

Geophysical Exploration at Cerén

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Introduction

Since 1979 a wide variety of geophysical instruments have been employed at the Cerén site in El Salvador in order to search for and map the Classic Period landscape and the architectural features built on it. This ancient landscape is presently buried by as much as 6 m of volcanic ejecta. The instruments utilized in this effort were ground-penetrating radar (GPR), electrical resistivity, electromagnetic induction, and seismic refraction. Magnetometers were also tried at a nearby site. The variable results obtained in these geophysical surveys are instructive for further work at Cerén and as a guide for future work at similarly buried sites around the world.

Results of these geophysical surveys determined that some methods were more effective in the rainy season when the ground was saturated and others after a prolonged dry season when the ground was quite dry. Some of the techniques attempted proved to be ineffective in any conditions. Ground-penetrating radar has emerged as the most successful method at Cerén due to its three-dimensional imaging capabilities and excellent resolution of features buried up to 5 m. Electrical resistivity was successful in finding large buried structures as anomalies quickly and efficiently, but this method lacked the depth resolution of GPR.

Both the GPR and resistivity techniques rely on electrical and magnetic contrasts that exist in the subsurface between the matrix (the volcanic overburden) and the stratigraphic horizons or archaeological features of interest. These contrasts are

caused primarily by changes in water content, which is a function of their permeability (the ease of water penetration) and porosity (the amount of water they can hold). Other differences, such as clay content and mineralogical differences that exist between features of interest and the surrounding material, may also play a role.

The GPR method measures the reflection of radar waves from buried interfaces of interest. The greater the water saturation of a unit, the more energy is reflected and the higher the amplitude of the resulting reflected waves. It was found that the highest amplitude reflections at Cerén occurred between the *tierra blanca joven* (TBJ); the Classic Period living surface) and the overlying tephra. Other high-amplitude reflections occurred from the floors and walls of buried house platforms, which were made of clay. The GPR method was most successful toward the end of the dry season when the ground was dry, allowing maximum radar energy penetration. Reflection of radar energy occurred from interfaces that retained some residual moisture. In contrast, electrical resistivity was most successful during the rainy season when the ground was wet and therefore most conductive. In these conditions, the induced electrical field was most effectively transmitted to the depth necessary to detect archaeological features. Contrasts in electrical resistivity, measured at the surface, proved to be an indication that buried structures might have been located below the surface.

Geophysical Research: Methods, Instruments, and Results

The wide range of geophysical instruments employed at and near the Cerén site during the past two decades provides an instructive case study for effectiveness at deeply buried sites in tropical volcanic terrains. Methods varied greatly in their ease of use, interpretation, and overall effectiveness. The various techniques used are presented below, in order from least to most effective, with greater detail presented for the more effective methods.

MAGNETOMETERS

Magnetometers have not been employed at Cerén, largely because of the poor results obtained in a preliminary study in 1972 at Chalchuapa, El Salvador, an earthen architectural site in a geological setting similar to Cerén. In the Chalchuapa study, Froelich Rainey used both cesium and proton magnetometers that were so affected by the strong magnetic fields produced from underlying lava flows that the less distinct magnetic signatures of overlying cultural features were overwhelmed (personal communication to P. Sheets 1972). It is possible that a paired set of more sensitive magnetometers moved in tandem over the ground surface might yield results that are more sensitive to the archaeological features built above these lava flows. This acquisition technique has not been tried at Cerén, as other geophysical methods have proved more successful.

SEISMIC REFRACTION

Supported by the National Geographic Society, the first geophysical explorations at the Cerén site were conducted in 1979 (Loker 1983; Sheets et al. 1985). Three techniques were employed (GPR, electrical resistivity, and seismic refraction) in a 1-hectare grid southwest of a newly discovered structure in Operation 1 (Fig. 3.1). The seismic instrument employed was an Electro-Technical Labs Recording Interval Timer (Model ER-75A-12). Geophones were spaced 5 m apart along transects, with 20 m from the "shot point" to the closest geophone. Energy was produced by sledgehammer percussion on a metal plate placed on the ground. Refracted wave arrivals were recorded at the geophones, printed on Polaroid film, and visually interpreted. Anomalies were barely discernible as subtle changes in the arrival times between geophones. The resulting data were at best barely able to detect buried structures that were already known to exist.

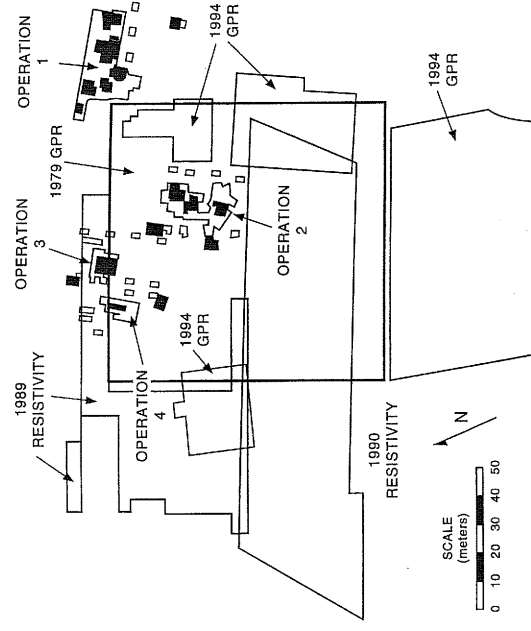


FIGURE 3.1. Base map of geophysical surveys conducted from 1979 to 1994 at the Cerén site. Known structures that are visible on GPR data and have been confirmed by excavations are shown in dark black. Test excavations are indicated within the mapped area.

Because of the equivocal results using linear transects, three other geophone arrays were utilized: broadside, fan, and circular (Loker 1983). These arrays were experimented with over an anomaly (now known as Structure 2 in Operation 2) that had been detected using GPR and resistivity methods. These geophone orientations yielded only a slight indication that some kind of anomaly might be present. It is possible that more sophisticated digital seismic instrumentation, calibrated to site conditions, with more advanced computer processing techniques, might yield better results. The seismic method has not been employed since 1979.

ELECTROMAGNETIC INDUCTION

James Doolittle and Frank Miller (1992) conducted electromagnetic induction studies at Cerén using a Geonics EM34-3 during the summer of 1992. This method induces a primary electromagnetic field into the ground. Depending on the electrical properties of the ground, a secondary field is produced within the sphere of influence of the primary field. The greater the conductivity of the underlying soil and sediment, the more the secondary field is dissipated. Changes in the secondary field are then measured and mapped spatially. Unfortunately, the electromagnetic induction device used by Doolittle and Miller conducted the majority of the energy to depths of 7–15 m, below the cultural horizons of interest. Two of the anomalies discovered were lo-

cated on the slope and summit of a small hill south of the site. Neither was associated with cultural remains. As a result, the anomalies detected probably had little to do with Classic Period features and were more likely detecting deep geological variations. A better choice of instrumentation would have been the EM31, which induces an electromagnetic field to depths of 3–5 m, where the zones of interest are located.

ELECTRICAL RESISTIVITY

Electrical resistivity measurements were taken at the Cerén site in 1979, 1980, 1989, and 1990 (Fig. 3.1), using an ABEM Terrameter SAS 300 in the Wenner electrode configuration. The surveys were conducted with a 5 m spacing between electrodes and 5 m between data points (Loker 1983) throughout presurveyed grids. In total, about 3.2 hectares have been surveyed using this instrument and technique. The most successful surveys were conducted during the rainy season or soon thereafter, when maximum ground moisture allowed for greatest electrical energy penetration. The first resistivity survey, conducted early in June 1979 when the summer rainy season had just begun, yielded poor but marginally usable results. This was probably because insufficient interstitial moisture was present for transmission of the electrical current into the ground. Had this first resistivity survey been conducted a week or two earlier, before any rain had fallen, no useful data would have been gathered and it is possible the method would not have been used further. Fortunately, that was not the case.

The advantages of resistivity over other geophysical methods are its ease of transport, simplicity of the instruments, immediate availability of quantitative data, and the ease of data processing and interpretation. Most importantly, this method successfully detected buried Classic Period buildings under some 5 m of volcanic ash.

Buried structures were detected as M-shaped anomalies in the data, when horizontal distance along a ground surface transect was plotted against the measured resistivity (Fig. 3.2). Many of these anomalies were later confirmed by excavations. The M shape may have been caused by the upward bowing of volcanic ash layers along the edges of buried buildings and the contrast in moisture retention between those ash layers and underlying clay buildings.

In the 1980 resistivity survey, a 1-hectare grid was laid out to the southwest of Operation 1 (Fig. 3.1),

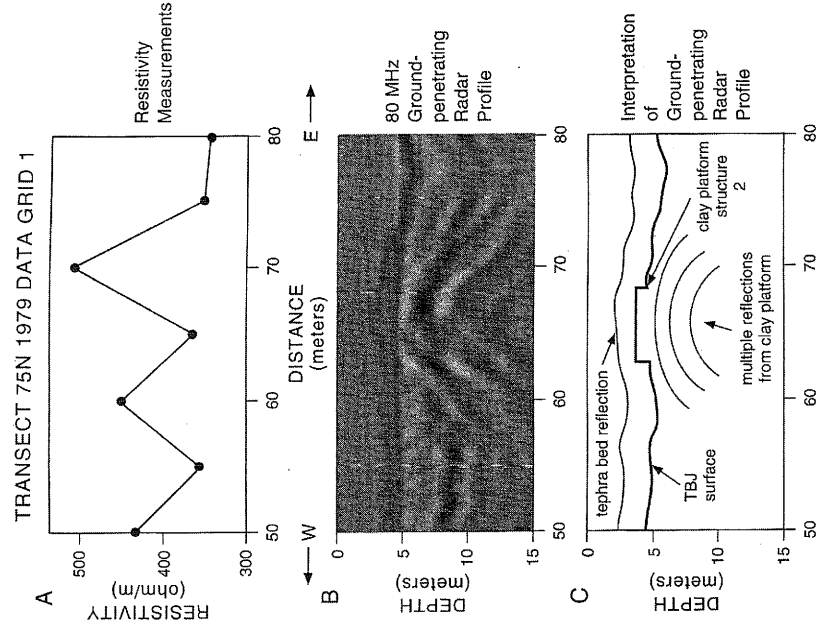


FIGURE 3.2. Resistivity and ground-penetrating radar data over Structure 2. (A) Raw resistivity data [measured in ohm/m] over the structure [data modified from Loker 1983]. A distinctive M-shaped anomaly is visible over the buried structure platform. (B) A reprocessed 80 MHz GPR profile. Data were originally collected in 1979 and digitized in 1994. Range gain and background removal filters were applied after digitization. Vertical white lines are the surface positioning marks. The multiple reflections recorded below the platform were caused by multiple reflections between the ground surface/air interface and the buried clay platform. (C) Interpretation of the subsurface from the GPR reflection data in (B).

and a total of 364 measurements were taken every 5 m along transect lines spaced 5 m apart (Spetzler and Tucker 1989). Within that grid, three strong M-shaped anomalies were detected; two were core-drilled. The cores penetrated clay floors, indicating that the anomalies were clearly cultural. They were later excavated and are now known as Structures 2 and 3, a household and a public building, respectively. That survey was done in January, soon after the end of the rainy season when the ground still retained considerable moisture, allowing good electrical current penetration.

In 1989 approximately 1.8 hectares were surveyed (Fig. 3.1) with the same instrumentation and

configuration within two grids (Spetzler and Tucker 1989). The 1989 work was done in July, well into the rainy season, and the increased soil moisture aided in energy transmission. One area surveyed was to the west of the excavations (Fig. 3.1) and the other approximately 150 meters farther west in an area not shown in Figure 3.1. Three anomalies were detected in the grid closest to the site, with two confirmed as buried clay structures by coring. Another anomaly was also tested, but its origin remains unclear. In addition, a very distinct anomaly was discovered in the grid farthest to the west in Lot 185, atop a hill. It has a distinctive M shape that has all the characteristics of the anomalies produced over Structures 2 and 3, and it was likely produced by a large Classic Period structure. This possible structure has not yet been confirmed by subsurface testing and is far removed from the remainder of the site.

The 1990 resistivity survey was conducted in a 55 × 90 m rhomboid grid (Fig. 3.1) south of the site (Spetzler and McKee 1990). The work was done in November, at the end of the rainy season when soil moisture was at a maximum. A linear anomalous zone of high-resistivity values was mapped that corresponds to a natural topographic rise, with a zone of low-resistivity values to the southwest. No distinctive M shapes were discovered. Two test pits were excavated in the high-resistivity area, but neither encountered cultural materials. It is likely that the resistivity anomalies in this area were produced by geological phenomena that were not visible in the test excavations.

In summary, resistivity has many advantages over other geophysical methods, including its ease of transport and operation, reasonable speed in covering large areas, ability to immediately interpret the raw data, and, most of all, success in detecting buried structures as anomalies. This method would still be in use at the site had it not been for the success of ground-penetrating radar surveys.

Ground-Penetrating Radar

Ground-penetrating radar has been used to explore for deeply buried archaeological features with increasing success during the last decade. It is the only widely used near-surface geophysical method that is capable of both detecting buried cultural materials and mapping them in three dimensions. Its subsurface resolution can be excellent when the proper equipment is calibrated to known field conditions.

GROUND-PENETRATING RADAR METHODOLOGY

The GPR method involves the transmission of high-frequency electromagnetic radio pulses into the earth and then measures the time elapsed between their transmission, reflection off a subsurface discontinuity, and reception back at a surface antenna (Conyers and Goodman 1997). As the sending and receiving antennas, which are usually attached to each other, are moved along the ground surface in a line, a continuous two-dimensional profile of subsurface reflections is recorded.

The propagation velocity of the radar waves through the earth depends on a number of factors, the most important one being the electrical and magnetic properties of the material through which they pass (Olhoeft 1981). If the velocity of the waves is known, the travel times of recorded reflections can be converted to distance and the two-dimensional profiles can be displayed with an accurate depth scale. Profiles within a grid are then computer-processed, important reflections are correlated, and maps of buried archaeological features and related stratigraphy are constructed.

Ground-penetrating radar waves radiate energy into the ground in a conical shape, with the apex of the cone being at the center of the transmitting surface antenna (Annan and Cosway 1992). The subsurface radiation pattern is therefore always "looking" not only directly below the antenna but in all directions from the apex of the cone.

When the velocity of radar waves traveling in the ground changes abruptly, usually at a subsurface interface, a portion of the energy is reflected back to the surface and recorded at the receiving antenna. Reflections from these interfaces are recorded in time that is measured in nanoseconds, or billionths of a second. Reflection interfaces can occur along natural bedding planes, or the contacts between archaeological structures and the surrounding material. Reflected signals that are received at the surface antenna are then amplified and recorded digitally on a computer hard drive or tape. Their demodulated amplitudes can subsequently be displayed on paper by a graphic recorder, stored on magnetic tape in the audio frequency range, or digitally recorded.

GROUND-PENETRATING RADAR AT CERÉN

Ground-penetrating radar is most successful when high-conductivity targets are embedded within a low-conductivity matrix. The volcanic tephra that

covered the sixth-century AD village has a very low conductivity because it is low in clay and very dry during the late winter and early spring, after many months of no rain. Largely because of a differing ability to retain what moisture is present, the contact of the ancient Classic Period living surface (the TB) horizon or the clay underlying it) with the overlying tephra produces a distinct velocity contrast, making it an excellent reflection surface that produces high-amplitude reflected radar waves. The same is true for the clay structures built on top of this surface.

The earliest use of GPR at Cerén was in 1979, when a SIR-7 subsurface interface radar system with a single 80 MHz frequency antenna was used (Loker 1983; Sheets et al. 1985). The antenna was mounted on the rear of an oxcart, which provided a very consistent speed of movement. The oxcart mounting also provided a consistent 10 cm spacing between the antenna and the ground surface. In the cart were a gas-powered electrical generator, DC converter, graphic recorder, FM tape recorder, and the geophysicist. The work was done in early June in a year with a delayed rainy season, after about 7 months of little or no rain, which facilitated good radar energy penetration because of the low moisture. The data were collected within a 1-hectare grid to the south of Structure 1 along traverses each 100 m long, with each transect spaced 5 m apart (Fig. 3.1). A total of 3,800 m of reflection data were recorded. One anomaly was noted on the paper records that were printed on a graphic recorder during acquisition. It was tested and determined to be ancient architecture, now known as Structure 2 (Fig. 3.2). It was also visible in processed electrical resistivity data. The reflection data from this first GPR survey were stored in analog form on magnetic tape by the U.S. Geological Survey and put in storage until they were digitized in 1993 (Conyers 1995a).

The GPR surveys conducted in 1979 had many disadvantages absent from the other methods that were employed during the early geophysical trials at Cerén. The most obvious was the bulk and weight of the equipment, which had to be shipped to the field in advance by air freight within seven crates. There were also problems with U.S. Customs, which did not want to allow the instrumentation out of the country for fear that the sophisticated electronics would fall into unfriendly hands. Ultimately the project had to engage the U.S. Congress in order to obtain a special waiver of the shipping ban. The fact that the 1979 GPR survey discovered only one anomaly with GPR that proved to be cul-

tural in nature, as well as the relatively greater success of resistivity measurements, almost biased the project against GPR. Only lately, with new digital acquisition and computer processing methods, has GPR produced results superior to the other instruments attempted at Cerén.

In 1979 GPR reflections were printed on paper as they were collected in the field, while simultaneously being recorded as small voltage changes on FM magnetic tape (Loker 1983). The one anomaly that was discovered on the paper copies at the time appeared to represent an arching of tephra, perhaps over a buried structure. This anomaly was tested by core drilling, which led to the discovery of Structure 2. It is now believed that this convex upward reflection was actually a series of reflection multiples generated off the floor of the buried structure (Conyers 1995b). Reflection multiples were created as the radar energy was reflected between the buried clay floor and the ground-air interface a number of times, creating a "ringing" effect in the profile. The clay platform itself is not visible in the 80 MHz frequency reflection data because of the long wavelength of the radar waves and a corresponding lack of resolution.

In August 1992 additional GPR data were acquired to the south of the site (Doolittle and Miller 1992). Due to the high ground moisture when the survey was made (mid-rainy season), radar energy was highly attenuated near the ground surface, and no anomalies or reflections of significance were identified.

The 1979 GPR data, which had been saved on magnetic tape, were digitized and reinterpreted in 1993 (Conyers 1995a). An additional 3,800 m of digital GPR data were also acquired in March 1994 using 300 MHz and 500 MHz antennas and a SIR-10 radar instrument. The total digital GPR database at the site now consists of more than 7,800 m of GPR data in five grids, covering approximately 2 hectares of surface area (Fig. 3.1).

All two-dimensional reflection profiles within the five grids were computer-processed to filter out much of the horizontal banding inherent in GPR data. Range gain control and band-pass filters were routinely employed during the 1994 data acquisition, which further enhanced these data. All of the grids collected in 1994 were surveyed, and topographic corrections were made to the data. The 80 MHz grid acquired in 1979 was not surveyed for surface elevations, and therefore no topographic corrections were possible. Fortunately, in 1979 the ground surface was essentially flat, with only a small rise in the southwest corner of the grid (Loker

1983), and therefore topographic corrections were not essential prior to data interpretation.

TIME-DEPTH ANALYSES

Many methods were employed to determine radar wave velocity, so that two-way GPR travel time could be converted to depth. The most accurate and straightforward method acquired radar data over known objects at known depths (Conyers and Lucius 1996). These tests were conducted just to the east of Operation 2. One test involved detecting a 2.5 cm (diameter) iron bar pounded into the side of a pit exactly 1.1 m below the ground surface. The 500 MHz antennas were then placed at the ground surface and slowly pulled over the metal bar while radar waves were projected into the subsurface. A reflection hyperbola, measured in radar travel time, was visible on the resulting profile, denoting the location of the iron bar. A similar test was performed in a nearby excavation where the southwest corner of Structure 13 had been partially exposed in Operation 2). A 2 m long portion of the structure's wall was measured 2.51 meters below the ground surface, and it was also visible on 300 MHz profiles collected over its buried extension (Conyers and Lucius 1996). In both of these tests, distance and time were directly measured, and therefore velocity could be calculated. The average radar wave velocity from the ground surface to the shallow iron bar was calculated at about 0.17 m/ns and to the deeper wall about 0.13 m/ns.

These analyses arrived at an average velocity for the overburden material while also demonstrating that radar wave velocity decreased with depth, probably due to a small increase in interstitial moisture. Overall, the estimated velocities through the tephra layers were quite high, comparable to that of dry sand, which has an average velocity of about 0.15 m/ns (Davis and Annan 1989).

Less direct velocity measurements were also made at the site in order to verify those made on the bar and the wall. These included transillumination and common midpoint tests, where radar waves are sent from one antenna to another, separated at known distances by the material to be measured (Conyers and Lucius 1996). Their results confirmed the direct velocity measurements obtained in bar and wall tests. An average velocity for the Cerén Sequence tephra was then used to convert all radar travel time to depth during profile processing.

To correlate radar reflections visible in GPR profiles to the known volcanic stratigraphy, two GPR profiles were acquired that ended at the edges of

test pits (Conyers 1995). Both 300 and 500 MHz profiles were acquired between these excavations. In this way the stratigraphy in the test pits could be directly correlated to the radar reflections visible in profiles. Using the average velocity determined from the time-depth tests, it was determined that the highest amplitude and most continuous reflector was generated at the contact between the buried sixth-century AD living surface (the TBJ horizon) and the overlying tephra. At this contact there was a noticeable change in moisture content as well as lithology, which likely generated this distinguishable reflection.

The TBJ reflection was correlated from profile to profile within the GPR grids and its depth was mapped. A paleotopographic map of the sixth-century AD living surface was constructed from more than 3,130 subsurface measurements (Fig. 3.3).

MAPPING BURIED STRUCTURES, THE ANCIENT LANDSCAPE, AND OTHER ANTHROPOGENIC FEATURES

Once the topography of the ancient TBJ living surface had been mapped, the location of the structures built on it and other cultural features were delineated. Identifying nonhorizontal or nonplanar features, such as standing walls or columns, in GPR data can be difficult due to the complex ray paths that transmitted and reflected radar energy can take in the subsurface. This is due in part to the conical-shaped transmission beam that creates multiple reflections from the same buried features as the surface antenna is moved across the ground. For this reason, a buried structure does not look like one would imagine in two-dimensional reflection profiles but appears more like a "distorted pseudo-section" (Olhoeft 1994).

Synthetic radargram modeling was developed in an attempt to model what buried objects and complex reflection surfaces "should" look like in a two-dimensional profile (Goodman 1994). Computer-simulated models trace the paths of radar waves during transmission and reflection through various modeled media that have defined dimensions and electrical properties. The computer models take into account the reflectivity that is likely to occur at various interfaces, signal attenuation with depth, and other electrical properties of units. Large numbers of potential radar wave paths are simulated on the computer, and reflections that would likely occur in the real world are recorded just as they would be in the field. The amplitudes of the predicted reflections are also predicted by the com-

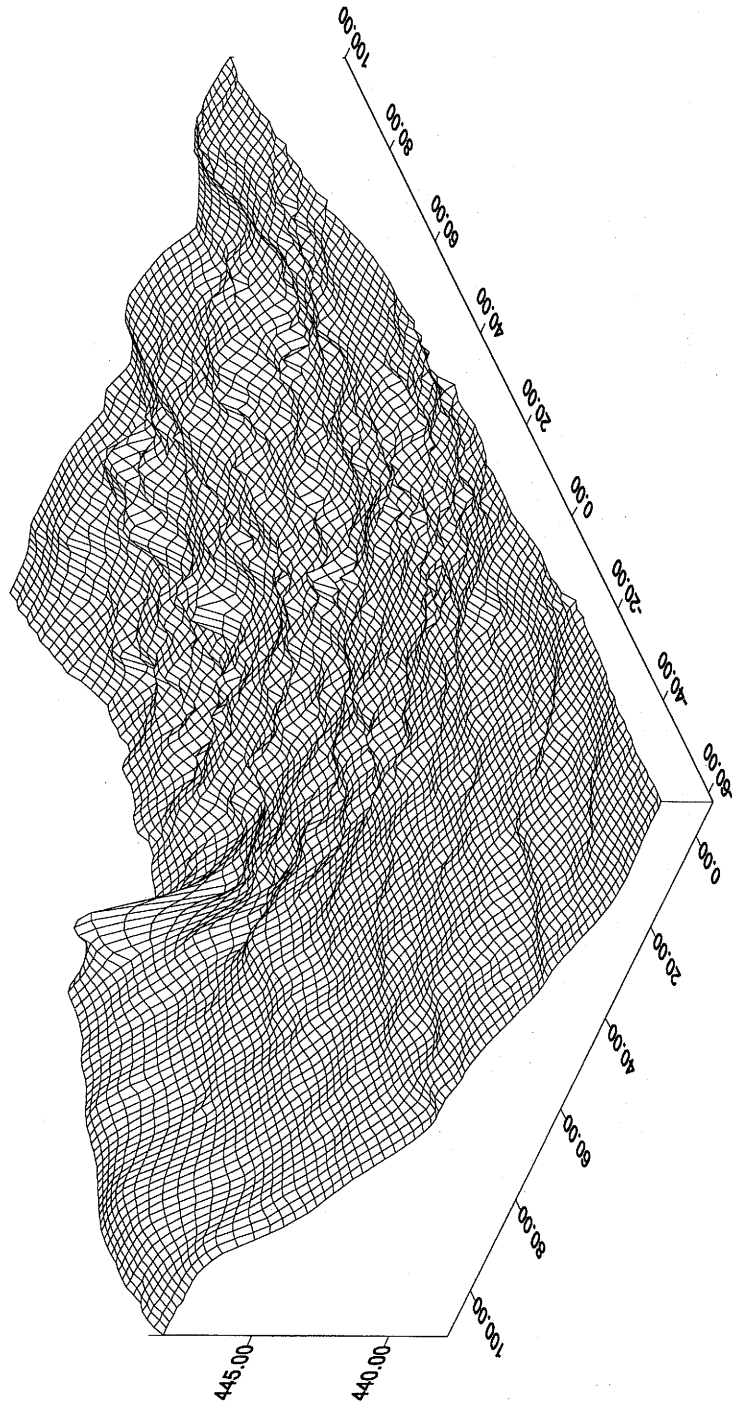


FIGURE 3.3. Three-dimensional map of the buried Classic Period living surface. The view is to the northwest at 35° from the horizon. The buried topography is exaggerated

three times. Small bumps along the north edge of the central valley are buried structures.

The resulting two-dimensional models are extremely valuable because they can be compared to actual field data in order to provide a model for what to look for and also as support for the resulting interpretations.

A number of synthetic computer models were created in order to model an area around representative buried structures (Conyers 1995b). In these models, velocities and electrical properties of the various overburden units that were obtained in the field were employed. One of the models replicated a buried structure with a raised platform and standing walls and columns. The structure was a representation of Structure 2, which is visible on three of the 80 MHz GPR profiles in Grid 1. When 300 MHz radar energy was simulated, a strong reflection was generated at the contact between the TBJ living surface and the overlying tephra. A high-amplitude point-source reflection hyperbola was also generated from the floor of the structure. The resulting hyperbolic floor reflection obscures the reflection derived from the TBJ living surface near the edge of the structure. Additional hyperbolic reflections were generated from the tops and sides of the walls and columns. A remarkable similarity was seen to exist between what the models predicted and what

was visible in many GPR sections, adding confidence to the interpretations below.

Hyperbolic reflections visible in GPR profiles, which the synthetic models indicated may denote buried structures, were recorded during profile interpretation. As demonstrated in the synthetic models, reflections of this sort can be derived from the tops and sides of structural platforms, as well as from the tops of walls and columns. Reflections generated from house platforms (especially multiple reflections, as in Fig. 3.2) are very distinct on 80 MHz profiles, while those from the top of standing walls or columns are so subtle they are almost invisible, due to the lack of resolution in these low-frequency data. The 300 MHz profiles, with their good subsurface resolution, recorded many subtle changes in topography at the TBJ horizon not visible in 80 MHz data. These profiles displayed some buried structure platforms that are raised as little as 20 cm above the TBJ living surface. Standing walls and other large features are also visible.

The correlation between the location of hyperbolic point-source reflections and multiple reflections and the buried structures known from excavation is excellent. Of the nine excavated or partially excavated structures located within the GPR grids,

eight can be readily identified by point-source reflections and a visible rise in the buried living surface near their foundations. In addition, eighteen probable structures were identifiable in GPR profiles that have not yet been confirmed by drilling or excavation (Conyers 1995a).

The most striking feature of the buried TBJ surface is the variation in topography across the site and the intricacy of the buried Classic Period drainage pattern (Fig. 3.3). The landscape prior to the eruption consisted of a small, elongated valley, located in the west-central portion of the GPR grids, surrounded by low bluffs to the north and east. A gradual southern slope rose out of the valley to the southwest, ultimately forming a large hill. Buried structures are located primarily on the northern and southern flanks of the central valley. Within the central valley were located a complex series of drainage channels, geographically restricted topographic rises, and small closed depressions. Drainage channels within the valley had a maximum depth of about 1.5 m and gently sloping banks. Numerous small closed depressions and mounds within some of these channels may have been created by clay-quarrying operations.

The GPR-produced map of the site illustrates the preference of the Cerén inhabitants for building their structures on the north flank of the valley. This area was the location of numerous other use areas, including gardens, orchards, and small maize fields that have been exposed in excavations (Sheets 1992a).

A wide flat plaza, located on the crest of the bluff along the north edge of the valley, was quite distinctive in GPR profiles as a continuous high-amplitude reflection. It is surrounded on the east, south, and west by structures that evidently had a civic function (Sheets 1992a). The northern edge of the plaza is not known, because it was destroyed during the 1976 bulldozing operations.

Three household clusters and numerous scattered houses are visible on GPR profiles within the northern portion of the radar grids. The structure density in this relatively small area indicates that the population density at Cerén may have been quite high at the time of the eruption. The presence of the plaza and its associated communal buildings, as well as the religious structures, just to the east of the GPR grids (Sheets 1992a), is evidence for the presence of many more people than conceivably could have lived in the households so far identified in excavations and the GPR surveys.

Other buildings that were likely part of the village but have yet to be discovered are probably

located to the northwest and west of the known extent of the site. Additional GPR surveys were conducted in March 1997 in these areas, but the data have not yet been completely interpreted. Preliminary interpretation has discovered at least two buried structures to the northwest of the site.

Conclusions

Electrical resistivity and ground-penetrating radar proved to be the most effective geophysical techniques for exploration at Cerén. Electrical resistivity measurements were the fastest way to locate large buried clay structures. The data were immediately available for processing and their interpretation was fairly straightforward. The equipment can be transported more easily and contour maps and resistivity profiles can be easily produced manually or on simple computer programs. More sophisticated processing can also be undertaken after returning from the field, although this was not done with the Cerén data.

One of the limitations of resistivity is its inability to determine the exact depth of anomalies. Only the most prominent buried structures were located by this method. Medium and small structures and details about the buried Classic Period living surface were undetectable. The method was also usable only during or immediately after the rainy season, when ground moisture was at a maximum.

In contrast, GPR was most successful toward the end of the dry season, after the volcanic tephra had dried out. Ground-penetrating radar equipment was more difficult to transport to and from the field than that needed for resistivity surveys. The resulting data also needed more sophisticated data processing and interpretation techniques. Even the modern digital systems, which are much smaller than the system taken to Cerén in 1979, must be packed in a number of shipping containers. Fairly powerful computers and sophisticated software are also needed to process the data. As a result, little data were available for interpretation in the field, a detriment when immediate results are a necessity. These problems are being quickly overcome with powerful portable computers and the miniaturization of GPR equipment.

The benefits of GPR far outweighed the difficulties encountered. Ground-penetrating radar detected both large and subtle buried features and measured their depth below the surface. Sophisticated digital data-processing techniques were able to filter out much of the "noise" that was collected

along with the useful reflection data, making hard-to-see features visible. Velocity tests allowed reflection times to be converted to approximate depth, creating a three-dimensional picture of the site. Computer modeling of known archaeological features also greatly aided interpretation. This "visualization" method allowed previously unrecognized anomalies to be recognized in two-dimensional profiles.

The three-dimensional interpretation techniques for GPR data allowed the ancient living surface reflector to be identified and its depth measured. The paleotopographic maps produced from these elevations illustrate the complex nature of the buried Classic Period living surface. The abundance of channels and ridges that existed on this surface between household clusters was startling to many of us who had expected subtle topographic variations. Only after GPR mapping could the archaeological richness derived from excavations be integrated into its ancient landscape.

Geophysical research demonstrates that the an-

cient village of Cerén was constructed around a small valley located between bluffs. Buildings were constructed on the highest topographic areas, and the valley bottom was likely the location of agricultural activity and clay quarrying. No excavations have yet been conducted in this valley or to the south, and therefore specific activities that might have been conducted in these areas must remain speculative.

The southern boundary of the village was discovered by GPR, along the southern margin of the 1979 GPR grid (Fig. 3.1). Land devoted to agriculture was likely located south of this area, although this has not yet been confirmed by excavation and cannot be discerned in GPR profiles. An additional eighteen structures are suggested from geophysical mapping within an area of a little less than a hectare. The buildings located by archaeological excavation and GPR are probably only a small percentage of the total that still remain undetected to the northwest and west of the present site.