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Introduction to Ground-Penetrating Radar

Ground-penetrating radar has a reputation as one of the more complex archaeological geophysical methods because it involves the collection of large amounts of reflection data from numerous transects within grids, often producing massive three-dimensional databases. The ability to detect many interfaces at different depths below the surface, the interpretation of those numerous reflections, and the difficulty in correlating them in many profiles within a grid therefore make GPR collection and processing a somewhat intimidating venture at first for the uninitiated. But its ability to produce high-quality three-dimensional images of the subsurface more than makes up for the method's relative complexity in data acquisition and processing.

Ground-penetrating radar data are usually collected along closely spaced transects within a grid, each of which consists of many thousands of radar waves that have been reflected from interfaces in the ground. It is an active method that transmits electromagnetic pulses from surface antennas into the ground, and then measures the time elapsed between when the pulses are sent and when they are received back at the surface. Radar travel times are measured in nanoseconds, which are billionths of a second. As the antennas are moved along the ground surface, individual reflections are recorded about every 2 to 10 centimeters along transects, using a variety of collection techniques. The form of the individual reflected waves (called a *waveform*) that are received from within the ground is then digitized into a refection *trace*, which is a series of waves reflected back to one surface location. When many traces are stacked next to each other sequentially, a two-dimensional vertical profile is produced along the transect that the antenna was moved (figure 2.1). Thousands of reflection traces in many profiles within a grid can then be analyzed to produce both two- and three-dimensional images of what lies below the surface.

Each of the reflected radar waves processed into profiles is recorded in elapsed time from their transmission to reception back at the surface (called *two-way travel time*). This time can be converted to approximate distance in the ground, giving each of the reflections precise depth information not available in other near-surface geophysical methods. The amplitudes of the reflected waves are particularly important because their variations are directly related to changes in the physical and chemical properties of different materials in the ground. When those amplitude differences are mapped spatially and with depth, accurate three-dimensional maps and images of buried archaeological features can be constructed.

Ground-penetrating radar surveys allow for a relatively wide aerial coverage in a short period of time, with excellent spatial resolution of buried archaeological features and their related stratigraphy. Often 50-by-50–meter grids of reflection

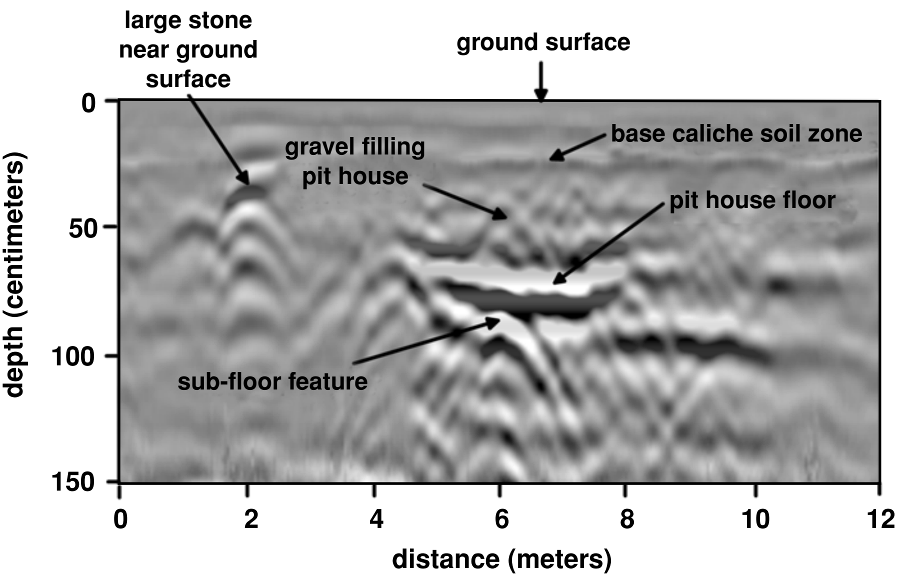

FIGURE 2.1
A GPR Reflection Profile. Distance along the profile is measured in meters, and two-way radar travel time, measured in nanoseconds, is converted to depth below the surface. This profile consists of 305 individual, sequentially stacked reflection traces. This profile was collected over a pit house floor near Alamagordo, New Mexico.

data can be collected in one day, with a 50-centimeter or less transect separation. Some radar systems have been able to resolve stratigraphy and other features at depths in excess of 40 meters, when soil and sediment conditions are suitable (Annan and Chua 1992; Bristow and Jol 2003; Davis and Annan 1992), but more typically, GPR is used to map features of archaeological interest at depths from a few tens of centimeters to 5 meters in depth. Radar surveys not only can identify buried features for possible future excavation but can also interpolate between excavations, projecting archaeological knowledge into areas that have not yet been or may never be excavated.

Ground-penetrating radar data are acquired by reflecting radar waves off subsurface features in a way that is similar to radar methods used to detect airplanes in the sky except energy is transmitted into the ground. Most GPR systems produce pulses from a surface antenna that are reflected off buried objects, features, or bedding contacts in the ground and detected back at the source by a receiving antenna that is located next to, or near, the transmitting antenna. As the radar pulses are transmitted through various materials on their way to the buried target features, their velocity will change, depending on the physical and chemical properties of the material through which they are traveling. When the travel times of the energy pulses are measured, and their velocity through the ground is known, distance (or depth in the ground) can be accurately measured.

Ground-penetrating radar units have recently become very portable, and complete systems can potentially be transported in one's backpack into remote areas (figure 2.2). Most systems are powered from any high-amperage battery such as a 12-volt car battery or with portable electrical generators or directly from 110- or 220-volt alternating currents. Some recently developed GPR units can power all of the radar equipment and computers necessary for data acquisition and field processing for many hours on a few small rechargeable batteries.

Some of the earliest model GPR systems recorded raw subsurface reflection data on paper printouts that precluded postacquisition processing. Although these radar systems, a few of which are still in use, can many times yield valuable subsurface information, the modern digital systems that record reflection data on a computer hard drive for later filtering, processing, and sophisticated data analysis are far superior. Most important, when the recorded data are in digital form, a computer can process, filter, and enhance the raw field reflections almost immediately after they are collected.

Accompanied by a trend in equipment miniaturization, rapid computer processing of acquired GPR data can now occur immediately after they are acquired,

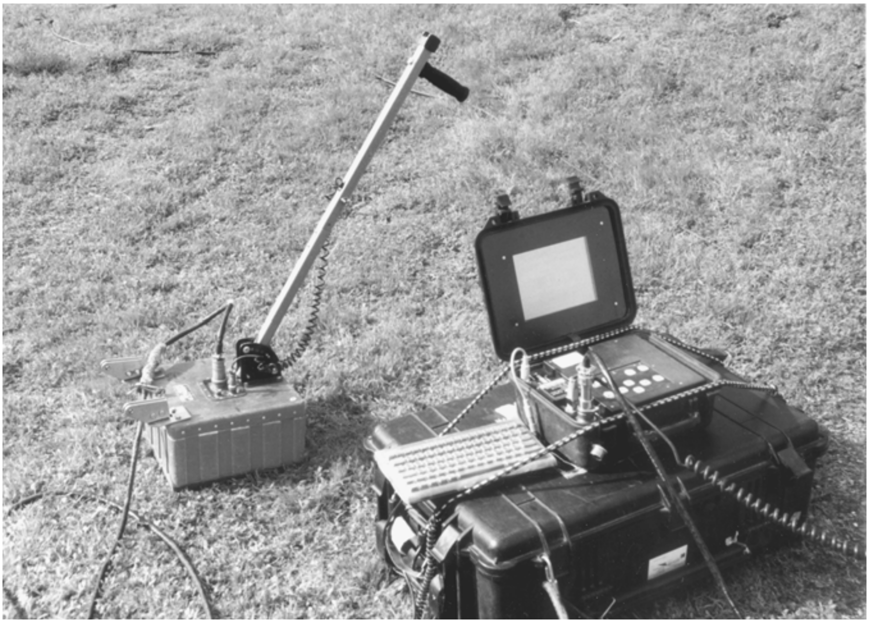

FIGURE 2.2
GPR Equipment. A GSSI subsurface interface radar (SIR) system with a 400-MHz antenna, using the packing case as a field table.

and interpretation can often begin while still in the field, allowing archaeologists to produce three-dimensional images of buried features just minutes or hours after data are acquired. When this is done, additional GPR data acquisition or the planning of excavations to confirm discovered features of interest can also begin almost immediately, making geophysical data collection, interpretation, and excavation an often iterative process.

The success of GPR surveys in archaeology 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 all geographic or archaeological settings, although with thoughtful modifications in acquisition and data processing methodology, GPR can be adapted to a great variety of site conditions. In the past, it was assumed that GPR surveys would only be successful in areas where soils and underlying sediment are extremely dry and therefore nonconductive (Vickers and Dolphin 1975). Although radar wave penetration, and the ability to reflect energy back to the surface, is often enhanced in dry ground, good GPR data have been collected in areas that are wet and contain an abundance of clay (Conyers 2004). Conditions such as this had always been avoided in the past as they were considered poor GPR areas, but this is not always the case, as will be detailed in some of the examples in this book. In contrast, poor GPR data have been collected in very dry and sandy areas, which are usually considered good GPR areas, suggesting that many more factors affect radar transmission and reflection than have been documented in the geophysical literature.

Prior to conducting a GPR survey, it is important to take into consideration what types of equipment to use, the field collection methods that will be employed, and numerous data acquisition parameters. These factors will vary considerably depending on the geographic and geologic setting of the surveys, surface obstacles, ground conditions, and the depth of the archaeological features and stratigraphy to be studied. Many archaeological geophysical surveys are conducted precisely because little is known about what lies below the ground. When this is the case, it is difficult to take all these variables into consideration, especially the nature of soils and sediments and the depth and types of archaeological materials that might be encountered. Acquisition parameters and equipment must therefore often be adjusted and modified while in the field, once some preliminary data are collected and analyzed. When this is the case, preliminary calibrations that are necessary in order for optimal data acquisition can often be a somewhat nerve-wracking experience, especially if bystanders are looking on expecting immediate results and asking the most common and annoying question: "Have you found anything yet?" When this occurs, all one can do is politely explain that a great deal of thought must go into preliminary analysis of field conditions before any results are available, and then get back to work. As will be discussed later, a good deal of deliberation must be given to what will be the optimum GPR data collection procedures for each study area before the first useful reflection profile is collected and stored on the computer storage medium.

Once GPR data have been acquired in the field and recorded digitally on a computer, a wide variety of data-processing and interpretation techniques are available. Depending on the archaeological questions to be asked and the quality of the radar reflection data acquired, these processing techniques can also be varied and modified to fulfill specific needs. To be able to fully understand and interpret GPR reflection data, the user must first understand the basic theoretical aspects of the electromagnetic energy propagation as well as GPR collection methods. Only then will postacquisition data-processing techniques and interpretation of the final product become meaningful.

Some of the very detailed and complicated aspects of the GPR method, which are not immediately applicable to general archaeological investigations—such as complex electromagnetic theory, equations used in data processing, and details about the schematic components of the equipment—are held to a bare minimum in this book. For the average archaeological user, these somewhat esoteric subjects can be addressed by a radar technician or electrical engineer, or studied in greater detail from the cited references. This book includes only aspects of those subjects that are most important for collecting, processing, and interpreting most GPR databases for most archaeological applications.

Ground-penetrating radar acquisition is becoming simpler and data processing more intuitive for most archaeologists. Even so, as recently as the mid-1990s, some supposedly technically sophisticated archaeologists have complained that GPR data are too complicated, expensive, and difficult to process for the archaeological community (Meats 1996). Many archaeologists, especially in Europe, still prefer magnetic and resistivity methods, because they have a longer history of success there and data from those surveys are usually less complicated to acquire and process. In the last few years, however, GPR has moved into the archaeological mainstream worldwide and is no longer a method reserved only for geophysicists with "black boxes" who perform some kind of "magic" in the field. Most archaeologists trained today have more than enough scientific background and computer skills to allow them to understand and use this high definition three-dimensional method. All it usually takes is some field experience, the background that will allow prudent acquisition procedures, a determination to try it out, and the patience to process and interpret data once they are acquired.

HISTORY OF GPR IN ARCHAEOLOGY

The first large-scale application of radar was during World War II when the British and later Americans used crude but effective systems to detect airplanes. The word *radar* is actually an acronym that was first coined in the 1930s for *ra*dio *d*etection *a*nd *r*anging (Buderi 1996). The first attempt at what could be called ground-penetrating radar was made in Austria in the 1920s to determine the thickness of ice in a glacier (Stern 1929). The ground-penetrating aspects of radar technology were then largely forgotten until the late 1950s when U.S. Air Force radar technicians on board airplanes noticed that their radar pulses were penetrating the glacial ice when flying over Greenland. A number of mishaps occurred because airborne radar analysts were detecting the bedrock surface below the ice and interpreted it as the ground surface, neglecting to see the large thickness of ice above and leading planes to crash into the glaciers. This realization that radar would readily penetrate ice ultimately led to numerous investigations into the ability of radar to detect a number of subsurface interfaces, including soil properties and the groundwater table. In 1967, a prototype GPR system was built by the National Aeronautics and Space Administration (NASA) and sent on a mission to the moon in an attempt to determine surface conditions prior to landing a manned vehicle (Simmons et al. 1972).

The applicability of GPR to locate buried objects or cavities such as pipes, tunnels, and mine shafts (Fullagar and Livleybrooks 1994) was immediately recognized in the 1970s, and its widespread use as a geotechnical tool began. Methods were soon developed to define lithologic contacts (Baker 1991; Basson et al. 1994; Bristow and Jol 2003; Jol and Smith 1992; van Heteren et al. 1994), faults (Deng et al. 1994), and bedding planes and joint systems in rocks (Bjelm 1980; Cook 1973, 1975; Dolphin et al. 1974; Moffatt and Puskar 1976). Soil scientists and hydrologists also began using GPR to investigate buried and surface soil units (Collins 1992; Doolittle 1982; Doolittle and Asmussen 1992; Doolittle and Collins 1995; Freeland et al. 1998; Johnson et al. 1980; Olson and Doolittle 1985; Shih and Doolittle 1984) and the depth and nature of the groundwater table (Beres and Haeni 1991; Doolittle and Asmussen 1992; van Overmeeren 1994; 1998). More recent work has shown the utility of GPR for mapping specific packets of sediment for the definition of ancient depositional environments (Bridge et al. 1995; Bristow et al. 1996; Jol et al. 1996; McGeary et al. 1998; van Overmeeren 1998). The applicability of using GPR techniques for locating unexploded ordinance and land mines has also been studied, with great promise (Bruschini et al. 1998; Daniels 2004). Civil and structural engineers have used GPR to map road pavement structures and have applied those data to the inspection of the interior of many different media (Hugenschmidt et al. 1998). Forensic scientists and law enforcement agencies' desire to find buried bodies or other materials has expanded the use of GPR in a number of instances, locating graves and sometimes actual human remains of murder victims or other bodies in the ground (Davenport 2001a, 2001b; Davis et al. 2000; Ivashov et al. 1998; Nobes 1999; Strongman 1992).

The archaeological community was quick to grasp the potential of using GPR to locate and help define buried archaeological features and associated sediment and soil layers. One of the first applications to archaeology was conducted at Chaco Canyon, New Mexico (Vickers et al. 1976), in an attempt to locate buried walls at depths of up to 1 meter. A number of experimental antenna traverses were made at four different sites and paper reflection profiles were analyzed in the field. It was determined that a few of the anomalous radar reflections represented the location of buried walls.

These rudimentary studies at Chaco Canyon were followed by a number of GPR applications in historical archaeology. Radar surveys were successfully used in the search for buried barn walls, stone walls, and underground storage cellars (Bevan and Kenyon 1975; Kenyon 1977). In these early studies what were described as "radar echoes" were recognized as being generated from the tops of buried walls, and depth estimates were made, using approximate velocity measurements for local soil characteristics.

Initial successes in historical archaeological applications were followed in the late 1970s at the Hala Sultan Tekke site in Cyprus (Fischer et al. 1980) and the Ceren site in El Salvador (Sheets et al. 1985). Both of these GPR surveys produced unprocessed reflection profiles in the form of paper records that were successful in delineating deeply buried walls, house platforms, and other buried archaeological features. These initial successes were primarily a function of very dry electrically resistive matrix material that was relatively "transparent" to radar energy propagation, allowing for deep energy penetration and producing relatively uncomplicated reflection records from buried archaeological features that were easy to interpret.

During 1982 and 1983, GPR surveys were conducted at a historic site in Red Bay, Labrador, in an attempt to locate graves, buried artifacts, and house walls associated with a sixteenth-century Basque whaling village (Vaughan 1986). This area was an extremely challenging test for archaeological GPR mapping because the soils were wet, and the overburden contained large cobbles and complicated stratigraphy that produced a variety of difficult to interpret reflection records. Nonetheless, artifacts and archaeological features that were buried by up to 2 meters of beach deposits and peat were discovered in many of the GPR profiles, which were later excavated and confirmed. This study is notable because velocity tests were performed and radar travel times to potential archaeological targets were corrected to approximate depths in the ground prior to being uncovered. It was determined that grave goods, consisting of bone, did not contrast enough with the surrounding beach deposits to appear as distinct reflections, but disturbed soil in some graves appeared as anomalous reflection zones on some radar profiles. Other significant reflections were found to have been generated from buried walls that consisted of piles of beach cobbles used for walls and foundations, but they were difficult to discriminate from other random rocks.

A comprehensive series of GPR surveys were conducted in Japan in the mid-1980s in order to locate buried sixth-century houses, burial mounds, and what were termed "cultural layers" (Imai et al. 1987). These studies were successful in identifying ancient pit dwellings with clay floors, which were buried in some cases by as much as 2 meters of volcanic pumice and loamy soil. The interface of the house floors with the overlying pumice produced very distinctive reflections that were readily recognizable on GPR profiles. Much of the site discovered by GPR mapping was then excavated to confirm the results. Three distinct stratigraphic horizons (their cultural layers) were found to be buried soil horizons containing many stone artifacts that were discarded during different periods of occupation. This important conclusion allowed for the mapping of these distinct soils and the associated archaeological features on and buried within them throughout portions of the site that had not been excavated.

Throughout the late 1980s and early 1990s, GPR continued to be used successfully in a number of archaeological contexts, but in most cases, these studies were what could be called “anomaly-hunting” exercises. Usually unprocessed or partially processed GPR profiles were viewed as paper records, or on a computer screen as they were acquired, and interesting reflections, which could possibly have archaeological meaning, were excavated. Unfortunately, the inability to discriminate archaeological from geological reflections in these studies often left archaeologists with the impression that GPR was a “hit-or-miss” method at best.

Prior to 1993, the most encompassing and successful archaeological application of GPR was that employed in the mapping of the houses and burial mounds in Japan, already discussed (Imai et al. 1987). These successes were followed up by numerous additional GPR surveys in Japan, conducted by Dean Goodman and his colleagues (Goodman and Nishimura 1993; Goodman 1994, 1996; Goodman et al. 1995; Goodman et al. 1998). Great strides were made in these studies that benefited from advances in computer processing speed and the development of software programs written by Goodman specifically for archaeological GPR data processing.

In the early 1990s, GPR manufacturers began to market systems that could collect reflection data as digital files, storing large amounts of data for later processing and analysis. About this same time, inexpensive and increasingly powerful personal computers were also becoming available that could process these digital data in ways that were not previously possible, at least on the typically low archaeological budgets. The pioneering studies of Goodman and his collaborators led to many important GPR acquisition and data-processing techniques, including amplitude slice maps, computer-simulated two-dimensional models, and three-dimensional reconstructions of buried features (Conyers and Goodman 1997; Goodman 1996; Goodman et al. 1998). The Japanese GPR studies discovered and mapped a wide variety of buried archaeological sites, including ceramic kilns, burial mounds surrounded by moats, and individual stone-lined burials (Goodman et al. 1995). In this work, a wide range of burial conditions were encountered, which were computer modeled prior to data acquisition in order to determine the best equipment to use and the setup configurations that would likely work best.

The realization that radar reflections, measured in time, could be defined in real depth when radar wave velocity was determined was one of the major GPR advancements for archaeology (Vaughan 1986; Imai et al. 1987). The identification of reflections that correspond to horizons of archaeological interest was also used in a limited way to map related stratigraphy and buried topography (Imai et al. 1987; Conyers 1995; Conyers and Spetzler 2002). Recently, the application of two-dimensional computer simulation and three-dimensional processing techniques (Conyers et al. 2002; Goodman et al. 1995, 1998, 2004) has shown that even radar data that does not yield immediately visible reflections can still contain valuable reflection data when computer processed. The use of these and other new processing and imaging techniques has recently greatly expanded the utility and speed of GPR exploration and mapping in archaeology.

Many archaeologists who employ GPR at their sites are mainly concerned only with identifying buried anomalies that represent features of interest (see, e.g., Butler et al. 1994; Sternberg and McGill 1995; Tyson 1994; Valdes and Kaplan 2000). Although this type of GPR application is valuable, in that buried features can be immediate identified, this book will illustrate how the radar reflection data acquired in these types of studies can be further enhanced by a number of computer processing, interpretation, and display techniques. With little additional effort, recently developed computer technology allows for the construction of maps that can be interpreted in ways that will yield much more information about a site than was thought possible just a few years ago.

In the future, GPR's ability not only to noninvasively map buried structures and other cultural features in real depth, but also to reconstruct the ancient landscape of a site and human interaction with it, will become increasingly important. Computer filtering and enhancement of GPR reflection data is also becoming widespread as researchers increase their familiarity with some of the computer-processing techniques discussed in this book and many others that are presently available. Recent research has demonstrated and quantitatively accessed the differences in data quality that varies with antenna frequencies, the spacing of transects and the density of reflections along transects, and the types of data analyses used to display the final product (Neubauer et al. 2002).

The ability of GPR to collect data in a three-dimensional block has recently led some researchers to begin analyzing the reflected wave amplitudes in complex and exciting ways (Conyers et al. 2002; Goodman et al. 1998, 2004; Moran et al. 1998; Leckebusch and Peikert 2001; Leckebusch 2003). If the higher amplitudes can be shown to denote the location of important buried archaeological features, then their locations in three dimensions can be visualized using a number of imaging software programs. In this way, the lower-amplitude reflections are effectively removed from the data set, leaving only those of importance, which can be visualized three-dimensionally. The location of certain radar amplitudes in space, which are proxies for the actual location of features in the ground, are then rendered to produce "virtual reality" images of what lies below the surface. This has been done by cutting through the block (Neubauer et al. 2002) or rendering out only the higher amplitudes and presenting the final product in three-dimensional, rotating images or videos (Conyers et al. 2002; Goodman 1998; Goodman et al. 2004; Heinz and Aigner 2003; Leckebusch and Peikert, 2001; Piro et al. 2003).

One area of study that has been given much recent attention is the integration of multiple data sets collected from different geophysical methods. This integration has been accomplished by fairly simple mathematical correlation (Savvaidis et al. 1999), numerical comparison (Piro et al. 2000) of GPR amplitudes in slice maps with other geophysical maps, the use of statistical modeling (Marukawa and Kamei 1999), and within geographic information systems programs (Kvamme 2003). Experiments have also been progressing in which multiple antennas are used to collect reflections simultaneously to enhance three-dimensional subsurface resolution (Pipan et al. 1996).