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Chapter 3

Ground-penetrating Radar Exploration and Mapping Techniques for Garden Archaeology

Lawrence B. CONYERS

Ground-penetrating radar (GPR) has recently gained wide acceptance in the archaeological community to quickly and accurately locate buried archaeological features, artifacts, and important cultural strata in the near surface. The GPR method has been especially effective in certain sediments and soils between about 20 centimeters and 5 meters below the ground surface, where the targets to be imaged are fairly large, hollow, or linear, or have significant physical and chemical properties that contrast with the surrounding medium. Features as diverse as Mayan house platforms and plazas,[1] burial tombs,[2] historic cellars, privies and graves,[3] camp sites,[4] and pit dwellings and kivas[5] have been discovered and mapped using the GPR method. The archaeological community has also recently seen the need for near-surface mapping using GPR in order to identify buried remains for protection and future preservation, or selective excavation. To date, this method has not been specifically used to identify and study gardens per se, although it has been used to identify and quantify different soil types,[6] map buried soil layers, find irrigation ditches and pipes, and quantitatively analyze soils changes spatially, all of which have applicability to garden archaeology. In addition the method is quite good at locating buried features that often occur in gardens, such as ponds and pools, fences, and pathways and roads.

Modern GPR systems are quite compact and easy to use. The typical system consists of surface antennas, a radar system to produce pulses and a computer to process and save the data, a video monitor, keyboard, and a power source (fig. 1). This system can be easily transported to the field by plane, car, and backpack. Processing of data can be done back in the laboratory, or in the field using a portable laptop computer.

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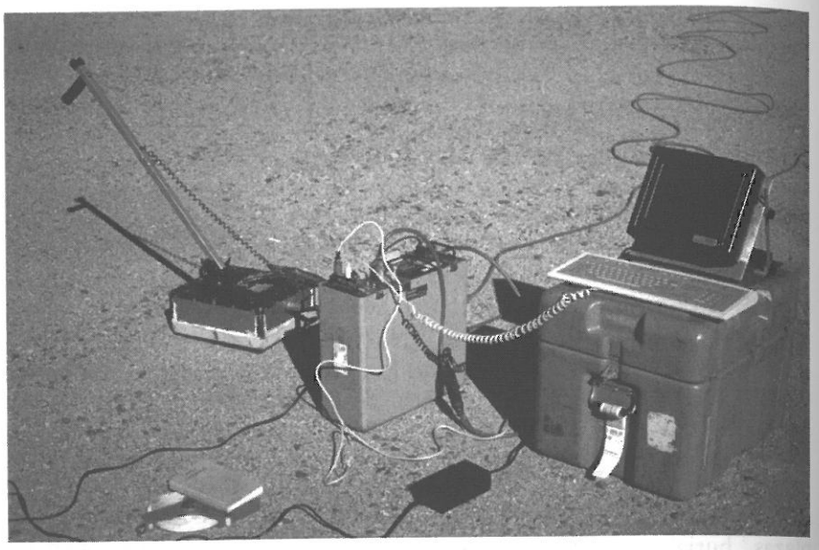
1 Conyers 1995.
2 Goodman & Nishimura 1993.
3 Bevan & Kenyon 1975.
4 Vaughan 1986.
5 Conyers & Cameron 1998.
6 Collins 1992; Collins & Kurtz 1998; Doolittle & Asmussen 1992; Doolittle & Collins 1995; Freeland *et al.* 1998.



1. The SIR-10 GPR system. The controller box, which produces the radar signal, is connected to the antenna and the computer by cables. All data are collected digitally and transferred to CD ROM for processing and as an archive. Reflection data are visible on the computer monitor during collection and processing (L. Conyers).

THE GPR METHOD

How GPR Works

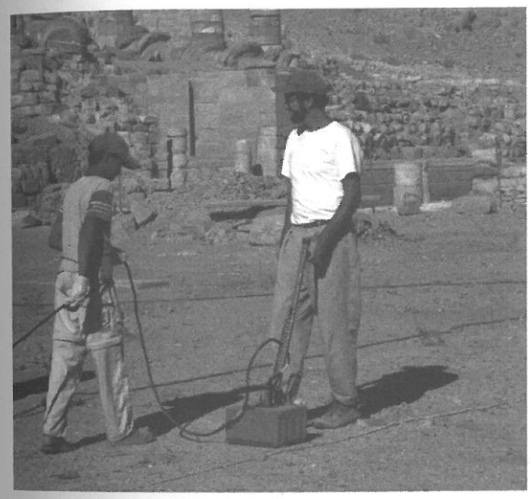
Ground-penetrating radar is a geophysical method that can accurately map the spatial extent of near-surface objects and archaeological features or changes in soil media and ultimately produce images of those materials. Radar waves are propagated in distinct pulses from a surface antenna, reflected off buried objects, features, bedding contacts, or soil units, and detected back at the source by a receiving antenna. As radar pulses are transmitted through various materials on their way to the buried target feature, their velocity changes depending on the physical and chemical properties of the material through which they travel.[7] The greater the contrast in electrical and to some extent magnetic properties between two materials at a subsurface interface, the stronger the reflected signal, and therefore the greater the amplitude of the reflected waves. When the travel times of energy pulses are measured, and their velocity through the ground is known, then distance (or depth in the ground) can be accurately measured to produce a three-dimensional data

[7] Conyers 2004; Conyers & Goodman 1997.

set.[8] Each time a radar pulse traverses a material with a different composition or water saturation, the velocity changes and a portion of the radar energy is reflected back to the surface, to be recorded at the receiving antenna. The remaining energy continues to pass into the ground to be further reflected, until it finally dissipates with depth.

. Recording Radar Reflections

In the GPR method, radar antennas are moved along the ground in linear transects and two-dimensional profiles of a large number of periodic reflections are created, producing a profile of subsurface stratigraphy and buried features along each line (fig. 2). When data are acquired in a series of transects within a grid, and the reflections are correlated and processed, an accurate three-dimensional picture of buried features and associated stratigraphy can be constructed.



2. A 400 MHz GPR antenna was used to collect reflection data at the Lower Market Site in Petra, Jordan (L. Conyers).

Ground-penetrating radar surveys allow for wide aerial coverage in a short time with excellent subsurface resolution of buried materials and geological stratigraphy. When soil and sediment conditions are suitable, some radar systems can resolve stratigraphy and other features at depths in excess of 40 meters.[9] More typically, GPR is used to map buried materials of interest at depths from a few tens of centimeters to 5 meters. Radar surveys can not only identify buried objects or horizons for possible excavation but also interpolate between excavations, projecting subsurface knowledge into areas that have not yet been, or may never be, excavated.

[8] Conyers & Lucius 1996.
[9] Davis & Annan 1992.

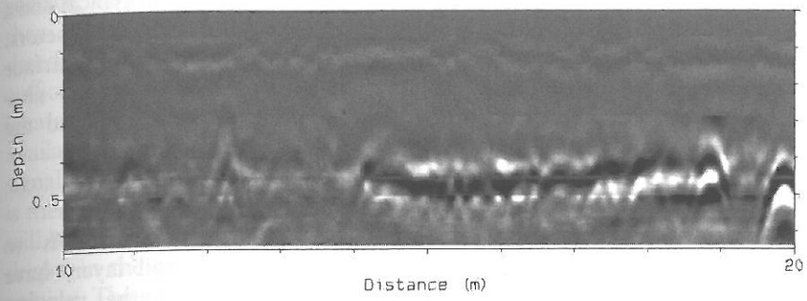
The buried discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, variations in water content, lithologic changes, or changes in bulk density at stratigraphic interfaces. Reflections can also occur at interfaces between anomalous archaeological features, and the surrounding soil or sediment. Void spaces in the ground or buried pipes or conduits made of either metal or plastic will also generate strong radar reflections due to a significant change in radar-wave velocity.

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. It is not a geophysical method that can be immediately applied to any subsurface problem, although with thoughtful modifications in acquisition and data processing methodology, GPR can be adapted to many differing site conditions. Although radar-wave penetration and the ability to reflect energy back to the surface is enhanced in a dry environment, moist soils can still transmit and reflect radar energy, and GPR surveys can yield meaningful data.

Radar reflections are always recorded in "two-way time," which is the time it takes a radar wave to travel from the surface antenna into the ground, be reflected off a discontinuity, and then travel back to the surface to be recorded. One of the advantages of GPR surveys over other geophysical methods is that the subsurface stratigraphy, archaeological features, and soil layers at a site can be mapped in real depth. This is possible because the timing of the received radar pulses can be converted to depth, if the velocity of the radar wave's travel through the ground is known.[10]

To produce reflection profiles, the two-way travel time and the amplitude and wavelength of the reflected radar waves derived from pulses generated at the antenna are then amplified, processed, and recorded for immediate viewing or later post-acquisition processing and display. During acquisition of field data, the radar-transmission process is repeated many times per second as the antennas are pulled along the ground surface or moved in steps. Distance along each line is recorded for accurate placement of all reflections within a surveyed grid. When the composite of all reflected waves along the transect is displayed, a cross-sectional view of subsurface reflection surfaces is generated (fig. 3). In this fashion, two-dimensional profiles, which approximate vertical "slices" through the earth, are created along each grid line.

[10] Conyers 2004.



3. Reflection profile across the Buchtel Garden, University of Denver Campus, Denver, Colorado, US. The subtle reflection is the remnant of the tilled bed and material placed on it when the bed was destroyed. This horizon is now buried approximately 45 cm below the surface (L. Conyers).

Depth of Penetration and Resolution

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. The frequency controls both the wavelength of the propagating wave and the amount of signal spreading and attenuation of the energy in the ground.

One of the most important variables in ground-penetrating radar surveys is the selection of antennas with the correct operating frequency for the desired depth and resolution of target features. Commercial GPR antennas range from about 10 to 1200 megahertz (MHz) center frequency. Variations in the dominant frequencies of any antenna are caused by irregularities in the antenna's surface or other electronic components located within the system. These types of variations are common in all antennas and each has its own irregularities, producing a different pulse signature and different dominant frequencies.

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 that should be used. Lower-frequency antennas are much larger, heavier, and more difficult to transport to and within the field than high frequency antennas. In contrast, 400 MHz antenna is quite small and can easily fit into a suitcase (fig. 2).

Subsurface feature resolution varies with radar energy frequency. Low-frequency antennas (10-120 MHz) generate long wavelength radar energy that can penetrate up to 50 meters in certain conditions, but are capable of resolving only very large subsurface features. For example, dry sand and gravel, or un-weathered volcanic ash and pumice, are media that allow radar transmission to depths approaching 8-10 meters, when lower-frequency antennas are used. In contrast the maximum depth of

penetration of a 900 MHz antenna is about 1 meter or less in typical soils, but its generated reflections can resolve features down to a few centimeters. A trade-off therefore exists between depth of penetration and subsurface resolution. These factors are highly variable, depending on many site-specific factors such as overburden composition and porosity, and the amount of moisture retained in the soil.

How Materials in the Ground Affect the GPR Signal

The primary goal of most archaeological GPR investigations is to differentiate subsurface interfaces. All sedimentary and soil layers have particular electrical and magnetic properties that affect the velocity, reflection, and dissipation of electromagnetic energy in the ground.[11] The reflectivity of radar energy at an interface is primarily the function of the magnitude of the difference in electrical properties between two materials on either side of that interface. This is because any significant change in velocity will cause some energy to reflect back to the surface. Stronger reflected signals are produced when the contrast in electrical properties between two materials increases.[12] Most visible radar reflections are generated at the interface of two thick layers with varying electrical properties.

The ability to discern radar reflections in the data is related to the amplitude of those reflected waves. Higher amplitude waves produce more visible reflections. Lower-amplitude reflections, such as those from subtle soil changes, usually occur when there are only small differences in the electrical properties between layers. Those subtle changes in the nature of buried soil or sediment layers are often all but invisible to the human eye, but very subtle waves are recorded in GPR profiles as small digital changes in their amplitudes. In order to enhance these changes, so they may be mapped, sophisticated amplitude analyses (discussed below) must be applied to the data set.

The propagation velocity of radar waves that are projected through the earth depends on a number of factors, the most important ones being the electrical and chemical properties of the material through which they pass.[13] Radar waves in air travel at the speed of light, which is about 30 centimeters per nanosecond (1 nanosecond is one-billionth of a second). When radar energy travels through dry sand, its velocity slows to about 15 centimeters per nanosecond. If the radar energy were then to pass through water-saturated sand, its velocity would slow further to about 5 centimeters per nanosecond or less. At each of these interfaces where velocity changes, reflections are generated.

Radar energy both disperses and attenuates as it radiates into the ground. When portions of the original transmitted signal reflect back toward the surface, they 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 a sufficient electrical (or magnetic) 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 propagates to increasing depths, the signal becomes weaker and is spread out over more surface area. Less energy is then available for reflection and it is likely only very low amplitude waves will be recorded. It is usually necessary to enhance reflections that come from deeper in the ground, using an amplitude adjustment method called range gaining. The gain factors to be applied to the reflections are usually adjusted specifically for each site, and are unique for those soils, and conditions at the time the survey is performed.

Computer Processing to Produce Images of Features in the Ground

The standard image for most GPR reflection data is a two-dimensional profile, with depth on the x-axis and distance along the ground on the y-axis (fig. 3). These image types are constructed by stacking together many reflection traces, obtained as the antennas are moved along a transect. Profile depths are usually measured in the two-way radar travel time, but times can be converted to depth, if the velocity of radar travel in the ground is obtained.[14] Reflection profiles are most often displayed in gray scale, with variations in the reflection amplitudes measured by the depth of the shade of gray. Color palettes can also be applied to amplitudes in this format.

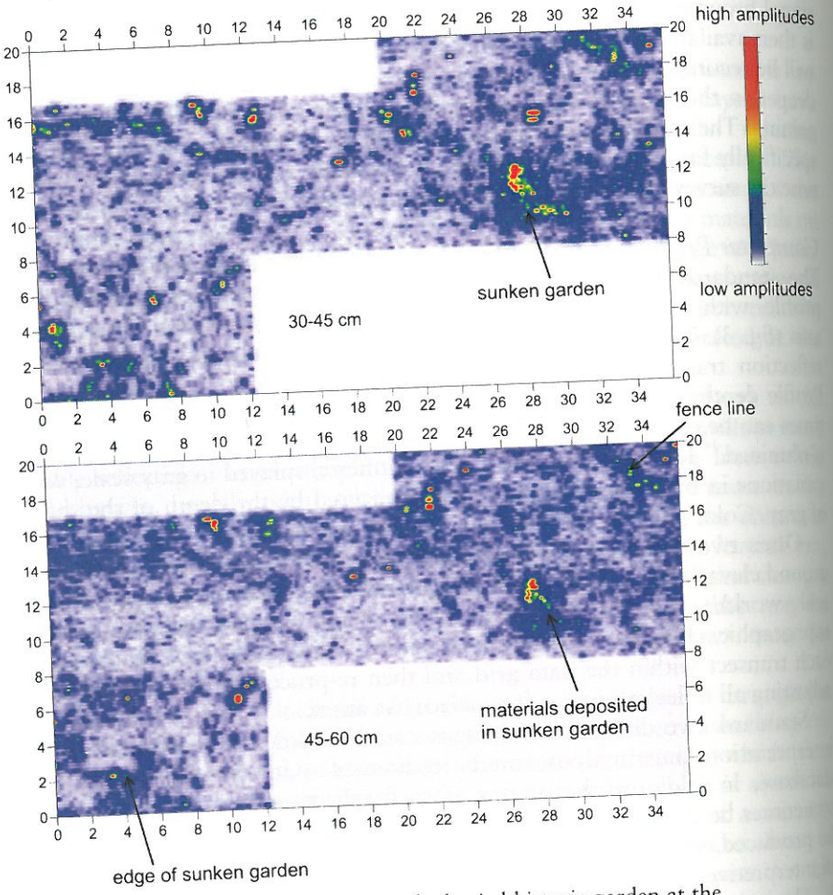
Often two-dimensional profiles must be corrected to reflect changes in ground elevation. Only after this is done will images correctly represent the real world. This process, which is usually important only when topographic changes are great, necessitates detailed surface mapping of each transect within the data grid and then re-processing each transect by adjusting all reflection traces for surface elevation.

Standard two-dimensional images can be used for most basic data interpretation, but analysis can be tedious if many profiles are in the database. In addition, the origins of each reflection in each profile must sometimes be defined before accurate and meaningful subsurface maps can be produced. Often detailed image definition comes only with a good deal of interpretive experience.

The primary goal of most GPR surveys is to identify the size, shape, depth, and location of buried remains and related stratigraphy. The most straightforward way to accomplish this is by identifying and correlating important reflections within two-dimensional reflection profiles. These reflections can often be correlated from profile to profile throughout a grid, which can be very time consuming. Another more sophisticated type of GPR data manipulation is amplitude slice-map analysis, which creates maps

[11] Collins & Kurtz 1998.
[12] Sellman *et al.* 1983.
[13] Olhoeft 1981.
[14] Conyers & Lucius 1996.

of reflected wave amplitude differences within a grid. The result can be a series of maps that illustrate the three-dimensional location of reflection anomalies derived from a computer analysis of the two-dimensional profiles (fig. 4). This method of data processing can be accomplished only with a computer using GPR data that are stored digitally.



4. Example of amplitude slice-maps of a buried historic garden at the Amache site, Colorado, US, showing changes in radar amplitude visible in plan view. Each slice represents about 15 cm into the ground (L. Conyers).

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 of those reflection traces 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 usually difficult to visualize and interpret. The standard interpretation of GPR data, which consists of viewing each profile and then manually mapping important reflections and other anomalies, may be sufficient when the buried features are simple and interpretation is straightforward. In areas where the stratigraphy is complex and 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.

An analysis of the spatial distribution of the amplitudes of reflected waves is important because it is an indicator of potentially meaningful subsurface changes in lithology or other physical properties. If amplitude changes can be related to important buried features and stratigraphy, the location of those changes can be used to reconstruct the subsurface in three dimensions. Areas of low amplitude waves usually 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 interpreted, amplitude differences must be analyzed in "time-slices" that examine only changes within specific depths in the ground. Each time-slice consists of the spatial distribution of all reflected wave amplitudes, which are indicative of these changes in sediments, soils, and buried materials.

Amplitude time-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. 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 time-slices, the computer compares amplitude variations within traces that were recorded within a defined time window. 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.

An analysis of the spatial distribution of the amplitudes, in the form of amplitude time-slices[15] can often produce high-resolution maps of the subsurface (fig. 4). Amplitude maps that are corrected for depth are especially useful in garden archaeology because amplitudes of reflected waves are an indicator of subsurface changes in lithology, soil chemistry, or 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 the presence or absence of 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.

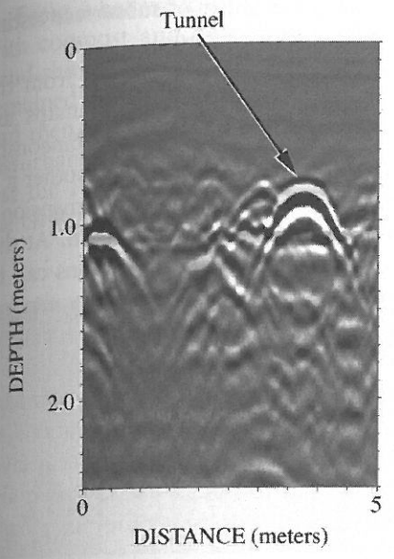
On Site Identification of GPR Features

It is often difficult to identify buried features and stratigraphy during data collection operations, even though most modern digital systems allow the user to view two-dimensional profiles on a computer screen immediately as they are being acquired. These "field profiles" are usually unprocessed, meaning they still contain background noise and are usually uncorrected for depth and distance along transects. With experience, however, distinct buried features can often be viewed and analyzed almost as fast as the antenna moves over them. This "real-time" data analysis can sometimes yield important information about the subsurface, allowing planned surveys to be changed or modified almost immediately. In addition, if important features are discovered immediately in this way, they can often be quickly tested by digging, probing, or coring, allowing confirmation of the origin of prominent reflections.

The most distinctive reflections that are immediately visible on the computer screen during data acquisition are reflection hyperbolas (fig. 5). These reflections are produced from "point sources" in the ground that can be buried pipes, tunnels, walls, or large rocks. They are caused by the wide angle of the transmitted radar beam, which allows the antenna to "see" the point source prior to arriving directly over it, and continue to "see" it after it is passed. The resulting reflection will therefore create a hyperbola as the antenna crosses over the object, recording it both coming and going.

Often clusters of these hyperbolas mean a buried pile of point sources, such as a collapsed wall or similar feature. During data collection, alert GPR operators can often visually place these types of objects on the ground by viewing them first on the computer screen, and then noting the location on the ground where the antenna is recording the reflections of note.

[15] Conyers 2004.



5. Example of a reflection hyperbola. In this example one created by a small tunnel (L. Conyers).

Although this technique is fraught with potential errors, it can in a gross sense give the archaeologist an immediate view of what lies buried below the surface. Usually it is best to make specific and detailed interpretations after data have been processed, where they can be filtered and spatially corrected. But if immediate analysis is necessary, field interpretations of this sort can be made, as long as the potential errors are understood.

Methods of Testing GPR Maps

Two-dimensional reflection profiles, once processed and corrected spatially, give an accurate representation of what lies below the surface. However, it is always important to recognize that reflection records do not necessarily mimic exactly what is in the subsurface. This is because radar energy does not usually travel in a vertical line from the surface antenna, to the object or surface of interest, and then directly back to the receiving antenna. Instead it spreads out from the antenna, and is therefore recording reflections from outside the plane of the transect, and in front and behind the surface antenna. In addition, radar waves often reflect multiple times from buried objects, as they "bounce around" between layers in the ground and other large objects before being recorded back at the surface. Waves of radar energy can also refract at boundaries between distinct layers, further creating a confusing picture of the subsurface. An understanding of the complexity of GPR reflection profiles comes with experience, as well as directly comparing

reflection profiles to the "real world," using a number of subsurface testing methods, such as excavation pits, augers, cores, or probes.

The same holds true for three-dimensional maps produced from the spatial analysis of the amplitudes of GPR reflections. These maps are produced from many thousands of reflections analyzed simultaneously. Often when testing the ground with excavations of one sort or another it is necessary first to compare the amplitude maps to the two-dimensional profiles to make sure the origin of the mapped images is known. At this point if subsurface confirmation of at least some of the reflections can be made, the overall confidence of the remaining portions of the maps is increased. But in all cases, some kind of subsurface confirmation of features imaged with GPR is preferable.

This kind of verification can be accomplished by standard archaeological excavations including shovel test pits, square excavations, or trenches. If the mapped features are strata of interest (for instance a layer that could be a garden soil), soil cores or auger samples can be taken and their depth compared to the GPR reflections in profiles or amplitude maps. Sometimes, if mapped features are fairly close to the surface, soil probes can discern hard layers (perhaps rocks or buried walls), which give less direct confirmation, but are easy to use and very quickly accomplished.

In all cases, making interpretations based on only GPR reflections can be prone to errors. While many very distinct features, such as standing walls or hard packed stratigraphic surfaces, are easily recognizable and can be interpreted with some confidence, more subtle features common in gardens are often difficult to discover and interpret. For this reason, integration of good subsurface information from cores, excavations, probes, or augers with GPR reflection maps and profiles is always a necessity.

Applications of GPR to Gardens

The Buchtel Garden Site

As a test case, ground-penetrating radar techniques were used to map the remains of a garden in an area on the University of Denver campus, where historic photographs showed the prior existence of a flower garden (fig. 6). This garden, called the Buchtel Chapel Garden, was about 10 meters in diameter and cultivated and planted with flowers annually from 1981 through 1984. In 1983 the chapel (seen in the background of Figure 6) was destroyed by fire, and only one of the bell towers was left standing. The following year, the circular garden in front of the chapel was leveled with heavy machinery and what remained of it was buried by grass sod.

From what we know from the groundskeeper, this bed was fertilized with compost and peat moss every spring using a motorized tiller and hand-shovels. In the fall the dead foliage was removed and the garden remained untended through the winter. Additional fill was imported, and then the site was covered with sod. The area has seen little, if any, disturbance since that time. As a result, it provided an excellent site to test the effectiveness of locating and mapping an historic garden using the GPR method.

6. The Buchtel Garden on the University of Denver campus in 1981, Denver, Colorado, US. The Buchtel Chapel, which partially burned in 1983, is in the background. Today, only the tower on the left remains standing (L. Conyers).

In October 2000, a 15x20 meter test grid was established in front of the old chapel, and GPR data were collected. A 500 MHz antenna was used with a Subsurface Interface Radar #10 System (SIR-10), manufactured by Geophysical Survey Systems, Incorporated (fig. 1), which can resolve bedding and soil features greater than 10 to 15 centimeters in thickness at depths ranging from 20 centimeters to approximately 1.5 meters. Reflection data were collected in a time window of 13 nanoseconds, which recorded reflections from the ground surface to a depth of about 75 centimeters. Each antenna transect was spaced 50 centimeters apart within the grid, and profiles were oriented north-south.

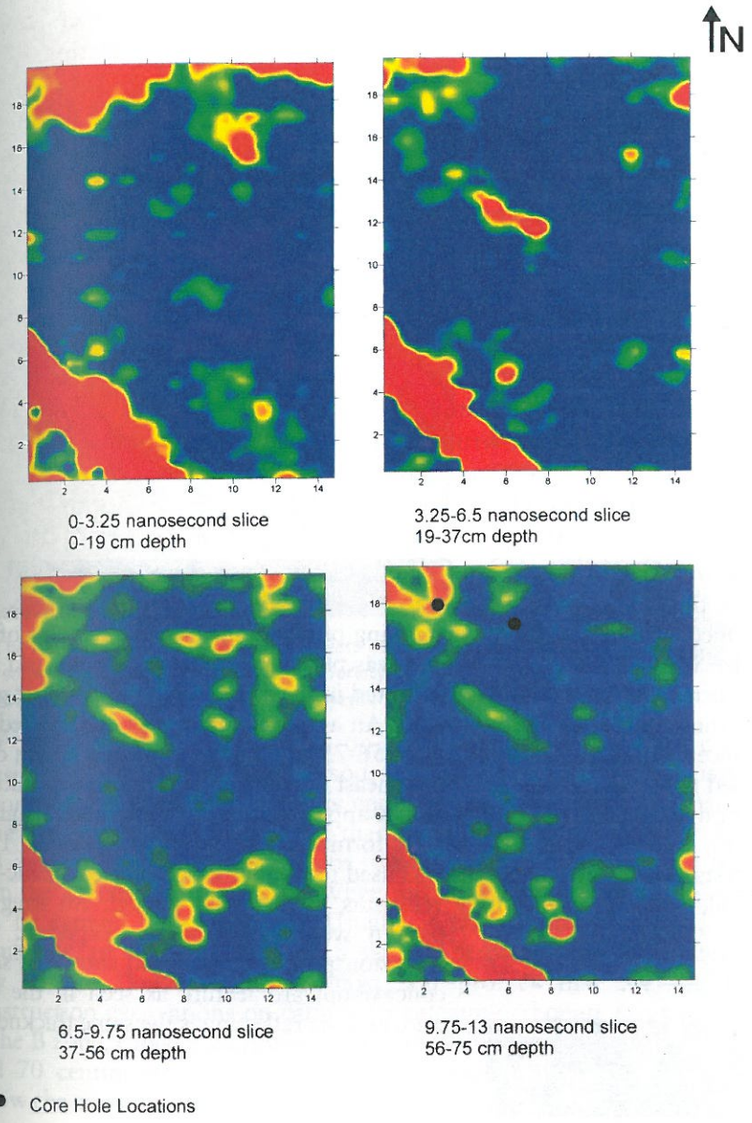
It became apparent during data collection that a significant reflection from about 6 to 11 nanoseconds was being recorded in the northwest

portion of the grid, which was hoped to have been generated from a subsurface interface representing some remains of the garden. Many other reflections from buried electrical conduits and sprinkler lines were also recorded in the data. The reflection data were analyzed soon after collection, and the time each reflection was recorded was converted to depth using a computer program that calculates radar velocity in the soil. Velocity is calculated by fitting hyperbolic point-source reflections generated by buried pipes or other point sources to a model reflection shape, creating an estimate of the velocity radar waves travel in the ground at a particular site. Using these models, a relative dielectric permittivity of 7.3 was determined, which means the velocity of radar travel is about 11.5 centimeters per nanosecond. Because radar waves always travel from the ground surface to the reflection surface in the ground and then back to the surface before being recorded, the two-way travel velocity must also be calculated. In these data two-way travel time is 5.75 centimeters per nanosecond.

To map the radar reflections in the ground, data in Grid 1 were imported into an amplitude slice program that yields three-dimensional maps of the reflections in the ground.[16] Reflections were then processed in time-slices of 3.25 nanoseconds in thickness. This process first analyzes the reflections in each slice and then correlates and grids the amplitudes of reflections spatially within those slices. All data within all antenna transects are included in this process. This data processing is similar to analyzing all the sediment and features in arbitrary levels in standard archaeological excavations, but in this case the amplitudes of reflections are the final product being mapped. Slices of 3.25 nanoseconds, or about 0-19 centimeters in the ground (fig. 7), were preferred because the target feature is at most a few tens of centimeters in thickness.

Each 3.25-nanosecond amplitude slice is about 19 centimeters in thickness in the ground. The red and yellow colors represent areas of high amplitude reflections, denoting buried materials of contrasting physical and chemical properties at that location (fig. 7). The blue areas are uniform soils or sediments that reflected little radar energy, indicative of homogeneous material. These areas probably represent soil that was not disturbed by construction activity or animal burrowing.

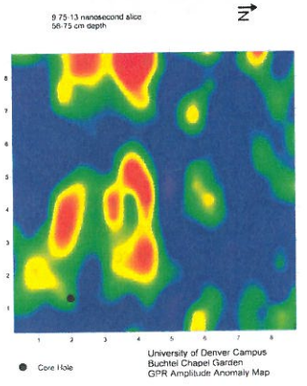
[16] Conyers 2004.



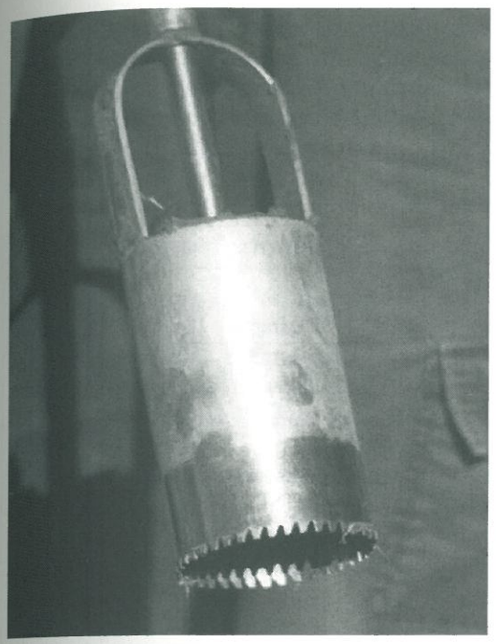
7. Amplitude time-slices of Grid 1 at the Buchtel Garden, University of Denver Campus, Denver, Colorado, US. Each slice shows the aerial extent of radar reflection amplitudes at different depths in the ground (L. Conyers).

In these GPR slice-maps, the concrete sidewalk, which trends northwest-southeast is plainly visible in the southwest portion of all maps (fig. 7). Radar energy was reflected multiple times between the surface antenna and this concrete barrier, causing it to be imaged in all the time-slices. A number of other linear features can be seen in these maps, which are the likely location of buried electrical conduits and water lines. In the deepest slice, from 56-75 centimeters depth, an interesting feature is visible in the northwest portion of the grid (fig. 7). An analysis of the individual reflection profiles through this reflection feature showed a subtle concave-upward reflection, which appeared to be the possible remains of the garden (fig. 3). At first this feature did not appear to be in the portion of the grid where the circular garden was expected. After a closer examination of the 1981 photograph (fig. 6), it was determined that the wrong chapel tower had been used to place the test grid (only one tower survived the 1983 fire, which is the one on the left in the photograph). When the high amplitude feature in the northwest portion of the grid was then relocated with respect to the one remaining chapel tower, we found it to be centered exactly in front of where the chapel would have stood in 1981.

Once we had a better understanding of where the possible remains of the garden were located, a second grid was placed over that area. This grid was 9x9 meters, and the data were collected in the same fashion as the first grid, with the same time window (fig. 8). An amplitude map was constructed for the slice from 9.75-13 nanoseconds (56-75 cm. depth), which shows an odd-shaped reflection feature in the southeast portion of the grid. It was initially disappointing that this feature did not appear circular like the original garden (fig. 6), but the groundskeepers' information about its removal in 1984 suggests that heavy equipment was used to remove much of the organic-rich topsoil, possibly leaving only remnants of the tilled subsoil. An irregular pattern would therefore be expected. The reflection profiles in this grid show the same concave-upward feature as seen in the first grid, and the reflection is the same thickness.



8. Amplitude slice-map from 56-75 cm in Grid 2 at the Buchtel Chapel Site, University of Denver campus, Denver, Colorado, US (L. Conyers).



9. The hand auger used to collect complete cores of the soils at the Buchtel Chapel site, University of Denver campus, Colorado, US (L. Conyers).

To test whether the buried interface imaged in both profiles might be the old garden, a hand auger (fig. 9) was used to recover two cores of soil profiles, one within the GPR reflection feature, and one outside (fig. 10). It was hoped, based on initial interpretations of the GPR profiles and maps, that the two cores would show a difference in stratigraphy, with one representing the remnants of the old garden and the other representing undisturbed soil. The velocity analysis was used to predict a depth of about 45 centimeters to the layer producing the strong GPR reflection.

The typical soil horizon found on the University of Denver campus consists of a surface O zone of sod, leaf, and grass debris and partially decomposed organic material. It is underlain by an organic-rich, loamy, A zone that consists of clay, organic matter, and some silt. Below the A zone a B soil horizon is usually present, which has much less organic matter than the A zone and more clay. When this zone is very enriched in clay, it can be termed a Bt horizon.[17] Usually it takes many hundreds, if not thousands, of years to build up a significant Bt horizon with abundant clay in the Denver area. In most soil profiles that are visible in construction excavations on campus, a calcium-carbonate layer is present in the B zone, called a Bk horizon. This whitish layer is usually between 20 and 70 centimeters thick, and is usually found 50 to 100 centimeters below the surface. The Bk soil horizons are formed as carbonate, dissolved in water percolating down from the surface, is precipitated in the underlying units. As with Bt horizons, it often takes many hundreds or thousands of years to build up a significant Bk horizon.[18]

Both the cores taken within the GPR reflection feature, and that outside, encountered soil horizons that were in many respects similar to

[17] Birkeland 1999.
[18] *Ibid.*

the normal undisturbed soils common to the area. There were, however, a few significant differences that can be directly related to the garden, and probably its removal and the site's modification. Descriptions of the cores including color changes and their reaction to hydrochloric acid (which indicates the presence of calcium carbonate) are shown in table 1.

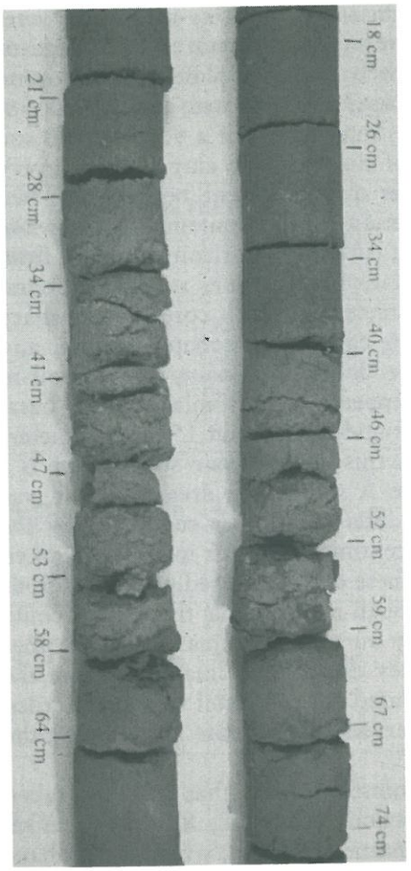
INSIDE FEATURE				OUTSIDE FEATURE			
Depth (cm)	Description	Color	HCl Reaction	Depth (cm)	Description	Color	HCl Reaction
0-7	Silty Clay Loam	7.5 YR 3/1	—	0-5	Silty Clay Loam	7.5 YR 2.5/2	—
7-14	Silty Clay Loam	7.5 YR 3/2	—	5-11	Silty Loam	7.5 YR 2.5/1	—
14-21	Clay Loam	7.5 YR 4/2	Weak	11-18	Silty Clay Loam	7.5 YR 2.5/1	—
21-28	Silty Loam	7.5 YR 4/2	Weak	18-26	Silty Loam	7.5 YR 4/2	—
28-34	Clay Loam	7.5 YR 4/2	Strong	26-34	Silty Loam	7.5 YR 4/2	strong
34-41	Silty Clay Loam	7.5 YR 4/4	$CaCO_3$ nodules	34-40	Silty Clay Loam	7.5 YR 4/2	weak
41-47	Silty Clay Loam	7.5 YR 4/3	strong-violent	40-46	Silty Clay Loam	7.5 YR 4/3	weak
47-53	Silty Clay Loam	7.5 YR 4/3	Strong	46-52	Silty Clay Loam	7.5 YR 4/3	strong
53-58	Silty Loam	7.5 YR 4/3	Strong	52-59	Silty Clay Loam	7.5 YR 4/3	strong-violent
58-64	Silty Loam	7.5 YR 3/2	—	59-67	Silty Loam	7.5 YR 3/1	—
64-74	Loam	7.5 YR 3/2	—	67-74	Silty Loam	7.5 YR 3/2	—
74-85	Loam	7.5 YR 3/2	—	74-80	Silty Loam	7.5 YR 4/2	—

Table 1. Soil analyses of cores within the GPR reflection feature and outside it.

The cores both revealed a surface soil zone (O and A layers) from 0 to about 30 centimeters depth, described as a silty clay-loam. This layer consists of sod at the surface, followed by a root zone, and decomposed organic matter in a clay matrix at the base (fig. 10). Below this topsoil layer the clay content of the soil increases in both cores, and the color of the soil became lighter brown, suggesting the top of a very weak B soil zone (and perhaps the formation of an incipient clay-rich Bt layer). Below this zone the stratigraphy was quite different between the two cores. The core inside the GPR reflection feature contains a thick white layer, which appeared at first to be a carbonate horizon (Bk soil), from 34-58 centimeters (fig. 10). A similar, but thinner, zone was found outside the feature from 46-59 centimeters. In both cores a very sharp contact was visible between this white calcium carbonate soil layer and the underlying dark brown soil. The underlying loamy brown soil in both cores below 58 centimeters appears very similar to the basal portion of the active A soil horizon, found from about 15-35 centimeters in both cores (fig. 10). It is likely that this lower brown soil horizon is a buried soil, that was once the active A soil in the area before it was buried by the white soil zone. This interpretation is supported by the presence of bark chips found at 60 centimeters depth in the core taken outside the GPR reflection feature. These chips are used around campus as mulch, especially in gardens. Although it is possible these chips could have found their way to this depth by burrowing animals or some other mechanism, it is more likely that they are residual materials from the garden. They were probably incorporated in the topsoil when the garden was active and then buried and preserved by the white layer during the removal of the garden.

Researchers were initially disappointed to find that the core taken within the GPR high amplitude reflection feature (fig. 8) did not reveal organic-rich sediment at about 45 centimeters depth, which would have indicated the actual remains of the garden were still present. This is the depth where a significant reflection was seen in the reflection profiles (fig. 3), and the location the aerial time-slice mapping showed to be the possible remains of the old garden (fig. 4).

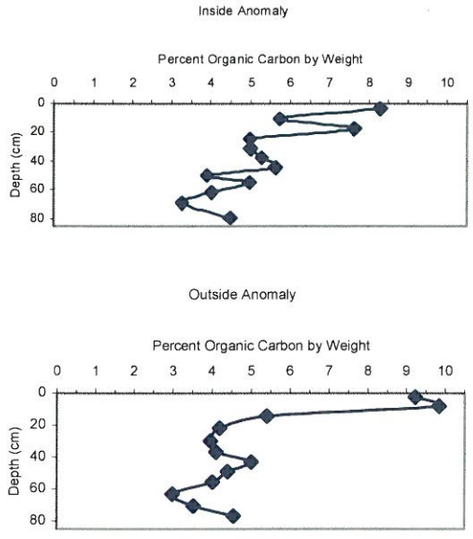
Instead the carbonate-rich whitish soil was found, which was initially thought to be a well developed Bk horizon. The presence of a Bk horizon would rule out the preservation of any remains of the garden in this area, as it would indicate little disturbance for hundreds (if not thousands) of years. An explanation for the white calcium carbonate layer was therefore crucial in the interpretation of the GPR data. Only one conclusion was immediately apparent: the significant lithologic change between the calcium carbonate-rich layer and the overlying and underlying loamy soils was what was being imaged in the GPR amplitude slice-maps.



10. Cores taken both within and outside the amplitude anomaly that represents the remnant of the Buchtel Garden, University of Denver campus, Colorado, US. The core on the left shows a $CaCO_3$-rich layer at 34-58 cm depth, which is the fill that was added after the garden was removed. The core on the right recovered the same unit, but deeper and less developed. Note the sharp basal contact of the white layer in both cores at 58 centimeters depth. Below this contact is the buried A soil zone, which is all that remains of the original garden bed (L. Conyers).

To help determine the genesis of the soils recovered by the auger, total organic carbon analysis (fig. 11) was performed on samples spaced about 5 centimeters apart in both cores. This test measures the amount of organic carbon that is burned off from each sample when subjected to high temperatures. Typically, undisturbed soils have an organic carbon content that is high at the surface and decreases with depth, because most of the organic matter is found in the sod, decomposed vegetation, and the near-surface root zone[19]. This decrease in carbon content with depth is apparent from 0-35 centimeters in the core taken outside the GPR reflection feature (fig. 10).

[19] Wild 1993.



11. Organic carbon curves calculated from soil cores inside and outside the GPR amplitude anomaly map shown in Figure 7 (L. Conyers).

Contrary to most soil zones, the soils in this core contain an increasing amount of organic carbon from about 35 to 50 centimeters, which then falls off normally from 50-60 centimeters. The zone of increasing carbon corresponds to the location of the thin white layer, which was hypothesized to have been imported into the area, covering the garden after its removal. Its high organic carbon content suggests that if it is fill material, it was mixed with organic carbon matter from another source prior to being imported from another garden nearby. Additional confirmation of its origin can be found in the increasing organic material in the dark brown soil zone below the white layer (fig. 12). This unit appears in the core to be a portion of a buried A zone that was covered by the white fill layer. Its higher organic content (and the presence of bark chips) is consistent with this interpretation.

In a general sense, these same changes in organic content were measured in the other core taken within the GPR reflection feature (fig. 7). In this core there is a general decrease in carbon with depth, but there are a number of deflections in the curve, especially within the white layer. The erratic changes in organic carbon content within this core are likely the result of a thicker, mixed fill material, containing two if not more varieties of soils imported from elsewhere, each with different organic content.

12. Buried ridges and furrows in a fossil agricultural field buried by volcanic ash, Ceren archaeological Site, El Salvador.

With more study, it became apparent that the white layer, which produced the high amplitude reflection on the GPR profiles, had other attributes very different than a "typical" Bk horizon. Its basal contact in both cores was very sharp and contained no filaments of carbonate that typically form at the base of typical Bk zones over time. These very fine carbonate filaments are produced when ground water, which contains dissolved carbonate, follows root zones or the small cracks that form during shrinking and swelling of clay soils, as it moves into the ground. The carbonate is precipitated along these routes first, and only after much time elapses does the carbonate coalesce into a laterally continuous Bk horizon. Instead, what was apparent in both cores at about 58 centimeters depth was a very sharp contact between the white carbonate layer and the underlying dark loamy soil (fig. 10), indicating it was deposited in one episode (probably very recently). No filaments had yet formed below the carbonate layer, indicating little time in which to precipitate carbonate.

It is apparent from the core descriptions that the layer being imaged in the GPR profiles is the white layer, seen both inside and outside the GPR reflection feature but of varying thickness. Although this layer is thinner and is found somewhat deeper in the ground outside the feature, it is still present, and should theoretically be visible in the slice-map, but it is not. This is most likely a function of its thinness, which is only about 7 centimeters (fig. 10). A 500 MHz antenna is only capable of resolving beds greater than about 10-15 centimeters in thickness. Therefore, no significant radar wave reflection was obtained from the white layer in the area outside the feature.

If the white layer indicates the presence of the old Buchtel Garden, what was its genesis, and how is it related to the garden? The GPR amplitude slice-maps (fig. 7) show it to be centered directly in front of the chapel, as indicated in the historic photograph (fig. 6). It is not, however, circular as was expected. This suggests that if the white layer imaged in the GPR maps was fill material, it was placed in the garden and then rearranged in some fashion. When referring back to the

information provided by the groundskeeper, it became apparent that during the removal of the garden, heavy machinery was used to both take out the topsoil for use elsewhere on campus, and bring in fill material to level the area prior to replanting with grass sod. This fill material was no doubt moved around a good deal during this operation, destroying the perfectly round nature of the bed.

Both the GPR data and the core information yield much more information about the destruction and subsequent reclamation of the garden area than they do about the garden itself. Most of the garden topsoil was removed, but the GPR data in this case produced very accurate images of other buried soil layers germane to an understanding of the garden. In this area the units that were most visible by GPR were those of the material that was used as fill, after the garden was removed. This was not immediately apparent using only the GPR analysis, and was only understood when the initial interpretations were used on conjunction with core analyses.

Other Garden Applications of GPR

Geophysical methods, including GPR, have a long history of use in the study of agricultural fields to map the spatial distribution of physical and chemical characteristics of soils that relate to important factors such as fertility, acidity, and organic constituents.[20] Although these types of surveys have not been performed on fossil agricultural soils, there is no reason the same methods cannot be applied in archaeological analyses. In most cases GPR has proved to be the most exact of the numerous geophysical methods used to map buried soil changes. It is the only shallow geophysical method that can map changes in soils types laterally, as well as measure the thickness and distribution of units with depth. The GPR method cannot, however, measure specific soil values of interest, like acidity or organic content. In order to do this actual samples of soils must be taken within an area of study, analyzed quantitatively and then these values must compared and correlated to GPR measurements. Amplitudes and depths of radar waves can then be inferred throughout a grid, if enough subsurface information of other sorts is available for control. In this way GPR amplitudes can be used as a proxy for many soil variables, but only if they are correlated to measurable soil values. Using amplitude analyses that measure the spatial distribution of the radar waves, the distribution of important soil characteristics can then be mapped.

Buried soil interfaces are often visible in GPR profiles when the physical and chemical differences between two layers are different enough to produce significant radar reflections.[21] These differences might be produced by changes in soil moisture, compaction, or lithologic

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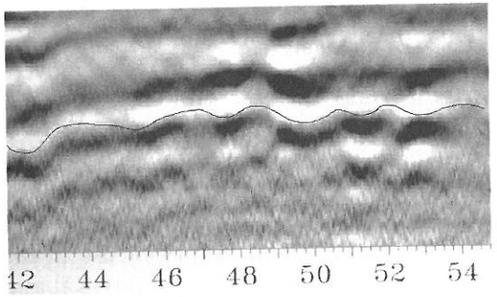
[20] Doolittle & Collins 1995; Freeland *et al.* 1998.

[21] Conyers 2004.

constituents.[22] Often GPR reflections are distinct enough to produce images of the subsurface orientation of these changes in buried soils. At the Ceren archaeological site in El Salvador, a buried Mayan agricultural field is preserved beneath volcanic ash.[23] The interface is visually distinct where uncovered (fig. 12) and often displays fossil ridges and furrows that were present in the maize fields at the time of burial. The interface between the buried soil and the overlying ash can be readily mapped across the site using GPR,[24] but more excitingly, the actual ridges and furrows at the top of the soil are visible in individual profiles (fig. 13).



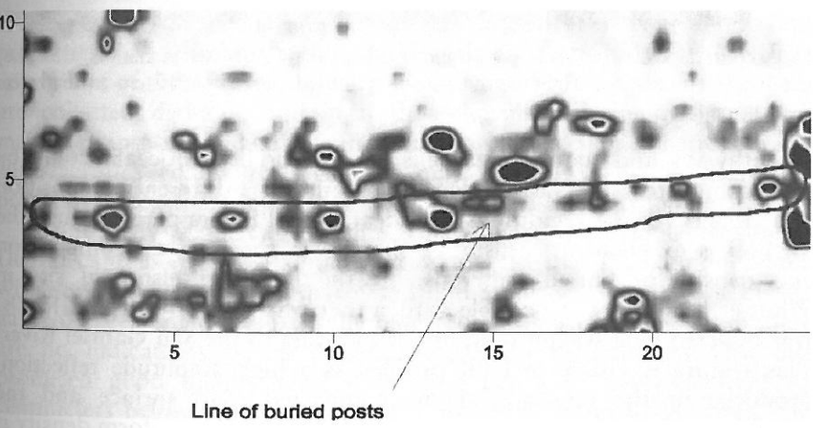
13. Ridges and furrows on the buried agricultural soil, Ceren site, El Salvador. The top of the buried soil is shown by a thin black line. The underlying reflections alternate from black to gray, with black being the highest amplitude reflections.

These buried soil features are visible in two-dimensional profiles not as actual ridges and furrows, but as changes in radar wave amplitude along the interface. This amplitude variation is caused by changes in the focusing and dispersion of radar energy. When radar waves were reflected from the furrowed portion of the interface, their energy was focused prior to transmission back to the surface, much as a parabolic dish can focus radar energy that is being transmitted into space. When the radar waves are focused, the resulting reflection from the concave upward interface is very high in amplitude, producing a dark gray reflection in reflection profiles. Conversely, when radar energy encounters a buried ridge, the energy is dispersed away from the surface due to a high angle of incidence of individual rays, and their resulting reflection away from the surface antenna. This results in a low amplitude reflection (light gray in color) over parts of the buried features, because a good deal of the energy has been lost in the ground from spreading and dispersion. Little radar energy is then available to be recorded at the surface antenna. A buried layer of this sort will therefore appear in profiles to alternate from high to low amplitude laterally (fig. 13).

Ancillary features of gardens are diverse and varied in archaeological

[22] Freeland *et al.* 1998.
[23] Conyers 1995.
[24] *Ibid.*

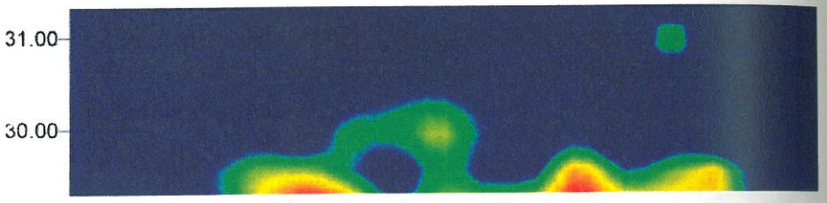
sites. Fences, walls, pathways, and small structures are often found within garden areas, which can often be located and mapped with GPR. Fences made of wood will often degrade over time, but their posts will leave molds in the ground that are sometimes visible in excavations as subtle changes in color or soil composition. These soil changes can also be imaged with GPR because measurable amplitude differences in reflected waves will occur where post molds are found. The ability of GPR to produce images of these types of subtle features was demonstrated at an archaeological test facility in Illinois[25]. In this controlled facility a number of features that simulated archaeological materials were buried by as much as 1.5 meters of soil and the site was compacted and replanted in grass. One of the features buried was a fence with posts about 20 centimeters in diameter 3 meters apart. The 500 MHz antenna was used to collect data over this linear feature and processed in standard two-dimensional profiles. The profiles crossing the buried posts (now post molds after a number of years of rotting in the Illinois soil) were not capable of producing images of the buried vertical features because the reflections were too subtle for the human eye to see. The amplitudes of the waves within the grid, however, contained digital data that measured the small changes between post molds and the surrounding soil matrix. When plotted in map view, the line of posts from this fence were clearly visible spaced 3 meters apart (fig. 14).



14. Buried posts from a fence at the CATS facility in Illinois, US. This is a slice from about 30-60 cm depth.

[25] Isaacson *et al.* 1999.

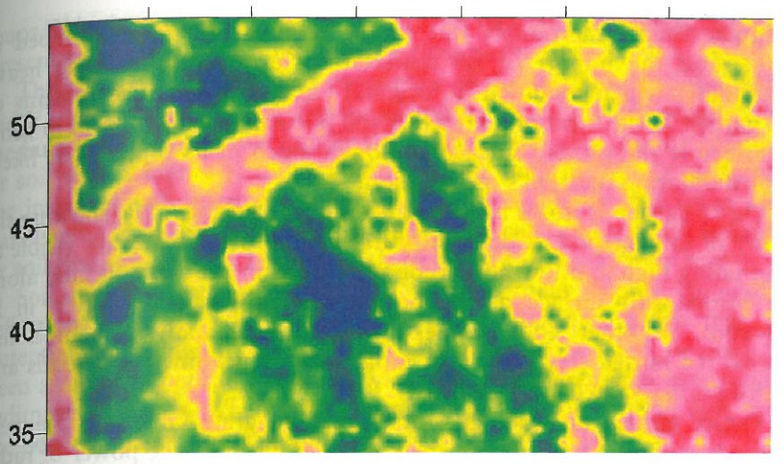
At the same facility in Illinois, ceramic pots were buried and then covered over. These items were at most 10 centimeters in diameter, which is usually too small for GPR to produce adequate images. Resolution of buried objects is limited by the wavelength of the radar energy transmitted into the ground and usually objects smaller than one wavelength will not produce reflections. The 500 MHz antenna transmits energy with a wavelength of about 30 centimeters in moist clay soil, like that found in Illinois[26]. It is therefore unlikely that a 10-centimeter-diameter pot would be visible using standard imaging methods. However, the amplitude slicing methods were capable of detecting a known pot in the data set, even though its reflection was so subtle it could not be seen in the individual profiles (fig. 15). It was found only because this was a test site and all objects placed in the ground were mapped, and therefore could be searched for in the data at known locations. It is unlikely something as subtle as this would have been discernable in data collected in unknown conditions, but a cluster or alignment of pots the same size might be.



15. Amplitude slice map from 30-60 cm depth at the CATS site in Illinois, US. The small object in the top right of the map is a buried pot about 10 cm in diameter (L. Conyers).

Pathways and roads in gardens are potentially noticeable only by their compacted soil, surrounded by material of a different composition and density. These conditions are ideal for GPR mapping because the method is excellent at measuring changes in the physical composition and density of buried materials. At the Pio Pico historical site in Whittier, California, a possible garden that was last active in the 1920s, was bisected by a wagon road or path leading to the San Gabriel River. This feature is visible in GPR profiles as a high amplitude reflection, produced at the interface of the compacted road surface and the overlying soil. In areas to the side of the road, soil of a uniform density is located at the same depth and has a different amplitude of reflection. When amplitudes are mapped, the compacted road is clearly visible, crossing soil units of very different density (fig. 16). More subtle pathway features are also likely to be imaged using this method.

[26] Conyers 2004.



16. A buried road crosses an agricultural area at the Pio Pico historical site in Whittier, California, US. This map illustrates the relative amplitudes of reflected radar waves from about 40-60 cm in the ground. The compacted surface of the road is about 4 meters in width, crossing from bottom right to upper left in this image (L. Conyers).

CONCLUSIONS

Contributions of GPR to Garden Archaeology

Ground-penetrating radar is a geophysical tool that can be used with great utility in discovering and mapping buried gardens that have little if any surface expression. Often subtle changes in soil chemistry or physical properties will produce discontinuities that reflect radar waves. The amplitudes of these waves will vary spatially, and with depth. If GPR data are collected digitally, and in a three-dimensional volume, time-slice mapping can potentially image these features. Some subtle changes in soil characteristics common to gardens may not be visible in individual profiles, but could become visible when processed by the computer.

A test study done at the Buchtel Chapel garden on the University of Denver campus provided a good test for the use of GPR data integrated with soil coring and analysis to find and study soil layers in a buried garden. This garden was partially removed and buried in 1984 and there are no indications of its presence today on the surface. This test produced good quality GPR data to a depth of approximately 75 centimeters below the surface using a 500 MHz antenna. A subtle soil change at about 45 centimeters depth was visible in the approximate location where the garden remains were thought to exist. Core analysis of this subtle soil showed the layer imaged in the GPR profiles to be calcium carbonate-rich fill material. Amplitude maps produced across this feature showed the aerial extent of this feature to be not circular, as the original garden was, but a different shaped feature all together. This

irregular shape is probably due to the removal of the garden bed in 1984, and the import of fill material to level the area using heavy machinery, which modified its original circular shape. The remains of the garden in the form of a buried A soil horizon are still present in some form below the ground surface, although much of its topsoil was likely removed during the area's reclamation.

Other garden features have also been imaged using GPR, showing the utility of this method. Ridges and furrows in plowed fields are visible as alternating high and low amplitude reflections in profiles collected along the buried soil surface at the buried Mayan village of Ceren in El Salvador. In other GPR studies the amplitude analysis method has discovered buried clay pots, post molds from fence lines, and roads and pathways associated with gardens.

Future garden archaeology studies that integrate GPR into the field methods will no doubt discover new ways to integrate the power of radar analysis to discover and map many other associated features. One powerful GPR tool, which has not yet been applied to garden archaeology, is the method's ability to map subtle changes in soils. This ability was demonstrated from the Buchtel Chapel Garden study where very slight soil changes were imaged and then confirmed by soil studies. This type of soil analysis is possible with GPR because the amplitude and aerial distribution of radar reflections is a direct response to changes in the physical and chemical makeup of the medium through which it is traveling. In a more intensive use of this GPR than has been attempted to date, quantitative analyses of soils in a garden could be correlated directly with reflections, and then those properties projected into unknown areas to produce detailed maps of buried garden soils. This approach will produce not only meaningful maps of garden features such as borders, fences, pathways, and buildings, but also changes within the planting beds themselves. The future use of GPR in garden archaeology will allow researchers to perfect some of these types of analytical methods, advancing the GPR method far beyond where it is today. The potential for GPR mapping to discover and accurately map many garden soil types and associated features in the subsurface with minimal disturbance has only begun to be appreciated.

Limits of GPR in Garden Archaeology

Although GPR is a powerful tool for imaging and mapping the subsurface, there are some limitations of its applicability in garden archaeology. The most obvious limitation is its depth of investigation. The trade-off that exists between depth of investigation and resolution can be important if buried features and stratigraphic interfaces of interest are buried too deeply. Below about 2-3 meters, low-frequency antennas (300 MHz and lower) are necessary for the transmission of radar energy. With those antennas, resolution is severely diminished, making many subtle changes in garden beds and associated features all but invisible in GPR profiles and

maps. If high resolution is necessary to map the units of interest, with the present technology, they must be fairly close to the surface.

The chemical and physical properties of the medium through which radar energy must pass can also be a limiting factor in GPR studies. Any medium that is electrically conductive, such as wet clay, or any sediment or soil with a high electrolyte content (those high in salts or carbonate for instance) will attenuate radar energy quite rapidly and often GPR data can be unusable in these areas. The same can hold true for sediment or soil that is magnetic, but materials of this sort are relatively rare.

Soil moisture can often severely disrupt radar energy, producing reflections that are difficult to interpret, obscuring those that are potentially meaningful. If an area has been recently irrigated, or there has been a recent heavy rain, pools of water can be differentially preserved in sediments and soils. When this happens, radar reflections occur only from the pools of water, not from the zones or objects of interest.

It is often difficult to know in advance whether ground conditions are conducive for GPR studies. Some have tried to predict GPR success based on soil survey maps or gross generalizations about the geology of an area.[27] While these types of analyses can be a useful guide in a general sense, actual GPR success in a specific area can be determined only by actually collecting and processing data.

One of the greatest limitations to the method is the most common problem with most GPR studies: the timing of the surveys. Usually GPR surveys are conducted prior to excavations, which is only natural because archaeologists would always like to know in advance what is under the ground before they dig. When surveys are done in this way, there are usually anxious excavators waiting for results, with unrealistic expectations that GPR surveys will tell them everything they want to know about the subsurface.[28] Sometimes this approach works well and exciting archaeological features just "jump out" of processed maps, leaving little ambiguity about their origin. These types of features are usually those that are most distinct, such as house floors, walls, and other architecture that would be hard to miss by even the most inexperienced interpreter. In garden archaeology, when the features to be mapped are usually much more subtle, features are difficult to find, and it is often challenging to make a definitive interpretation. In these cases, interpretations that would please both the excavator and the geophysical archaeologist can be arrived at only by merging and integrating information from excavations and GPR data. The timing of many projects precludes this iterative process of give and take, making many GPR maps less useful to archaeological projects than they should be. The correct way to use GPR in garden archaeology would be to first collect the data and interpret it, with the knowledge that

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[27] Collins & Kurtz 1998.
[28] Conyers 1999.

little is really known about the subsurface. Then test interesting features and horizons that can be seen in profiles and maps using excavations or coring and augering. The data from this surburface testing must then be integrated back into the GPR data so that horizons and features of interest can be remapped, using information obtained from the ground. This timing necessitates what amounts to a "first look" at the GPR, then a reinterpretation of it, and often a second round of reinterpretation, as new information comes to light. Garden archaeologists must expect this type of prolonged analysis and budget for it in terms of time and expenses.

These limitations of GPR in garden archaeology can be overcome with thoughtful planning and diligent data processing and interpretation. The potential for GPR to not only discover, but accurately map, many gardens and their associated features, with minimal disturbance, has only begun to be realized.

	resistivity sounding	resistivity profile	magnetic susceptibility	electromagnetic conductivity	ground-penetrating radar	seismic refraction	soil penetrometer	soil chemistry	magnetometer	metal detector
Fertilization	***	**	****	**	*	*	*	****	*	*
Cultivation depth	***	*	****	*	**	**	****	*	*	*
Cultivation boundary	*	***	***	***	*	***	***	**	*	*
Buried topsoil (fill)	**	**	****	**	****	***	***	**	**	**
Scraped topsoil (cut)	**	**	****	**	*	***	**	**	*	*
Soil stratification	****	*	**	*	***	**	*	***	*	*
Landscaping	**	**	****	**	***	***	**	**	*	*
Buried terrace	*	****	***	****	***	**	**	*	**	*
Plow scar	*	**	**	**	***	*	**	*	*	*
Filled trench	*	****	***	****	****	**	***	*	**	*
Bedrock	***	**	*	**	**	****	****	*	**	*
Fence line	*	**	**	**	*	*	*	***	***	**
Path	*	***	*	***	***	**	****	*	**	*
Former plant	*	**	*	**	**	*	*	*	*	*
Planting pit	*	**	**	**	***	*	**	*	*	*
Pipe or drain	*	*	*	***	****	*	*	*	***	***

**** Excellent *** Good ** Fair * Poor

Table 2. The suitability of geophysical surveys for detecting garden features. While there are many factors that will decide on the success of a survey, these rankings may provide some guidance.

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Part III

Excavating the Garden: Bringing the Garden to Light

The third part of the volume is the core of the handbook, as it provides methodological considerations and techniques for carrying out the dig. It follows the rationale of Part II, that is, to engage excavators to adapt the information provided by the authors to their own context and invent their own methodology. Kathryn Gleason was asked to use her expertise at garden excavations in the Old World to discuss the constraints and the issues that archaeologists might face during a dig. As Gleason states, "Garden archaeology is just good dirt archaeology," yet specific modifications need to be discussed. The author describes in four chapters the different stages of the excavation by stressing how digging exterior spaces – gardens – differs from conventional practice.

The first chapter explains the main concerns that an archaeologist should be aware of before starting a garden excavation. *Materiality* (dirt is artifact and context), *Scale* (gardens can cover very large areas), and *Levels* (gardens' surfaces are never perfectly level) are the three main aspects that differentiate gardens from architectural remains, orient the excavation, and therefore, demand a specific strategy. The second chapter details the dig itself, following the key steps of an excavation starting from the different types of baulks and trenches, to the delicate phase of locating and identifying the garden layer and the surface features, to discussing situations where the garden surface is not preserved. It concludes with advice on the field recording system that should be used. The third chapter presents an overview of the integration of environmental archaeology in the process of work. The last chapter moves from the soil to the design of the garden – gardens being the result of a complex dialectic between soil and culture. It offers the insight of Kathryn Gleason and Michele Palmer's background in landscape architecture to aid in the interpretation and reconstruction of garden remains. (AAM)