

Archaeology

Looks to New

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GROUND-PENETRATING RADAR TECHNOLOGY ALLOWS SUBSURFACE IMAGING OF BURIED ARCHAEOLOGICAL SITES

You may have wondered how archaeologists find treasures buried beneath the ground by sand and time. Sometimes they follow surface clues like scattered artifacts, standing architecture, or perhaps a small change in topography, which can pinpoint locations to excavate. At other times, more random digging or just plain luck must suffice as a discovery method. Although many great discoveries have been made in these ways, there are probably an even greater number of finds still waiting to be made, lying buried in places where archaeologists simply have not thought of testing. Often, new discoveries come to light only as a result of construction activity or erosion of the ground cover during a storm. In such cases, important materials can be partially or wholly destroyed before the arrival of an archaeological team. Even in extensively excavated archae-

ological sites, there are questions about what might lie just beyond an excavation's window into the subsurface. All of these problems involving buried sites might be solved if there were a reliable and accurate way to see below the ground surface.

Archaeologists have sometimes employed magnetometry, electrical resistivity and electromagnetic conductivity to discover and map the location of objects and features buried below the ground. These non-invasive geophysical techniques measure changes in the physical properties of near-surface soils and sediments. Thus, they are sensitive to abrupt changes in material, such as a boundary between soil and a buried stone wall or the presence of anomalous materials like metal or baked clay. Under optimal conditions a subsurface map of possible archaeological features of interest might be produced. Although these methods work well under a limited range of site conditions, none is

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capable of determining precisely the depth at which the subsurface properties change and, therefore, that third dimension must be inferred or estimated.

In contrast, another geophysical technique called ground-penetrating radar (GPR) not only detects subtle changes in the soil and sediment properties, including the presence of buried archaeological features, but it also measures the depth at which those changes occur. This geophysical procedure sends a series of radio waves into the ground and records the reflections of those waves from subsurface discontinuities. The travel time of the waves provides a way to measure the depth of the discontinuity. Modern data processing and image-generation programs can then produce three-dimensional maps of buried archaeological features.

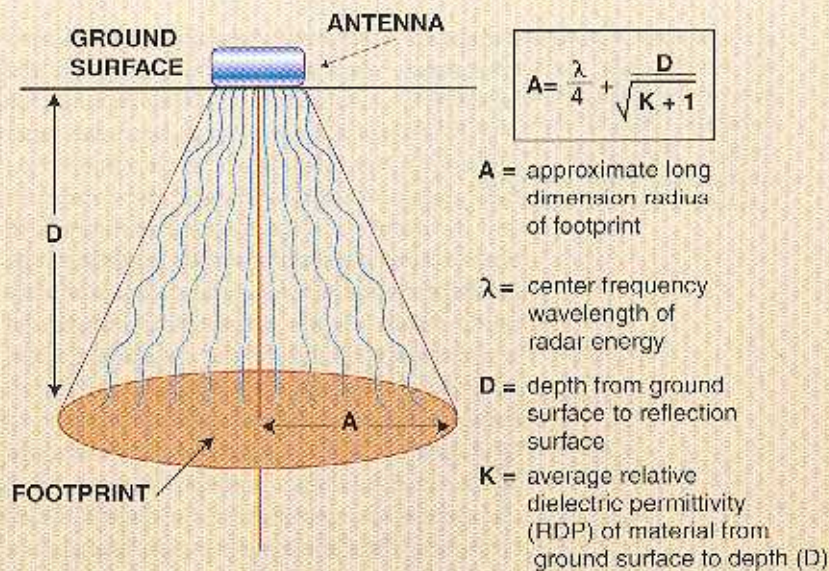
In the field, the GPR technique usually employs a single surface radar antenna to transmit very short pulses of electromagnetic energy (radar waves) downward. An accompanying receiving antenna records the waves that are reflected off discontinuities within the ground. Reflections might be generated at interfaces between buried archaeological features and the surrounding material, or perhaps from natural changes in soil properties or interfaces between stratigraphic horizons. The depth at which reflections were produced is calculated from the two-way travel time — how long the wave took to travel from the surface source, to the subsurface discontinuity and back to the surface receiver. Knowing the travel time, and calculating the wave velocity

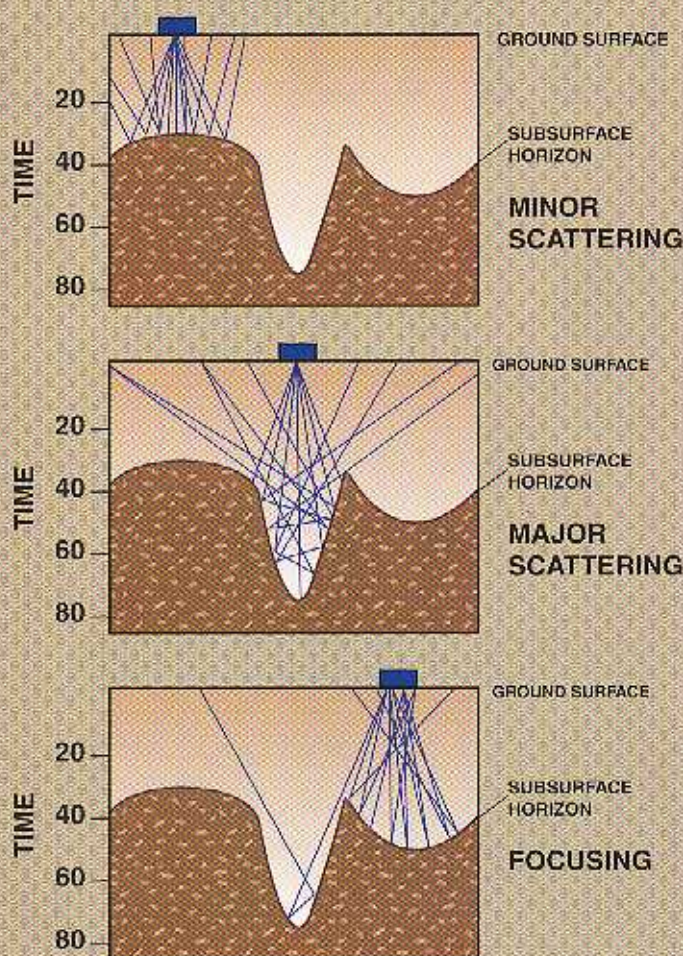
in the subsurface medium, allows one to calculate for distance. Radar wave travel times are measured in nanoseconds (ns), or billionths of a second.

When GPR is used for archaeological exploration and mapping, the radar antennas are moved in lines along the ground surface, sending and receiving many radar pulses per second, and recording both the amplitude and travel time of the reflected waves. Reflected wave amplitudes are a measure of the contrast in the physical and chemical properties of buried materials. The larger the contrast, the greater the amplitude of the reflected waves.

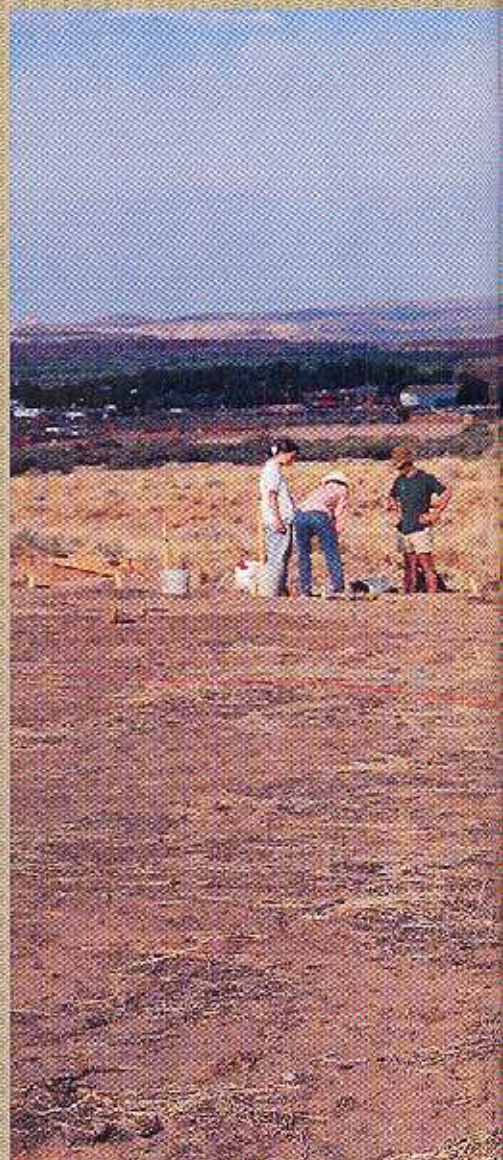
In the early years of this method, from about 1975-1990, reflections were usually printed on

The elliptical cone of radar penetration. The equation defines the cone geometry and the footprint radius at different depths.





Diagrammatic cross-section of a buried surface illustrating scattering and focusing of radar waves at different antenna locations.



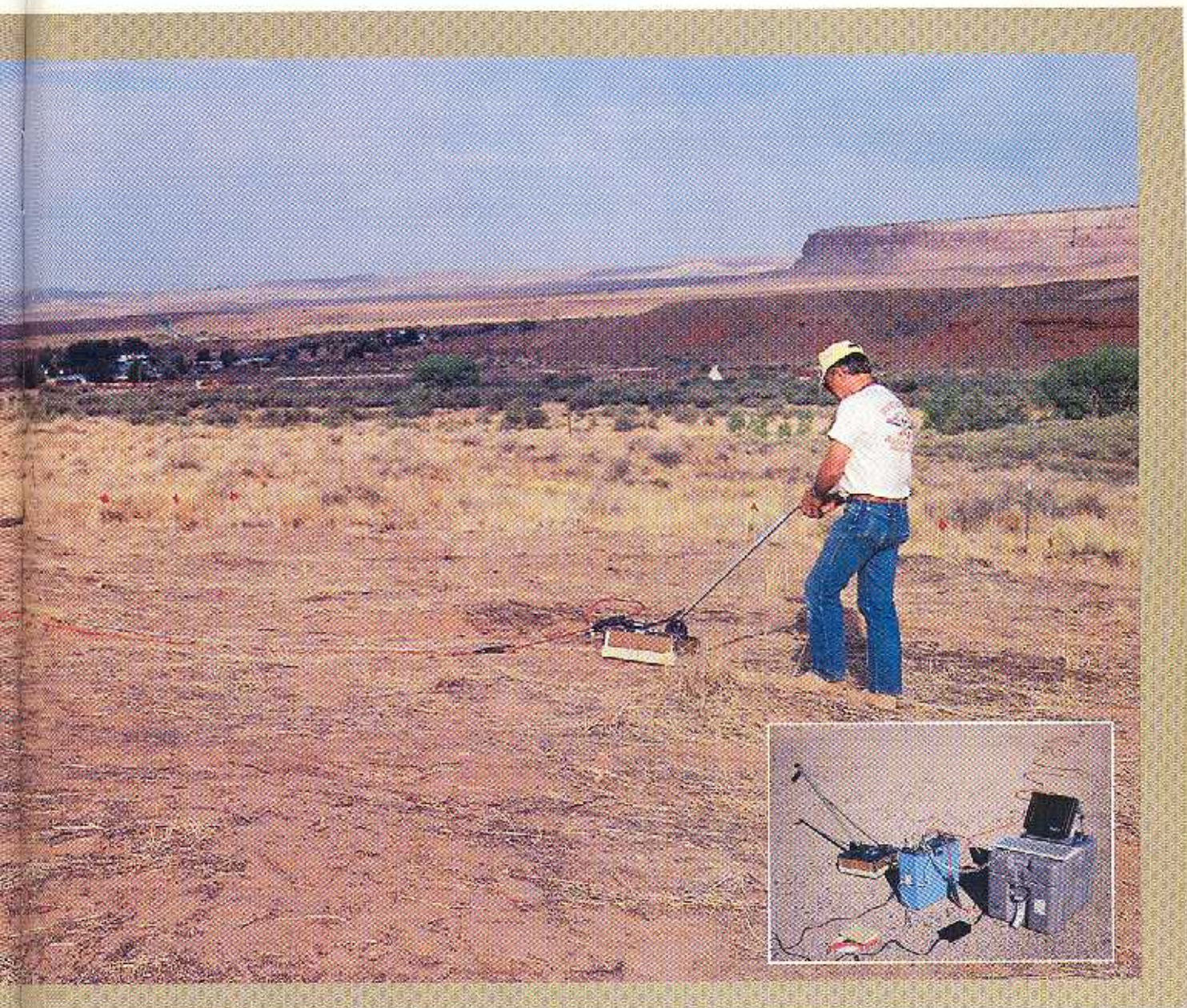
LAWRENCE B. COLLIER

paper and interpreted visually. If antenna traverses were parallel to one another, and the same type of anomalous reflections could be seen in several of the profiles at about the same position in the traverses, it was assumed that they were produced by a single buried feature and its extent could be mapped spatially. This type of data collection provided for little image processing or enhancement. Its success usually relied solely on the geophysical knowledge and intuitive ability of the interpreter, who many times was not sure what type of buried feature was generating the reflection.

In general, the archaeological community shunned this type of geophysical mapping because of a perception that it was a "black box" tool. Mysterious energy or "signals" of some sort went into the ground, generating

indecipherable images that could be interpreted only by geophysical "experts". As a result of this attitude, and an "intellectual discontinuity" between archaeological and geophysical cultures, many early attempts at GPR mapping in archaeology produced inconclusive results. Sometimes the method "worked" and other times it did not. While geophysicists continued to develop and refine the GPR method and produced numerous technical papers on the subject, for many archaeologists what mattered most was whether or not GPR could produce images usable for archaeology. The few archaeological GPR successes were trumpeted, while the method's failures were used as proof by some that GPR "didn't work for me."

Archaeological GPR has now come of age. Radar reflection data can be collected and



stored digitally, which permits sophisticated data processing and analysis, producing user-friendly displays of subsurface features.

In addition, the availability (and affordability) of powerful personal computers and software programs allows for the storage and processing of large three-dimensional GPR data sets (a typical 50 x 50 meter GPR survey can generate 500 megabytes of data). The earlier "noisy" GPR reflection data that so often mystified the casual interpreter of paper GPR printouts can now be processed and corrected to produce clean crisp reflection records of subsurface layers. These processed reflection profiles can sometimes be quite easy to interpret visually, if aerially extensive features like pit house floors are the target of exploration. If the buried features of interest are more complex,

like vertical walls, sinuous tunnels, or collapsed or contorted occupation surfaces, even the most seasoned geophysicist can be baffled when attempting to interpret complicated reflection profiles. Fortunately, computer advances now allow automated GPR data processing and image processing, which can partially overcome these difficulties.

Amplitude slice mapping typifies some of the advances in GPR data processing. The relative amplitudes of reflections at specific depths (as determined by converting radar travel time to distance) are compared for all the reflections collected within a grid. To make these amplitude comparisons thousands of individual reflections are separated into horizontal slices,

A high-frequency antenna is dragged along the surface in transects while radar waves are reflected from buried features. Inset above is a GPR system with antenna, radar generator, computer processor and screen.



Collecting GPR data at the Forum Novum, Italy. The antenna is dragged across the field. Note that there are no surface indications of the archaeological features that are preserved below.

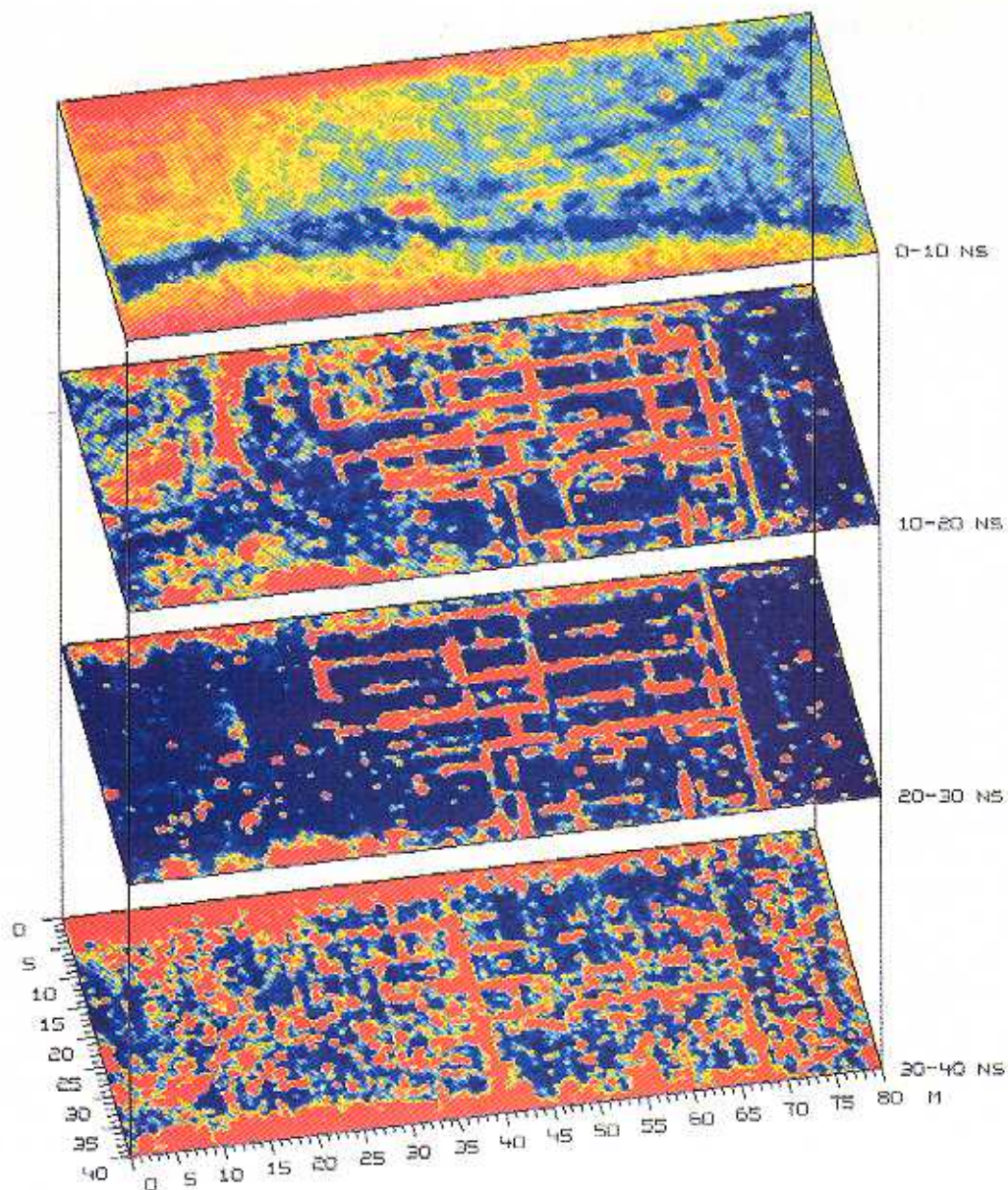
each corresponding to distinct depth in the ground. Within those slices hundreds of thousands of digital samples, corresponding to reflection amplitudes, are compared and saved. The location of higher amplitudes, produced by large differences in the properties of the buried materials, are then correlated, gridded and mapped spatially within each of the slices. In order to make a visual image that the human brain can interpret, colors of the rainbow (or perhaps shades of grey) are then applied to the regions in the slice that correspond to various reflection amplitudes. For instance, areas with higher amplitudes can be colored red, while those with little or no subsurface reflection, and therefore more homogeneous material, are colored blue. When this is done each sliced level becomes analogous to a careful excavation in horizontal levels, where all physical and chemical changes in buried materials are precisely mapped. When these differences in material properties can be correlated directly to the presence or absence of archaeological features or artifacts, the slice maps will illustrate many important components of buried archaeological sites.

The orientation and thickness of amplitude slice maps can be varied to fit individual site

parameters. For instance, slice maps need not be horizontal. Individual slices can be programmed to follow stratigraphic layers, buried living surfaces or any orientation and thickness desired.

Ideally, changes in the amplitudes of reflected radar waves can be correlated directly to archaeological features, as was the case at Forum Novum, a Roman archaeological site about 100 kilometers north of Rome, Italy. This ancient marketplace is being studied by archaeologists from the University of Birmingham, England in cooperation with the British School of Archaeology in Rome. Many public buildings, including a market place, warehouses, and mausoleums have been uncovered in the northern part of the site. These archaeological features, dating to as early as 300 B.C., appeared to project to the south, into a flat cleared area with no surface indicators of buried features. Aerial photograph interpretation, magnetometer and electrical resistivity surveys provided only marginally useful hints of what might be buried below the surface. In the hope of producing more definitive images of the subsurface, a GPR survey was conducted in this open area and the data were processed using the amplitude slice map method.

The amplitude slice from near the surface to 10 nanoseconds (a depth of about 50 centimeters) illustrates only some soil compaction features created by two gravel roads that merge in the mapped area.



Amplitude slice-maps from the Forum Novum Site, Italy. The slice from 0-10 ns (nanosecond, equivalent to 0-50 centimeters in depth) shows a subtle "Y" shaped anomaly, caused by differential compaction of two intersecting gravel roads. In the next two deeper slices (50 to over 100 centimeters) the Roman walls are clearly visible. Reflections from partially standing walls of individual rooms, doorways, and corridors appear in red. Areas with few reflections are shown in blue and represent soil and rubble fill. The deepest slice includes materials on the preserved floors of the rooms, yielding a more complex picture at this depth.

However, in the slice from 10 to 20 nanoseconds (about 50-100 centimeters in the ground), the buried Roman walls become visible. These horizontal slices graphically depict the layout of this portion of ancient Forum Novum, including individual rooms, doorways, courtyards and even possible roads. Partially collapsed walls, surrounded by wall rubble and soil, create the distinct radar velocity contrasts in the subsurface, producing high amplitude reflections. These reflections from the standing walls were then correlated and mapped throughout the area surveyed, producing a map that resembles an architectural layout of the site.

Although the exact function of this region of the ancient city can only be inferred from the GPR site plans, future digging will be con-

centrated only in certain room blocks, which will comprise a systematic and statistically representative sample of the subsurface. A complete unearthing of this area, which would be very costly and time consuming, can thereby be avoided.

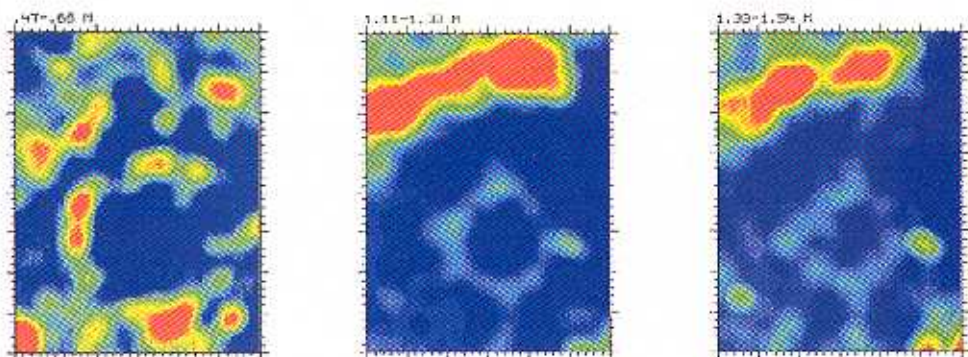
In some situations the GPR reflections are not nearly as easy to identify and correlate due to stratigraphic complexity or a seemingly random clutter of reflections, many of which may not be of archaeological importance. In the American Southwest near the town of Bluff, Utah, a Chaco Period (A.D. 900-1150) pueblo with massive walls has recently been excavated by the University of Colorado, Boulder. A shallow depression in the ground nearby was thought to be the collapsed remains of a great kiva, a large roofed, semi-subterranean



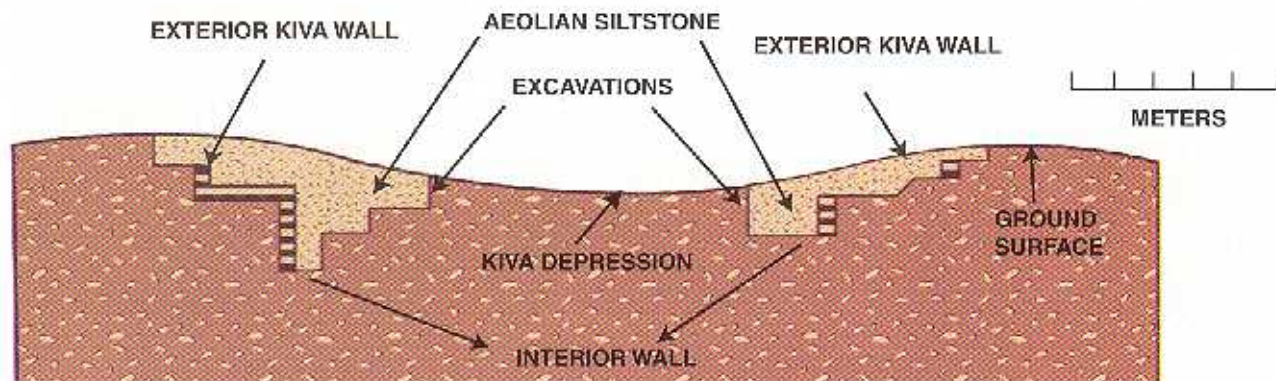
Site of the great kiva at Bluff, Utah, about to be surveyed by GPR. The base station with the computer is set up under the umbrella. The shallow depression to the left of the researchers is the only surface indication of a possible buried feature.

structure that may have been used for ceremonial activities by the inhabitants of the nearby pueblo. As a guide for future excavations of the possible kiva, GPR data were first collected in a 30 x 40 meter grid over the depression. Reflection data were processed using horizontal amplitude slice maps. In the slice from about 50 centimeters to a meter depth, the outer wall of the structure is clearly visible. In some places this wall appears to have col-

lapsed, but in other areas the GPR data showed it still to be standing. This phenomenon was later confirmed during excavations. Even more intriguing were images in the deeper slices that appeared to show a smaller radius wall located within the outer wall. Such structures within great kivas are not unknown in the American Southwest, but are rare. This inner deep "squatish" wall could not be seen on the individual reflection profiles, presumably because



A series of slice maps (30 x 40 meters) of the GPR survey at the great kiva site were generated. In the center of the shallow slice (left) a circular feature is indicated by the red and yellow colors, which represent high amplitude reflections. Subsequent excavations confirmed the presence of the outside wall of the kiva. Where the wall is partially collapsed only blue colored fill material is shown. This same material also fills the inside of the kiva. Deeper slices, middle and right, at 1.11 to 1.33 and 1.33 to 1.50 meters in depth, reveal low amplitude reflections from separate interior walls of the kiva.



it produced only low amplitude reflections that were overwhelmed at that depth by the abundance and clutter of other non-archaeological reflections. The computer was able to get around this problem by searching for the subtle amplitudes at specific depths and then mapping only those that formed themselves into linear or circular outlines. Subsequent excavations, using the GPR maps as a guide, proved the existence of both the outer and deeper inner walls in what appears to have been a main deep central chamber of the kiva, with shallower antechambers. At this site the strength of the amplitude slice map method was its ability to image buried features not visible to the human eye in many individual profiles and then correlating and mapping them within the grid as a whole.

Ground-penetrating radar surveys have value for rapid non-destructive discovery and mapping of buried archaeological sites. If GPR mapping is employed in areas where such sites are suspected, buried remains can be identified and then avoided, preserving them from the destructive effects of construction or erosion. Ground-penetrating radar can also assist archaeological research project planning. Few excavation designs call for digging more than a small fraction of a site, due to time and monetary constraints. Archaeologists are therefore required to make interpretations about site layout, prehistoric human behavior and site formation processes based on very limited examination of the subsurface. The GPR method is one way that sites can be accurately, and relatively inexpensively, identified and the number, size, character and location of buried remains mapped. When images of the subsurface can be produced prior to excavation, strategies can be formulated to efficiently test only the targets of interest, while bypassing others.

The production of three-dimensional GPR images, which are meaningful to archaeolo-



Cross-section of the great kiva showing interior and exterior walls.

Test trench which helped confirm the stratigraphy and archaeological features revealed by the GPR survey.

gists, is now possible. One trick is to allow the computer to process complex digital data bases, from which it constructs images that are comprehensible to the human eye. □

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DEAN GOODMAN heads the Geophysical Archaeometry Laboratory with offices in California and Japan. He is currently working on new GPR visualization techniques for archaeological mapping.

Suggested readings:

Ground-penetrating Radar: An Introduction for Archaeologists, by Lawrence B. Conyers and Dean Goodman. Alibi Press, Walnut Creek, CA, 1997.

Goodman, D., Y. Nishimura and J.D. Rogers: GPR Time-slices in Archaeological Prospection, *Archaeological Prospection*, v. 2, pp. 89-99, 1995.

Conyers, Lawrence B. and Catherine M. Curran: Ground-penetrating Radar Techniques and Three-dimensional Computer Mapping in the American Southwest, *Journal of Field Archaeology*, v. 25, n. 4, 1998.