Radar energy that is reflected off a buried subsurface interface that slopes away from a surface transmitting antenna will be reflected away from the receiving antenna and will be lost. This sloping interface would therefore go unnoticed in reflection profiles. A buried surface with this orientation would only be visible if an additional traverse were located in an orientation where that the same buried interface is sloping toward the surface antennas. This is one reason why it is important to always acquire lines of reflection data within a closely spaced surface grid, and sometimes in transects perpendicular to each other.

Some features in the subsurface may be described as “point targets”, while other are more similar to planar surfaces. Planar surfaces can be stratigraphic and soil horizons or large flat archaeological features such as floors. Point targets are features such as walls, tunnels, voids, artifacts or any other non-planar object. Depending on a planar surface’s thickness, reflectivity, orientation and depth of burial it is potentially visible with any frequency data, constrained only by the conditions discussed above. Point sources, however, often have little surface area with which to reflect radar energy and therefore are usually difficult to identify and map. They are sometimes indistinguishable from the surrounding material, many times being visible only as small reflection hyperbolas visible on one profile within a grid (Fig. 1).

In most geological and archaeological settings the materials through which radar waves pass may contain many small discontinuities that reflect energy, which can only be described as clutter (if they are not the target of the survey). Resolution of clutter is totally dependent on the wavelength of the radar energy being propagated. If both the features to be resolved and the discontinuities producing the clutter are on the order of one wavelength in size, then the reflection profiles will appear to contain only clutter and there can be no discrimination between the two. Clutter can also be produced by large discontinuities, such as cobbles and boulders, but only when a lower frequency antenna that produces a long wavelength is used. In all cases the features to be resolved, if not a large planar surface, should be much larger than the clutter, and greater than one wavelength of the propagating energy in dimension (Conyers 1004a: 65).

The raw reflection data collected by GPR is nothing more than a collection of many individual traces along two-dimensional transects within a grid. Each reflection trace contains a series of waves that vary in amplitude depending on the amount and intensity of energy reflection that occurred at buried interfaces. When these traces are plotted sequentially in standard two-dimensional profiles the specific amplitudes within individual traces that contain important reflection information are sometimes difficult to visualize and interpret. Rarely is the standard interpretation of GPR data, which consists of viewing each profile and then mapping important reflections and other anomalies sufficient, especially when the buried features and stratigraphy are complex. In areas where buried materials are difficult to discern, different processing and interpretation methods, one of which is amplitude analysis, must be used. In the past when GPR reflection data were collected that had no discernable reflections or recognizable anomalies of any sort the survey was usually declared a failure and little if any interpretation was conducted. With the advent of more powerful computers and sophisticated software programs that can manipulate large sets of digital data, important subsurface information in the form of amplitude changes within the reflected waves has been extracted from these types of GPR data (Conyers 2004a: 148).

An analysis of the spatial distribution of the amplitudes of reflected waves is important because it is an indicator of subsurface changes in lithology and other physical properties. The higher the contrasting velocity at a buried interface, the greater the amplitude of the reflected wave. 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 subsurface in three-dimensions. Areas of low amplitude waves indicate uniform matrix material or soils while those of high amplitude denote areas of high subsurface contrast such as buried archaeological features, voids or important stratigraphic changes. In order to be correctly interpreted, amplitude differences must be analyzed in discrete slices that examine only the strength of reflections within specific depths in the ground. Each slice consists of the spatial distribution of all reflected wave amplitudes at various depths, which are indicative of these changes in sediments, soils and buried materials.

Amplitude slices need not be constructed horizontally or even in equal time intervals. They can vary in thickness and orientation, depending on the questions being asked (Conyers and Goodman 1997). Surface topography and the subsurface orientation of features and stratigraphy of a site may sometimes necessitate the construction of slices that are neither uniform in thickness nor horizontal. To compute horizontal amplitude slices the computer compares amplitude variations within traces that were recorded within a defined time window (that can become depth-windows if velocities are known). When this is done both positive and negative amplitudes of reflections are compared to the norm of all amplitudes within that window. No differentiation is usually made between positive or negative amplitudes in these analyses; only the magnitude of amplitude deviation from the norm. Low amplitude variations within any one slice denote little subsurface reflection and therefore indicate the presence of fairly homogeneous material. High amplitudes indicate significant subsurface discontinuities, in many cases detecting the presence of buried features. An abrupt change between an area of low and high amplitude can be very significant and may indicate the presence of a major buried interface between two media. Degrees of amplitude variation in each time-slice can be assigned arbitrary colors or shades of gray along a nominal scale. Usually there are no specific amplitude units assigned to these color or tonal changes.

Using three-dimensional GPR reflection data, buried features can be rendered into isosurface images, meaning that the interfaces producing the reflections are placed in a three-dimensional picture and a pattern or color is assigned to specific amplitudes in order for them to be visible (Conyers et al. 2002; Conyers 2004a: 163; Goodman et al. 2004; Leckebusch 2003). In programs that produce these types of images certain amplitudes (usually the highest ones) can be patterned or colored while others are made transparent. Computer-generated light sources, to simulate rays of the sun, can then be used to shade and shadow the rendered features in order to enhance them, and the features can be rotated and shaded until a desired image results.

3 EXAMPLE OF THREE-DIMENSIONAL GPR MAPPING FOR LANDSCAPE

One area of landscape analysis success with GPR is the high altitude desert areas of Utah, USA, which contains abundant buried archaeological remains, including pit houses, kivas (semi-subterranean circular pit features used for ceremonial activities) and storage pits (Conyers and Cameron 1998). In this area whole valleys might contain buried archaeological features that are all but invisible on the surface, aside from scattered pottery sherds. The climate and geological processes active in this area have produced an abundance of dry sandy wind-blown sediment that often covers and obscures the underlying archaeological features (Conyers and Osburn 2006).

Traditional archaeological exploration and mapping methods in this area that have been used for the discovery of buried sites includes visual identification of artifacts in surface surveys, random test pit excavation and the spatial analysis of subtle topographic features, all of which might indicate the presence of buried architecture. These methods are extremely haphazard and random, often leading to mis-identification or non-identification of many features. In order to test the GPR method for archaeological landscape analysis in this area, a number of tests were performed in one valley, called Comb Wash in southeastern Utah, USA (Fig. 2).

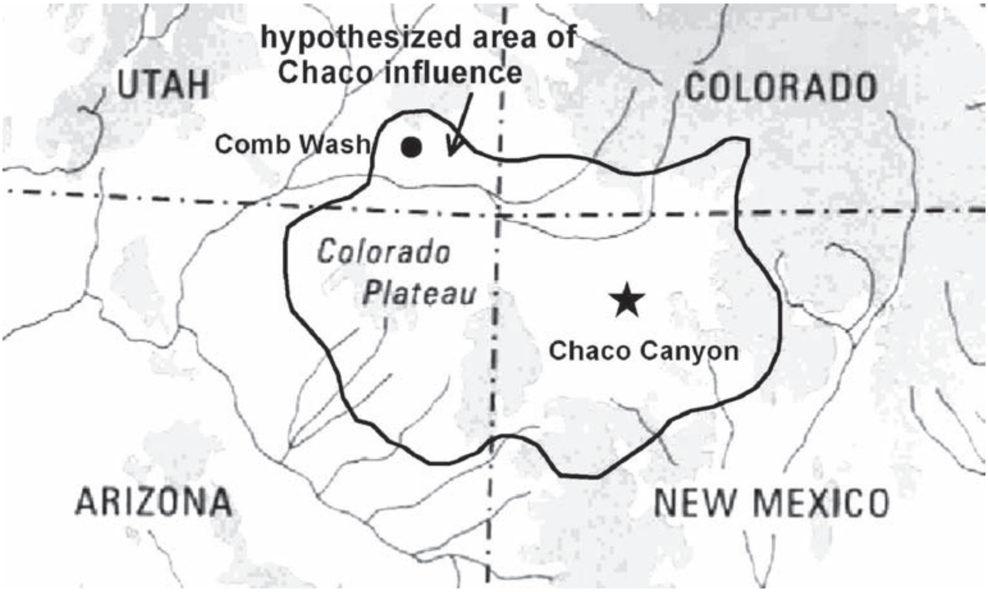


Figure 2. Base map showing the Comb Wash study area in relationship to the dominant are of Chaco Canyon, New Mexico, USA.

Surface analysis and minor testing over the last 3 decades indicated that this area contained an abundance of buried features thought to be the product of influence from a dominant culture in the area, called Chaco (Lekson 2006). Initial interpretations indicated that most of the Comb Wash area was inhabited by people that were in direct contact with Chaco (located hundreds of kilometers to the southeast) in New Mexico (Cameron 2001, Hurst 2000).

The Chaco period of influence in this region of the American Southwest, beginning about A.D. 900, is characterized by widespread and distinctive architectural styles that have been linked to a shared ideology (Lekson 2006). It was during this time that many of the most impressive buildings with complex architecture and massive stone construction were constructed. These large structures are characterized by above-ground room blocks (called pueblos) and associated semi-subterranean circular pit structures termed kivas, which were used for ceremonial and other activities. Often during Chaco times these kivas and pueblos were "over-built" presumably to impress others, and are often referred to with the moniker "great" by archaeologists who study this region. Kivas that were very large and indisputably Chaco in origin or influence are therefore termed Great Kivas. Archaeologists have proposed many hypotheses about the way Chaco leaders might have exerted influence on the surrounding region, but there is no consensus among scholars as to why or how this was accomplished (Lekson 2006).

Usually when Great Kivas and other large buildings from the Chaco period are found at sites on the margin of the Chaco influence they are referred to as Chaco-outliers, and economic and religious connections with the Chaco center are hypothesized. Some scholars have proposed that the outliers represent military strong posts, or that the people living there were subsumed under a tribute and redistributive system controlled by Chaco (Lekson 2006). Throughout the linear valley at Comb Wash, Utah four large circular depressions were hypothesized to be buried Great Kivas. The valley was therefore hypothesized to have been a regional center of Chaco integration, which was integrally tied to the larger Chaco center far to the southeast.

To test these ideas, GPR data were collected in large grids over these depressions in 2003. Previous work in the vicinity had shown that the GPR method could produce images of buried kivas with good resolution (Conyers and Cameron 1998). The excellent resolution of these buried features in GPR reflection profiles is a function of the distinct interfaces between the stone walls and compacted earth and masonry floors with the sandy matrix, producing distinct radar reflections (Figure 1).

Four GPR grids were collected on the Comb Wash depressions found along the valley floor with antenna transects spaced at 50 centimeters. The GSSI SIR-2000 control system with 400 MHz center frequency antennas was used with 50 reflection traces collected per meter in time windows ranging from 30 to 50 nanoseconds. Reflection profiles show distinct vertical walls and floors of pit features (Figure 1). In all four grids amplitude slice-maps were constructed in 5 nanosecond (two-way time) slices, each of which is approximately 30 centimeters thickness in depth (Figs. 3–5).

It was anticipated that large circular amplitude features of Great Kivas would be imaged using this data processing method, mimicking the size of the surface depressions and following on the ideas that this valley was well integrated with Chaco, based on the size of these buried kivas. These surface depressions range in diameter from 10–15 meters, which is the usual size of Chaco period Great Kivas elsewhere. Instead the GPR reflection amplitude slice-maps yielded a much different picture of these buried sites. Two of the four sites (Sites 1 and 2) showed much smaller circular pit house features ranging in diameter from 5 to 7 meters (Figures 3 and 4). At these two sites the GPR maps also showed a palimpsest of multiple superimposed pit features, indicating at least two, but potentially more periods of construction and modification in this one area. Site 3 showed only one pit feature constructed into bedrock, also about 6 meters in diameter (Figure 5). The fourth test site yielded no features that could be identified as architectural whatsoever in the amplitude maps and the depression presumably is not archaeological in origin.

To test the origin and age of the resulting GPR amplitude features at Sites 1 and 2, augers and standard open excavations were conducted. Vertical stone walls were uncovered in the locations where the highest reflection amplitudes were mapped, definitively showing that these are

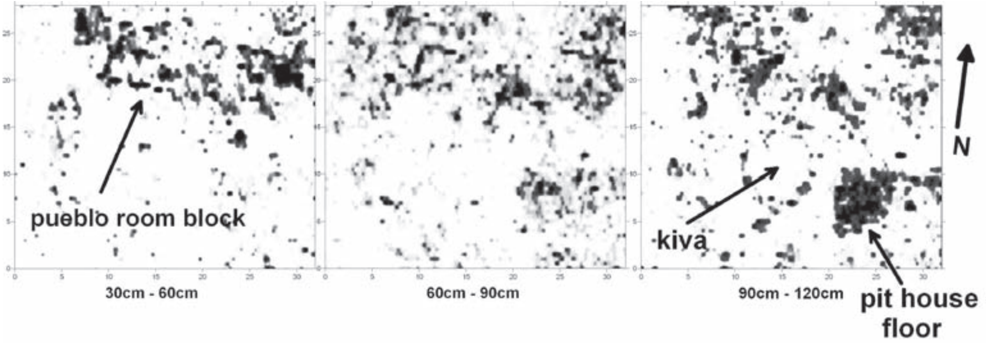


Figure 3. Amplitude slice-maps of Site 1 and Comb Wash, Utah showing near-surface room block with deeper pit house and kiva structures.

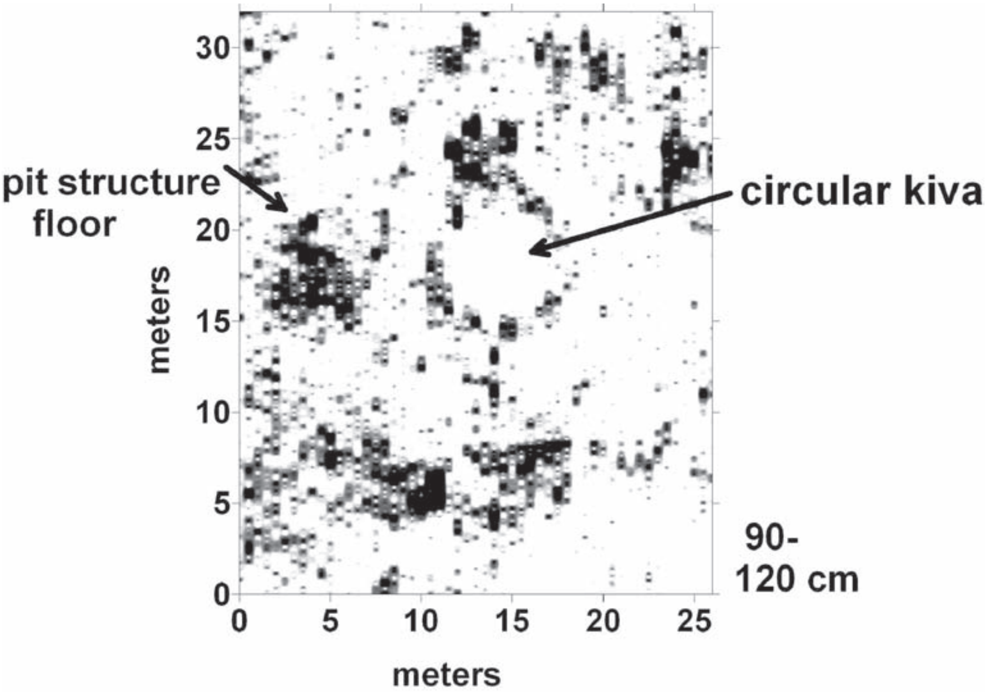
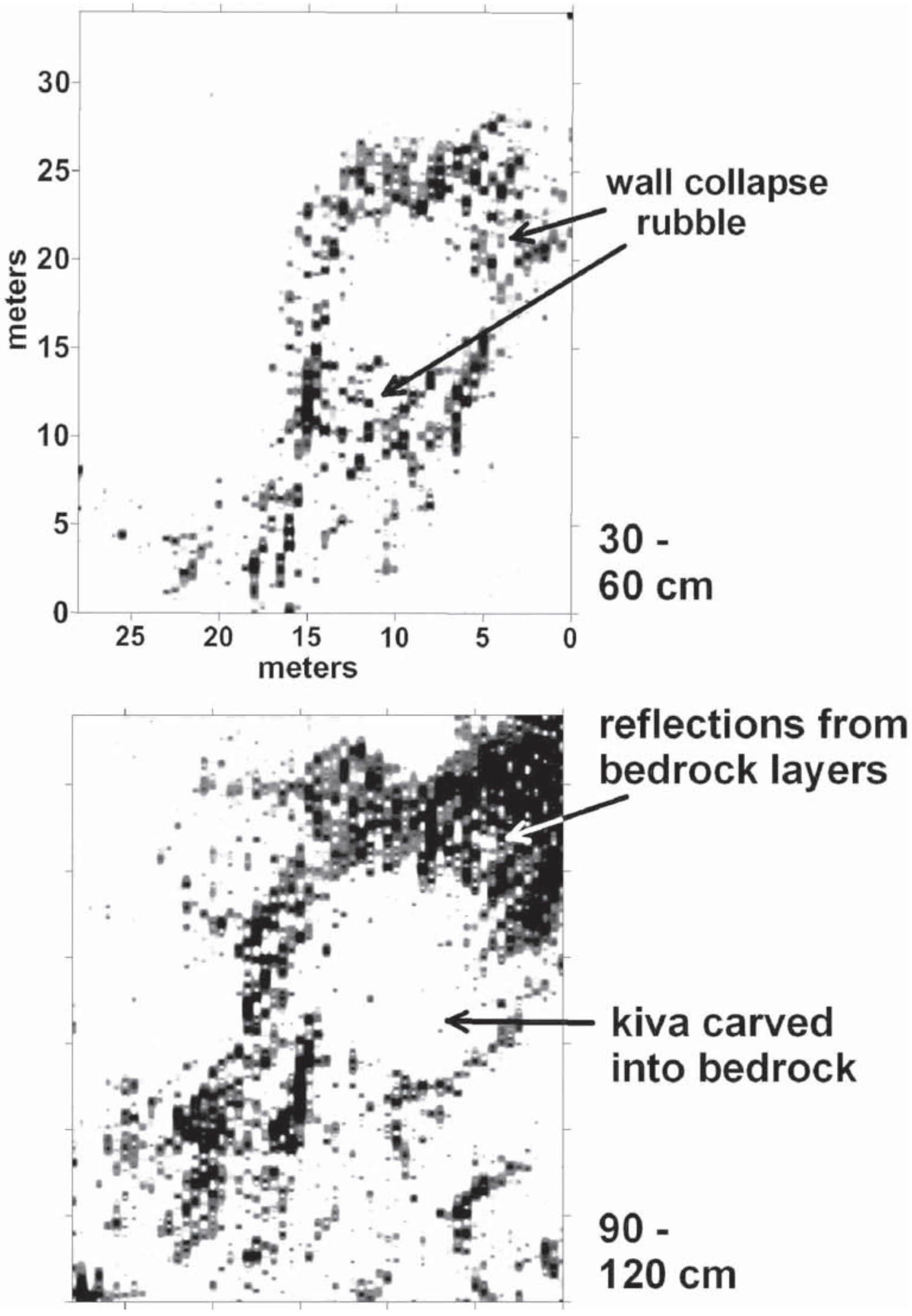


Figure 4. Amplitude slice-map of Site 2, showing similar features as Site 1 with a buried kiva and pit structure floor.

masonry-lined structures are much like other excavated Great Kivas, but much smaller. Ceramic artifacts encountered in association with the floors of these structures date to both before, during and after the period of presumed Chaco influence in the area. These excavations also confirmed multiple phases of construction at these sites, which had been hypothesized from the GPR amplitude maps. At two of the sites at least 2 kiva and pit structure building and subsequent abandonment episodes over many centuries were demonstrated. Their small size and the abundance of everyday cooking artifacts and other utilitarian tools supports the hypothesis that these were kivas used for multiple functions and not just ceremonies, as would have occurred in Chaco Great Kivas.



wall collapse rubble

30 - 60 cm

reflections from bedrock layers

kiva carved into bedrock

90 - 120 cm

Figure 5. Amplitude slice-map of Site 3 showing a kiva carved into bedrock.

In addition to kivas and other pit features, GPR reflection data mapped the remains of small room blocks to the north of two of the underground kivas in the upper 50 cm slice (Figure 3). The remains of these larger stone features were partially visible on the ground surface as rubble piles, which had been assumed, prior to GPR imaging, to be the surface remains of buried antechambers connected to the Great Kivas, which had been described elsewhere in the area (Hurst 2000). The GPR maps, however, showed no architectural elements preserved below the upper 30–60 centimeters in these areas, and the spatial patterning of the reflections in the upper slices show instead the foundations of above ground buildings that were composed of between 6 and 8 rooms each (Figure 3). These buildings likely served the habitation and storage functions for this small group of people, built to the north of the kivas in order to block the cold winter winds.

Site 3 GPR mapping illustrated a kiva cut into bedrock whose walls had partially collapsed long after abandonment (Figure 5). No room block was seen in the GPR maps at this site perhaps because its stone building materials were originally set on bedrock and had been recycled and re-used elsewhere long ago. The kiva at Site 3 was also 6–7 meters in diameter, indicative of a small group size.

In the case of the Comb Wash GPR analysis, four features that had been assumed to be the product of Chaco influence were determined to be simple family dwellings. In the context of this area's integration with the powerful cultural center to the southeast, GPR mapping along with information from a few excavations, provided the definitive tools that refuted this long held interpretation. When the buried features mapped by GPR were placed within an overall landscape context it was seen that Comb Wash was little more than a simple agrarian community that may have been peripherally influenced by Chaco, but hardly dominated by this powerful entity. The GPR method, selectively applied to what were considered to be the most important buried sites in the overall landscape, provided this new interpretation.

4 CONCLUSION

Ground-penetrating radar has the unique ability of near-surface geophysical methods to produce three-dimensional maps and images of buried architecture and other associated cultural and natural features for landscape analysis. Using high-definition two-dimensional reflection profiles, three-dimensional maps of amplitude changes can define physical and chemical changes in the ground that are related to archaeological buried materials of importance. When these data and maps are used to test ideas about human adaptation to landscapes, they offer a powerful and time-efficient way to study ancient human behavior, social organization and other important archaeological concepts.

In the processing of GPR reflection data for landscape analysis, maps and images must be generated and integrated with information obtained from other buried cultural artifacts to provide age and context for the mapped sites. This can be done by placing these cultural data from excavations within horizontal amplitude maps that produce images of only certain amplitudes within a three-dimensional volume of radar reflections. In all cases, the results of these amplitude images must be differentiated from the surrounding geological layers. When these multiple datasets are interpreted archaeologically, they can provide a powerful tool for the integration of archaeological sites within a landscape context.

REFERENCES

Annan, A.P. and J.L. Davis, 1992. *Design and development of a digital ground penetrating radar system*. In J.A. Pilon (editor), *Ground penetrating radar*. Geological Survey of Canada, Paper 90–4: 49–55.

Cameron, Catherine M., 2001, The Northern San Juan Region in the Post-Chaco era. In Bluff/Comb Wash Project Research Design. Department of Anthropology, University of Colorado, Boulder.

Conyers, Lawrence B., 2004a, Ground-penetrating Radar for Archaeology. AltaMira Press, Walnut Creek, California.

Conyers, Lawrence B., 2004b, Moisture and soil differences as related to the spatial accuracy of amplitude maps at two archaeological test sites. Proceedings of the Tenth International Conference on Ground Penetrating Radar, Delft, The Netherlands, June 21–24, 2004.

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 Dean Goodman, 1997, Ground-penetrating Radar: An Introduction for Archaeologists. AltaMira Press, Walnut Creek, California.

Conyers, Lawrence B., Ernenwein, Eileen G. and Leigh-Ann Bedal, 2002, Ground-penetrating radar (GPR) mapping as a method for planning excavation strategies, Petra, Jordan. E-tiquity Number 1 http://e-tiquity.saa.org/%7Eetiquity/title1.html.

Conyers, Lawrence B. and Tiffany Osburn, 2006, GPR Mapping to test anthropological hypotheses: A study from Comb Wash, Utah, American Southwest. Proceedings of the 11th International Conference on Ground-penetrating Radar, June 19–22, 2006, Columbus, Ohio, USA.

Davis, J.L. and A.P. Annan, 1992, Applications of ground penetrating radar to mining, groundwater, and geotechnical projects: selected case histories. In Pilon, J.S., Editor, Ground Penetrating Radar. Geological Survey of Canada paper 90–4, Ottawa: 49–56.

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

Goodman, Dean and Piro, Salvatore, Nishimura, Yasushi, Patterson, Helen and Vince Gaffney, 2004, Discovery of a 1st century AD Roman amphitheatre and other structures at the Forum Novum by GPR. Journal of Environmental and Engineering Geophysics 9: 35–42.

Hurst, Winston B., 2000, Chaco outlier or backwoods pretender? A provincial Great House at Edge of Cedars Ruin, Utah. In Great House Communities Across the Chacoan Landscape. Edited by J. Kantner and N.M. Mahoney. Anthropological Papers of the University of Arizona, n. 64, University of Arizona Press, Tucson, pp. 63–78.

Kvamme Kenneth L., 2003, Geophysical surveys as landscape archaeology. American Antiquity 63 (3): 435–457.

Leckebusch, J., 2003, Ground-penetrating radar: A modern three-dimensional prospection method. Archaeological Prospection 10: 213–240.

Lekson, Steven H., 2006, The Archaeology of Chaco Canyon: An Eleventh-Century Pueblo Regional Center. School of American Research Press, Santa Fe, New Mexico. The above material should be with the editor before the deadline for submission. Any material received too late will not be published. Send the material by airmail or by courier well packed and in time. Be sure that all pages are included in the parcel.