Archaeological Prospection, Vol. 3, 25–38 (1996)

Velocity Analysis in Archaeological Ground-Penetrating Radar Studies

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ABSTRACT In ground-penetrating radar (GPR) investigations of archeological sites, the accurate conversion of two-way travel times to distance or depth can be made only if radar wave velocities are known. Because radar data are typically collected in a manner that does not facilitate the determination of velocity, special efforts must be given to measure the speed of radar waves in the subsurface. Field tests can be performed on objects at known depths where radar wave travel times can be measured directly. These tests can be integrated with the correlation of known stratigraphic units to radar reflections in order to confirm the velocity measurements and map subsurface interfaces. Transillumination tests can be performed in adjoining excavations in order to determine velocity variations with depth. Common mid-point type tests are helpful in estimating near-surface velocity changes but are less valuable in determining velocity at greater depth. Data from these tests can be used to derive velocity gradient curves and identify possible buried reflection surfaces. The integration of many velocity tests can assure accurate conversions of travel time to depth over a large study area. Mapping of surfaces or features in true depth as opposed to radar travel time can confirm the correlations of GPR reflections to known subsurface units and enhance the understanding of an archaeological site.

Key words: ground-penetrating radar; velocity; archaeology

Introduction

The use of ground-penetrating radar (GPR) in archaeological exploration has for much of its history been used primarily to discover anomalies that may represent buried features. Subsurface reflections are usually displayed in two-dimensional profiles, or three-dimensional contoured data derived from two-dimensional displays, with the vertical scale plotted as the two-way travel time of radar wave reflections. These types of data presentations are usually sufficient for many archaeological investigations because most archaeologists have the limited objective of finding buried anomalies that may represent archaeological features, which can be excavated later. The actual depth and geometry of the features, and the nature of the surrounding stratigraphy that may be related to those features, is usually of secondary interest.

Recently, GPR data have been used in a more quantitative and calibrated fashion to map reflections that correspond to stratigraphic layers of importance (Imai *et al*, 1987), buried living surfaces (Conyers, 1995), or other important archaeological targets. In these types of studies radar wave reflections must be correlated directly to subsurface features of interest. In order to make these correlations accurately, the two-way radar wave travel times measured in GPR surveys must be converted to distance accurately, i.e. depth below the ground surface or elevations above a datum. This report describes a number of field tests that were performed to determine radar wave velocity at the Ceren Site in El Salvador in order to illustrate some of these velocity measurement techniques.

Site description

The Ceren Site is a Classic Period southern Mesoamerican agricultural village that was buried almost instantaneously by volcanic

CCC 1075–2196/96/010025–14

Received 7 December 1995
Accepted 15 February 1996

material about AD 590 (Sheets, 1992). The ancient living surface and all buildings, artefacts, agricultural fields, and floral and faunal remains are now buried by as much as 6 m of pyroclastic debris. Portions of the ancient anthropogenic landscape have been exposed in four large excavations and numerous test pits. Domicile, storage, civic and religious structures have been identified as well as patios, work areas and a large civic plaza.

The ancient buried living surface is called the tierra blanca joven (young white earth), or TBJ for short. This is the surface that must be identified using GPR. The top of the TBJ was the surface on which people walked, structures were built, and crops were grown. Owing to rapid burial by the volcanic eruption this surface was almost perfectly preserved under the overlying volcanic tephra (Sheets, 1992). Fifteen different volcanic units were deposited above the clayey TBJ surface (Miller, 1989), which consist of alternating fine- and coarse-grained pyroclastic beds having virtually identical chemical properties, but vary in porosity and residual water saturation.

GPR velocity studies

Most GPR systems transmit radiofrequency electromagnetic pulses periodically into the ground. The pulses propagate through the earth and are partially reflected back to a surface GPR antenna when they encounter changes in relative dielectric permittivity (RDP), electrical conductivity, or magnetic permeability (Powers, 1995). Dielectric permittivity is a measure of the capacity of a material to store an electrical charge (i.e. polarize) under an applied electric field. Relative dielectric permittivity is the dimensionless ratio of a medium's dielectric permittivity to that of free space (a vacuum). The propagation velocity of radar waves is controlled primarily by the RDP of a medium.

To transform the two-way travel time of radar waves (from the transmitter to a reflector and back to the receiver) to an approximate distance or depth, the propagation velocity of the radar waves must be known. In a low-loss medium (i.e. one in which electrical conductivity is low), radar wave velocity can be determined from the following formula (Powers, 1995, p. 33):

$$V_r = \frac{V_c}{K^{1/2}} \qquad (1)$$

where, V_r is the velocity of the radar wave in the medium (in centimetres per nanosecond (cm ns^{-1}); (1 ns $= 10^{-9}$ s), V_c is the velocity of electromagnetic waves in a vacuum (29.98 cm ns^{-1}), and $K^{1/2}$ is the square root of the medium's relative dielectric permittivity (K). Or, by rearrangement, if the velocity is known, the relative dielectric permittivity, K, can be determined.

The GPR data are typically collected in a manner that does not facilitate the determination of radar wave velocities, and therefore only rough estimates are available. There are two general methods to determine radar wave velocity in the subsurface, reflected-wave methods and direct-wave methods. Reflected-wave methods require that radar waves be reflected from objects or stratigraphic interfaces at depths which can be measured. In direct-wave methods, radar waves are transmitted through the ground, from one antenna to another, along a measured distance. In both methods velocity is determined by measuring the time it takes radar waves to travel known distances.

Multiple velocity tests should be conducted in a study area because it is common for the velocity of overburden material to change laterally as well as with depth. Velocity variations are caused most commonly by changes in water saturation and lithology. Dry quartz sand has an RDP of about 4, resulting in a radar wave velocity of 14.99 cm ns^{-1}. The RDP of water is about 80, causing radar waves to travel much more slowly, at about 3.33 cm ns^{-1}. In most settings, the water content of soil and sediment will increase with depth and the average radar wave velocity of the material will correspondingly decrease. The degree of residual water content in the vadose zone and the depth to a water table can fluctuate because of topography, stratigraphy and drainage features. In archaeological contexts, anthropogenic activities can often create layers which contrast in velocity from those that surround them, complicating velocity measurements.

It is important to recognize that velocity measurements at a site are valid only for GPR data collected when the tests are performed. The velocity of radar waves at a site can vary dramatically with the seasons. Changes in soil and sediment moisture can also occur rapidly, even as a survey is being carried out, due to torrential rainfall, snowmelt or flooding. For example, velocity tests performed at the Ceren Site during the rainy season yielded a RDP of 12 (velocity of 8.7 cm ns^{-1}), for the volcanic overburden material (Doolittle and Miller, 1992), whereas tests performed in the same area at the end of a 6-month dry season measured a RDP of about 5 or a velocity of 13.4 cm ns^{-1} (Conyers, 1995). In this case, if the velocity tests performed during one season were used to process and interpret GPR data acquired just a few months later, the calculated depths of significant radar reflections would be extremely inaccurate.

Ground-penetrating radar antennae usually transmit and receive over a range of frequencies from about half to twice the centre frequency (2 octaves). Therefore, if two antennae are used to conduct velocity tests using direct-wave methods, they do not necessarily have to have the same centre frequencies. For instance, a 500 megahertz (MHz) centre-frequency antenna, which radiates radar energy from approximately 250 MHz to 1000 MHz, can be used to transmit radar waves to a 300 MHz centre-frequency antenna (which responds to frequencies from approximately 150 MHz to 600 MHz) because their bandwidths overlap. It is best, however, to use antennae as close as possible in centre frequency.

Reflected-wave methods

The most accurate and straightforward method to measure velocity is to identify reflections in GPR profiles caused by objects, artefacts, or zones of interest, which occur at known depths. These methods allow for a direct determination of the *average* velocity of radar waves from the surface antenna to a measured depth. In the past, these types of velocity tests have been conducted at archaeological sites on objects as diverse as buried whale bones (Vaughan, 1986), copper wire (Kenyon, 1977), and empty metal paint cans (Doolittle and Miller, 1992).

The reflected-wave tests performed at the Ceren Site are referred to as the 'bar test', 'wall test' and the 'stratigraphic correlation test'. The bar test involved pounding an iron concrete-reinforcing bar into the side of an excavation and identifying it on a GPR profile. Metal objects are near-perfect reflectors and the reflections generated from them are easily identifiable on most GPR profiles. The wall test was analogous to the bar test except that the top of a buried adobe wall, an end of which had been exposed in an excavation, was identified on GPR profiles. The stratigraphic correlation test incorporated the velocity measurements derived from the bar and wall tests to help identify reflections generated from important stratigraphic horizons exposed in test pits.

The bar test

At the Ceren Site, the 'bar test' involved the detection of a 2.5-cm diameter iron reinforcing bar at different depths. In one test, this bar was pounded into the side of an excavation exactly 1.1 m below the ground surface. A pair of 500 MHz antennae were placed on the ground surface and slowly pulled over the bar while reflections were recorded. To obtain the best results, the long axes of the surface antennae were oriented parallel to the length of the bar. This orientation created an electric field oriented parallel to the bar and produced the maximum amount of reflection (Annan and Cosway, 1994). If the antenna axes had been oriented perpendicular to the bar, only a small portion of the transmitted radar energy would have been reflected, and it would likely not have been visible in reflection profiles.

Because radar antennae transmit electromagnetic energy in a broad cone, subsurface features are visible in front and to the rear of the antennas. The resulting anomaly is a steeply-curved reflection, commonly called a reflection hyperbola (Figure 1).

In the bar test an average velocity of 16.92 cm ns^{-1} (110 cm 6.5 ns^{-1}) was obtained, which is a very high velocity for GPR waves in most earth materials due to the juvenile nature of the

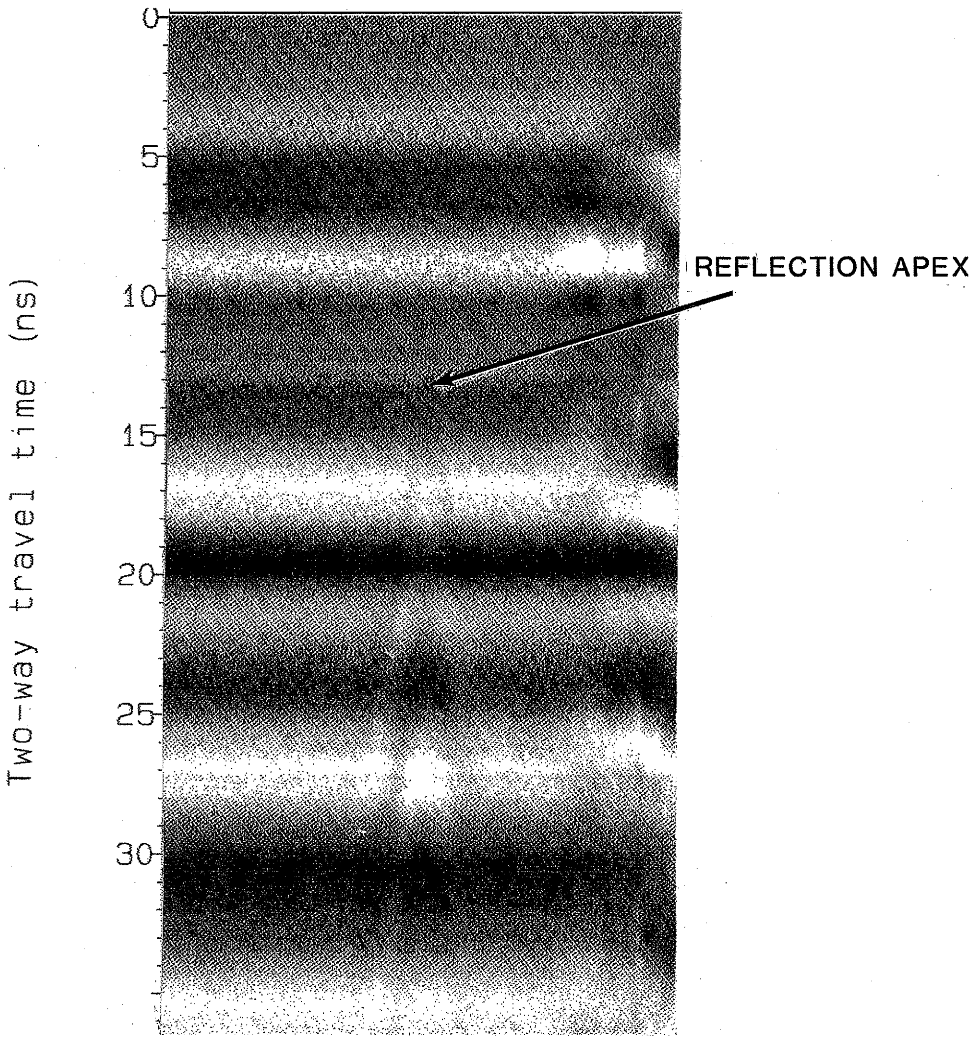

Figure 1. Reflection hyperbola generated by a metal bar. The bar was buried 110 cm below the ground surface. The reflection hyperbola apex is visible at 13 ns (6.5 ns one-way time).

volcanic tephra and its extreme dryness when this test was conducted. Equation 2 below can be used to determine the average relative dielectric permittivity (K) of the material between the surface and a depth (d) using the two-way travel time (t).

$$K^{1/2} = \frac{V_c\,(t/2)}{d} = \frac{29.98\ (6.5)}{110} = 3.14 \qquad (2)$$

The wall test

Another reflected-wave test was performed near the bar test where the corner of a buried structure with standing walls had been partially excavated. A 2-m high portion of the structure's adobe wall projected into the tephra overburden where this second test was performed. The top of the structure's wall was measured at exactly 2.51 m below the ground surface. A number of GPR profiles were then acquired perpendicular and parallel to the wall using paired 300 MHz antennae. Other test profiles were located nearby, but not over the structure, so that a representative section without archaeological features could be obtained for comparison. The two most diagnostic GPR profiles from these tests are shown in Figure 2.

Table 1. Velocity analyses results from bar and wall tests.

Test	Depth (m)	Total distance (cm)	Two-way time (ns)	Relative dielectric permittivity (RDP)	Velocity (cm ns^{-1})
Bar	0–1.1	220	13	3.14	16.92
Interpolation	1.1–2.51	282	25	7.06	11.28
Wall	0–2.51	502	38	5.15	13.21

In the profile which perpendicularly crosses the wall (Figure 2) the top of a volcanic ash unit can be seen creating a dune to the right of the standing wall. This ash dune was also exposed along the side of the excavation. The average velocity obtained in this test using equation (2) is 13.21 cm ns^{-1} (RDP = 5.15), a slower average velocity than calculated in the bar test because the radar energy travelled deeper into units with greater interstitial moisture.

The results of these two time-depth calculations on objects at measurable depths are shown in Table 1. Velocities for intermediate layers also were interpolated from these two measurements.

Stratigraphic correlation test

Once accurate estimates of velocity for different depths are obtained from direct measurements, a correlation of radar reflections to stratigraphy can be made. At the Ceren Site, a stratigraphic correlation test was performed on east–west GPR profiles, which were bounded on either end by recently excavated test pits. All overlying volcanic units, and the TBJ living surface, were exposed and measured in the test pits.

Paired 500 MHz and 300 MHz antennae were used to collect reflection data along the stratigraphic correlation line (Figure 3). The GPR data were acquired up to the edges of each excavation so that the resulting reflections could be correlated directly with the known stratigraphy. The 500 MHz antennae could detect features to about 30 ns (about 2.5 m in depth) whereas the 300 MHz antennae were useful to 80 ns (about 5 m in depth).

The most continuous and highest amplitude reflection in the 300 MHz profile was measured at 62 ns (two-way time), on the western edge of the line (Figure 3). In most GPR profiles these types of strong reflections are usually caused by large velocity contrasts between units of different lithology or water content. Using the average velocity of 13.2 cm ns^{-1} obtained from the wall test, an approximate depth for the reflection on the west end of the test line was calculated to be 409 cm using Equation 2. The first dramatic lithologic discontinuity that could likely cause this high amplitude reflection is the interface between the clay-rich TBJ living surface and the overlying volcanic tephra, located at a depth of 420 cm below the surface. Recalculating velocity using this depth results in 13.55 cm ns^{-1} (RDP = 4.9), only slightly faster than the velocity calculated in the wall test (Table 1). Subsequent interpretation of more than 4000 m of GPR data acquired prior to conducting excavations confirm that almost all topographic features mapped from this reflection correspond to those visible on the TBJ surface in excavations. Confidence is therefore high that this high amplitude reflection represents the TBJ–tephra interface (Conyers, 1995). Additional correlations of other prominent stratigraphic layers measured in the test pits to reflections visible in GPR profiles confirms both shallow and deep velocity measurements (Figure 3).

Direct-wave methods

Direct-wave methods provide an additional way to measure the velocity of radar waves in the ground, although usually with less precision than reflected-wave methods. Direct-wave methods require that GPR antennae be moved or placed several metres apart in nearby excavations or on the ground surface. One antenna transmits to the other and the one-way travel time between the two is measured. The radar wave velocity can then be calculated knowing the distance between the two antennae. The two most common direct-wave methods are the transillumination and common mid-point (CMP) methods.

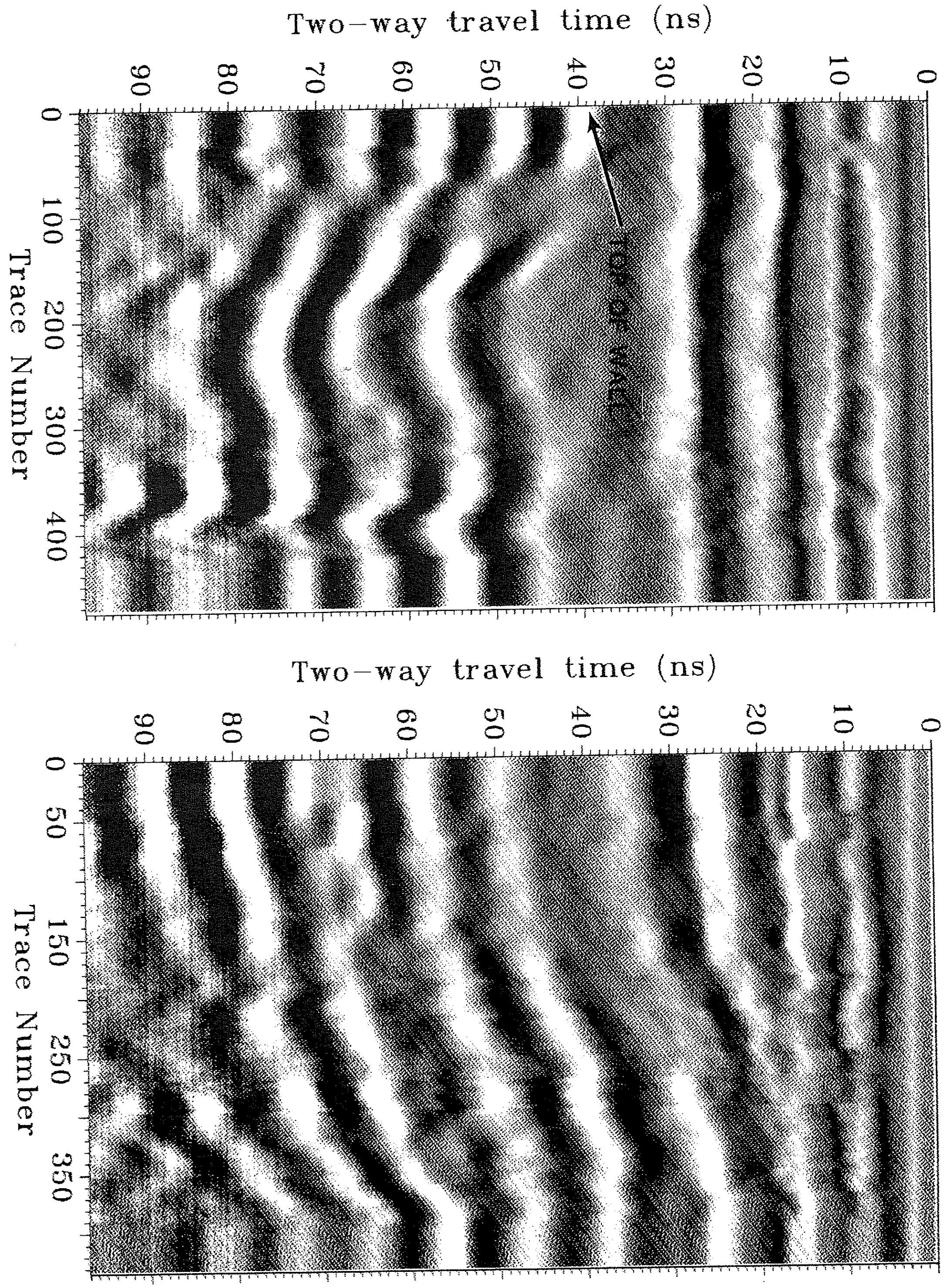

Figure 2. The GPR profiles of the wall test. The left profile was acquired perpendicular to a buried wall, the top of which was measured 251 cm below the ground surface. The top of the wall is visible at 38 ns. The right profile was acquired 2 m to the east of the buried building where only regional dip of the volcanic stratigraphy is visible.

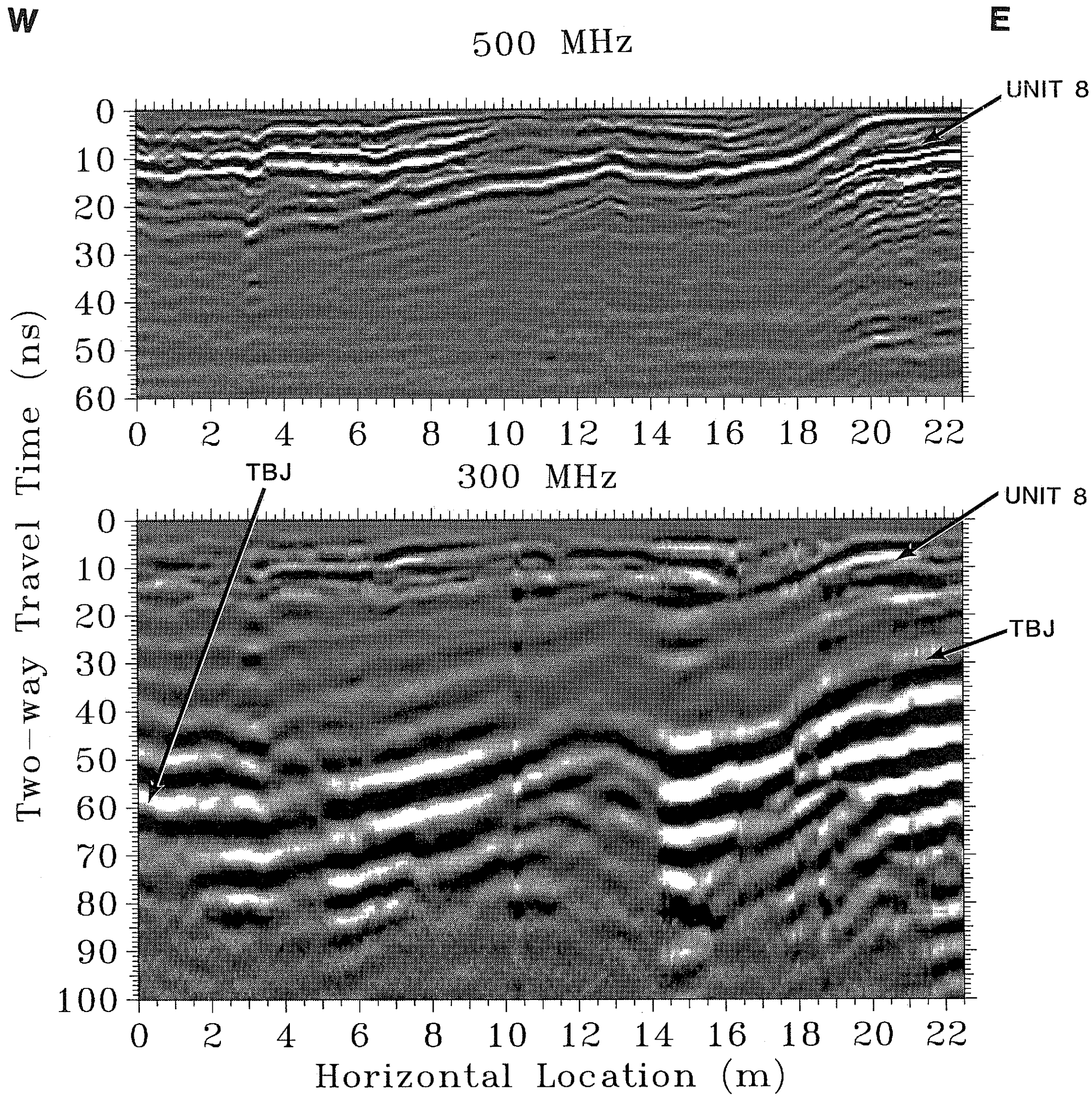

Figure 3. Profiles for 500 and 300 MHz along the same transect. Reflections tie to measured depths of stratigraphic layers at either end of the profiles. The high-amplitude TBJ reflection is correlative in the 300 MHz data and shallower volcanic units such as Unit 8 are correlative using both 300 and 500 MHz data.

The transillumination method projects radar energy between two antennae directly separated by the material for which velocity needs to be measured. This method has not been commonly used in archaeological velocity tests but has been used with success in testing the integrity of concrete or stone pillars (Bernabini *et al*, 1994). Common mid-point methods (Fisher *et al*, 1994) are also called radar surface arrival detection (Sutinen and Hanninen, 1990) or wide-angle reflection and refraction (WARR) (Imai *et al*, 1987). The CMP tests place two antennae on the ground surface and, as radar waves are transmitted between the two, they are either separated from a common point or begin at a separation and are moved together.

Dual antennae, which are mounted together in the same unit, can be used for direct-wave tests if two units are available. Only one antenna in each unit is activated, one to send and the other to receive. If the GPR system has two channels, then a separate cable is connected to each antenna unit. The same type of configuration can be accomplished on a single channel GPR system if there is a cable splitter that separates transmission and reception lines.

Transillumination methods

The transillumination method can be used in archaeological settings when there are two nearby excavations or outcrops and the section of material to be tested is exposed in each. The faces of the excavations or outcrops should be as close to parallel as possible. It is best if the tests are performed soon after the material is exposed so that evaporation or seepage of water along the faces does not significantly change the water saturation characteristics of the material.

Two antennae, one to transmit and the other to receive, are then placed on the walls of the two excavations, with their transmission and reception sides facing each other, aligned so that the long axes of the antennae are parallel. It is important that the two antennae be separated by at least the distance of the transmitting antenna's radiating nearfield zone (Ulaby *et al*, 1981). This is the zone where the transmitting antenna's energy is being both radiated as well as stored (Duke, 1990). This distance ranges between approximately 1 and 3 m, depending on the antenna frequency and the relative dielectric permittivity of the medium. If the two are closer than this the first signal received may be difficult to identify.

A series of transillumination tests can be made starting at the base of the excavations, moving upward. The two antennae can be moved in steps, or continuously, as radar energy is transmitted between the two. Care must be taken to match the locations and separations of the antennae with individual radar traces. In some GPR systems, a mark can be placed into the radar record to note the vertical antenna positions.

When the material to be tested is highly layered it is important that the electric field generated by the transmitting antenna be oriented parallel to the bedding planes. To do this, the long axes of antennae must be placed parallel to the bedding planes. In this orientation, the electric field generated by the antenna will oscillate parallel to the layers and there may be maximum isolation of the radar waves within each layer. The cone of illumination, which is elongated perpendicular to the electric field generated by the transmitting antenna, may, however, transmit radar energy into adjacent layers, regardless of the orientation of the antennae. If the material to be tested is fairly homogeneous and unlayered, the orientation of the antennae with respect to the material is not as important, as long as the transmitting and receiving antennae are oriented in the same direction.

The transillumination method was used at the Ceren Site in a large excavation where a wide section of volcanic ash was preserved. Eight different ash units were exposed along the sides of the wall with the TBJ living surface at the base. A 300 MHz antenna was put on one side of the exposure and a 500 MHz antenna on the other (Figure 4), with the 500 MHz antenna used to transmit and the 300 MHz to receive. The horizontal distance between the two antennas was 2.6 m at the top of the preserved section of tephra and, due to the sloping walls of the excavations, was approximately 2.8 m at the base.

Seven transillumination measurements were made in steps from the base upward. The first step in the test transmitted radar waves through the lowest part of the exposed ash and the TBJ, which appeared to be more moist than the units above. Six additional measurements were conducted on specific ash units above the lower ones, moving the antennae to within about 25 cm of the surface (Figure 4). To determine when within the record the transmitter was firing, the antennae were placed exactly 2 m apart in air. Knowing the velocity of radar waves in air and their separation, the time that the transmitter fired can be calculated from the first air wave arrival (equation 1).

The results of the transillumination test are shown in Figure 5. For tests 1 through to 5 all radar energy that was received passed directly through the section of ash and there was no apparent 'leakage' of energy over the top of the preserved section in the form of an air wave. Possible air wave arrivals for each test are calculated using equation (1), knowing the

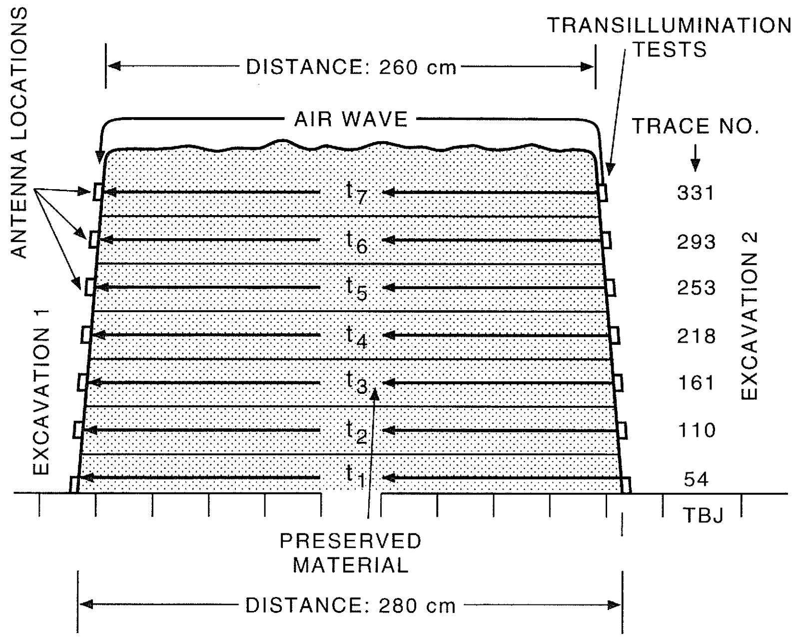

Figure 4. Transillumination test set-up. One way travel times (t_1–t_7) were measured in seven steps performed along two facing excavations with the preserved material being tested between. Air wave travel times around the top of the excavation were also calculated.

distance from one antenna to the other around the preserved section of material (Figure 5). In tests 6 and 7 the first arrivals are most likely air waves, casting some doubt on the velocity determination for these uppermost tests. The period of little or no response at the top of each trace is the time elapsed between when the pulse was sent by the transmitting antenna and when it was received at the antenna on the opposite side of the exposure.

Knowing the separation of the antennae and the one-way travel time of the radar energy between the two antennae at each step, velocities and relative dielectric permittivities can be calculated (Table 2).

When the velocity measurements at each of the seven steps are plotted against the depth of the antennae below the ground surface, a velocity profile can be constructed (Figure 6). It illustrates how velocities in this exposed section of material decreased with depth, most likely indicating a gradually increasing residual water content. Minor deviations in the curve may indicate velocity changes between volcanic units, which may reflect radar energy.

Common mid-point methods

The simplest and quickest velocity measurement that can be performed in the field is the common-mid point (CMP) test because no excavation is necessary and buried targets do not have to be identified. The CMP method is similar to the transillumination method in that radar energy is transmitted from one antenna which is separated from another, the difference being that the antennae are located on the ground surface. Common mid-point tests are performed by placing two antennae side-by-side on the ground with the long axis of the antennae parallel, and then separating them from each other either continuously or in steps. A series of direct one-way, or wide-angle reflected, radar travel times between the two antennae are then measured, and if the energy travel paths in the ground can be deduced, the velocity of the near-surface layers can be measured. The antennae also can be placed apart and moved together, with their paths crossing at a common mid-point, and then moving away from each other (Fisher *et al*, 1994).

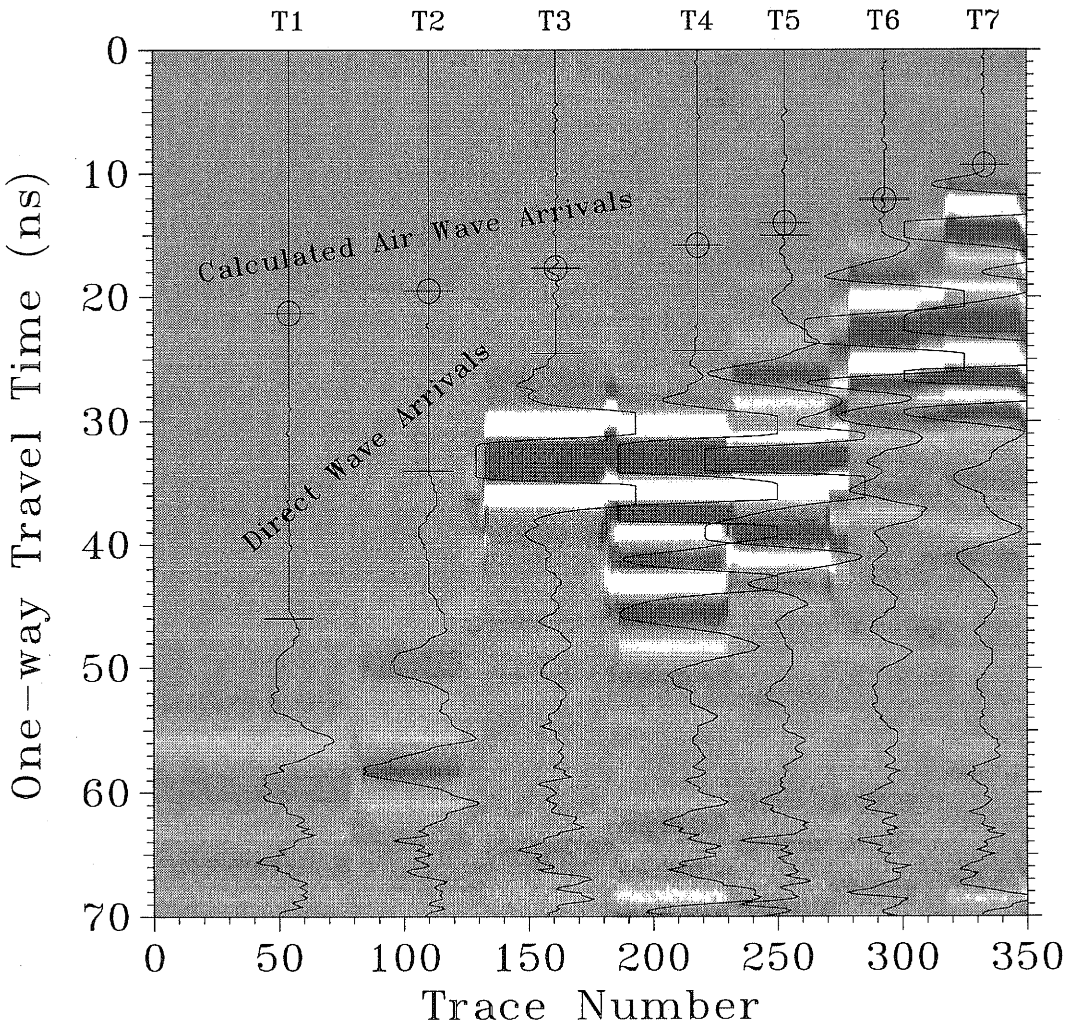

Figure 5. Wave arrivals from the transillumination tests. A grey scale GPR profile with overlain representative traces measure the time of first arrival measured at the seven steps shown in Figure 4. The first arrival is identified by the horizontal bar on each trace. The calculated air wave arrivals are shown by the circled horizontal bars. In tests 6 and 7 the air wave and direct wave arrivals are coincident.

There are a number of variations of CMP tests that can be performed, all of which are based on the same premise (Grasmueck, 1994). One variation keeps one antenna stable while the other is pulled away. Data from this kind of test can be used in exactly the same manner as that derived from a standard CMP test and is commonly used when only one person is available to move the antennae. Another test keeps the separation distance constant as both antennae are moved from station to station over the ground surface (Grasmueck, 1994). If enough CMP tests are conducted they can produce a spatial distribution of near-surface velocities over an area.

The CMP data are typically displayed as a standard two-dimensional GPR profile, with the antenna separation distance or trace number on the horizontal axis and travel time on the vertical axis (Figure 7). Usually, CMP tests only measure velocities of surface soil, or material which is located very near the surface. They should not be viewed as a way of determining velocity at any great depth unless the ground is unusually

Table 2. Results of transillumination tests.

Test number	Trace	Depth (cm)	Distance (cm)	Time (ns)	Velocity (cm ns^{-1})	Relative dielectric permittivity (RDP)
7	333	25	260	9.3	28.0	1.1
6	293	52	260	12	21.7	1.9
5	253	79	265	15	17.7	2.9
4	218	104	270	24.3	11.1	7.3
3	161	124	275	24.5	11.2	7.1
2	110	144	280	34	8.2	13.2
1	54	164	280	46	6.2	23.2

electrically resistive and it is possible to identify actual wave travel paths (Fisher *et al*, 1994).

To calculate the radar wave velocity in near-surface layers it is necessary to know the distance between the antennae at periodic distances or at their maximum separation. If location marks are not placed on the radar records the separation distance can be calculated by rearranging equation (1) and replacing V_r with (d/t), where d is the maximum separation distance between antennae, t is the one-way travel time and K is the relative dielectric permittivity.

$$d = \frac{V_c t}{K^{1/2}} \quad (3)$$

As an example, a CMP test performed at the Ceren Site is shown in Figure 8. In this test the transmitting antenna was kept stable while the receiving antenna was moved away from it. The separation distances were not recorded so the horizontal axis is displayed as the trace number of the recorded data. At the maximum separation distance (trace 300), the first arrival was measured at 13 ns. Knowing the speed of radar energy in air (29.98 cm ns^{-1}) the maximum separation distance can be calculated, using equation (3), as 389.74 cm.

Knowing the distance a similar calculation can be performed for the ground wave, which was recorded at 31 ns at maximum separation (Figure 8). Rearranging equation (3) the RDP of the layers near the ground surface can be calculated, using the ground wave travel time of 31 ns and distance of 390 cm, as about 5.7.

$$K^{1/2} = \frac{29.98 \text{ cm ns}^{-1} \times 31 \text{ ns}}{390 \text{ cm}}$$

Conclusions

The most accurate GPR velocity tests are those performed in the field that directly measure the radar travel times to and from targets at known depths. In all cases when soil or stratigraphic layers are relatively horizontal these tests are measuring average velocity from the ground to depth. The targets should be metal in order to maximize radar reflection strength. At depths greater than a few metres, iron bars or other

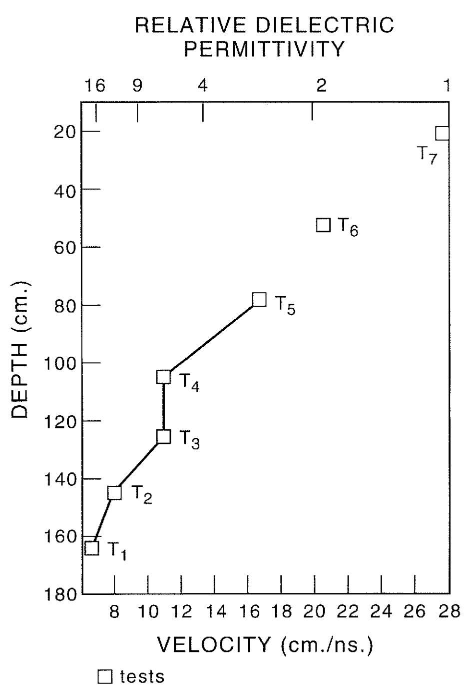

Figure 6. Velocity profile derived from the transillumination test data. The velocity decreases linearly with depth. The minor deflection at 100 cm (t_4) indicates a possible subsurface velocity discontinuity. The arrivals at t_6 and t_7 may represent the arrival of air waves and therefore do not likely represent the actual velocity of the material being tested.

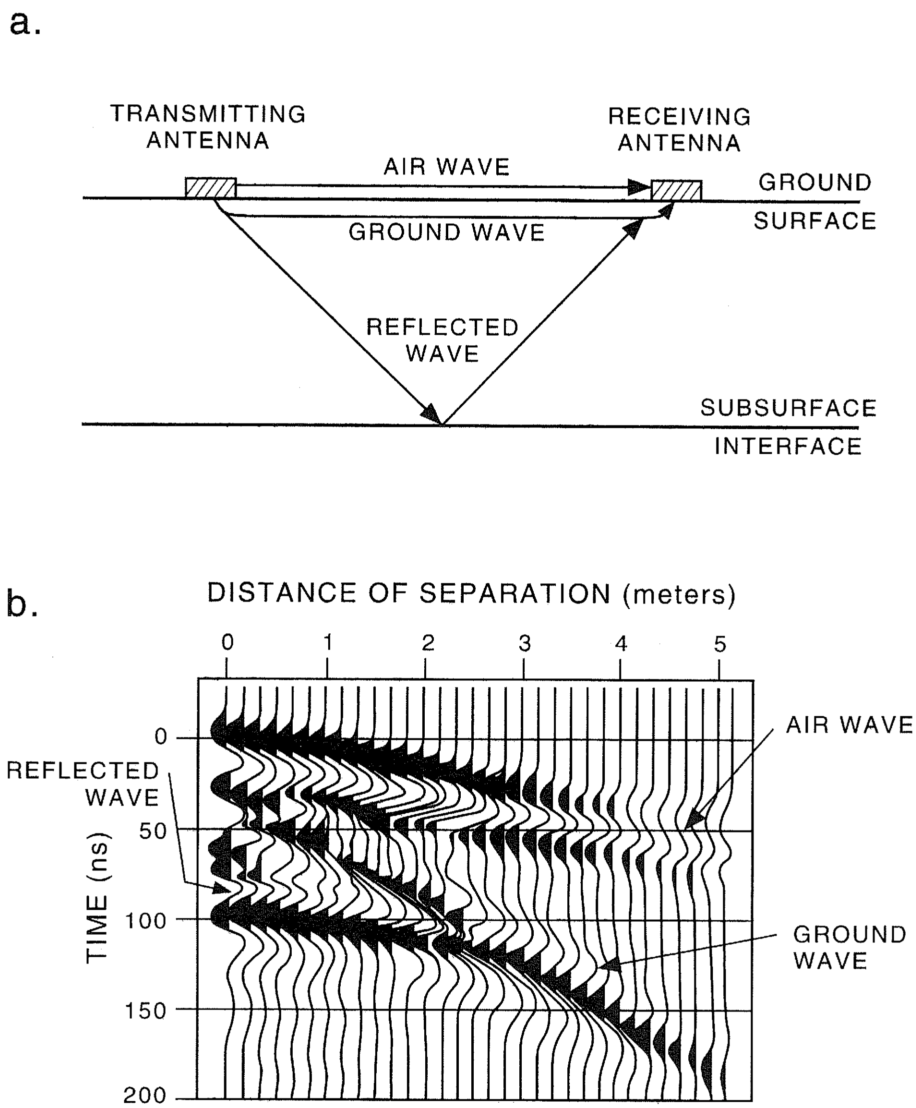

Figure 7. Common mid-point type tests. In (a) radar energy moves from the transmitting antenna along multiple paths (air, ground and reflected waves) to the receiving antenna. When reflection arrival times are plotted in profile (b) the airwave is recorded first with the ground wave and all subsequent arrivals received later.

relatively small objects may not be visible in profiles, and larger objects, such as the buried structure wall used as an example above, need to be imaged. When objects of this sort are not available it may be possible to integrate shallow velocity measurements with stratigraphic correlation tests to arrive at deeper velocity values. The correlation of stratigraphic horizons to reflections can be suspect unless there are known large lithological or water saturation changes in the stratigraphic layers being imaged. If possible, one or more trenches or pits should be excavated to the depth necessary to reveal all units that will be illuminated and to facilitate correlations with radar records.

If two or more excavations, especially if recently dug, are available in close proximity, transillumination tests can be performed. The velocity data gathered from these tests can yield velocity gradient curves, which may delineate zones in the subsurface most likely to reflect radar energy.

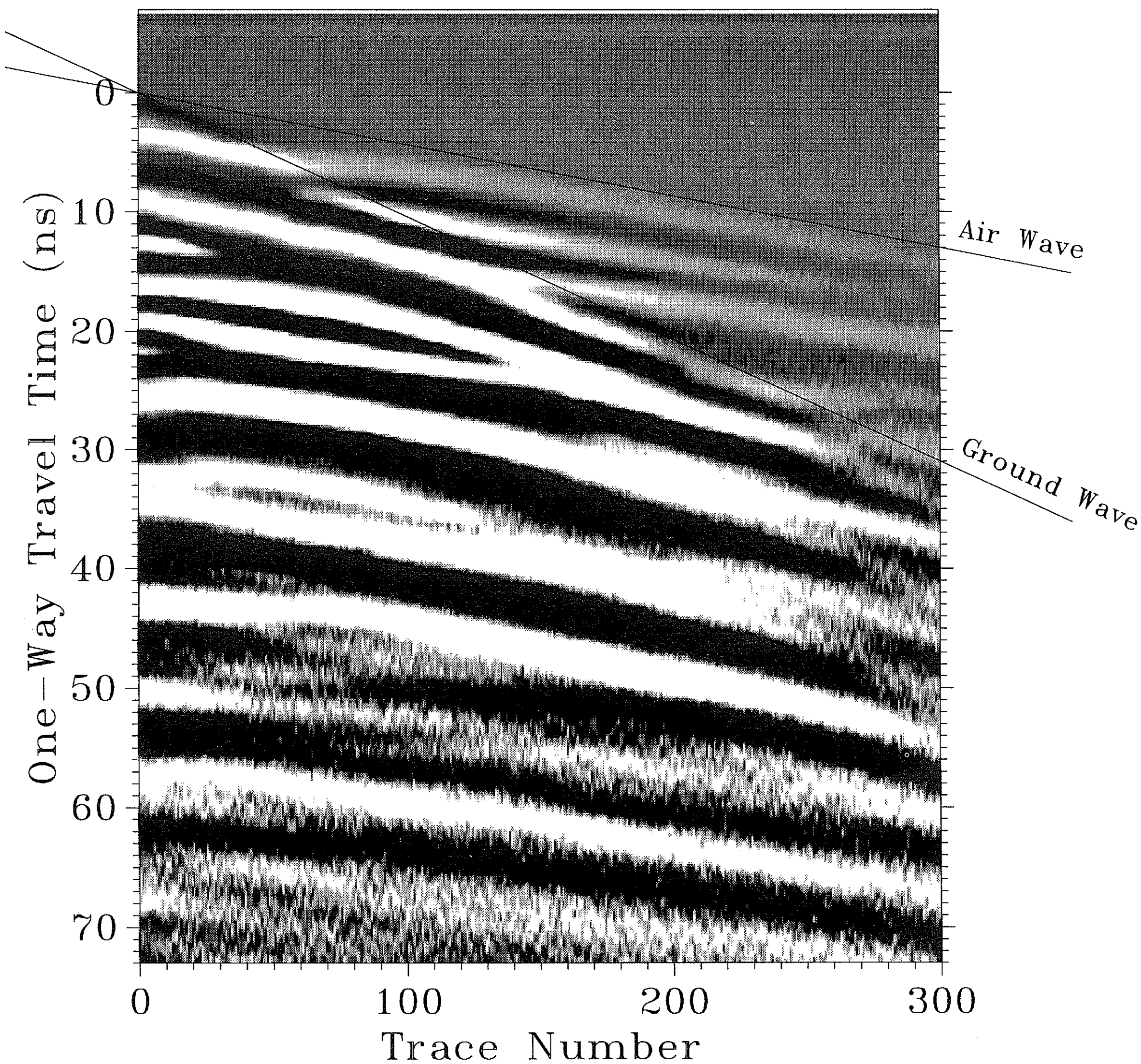

Figure 8. A CMP type test at the Ceren Site. The test was performed using a 300 MHz antenna to transmit and a 500 MHz to receive. Received data was recorded continuously during separation. The airwave and ground wave are recognizable as the first two distinct reflections, which intersect at time zero.

Data from transillumination tests should be used with caution because it may be difficult to determine the travel paths of the radar waves within the material. If the layer being measured has a higher RDP or electrical conductivity than adjacent layers, then the first arrivals on the radar record may be those which travelled in the higher velocity adjacent material and not those that followed the most direct route. For best results transillumination tests should be performed in conjunction with reflected-wave tests. The combination of both tests will yield both average vertical velocity measurements as well as a velocity gradient with depth.

If excavations are not available at a site, the velocity of near-surface zones can be estimated using common mid-point type tests. These tests can estimate shallow velocities, but are usually not very valuable in obtaining information from more than a few tens of centimetres within the ground.

Any data derived from field velocity tests must be applied only to GPR reflection data that was acquired at about the same time. Ground conditions can change dramatically with moisture changes and subsurface radar velocity will vary accordingly.

Velocity tests should be performed as a matter of course during archaeological GPR surveys. For the most part, they are not difficult or time consuming and can yield valuable information that is necessary in order to process GPR data. The GPR reflection profiles that show depth to important features or stratigraphic layers are accurate only if accurate velocity-to-depth conversions are applied during data processing. Velocity information can also be very useful in constructing two-dimensional synthetic computer models (Goodman, 1994; Powers, 1995), in mapping archaeologically important stratigraphic horizons (Conyers, 1995), and in more advanced processing of GPR data such as migration (Grasmueck, 1994).

Acknowledgements

Many thanks go to Payson Sheets at the University of Colorado for his continued interest and enthusiasm in the use of remote sensing projects at the Ceren Site. Equipment was loaned to the project by the US Geological Survey in Denver, Colorado and Geophysical Survey Systems, Inc. of North Salem, New Hampshire. Thanks also go to Gary Olhoeft and Mike Powers of Colorado School of Mines for help and advice.

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