1 Introduction to Ground-penetrating Radar in Geoarchaeology Studies

Abstract: Geology and archaeology have long been integrated as a way to understand site formation processes, place artifacts within an environmental context, and as a way to study ancient people within the landscapes where they worked and lived. An analysis of sedimentary environments has long been necessary in this endeavor, but is often constrained by a lack of excavations, exposures, and other data to study areas in a three-dimensional way. Ground-penetrating radar (GPR) has unique three-dimensional abilities to place ancient people into an environmental context by integrating both archaeological and geological information within the buried context of a site over wider areas that is usually possible. The GPR method can accomplish this because it is based on the analysis of reflections produced from the interfaces and layers of geological units in the ground that are then studied three dimensionally. When this is done, robust analyses of buried geological and archaeological materials can be done for subsurface areas not visible at the surface in order to generate more holistic analyses of geoarchaeological studies.

Keywords: environmental context, sedimentary environments, three-dimensional analysis, buried materials and strata, stratigraphy, reflection generation, environmental reconstruction

Introduction

There has been a long period of collaboration between geologists and archaeologists, as it is impossible to separate the geological record from archaeological materials preserved within sediments and soils. These cross-disciplinary geoarchaeology studies involved stratigraphic analysis, environmental reconstructions, site selection for future excavations, and an analysis of site preservation and postabandonment processes (Butzer 1971; Rapp and Hill 2006). More recently, these types of collaborative geological and archaeological studies have included landscape analysis that places people within an often complex and changing environment (Bruno and Thomas 2008; Constante et al. 2010; Stern 2008). The inclusion of geophysical analysis within geological and archaeological studies has occurred more recently and is beginning to make an impact in many research projects (Campana and Piro 2008; Kvamme 2003) as buried deposits can be studied and integrated with more limited excavations and exposures. These geophysical studies for the most part employ magnetics, electromagnetic induction and electrical resistivity, and ground-penetrating radar (GPR). The use of these types of geophysical methods allows

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a more complete and broader aerial analysis of complex buried (and otherwise invisible) archaeological and geological materials than was possible in the past (Johnson 2006).

This book is devoted to one of these geophysical methods, GPR, and especially the integration of its unique imaging properties to measure and display materials in the ground along with geological and archaeological data. The GPR method transmits **radar** (electromagnetic waves) energy into the ground and then measures the elapsed time and strength of reflected waves as they are received back at the ground surface (**Figure 1.1**). Many thousands or hundreds of thousands of reflected waves are collected along the transects of **antennas** as they are moved along the ground surface to produce reflection profiles of buried layers and features analogous to viewing profiles in excavation trenches (**Figure 1.2**). When many reflection profiles are collected in a grid, three-dimensional images of buried materials in the ground can be constructed (Conyers 2013, p. 166). Ground-penetrating radar therefore has the unique ability to not just produce images of both geological and archaeological units in the ground, but to do so in three dimensions (Conyers 2012, p. 20).

Ground-penetrating radar's ability to produce two- and three-dimensional images of soils and sediments within depths that are usually of importance for archaeology (a few centimeters to 3–4 m burial at most) means that complex images of geological materials associated with archaeological deposits is possible. While some archaeological thinking views the geological matrix of a site as a volume of material that must be removed and discarded to get to the important artifacts and features, most recognize that there is important information to be gained by studying it (Davidson and Shackley 1976; Waters 1992, p. 15). It is this appreciation that geology cannot be divorced from archaeological research that forms the basis for the field of geoarchaeology. This cross-disciplinary focus can become even more important when GPR is integrated with the other datasets to project important information from the visible areas in outcrops or excavations into the invisible and still buried areas of a site.

Often much of what can be seen in GPR profiles and three-dimensional **amplitude maps** is more geological than archaeological, and there can often be confusion as to what is anthropogenic in origin, or instead the geological matrix (Conyers 2012, p. 19). Successful

Figure 1.1 Collecting GPR profiles with a GSSI SIR-3000 control system and 270 MHz antennas.

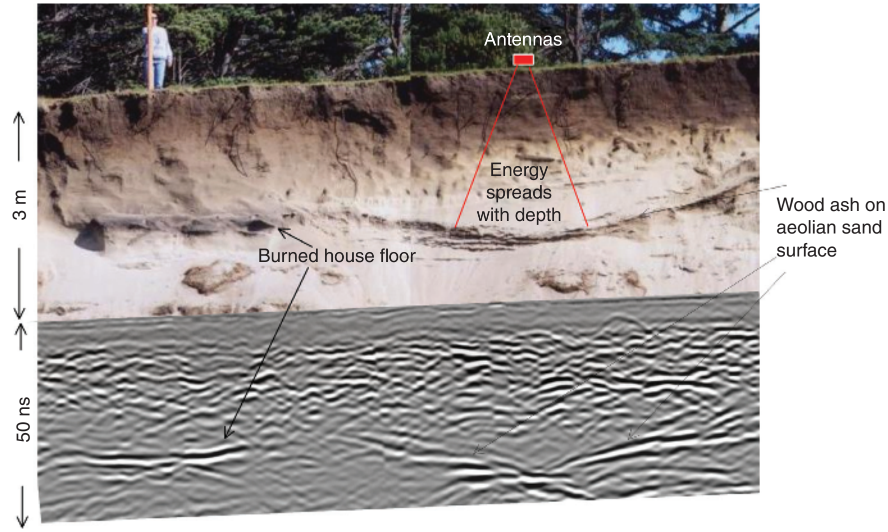

Figure 1.2 Comparison of a 400 MHz reflection profile collected within a 50 ns time window to a 3 m thick outcrop of cross-bedded aeolian dune sands with a burned house floor. Reflection energy spreads from the surface transmission antenna, creating an average of reflections received back at the ground surface from subsurface interfaces. From Conyers (2012). © Left Coast Press, Inc.

differentiation of the two, and an interpretation of radar **reflections** derived from all the units in the ground, is therefore crucial. As most archaeological sites are the result of burial and preservation by geological forces and processes, the various features in the ground that have been modified and altered by physical and chemical forces must be understood. This can be difficult even when exposures are visible to the human eye, but especially challenging when various buried features are visible but not necessarily understood in GPR images. The application of GPR to both geological and archaeological features and their interpretation within standard GPR-processed images is the goal of this book.

Scales and Applications of Geoarchaeological Studies with GPR

Geoarchaeological studies range in scale from very small scale analysis of micromorphology of soils and sediments using the microscope to large landscapes covering huge tracts of land (Goldberg et al. 2001; Rapp and Hill 2006). The GPR method of acquisition and data processing methods has very specific resolutions at measurable depths, which necessitates that it be employed within a middle-range of the usual standard geoarchaeology studies. These scales of study typically involve a few hectares aerial extent at most, with depth of analysis of 3–4 m and feature resolution usually larger than about 20 cm in the maximum extent. There are some notable examples of very large data sets recently collected by **multiple array systems** towed by motorized vehicles that can study many tens or even hundreds of hectares (Gaffney et al. 2012; Trinks et al. 2010) but these are still relatively rare. Within the scope of most geoarchaeological applications (French 2003, p. 6), and with most of the examples presented here, the study area may be on the order of a few hundreds of square meters in dimension to depths of about 6–7 m.

Geological analysis within the context of archaeology, which can be expanded on and broadened using GPR, can be used to study landscape evolution (Ricklis and Blum 1997) where settlement changes are a function of environmental fluctuations. Specifically, GPR datasets can define fluvial units that are the product of erosion and redeposition (Behrensmeyer and Hill 1998) and associated soil units, which are a function of landscape stability over many centuries (Birkeland 1999; Ferring 2001; Holliday 2001). An analysis of these geological units using an integration of stratigraphic units (Shackley 1975) with GPR datasets (Conyers 2009), within a dynamic landscape will also allow for the study of site formation processes (Schiffer 1972).

Studies that are expanded beyond site formation processes can show the effects of humans on a landscape and their adaptation to environmental change over time (Campana and Piro 2008). This is done by focusing on the geological matrix of a site first, defining depositional environments and changes in those environments laterally and vertically over time. The archaeological record is then placed within this context to understand human adaptation to and modification of their environment. This definition and understanding of environments is one of the key foci in GPR integration with geoarchaeology. This book will provide examples of various common environments discernable in GPR data sets, and then place human activities within those contexts.

The important geological packages of sediments and associated geological units that can be studied and analyzed with GPR are most of the terrestrial depositional environments (such as rivers, floodplains, sand dunes, beaches and other coastal environments), bedrock features that were part of an erosional landscape and later buried, and soil horizons that were living surfaces providing some degree of stability in the past. These types of buried features must usually be defined first in excavations and outcrops, and then projected into areas where they are buried and invisible except by using GPR techniques.

A key to understanding past environments is to first define the general stratigraphy of buried units and understand how those units are visible in common GPR images. This is not always as straightforward as would be hoped, as the varying chemical and physical properties of buried materials sometimes allows reflection of radar waves, and at other times does not. Depth of energy penetration, radar wave attenuation, the spreading of transmitted radar waves as they travel in the ground, and a variety of other variables relating to radar wave properties can often confuse and mislead some interpreters. Often these problems are solvable, and many examples regarding resolution, depth of analysis, and interpretation of the results of data processing are included. For the most part the larger scale geological units, and sometimes their associated sedimentary structures, are readily visible with GPR, and these can readily define specific ancient environments. When GPR interpretations are enhanced with subsurface information derived from augering, cores, and small scale excavations, a three-dimensional analysis of broad landscape features and past environments is usually possible. Facies analysis of larger scale geological units can then be integrated with anthropogenic features and sometimes associated soils to place humans within ancient and historical landscapes.

Basics of the GPR Method

Ground-penetrating radar data are acquired by reflecting pulses of radar energy produced from a surface antenna, which generates waves of various wavelengths that propagate downward (**Figure 1.1**). They spread as they move into the ground in a cone (**Figure 1.2**), which is a function of the physical and chemical properties of the materials through which they pass (Conyers 2013, p. 47). As these waves move through the ground they are reflected from buried objects, archaeological features and stratigraphic bedding surfaces. The reflected waves then travel back to the ground surface to be detected and recorded at a receiving antenna, which is paired with the transmitting antenna. The two-way **travel times** of the waves moving through the ground are measured at the receiving antenna and their arrivals recorded in elapsed time of travel, in **nanoseconds**. As the propagating radar waves pass through various materials in the ground their velocity will also change, depending on the physical and chemical properties of the material through which they are traveling (Conyers 2013, p. 107). If the constituent differences at interfaces of materials occur abruptly along boundaries between very different materials in the ground the radar waves' propagating velocity will also change when they pass across the contacts. When this occurs a reflected wave is generated that can move back to the ground surface from the reflection interface. Not all radar waves will travel back to the ground surface at a reflection interface and some energy will continue to propagate deeper in the ground to be reflected again from more deeply buried interfaces, until all the energy finally dissipates with depth. Only the reflected energy that travels back to the surface antenna is recorded and visible for interpretation. If buried surfaces that reflect energy are oriented in a way that reflected waves move away from the surface antenna, that energy will not be recorded, making those interfaces effectively invisible using the GPR method.

Reflections generated from radar waves propagating in the ground are created at interfaces where differing materials are in contact along a boundary and are different enough so that the velocity of moving waves that intersect the interface changes abruptly (Conyers 2013, p. 27). An example of a composition change that affects velocity in this way might be where a clay floor rests on an underlying sand bed (**Figure 1.2**), and where these materials are then buried by a different material. The contacts of the base of the clay floor with the underlying sand as well as the top of the floor covered with different sand are two interfaces that could generate wave reflections. The radar waves propagated from the ground surface antenna would be moving at a fairly rapid rate in the overlying material, slow abruptly as they passed into the clay floor, and move at an increased rate again as they passed out of the clay floor into the underlying sand. Each abrupt velocity change would theoretically create a reflected wave (Conyers 2013, p. 28). In contrast, a gradational change in materials over some distance would not produce a reflection as there would not be any abrupt change in radar velocity and no reflected wave would be generated. This kind of gradational change might be found when the sediment in one layer changes from silt to sand over a distance of a meter or so. In general, the greater the change in velocity across a boundary, the greater the **amplitude** of the wave that is reflected back to the surface and recorded.

Reflection profiles are the basic interpretive tool for GPR and are created as radar antennas move along the ground surface transmitting waves downward into the ground. A sequential **stacking** of many hundreds of reflections (termed traces) consisting of reflected waves from different depths in the ground is then produced. Each **trace** is recorded at a discrete position along an antenna transect, and the display of all these is used to produce a two-dimensional vertical slice in the ground (**Figure 1.2**). Profiles of reflections are the standard images used for geoarchaeological interpretations of buried materials in the ground. These will be used throughout this book, as they are the tool to identify and understand geological layers as well as archaeological components within those geological packages. Many reflection profiles collected in a grid can also be processed together in order to produce individual maps of various depth slices in the ground and renderings of features in three dimensions.

Integrating GPR with the Geological and Archaeological Record

Usually prior to conducting a GPR survey, there is a basic knowledge of the geological units and human occupation of an area. This kind of background information can be obtained from previous investigations, the published literature, or from others who have worked in the area previously. Without at least a basic understanding of what geological and archaeological materials to expect in the ground, results of a GPR survey would remain speculative at best (Conyers 2012). Only after obtaining this information can a knowledgeable and at least partially informed study commence. It is best to begin by collecting GPR profiles close to excavations or outcrops where exposures of the units of interest can be studied (Conyers 2013, p. 149). In this way, GPR reflection profiles can be “tied” directly to what is visible and known in exposures (**Figure 1.2**). This way of initiating a project is usually quite direct and can yield immediate results, with specific radar reflections generated from buried layers of interest easily defined and understandable. Radar reflection recording times can also be directly compared to depth of units in the ground and the velocity of radar travel times calculated (Conyers 2013, p. 153).

However, this optimal strategy using direct comparisons between the visible and the radar images prior to conducting a broader GPR investigation is often not possible. This could occur when there are no outcrops or excavations available or when time constraints or lack of permission for subsurface testing has not been obtained. The absence of specific geological or archaeological knowledge prior to GPR research need not impede at least initial investigations, if at least a general knowledge of what is expected in the ground is present.

This situation was confronted in coastal Portugal, where excavations to the west of a dry lake uncovered Late Paleolithic artifacts associated with a temporary hunting camp (Conyers et al. 2013; Haws et al. 2011). These artifacts were found in aeolian sand close to an unconformity with underlying Jurassic bedrock and overlain by a Late Pleistocene soil unit (**Figure 1.3**). They were therefore confined within a stratigraphic package that could be defined using GPR profile analysis where these units were visible.

A GPR survey was conducted around those excavations and an ancient stream channel incised into the Jurassic bedrock was found adjacent to the artifact concentration, which flowed from coastal hills just to the west, eastward toward a main river system that drained this area of western Portugal (Conyers et al. 2013). The same age artifacts (Magdalenian) were also found as surface scatters in plowed ground along the margin of the dry lake bed just to the east in what was presumably the ancient floodplain of the larger river. This suggested that these people were exploiting resources along the margin of this ancient lake environment within the floodplain.

With only this general information to help with interpretation a set of GPR profiles were collected within and to the east of the dry lake bed using 270 MHz antennas (**Figure 1.3**). Some exceptionally high-resolution reflection profiles were obtained in this plowed area used for a pine tree plantation, which had recently been harvested and was lying fallow. After these profiles were collected the recorded radar reflections were

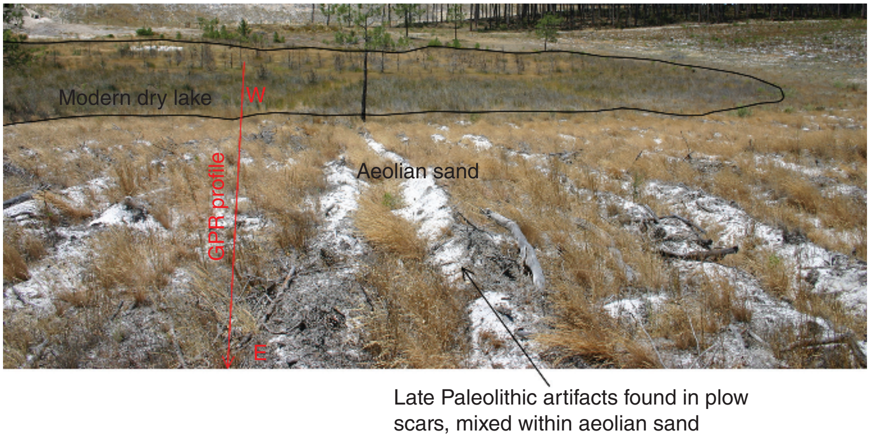

Figure 1.3 Location of the GPR reflection profile used to place Paleolithic artifacts into a geological context in western Portugal.

adjusted for surface topography and then displayed after minor background **noise** removal and resetting of the reflection amplitudes so they could be visible (Conyers 2013, p. 134).

In this case all that was known prior to the GPR survey was that an ancient stream system was located to the west of the survey area toward the floodplain. A dry lake bed was visible on the surface, which might have been present in antiquity and was located at the level of the main river floodplain (now a river terrace surface above the modern floodplain). It appears that humans had discarded Late Paleolithic stone artifacts in the general vicinity, but their relationship to the lake or anything present under the ground surface was not known. The artifacts were found out of place within the aeolian sand, which mantels this area today. They were likely moved from their original stratigraphic positions both vertically and horizontally as this area has been greatly disturbed by plowing, planting of trees for pine pitch extraction, and general bioturbation. They were discovered on the ground surface by standard archaeological pedestrian survey.

Each of the GPR reflection profiles collected in this large area displayed very different buried materials, and as only one day of data collection was devoted to this project only. A very coarse grid of transects spaced between 25 and 50 m apart was collected. This grid of profiles did not allow good correlation of geological units between adjacent profiles, and therefore only two-dimensional images of the ground could be generated. These images were informative and important, but only allowed for the generation of working hypotheses regarding the geological and environmental history of this area.

This project was initiated knowing that it would necessarily be a preliminary study that could provide data for more complete geoarchaeological analyses in the future. However, some very interesting geological units are visible in the profiles, and a basic understanding of the geological history of this area of the floodplain was possible. This allowed for a tentative placing of the Late Paleolithic people, who exploited this coastal area, into a well-defined ancient landscape.

The GPR reflection profile that began in the middle of the dry lake bed, and continued about 93 m to the east, clearly shows Jurassic bedrock at about 7 m depth, consistent with projections of that bedrock unit from our excavations just to the west of the lake (**Figure 1.4**). Resting directly on an unconformable surface with Jurassic are Pleistocene

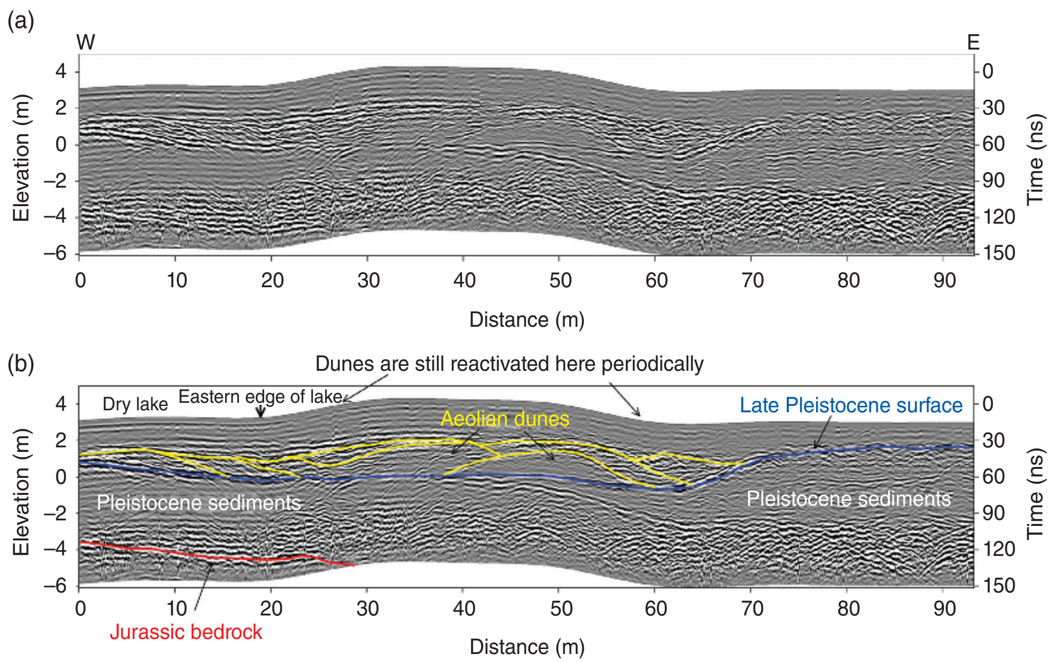

Figure 1.4 Two hundred and seventy megahertz reflection profile from western Portugal used to define subsurface sediment packages from late Pleistocene through recent times. Profile (a) is unannotated while (b) shows the inferred sediment packages, correlated to outcrops about 1 km away.

sediments of unknown age, which have the appearance in the two-dimensional GPR profiles of sand dunes. These units have been described elsewhere along the Portuguese coast as near-shore and aeolian environments (Benedetti et al. 2009), but have not been studied in this immediate area along what would have been an interior floodplain environment. On beach cliffs about 4 km to the west on the other side of the coastal hills, these Pleistocene age units date to about 62,000 years BP.

What is more important to the goals of this study is the reflection surface in the GPR profile (colored in blue in the lower annotated profile in Figure 1.4), which is consistent stratigraphically with a buried soil visible in outcrop about 1 km to the west. This unit was formed during a period of landscape stability during the Late Pleistocene when a well-developed soil was formed (Conyers et al. 2013). It was just below this buried soil unit, dating to about 11,500 BP, where late Paleolithic age artifacts were found in place along the edge of a small fluvial channel incised into the Jurassic bedrock. Overlying this late Pleistocene surface (Figure 1.4) are a sequence of sand dunes, clearly visible as a progressively thickening sand package of large-scale forest beds in individual dunes, preserved west of the present-day dry lake bed. These dunes appear to overlay the continuous late Pleistocene surface, which is likely the buried soil known from outcrops to the west. The aeolian sand units thicken to the east, toward the river, and possibly are the damming feature that created the now-dry lake, still visible on the surface.

It was initially hypothesized that this lake (Figure 1.3) was formed by salt collapse in the Jurassic bedrock, which has been documented elsewhere in this part of western

Portugal (Benedetti et al. 2009). The GPR profile indicates that a more likely origin for the lake is the thick aeolian sand unit that blocked water runoff derived from the high coastal bedrock ridge to the west. There is no evidence of any collapse features in the Jurassic bedrock or other units visible in the GPR profiles collected along the margin of the lake, or at least a collapse feature that would be visible in the upper 7–8 m of this sedimentary package (**Figure 1.4**).

This small geoarchaeological study incorporating GPR with a minor amount of geological and archaeological background demonstrates the utility of posing geological and environmental change hypotheses and then testing them with some basic interpretations using GPR images. While these results from Portugal must remain preliminary until additional three-dimensional analysis of sedimentary units can be accomplished with more tightly spaced GPR reflection profiles, some important conclusions can still be made. In this case a basic stratigraphic analysis of geological units within the floodplain was accomplished and one hypothesis about the origin of the lake was tested.

This stratigraphic study shows that sand dunes and other unknown Pleistocene sediments rest unconformably on Jurassic bedrock, which is consistent with stratigraphy visible in outcrops some kilometers to the west. While there are some interesting units in the sediments below the late Pleistocene soil, especially as visible on the eastern edge of the reflection profile (**Figure 1.4**), nothing is known of their precise age and origin. They are labeled "Pleistocene sediments" on the profile and have the appearance of cross-bedded sand dunes and other less reflective sedimentary units. The late Pleistocene surface lies directly on these sediments, colored in blue, which is most likely the soil unit exposed about 1 km to the west in a number of outcrops. Stratigraphically just below this soil unit late Paleolithic artifacts were discovered in place, in what was interpreted as a hunting or other short-term camp (Conyers et al. 2013; Haws et al. 2011). At the very end of the Pleistocene sand dunes then covered the soil unit, with thicker accumulation eastward toward the river. These dunes likely acted as a dam for water running off the uplifted coastal hills to the west and a lake was formed after the artifacts were deposited in the unit to the west near the base of this sand layer. It then appears that Late Paleolithic people continued to be drawn to this area after the lake formed and additional stone tools were deposited near its margin, which were incorporated into the accumulating dune units visible on the GPR profile to the east of the lake. These dunes continued to be actively deposited through much of the Holocene, and are visible as unconsolidated surface sand today (**Figure 1.3**). The artifacts found on the surface in this area were likely brought to the surface by plowing or possibly reactivation of the dunes over time, exposing and then reworking materials from deeper in the sedimentary sequence.

This simple example of the utility of GPR in geoarchaeology shows how a small amount of archaeological materials, when placed into a stratigraphic sequence that is generally dated, can produce working hypotheses regarding the location and nature of ancient environments and environmental change over time. When the ancient people who left these tools are then placed within that framework other conclusions can be made about those hunting and gathering people who exploited the landscape and what resources were important to them.

These very basic conclusions can be expanded in the future with additional GPR profile collection in a finer grid of data, and with coring and age dating of these buried units. In this example one GPR profile allowed for important hypotheses regarding how environments changed and evolved during about a 40,000 year time period. The basic sedimentary packages, within which the artifacts were found, were defined geophysically, and new hypotheses formulated about the environmental history of this area and people's exploitation of the ancient landscape. While much in this simple example remains speculative, it shows how the integration of information from three separate disciplines (archaeology, geology and geophysics) can yield a great deal of important data that can "drive" new ideas and hypotheses about this coastal floodplain in western Portugal and its late Paleolithic history.

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