

- Rubioff, D., and B. S. Holland. 2005. Between Two Extremes: Mitochondrial DNA is Neither the Panacea nor the Nemesis of Phylogenetic and Taxonomic Inference. *Systematic Biology* 56:952-961.
- Savolainen, V., R. S. Cowan, A. P. Vogler, G. K. Roderick, and R. Lane. 2005. Towards Writing the Encyclopaedia of Life: An Introduction to DNA Barcoding. *Philosophical Transactions of the Royal Society B* 360:1805-1811.
- Schander, C., and E. Willassen. 2005. What Can Biological Barcoding Do for Marine Biology? *Marine Biology Research* 1:79-83.
- Speller, C. F., D. Y. Yang, and B. Hayden. 2005. Ancient DNA Investigation of Prehistoric Salmon Resource Utilization at Keatley Creek, British Columbia, Canada. *Journal of Archaeological Science* 32:1378-1389.
- Steinke, D., M. Vences, W. Salzburger, and A. Meyer. 2005. Taxt: A Software Tool for DNA Barcoding Using Distance Methods. *Philosophical Transactions of the Royal Society B* 360:1975-1980.
- Tautz, D., P. Arctander, A. Minelli, R. H. Thomas, and A.P. Vogler. 2002. DNA Points the Way Ahead in Taxonomy. *Nature* 418:479.
- Ward, R. D., T. S. Zemplak, B. H. Innes, P. R. Last, and P. D. N. Hebert. 2005. DNA Barcoding Australia's Fish Species. *Philosophical Transactions of the Royal Society B* 360:1847-1857.
- Willerslev, E., and A. Cooper. 2005. Ancient DNA. *Proceedings of the Royal Society B* 272:3-16.
- Yang, D. Y., A. Cannon, and S. R. Saunders. 2004. DNA Species Identification of Archaeological Salmon Bone from the Pacific Northwest Coast of North America. *Journal of Archaeological Science* 31:619-631.
- Yang, D. Y., and K. Watt. 2005. Contamination Controls When Preparing Archaeological Remains for Ancient DNA Analysis. *Journal of Archaeological Science* 32:331-336.

## An Analysis of Ground-Penetrating Radar's Ability to Discover and Map Buried Archaeological Sites in Hawai'i

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### Introduction

The near-surface geophysical method called ground-penetrating radar (GPR) has to date seen limited use in Hawai'i for the discovery and mapping of buried archaeological sites. Its success in other areas of the world with similar ground conditions to Hawai'i, however, suggests that it could be utilized more extensively in the islands. Working with the Joint POW/MIA Accounting Command's Central Identification Laboratory (JPAC-CIL) to examine the effectiveness of GPR in Hawai'i, we studied the method's resolution and depth of investigation at a number of test sites on the islands of O'ahu and Hawai'i. The various sites had different ground conditions where varying environmental and moisture regimes and bedrock types affected the method's efficacy. The goal was to compare and contrast depth of GPR energy penetration and buried feature resolution in these various areas as a way to evaluate its potential effectiveness throughout the island chain. In this process, windward and leeward tests were made in both weathered and fresh basalt, deep clay soils, as well as coral bedrock and unconsolidated coral sand. The results of those tests, as well as an analysis of the ground conditions encountered, as they pertain to the effectiveness of GPR, are discussed here as a first step in building predictive models for the method's usefulness throughout Hawai'i.

### The GPR Method

The GPR method functions by measuring the elapsed time between when pulses of radar energy are transmitted from a surface antenna, reflected from buried discontinuities, and then received back at another surface antenna (Conyers 2004).

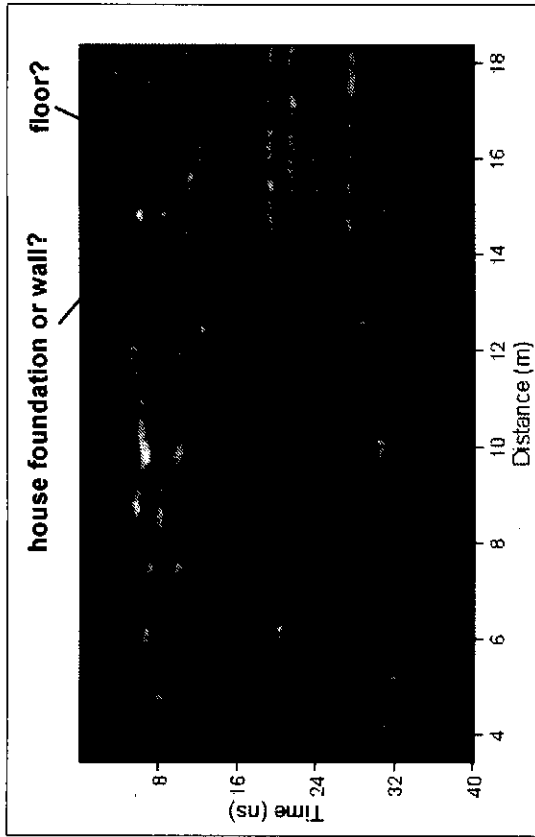


Figure 1. GPR reflection profile showing possible wall and floor of Queen Emma's house at Hickam Air Force Base, O'ahu.

When the paired antennas are moved along transects on the ground surface, two-dimensional profiles of buried stratigraphy can be produced by stacking many hundreds or thousands of reflections together to produce what are termed reflection profiles (Figure 1). Changes in the strength (measured as wave amplitudes) and the geometry of reflections in profiles can then be related to the distribution and orientation of subsurface units and features of interest. These changes might be stratigraphic layers, archaeological materials, or a variety of other objects or biogenic disturbances in the ground (Conyers 2006a). Many tens, or sometimes hundreds, of reflection profiles collected in a grid can then be analyzed within a three-dimensional "cube" of reflection data as a way to produce complex images of buried materials (Conyers 2004:148) in ways not possible using other near-surface geophysical methods (Johnson 2006).

Ground-penetrating radar is a geophysical technique that is most effective at buried sites where artifacts and features of interest are located within 2–3 meters of the surface, but it has occasionally been used for more deeply buried deposits (Conyers 2004:16). This depth of resolution and high degree of subsurface resolution makes it a geophysical method particularly applicable to Hawai'i, as deeply buried or complexly stratified archaeological deposits are much less common there than in other areas of the world.

A growing community of archaeologists has been incorporating GPR, as well as other near-surface geophysical methods, as a routine field procedure for many years (Conyers, 2004, 2006a; Gaffney and Gater 2003, Johnson 2006). When this is done, GPR maps and images become primary data that can be used to guide the placement of excavations, or to define sensitive areas containing cultural remains to avoid. For this reason, the method is particularly applicable to cultural resource management (CRM) projects where target areas need to be evaluated quickly and accurately in three-dimensions (Johnson 2006). Archaeological geophysicists have also used the GPR method as a way to place archaeological sites within a broader environmental context, test working hypotheses regarding past cultures, and to study human interaction with, and adaptation to, ancient landscapes (Conyers and Osburn 2006; Kyamme 2003).

The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography, and vegetation. It is not a geophysical method that can be immediately applied to any subsurface problem, although with thoughtful modifications in acquisition and data processing, GPR methods can be adapted to many differing site conditions. Our tests of GPR in a variety of Hawaiian sites produced successes at some, and failures at others, which are addressed here. Others who have worked with GPR in Hawai'i have documented similar results, with some suggesting that the technique is only marginally applicable to many Hawaiian soils because most are composed of wet clays (Doolittle 2006). Another supposition that has been used to explain equivocal GPR results in some areas of Hawai'i is that some Hawaiian soils and rocks have a high magnetite content, derived from the basalt parent material, which destroys radar energy in the ground (Olhoeft 1998). It is well known that both wet clay and magnetite are limiting factors in radar energy propagation (Doolittle 2006). However, in other basalt bedrock areas of the world published results appear to contradict these general assertions (Cassidy et al. 2004; Grant and Schultz 1994; Heggy et al. 2006; Miyamoto et al. 2005).

### GPR Testing Methods In Hawai'i

Our goals were to test the GPR method's effectiveness in mapping buried archaeological sites and to prospect for modern and ancient human burials at a number of test areas on O'ahu and Hawai'i. These tests were carried out in December 2005 during a period of very dry ground conditions. In all these tests buried cultural materials and human remains were either known or suspected to exist in the tested areas, which could be used as targets. The acquired GPR reflection profiles were then processed into profiles and sometimes amplitude maps after the data were filtered and reflections were enhanced using standard GPR data processing techniques (Conyers 2004:119). An analysis of the depth of penetration and feature resolution was then made and related to specific soil and other environmental conditions at each test site. While our selection of test areas was statistically biased, as sites were chosen mostly by ease of accessibility and informants with local knowledge and connections that allowed us access to the sites, a variety of ground conditions were encountered. At each site we evaluated the relative success qualitatively, based on what was known about the soils, sediments, and bedrock characteristics. As most archaeological surveys must be performed without having prior detailed knowledge of ground conditions, we chose to limit our research to data collection and analysis, and then determine after the fact what chemical or physical conditions of the ground might have been affecting the results by comparing them to published reports concerning soil and rock types in Hawai'i. Laboratory analysis and detailed stratigraphic testing was beyond the scope of this study, but is a method that would lend itself in the future to a much greater understanding of the complex factors related to GPR analysis in Hawai'i.

### Factors That Affect GPR

Resolution of buried materials and the depth of investigation are the most important factors that must be taken into account at all archaeological sites where the GPR method is contemplated. These two variables are inversely related and an analysis of them is crucial when choosing the appropriate frequency

antenna to use for data collection. Higher frequency antennas, above about 400 megahertz (MHz), are capable of better subsurface resolution, but transmit energy to shallower depths (Conyers 2004:39). For instance, a 400 MHz antenna can resolve objects and stratigraphic interfaces as small as about 20 cm in maximum dimension, but only rarely are effective below depths of 2–3 m. In contrast, lower frequency antennas (in the 100–200 MHz range) can theoretically transmit energy that penetrates 5 m or more, but are incapable of resolving objects or interfaces smaller than about 60 cm in dimension. In many soil conditions, especially those encountered in Hawai'i, our results indicate that depth of penetration is the most important factor in determining GPR effectiveness as some ground conditions in Hawai'i attenuate radar energy at quite shallow depths, no matter what the frequency of the transmitted energy.

Transmitted radar energy attenuation with depth is mostly a function of the electrical conductivity of surface soils, weathered bedrock, or sediment through which energy must pass (Doolittle and Collins 1995). High electrical conductivity material effectively destroys transmitted radar energy at shallow depths by removing the electrical component of the electromagnetic wave and propagation therefore ceases (Conyers 2004:49). Although there are some claims that lower frequency antennas are capable of greater depth penetration in even electrically conductive ground, our experience from a number of Hawaiian sites suggests that if the ground is highly electrically conductive, radar energy of any frequency will be attenuated at shallow depths. In some cases, Hawaiian soils attenuated GPR energy within the upper 30–40 cm and known features that were deeper in the ground were not visible. This depth constraint therefore limits the method's effectiveness in some areas, which was not predicable prior to collecting and analyzing the data. Other researchers have addressed the various soil factors that might limit radar energy penetration by computing what is termed GPR suitability indices (SI) based on information derived from published soil maps (Doolittle 2006). In this analysis, soil properties are categorized by their relative amounts of clay, mineralogy, the amount of dissolved salts or other electrically conductive materials in the ground, and the amount of

water retained. The SI maps of Hawai'i (Doolittle 2006) show most of the islands have moderate to low potential based on these suitability indices, with the exception of the more recent lava flow areas of east Maui and the island of Hawai'i. As these generalized maps do not give specific details about each of the soil units, or any analysis of buried feature resolution at various depths, the goal of the present study was instead to collect GPR data sets in these various ground conditions and then attempt to determine what it was about those conditions that allowed the method to be effective or not. As most of the test areas contained targets located in the upper 2–3 m (aside from the lava tube tests on Hawai'i), depth of investigation was considered to be the most important variable in evaluating the method's effectiveness. The idea was that if radar energy could be transmitted to those depths, either the 400 or 270 MHz antennas would be more than adequate for resolving the buried targets of interest.

Radar energy loss, termed attenuation, always occurs as energy moves into the ground. This attenuation is a function of four general factors, each of which we attempted to account for in our test areas (Reynolds 1997; Heggy et al. 2006). Coupling losses occur when the radar antennas are not placed in direct contact with the ground, or when the ground surface is uneven, allowing radar energy to be scattered and lost before it effectively "couples" with the ground. This loss factor can be mostly overcome by making sure antennas are moved slowly and carefully along the ground surface. Another factor is geometric spreading that occurs as energy moves into the ground. This loss is a function of the conical shape of the transmitted radar pattern that spreads the energy out over a larger and larger surface area as it travels deeper in the ground (Conyers 2004:62). Spherical spreading with depth decreases the amount of energy that can be reflected back to the surface from any one buried object or interface below the surface, lowering the effective resolution of any reflections generated from it. This is a factor inherent in the method and cannot be adjusted for using standard GPR equipment. A third site-specific factor is energy scattering, which is caused as radar energy reflects in random directions from buried objects or discontinuities in the ground, redirecting some of it away from the surface receiving antenna

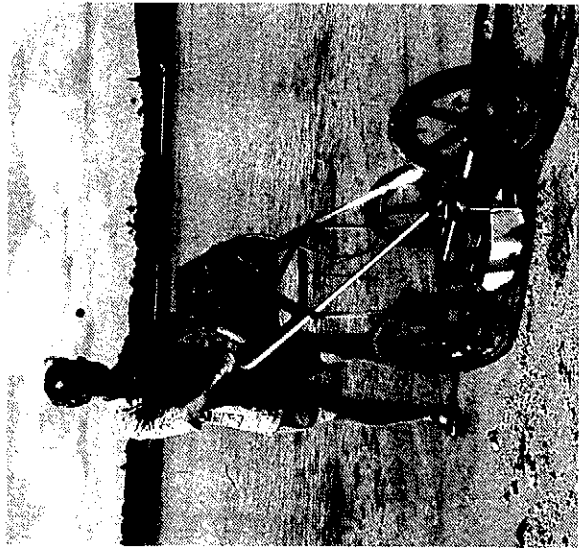


Figure 2. The GSSI SIR-3000 system with survey wheel, 400 MHz antenna and control unit with flash memory chips for data storage and playback.

so that it is not recorded. A similar site-specific factor, and the one that is most variable and important in determining the GPR method's effectiveness in Hawai'i, is electromagnetic attenuation. As radar energy is composed of both electrical and magnetic waves, which move in a cojoined fashion (Conyers 2004:24), the removal of either one or the other by electrically conductive or magnetically permeable ground effectively destroys the transmitted energy. In general, soils that are wet and have high clay content, especially clays of a certain mineralogy, will have high electrical conductivities as measured by their cation exchange capacity (CEC). In those clay soils, ions absorbed on some clay minerals will undergo exchange reactions with ions in the water, which increases the electrical conductivity of the ground (Doolittle and Collins 1995; Schultz 2005).

While most studies of GPR effectiveness evaluate clay as a general constituent, clay mineral types vary considerably with respect to their electrical properties (Grim 1968; Saarenketo 1998). For instance, kaolinite clay has a very low CEC, and therefore readily allows the transmission of radar energy, while montmorillonite clay is very conductive (high CEC) and most radar energy is lost at very shallow depths in ground in this constituent (McDonald et al. 2005). In Hawai'i these and other clays are common, and are geographically distributed based on

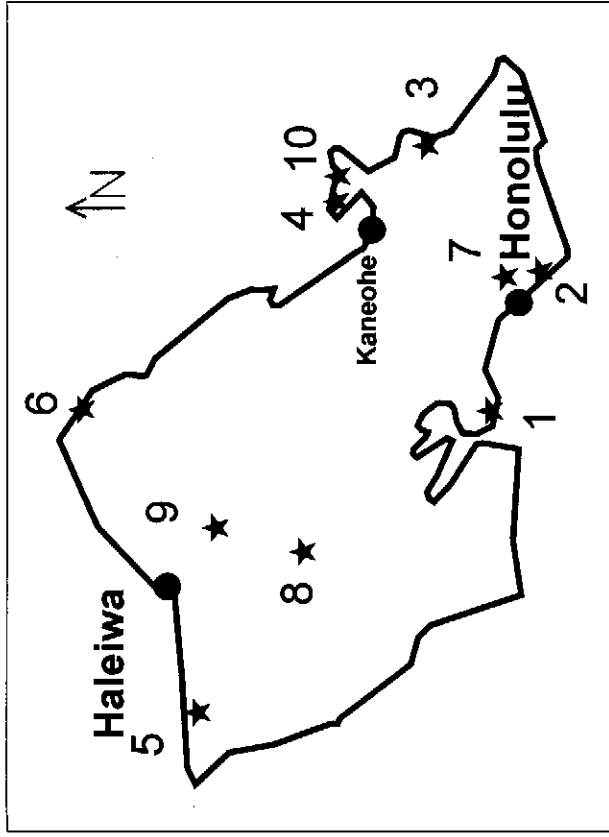


Figure 3. Base map of the O'ahu GPR tests.

1. Queen Emma's house and Battery Hazbrouk; Hickam Air Force Base, 2. Waikiki Kona District, 3. Bellows Air Force Base, 4. Clipper Golf Course, Marine Corps Base Hawaii, 5. Dillingham Air Field, 6. Laie, 7. Punchbowl Cemetery, 8. Schofield Barracks cemetery, 9. Opaoua Fire Base, 10. Cinder Cone at Kane'ohe Marine Base.

bedrock types and the amount of moisture and weathering time (Foote et al. 1972; Vehara 2005). The size, surface area, cation-exchange capacity, and water holding capacity of clay minerals therefore can vary greatly in Hawai'i. In general, highly weathered soils can often contain mostly kaolinitic, gibbsitic, and halloysitic soils, which have a low cation-exchange capacity and therefore better radar energy penetration (Grim 1968). We encountered no soils in Hawai'i with these properties, although kaolinite clays are known to exist on Kauai (Foote et al. 1972; Macdonald et al. 1983) and perhaps some very weathered windward areas of O'ahu.

### Hawaiian Tests

In all tests the Geophysical Survey Systems, Inc. (GSSI) Subsurface Interface Radar System model 3000 (SIR-3000) was used to collect GPR data. The unit was mounted on a cart system, with a survey wheel used to place reflections in space along survey transects (Figure 2). Both 270 and 400 MHz anten-

nas were used depending on the depth of the known buried features (with the 400 MHz most widely used, as the critical depth of burial at most test sites was in the upper two meters). Reflection data were transferred to a laptop computer and processed using software that is publicly available (Conyers 2005). This software allowed reflection profiles to be viewed and analyzed for effective depth penetration, and at some sites grids of many closely spaced profiles were used to produce amplitude maps of buried features of interest.

A total of 10 locations were studied, sometimes with numerous tests and grids of data at each (Figure 3). Each test location will be discussed below and categorized by the types of soils, sediments, or rock types encountered.

### Weathered Coral Soils

A number of data grids were collected at Hickam Air Force Base in Honolulu (Figure 3) on ground that is composed of a very thin surface soil underlain by weathered coral bedrock with admixtures of coral and shell sand. This weathered bedrock is mostly fill, originally dredged from nearby Pearl Harbor. Its composition mimics the type of carbonate ground that would be found in uplifted coral or lithified beach-rock units along some portions of the Hawaiian coastline (Macdonald et al. 1983). The tests were performed to assess the resolvability of buried bones and objects placed in the ground to mimic human remains and also to search for the possible remains of the country retreat of Queen Emma (1836–1885) who lived here until her death. The structure was last mapped in 1897 at the site of Fort Kamehameha, purchased from the estate of Queen Emma in 1907 by the U.S. Government and eventually renamed Hickam Air Force Base (Anderson et al. 1998; Putzi and Dye 2005). The 400 MHz antennas were used with data collected in a 40 nanosecond (ns) time-window (Conyers 2004:39), which corresponds to a depth of about 2.6 m in the ground (calculated using an average of 7.5 cm/ns velocity of radar energy). These calculations of velocity were made at all test sites by fitting the hyperbolic shaped reflections generated from rocks and other "point source" reflections in the ground to hyperbolas of a known geometry, using a program called *Fieldview* (Lucius

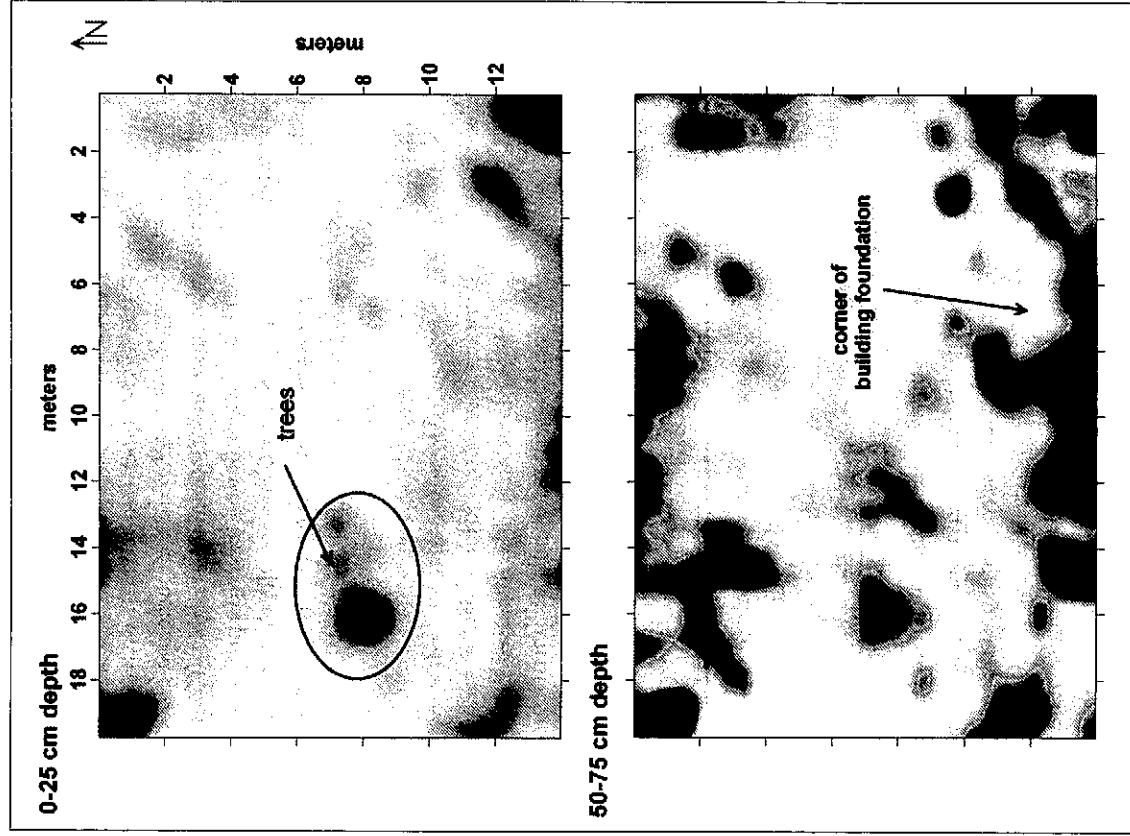


Figure 4. Amplitude slice-maps of the Hickam Air Force Base grid showing the possible corner of Queen Emma's house. Darker shades of gray designate the location of high amplitude reflections while white show areas of little or no radar reflection.

and Powers 2002; Conyers and Lucius 1996). As reflection hyperbola geometry is a function of the velocity of the material in the ground, this program can produce very accurate estimates of this important radar travel times to approximate depth in the ground (Conyers 2004:117).

Good reflections were recorded throughout the recording window in this area (Figure 1). Some energy

attenuation was noticeable below about 1 m or so, but coherent reflections were still visible to the maximum depth recorded (Conyers 2004:91). Amplitude analysis was performed on reflections recorded in a 14 x 20 m grid of profiles collected at 50 cm intervals. In this data processing step, the amplitudes of all recorded reflections are displayed in horizontal slices of a given thickness. These amplitudes represent the relative differences of adjacent buried materials, which are extracted from the profiles and viewed as horizontal maps. In this way, amplitude maps are analogous to analyzing soil changes in arbitrary excavation levels in standard archaeological field excavations (Conyers 2004:148). When this mapping step was performed, the square corner of what appears to be the foundation of Queen Emma's house became visible in the general area indicated by the historic maps (Figure 4).

As most coral bedrock and coral sand in Hawai'i are found along the coast, the proximity of this type of ground to salty or brackish water is a factor that must be considered with GPR, as the dissolved salts in this ground water will act as a conductor and attenuate radar energy at a very shallow depth (Doolittle 2006). Most of our tests in the Hickam area were located 100 meters or more inland from the bay, and good GPR reflection data indicated that ground water in this area was mostly fresh. There was little energy attenuation within the time window that data were collected, with good reflections recorded to at least 2 m depth. Most radar reflections recorded from within the coral bedrock were weak, but still discernable, suggesting there was some energy attenuation with depth. This is probably due to the somewhat electrically conductive constituents of carbonates, which are known to attenuate radar energy (Doolittle 2006). This energy loss was partially overcome by increasing the gains during data processing, which is a method of artificially enhancing reflection amplitudes recorded from deeper in the ground so they may become visible (Conyers 2004:91). In these types of Hawaiian environments, the GPR method should therefore be considered reliable and effective, at least for mapping features to about 2 m depth.

To test how close to the bay the antennas could get and still collect good data, we placed the radar antennas directly on the beach in the salt water at the

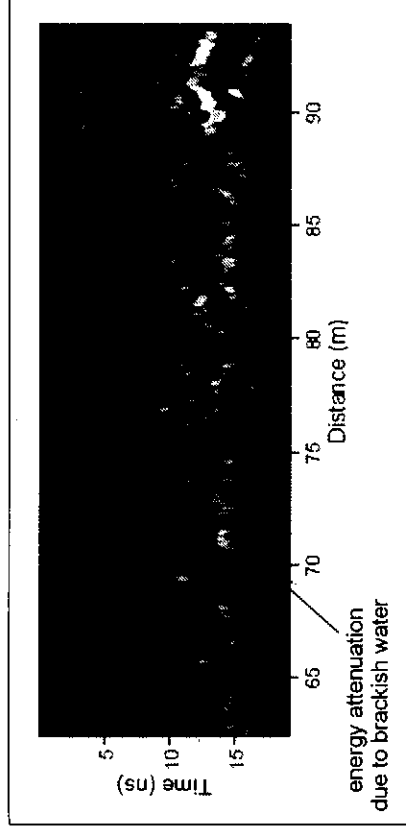


Figure 5. GPR reflection profile from Waikiki's Kona District showing energy attenuation at the base due to brackish water, but a highly reflective possible house floor above.

### Carbonate dunes

The numerous coral and shell fragments that make up dunes in low-lying areas of the coast, as well as most of the modern Hawaiian beaches (Macdonald et al. 1983), were also tested to determine resolution and depth penetration. A 20 x 30 m grid of GPR reflection data was collected using the 400 MHz antennas with 50 cm profile spacing at Bellows Air Force Base on O'ahu's windward side (Figure 3). This test, about 250 meters inland from the beach, was in an area where human burials had been discovered by archaeological excavations, with indications of habitation structures and middens nearby (Kam 1986; Putzi and Dye 2005). In this data set, excellent reflections were recorded to about 2 m depth and a number of buried features were imaged including the midden that had previously been tested and a second previously-unknown midden in a different part of the grid (Figure 6). Reflection profiles also recorded a metal water line running through the grid and Hawaiian burials that had been uncovered nearby and then re-buried many years ago (Figure 7).

All reflection profiles from the Bellows grid were processed into amplitude slices, each approximately 25 cm thick (Figure 8). These maps clearly show the two known re-burials, one previously known midden of fire cracked rock and bone and shell tools (the one to the south of the water pipe), and a much larger midden to the north. Resolution was so good in this grid that individual objects that are probably the fire cracked rocks or other midden debris can be seen as high amplitude reflections (Figure 8). This test at Bellows shows the excellent results that GPR

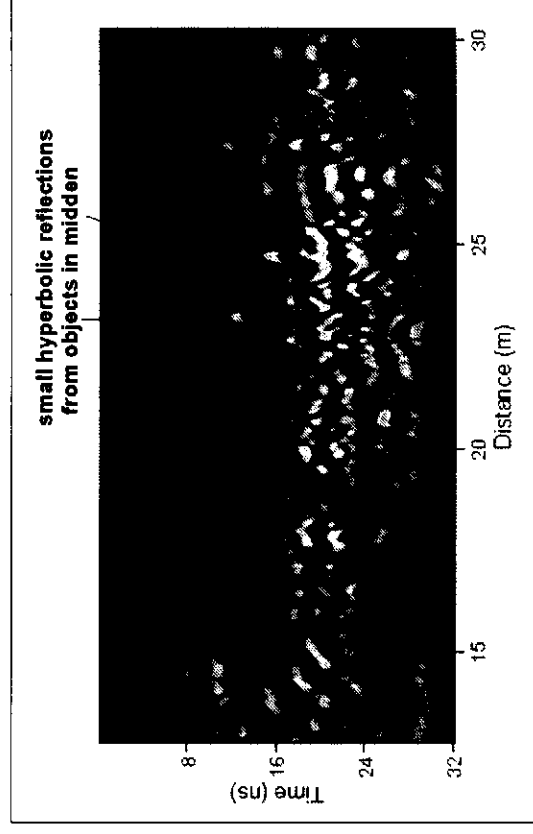


Figure 6. GPR reflection profile showing small hyperbolic reflections from objects in an ancient midden, Bellows Air Force Base, O'ahu.

beginning of a profile, and then collected a line up the beach face on top of stabilized sand dunes at the Battery Hasbrouck area of Hickam Air Force Base (Figure 3). Energy attenuation along this line was noticeable only within about 4 m of the salt water, with good reflections recorded to about 1.5–2 m depth farther inland. This test indicates that GPR is a very effective tool to about 2 m depth along the coast in coral-carbonate areas within just a few meters of the salt water. That would not be the case where there is saltwater intrusion into the shallow near-shore aquifers.

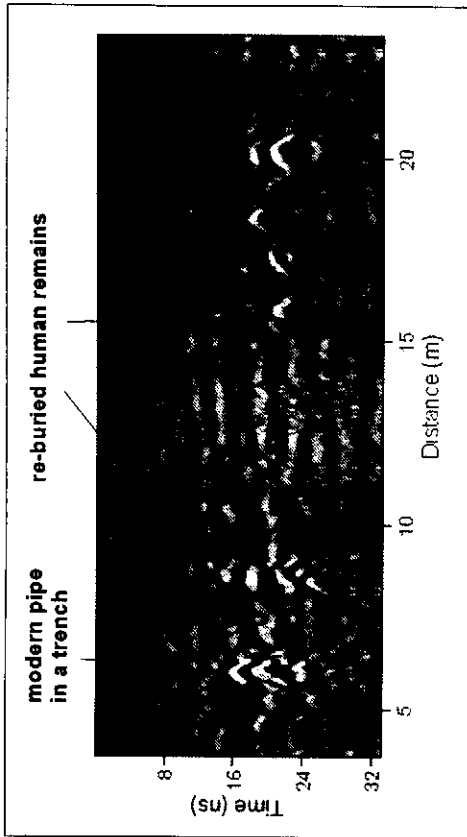


Figure 7. GPR reflection profile showing re-buried human remains and a modern water pipe, Bellows Air Force Base, O'ahu.

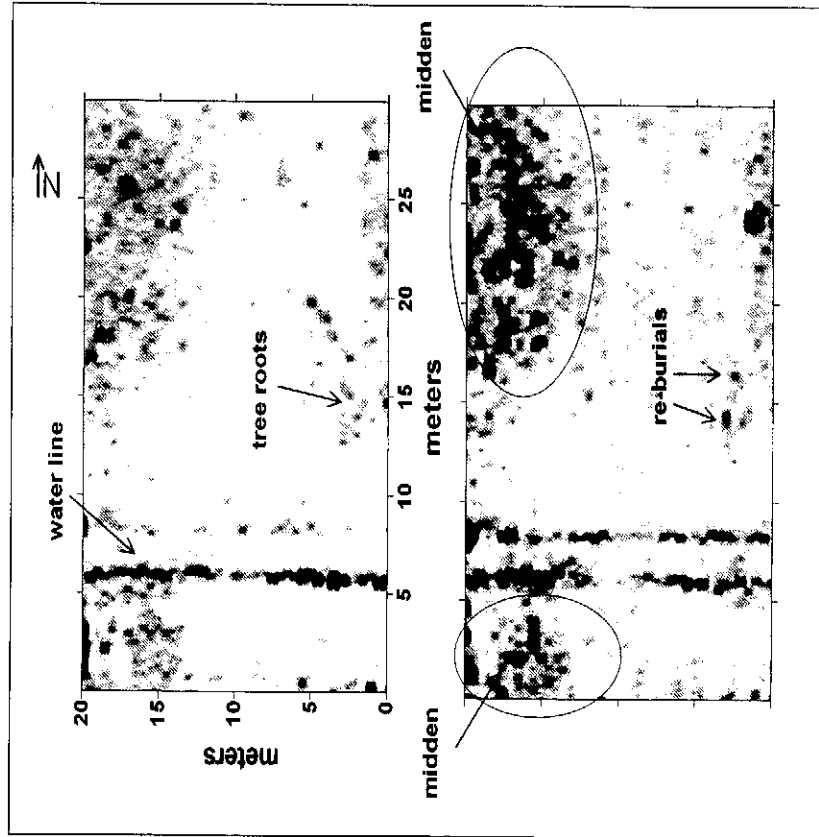


Figure 8. Amplitude slice-maps of the features mapped at Bellows Air Force Base, O'ahu including two ancient middens, re-buried human remains and a modern water pipe.

can provide in carbonate sand, in this case with good resolution to at least 2 m depth.

As active carbonate dunes can often contain archaeological materials along the coast, test profiles were collected along the modern beach at Marine Corps Base Hawaii (MCBH), also on the windward side of O'ahu, just west of the Kāne'ōhe Clipper Golf Course (Figure 3). Although the stratigraphy there is quite complex, reflections from a number of buried features are visible in reflection profiles. These include probable cross-beds within dunes and buried surfaces of inter-dune compacted surfaces that were later covered by the advancing dunes (Figure 9).

Good reflections were recorded at this test site to about 2 m using the 400 MHz antennas. If the archaeological targets of interest were artifacts or features on or within ancient living surfaces (perhaps inter-dune habitation surfaces), which were later covered by the dunes, the GPR method would be an excellent tool for accurate mapping.

Ancient Hawaiian burials were often placed in sand dunes both along the coast and in dune deposits farther inland. Just south of the runway at Dillingham Air Field on O'ahu's northwest coast (Figure 3), one such burial ground was tested in carbonate sand where both historic and ancient burials were known to be present. Some of this area had been disturbed by earth moving equipment in the past, and it was unknown if or where intact burials might still be present. Using the 400 MHz antennas, good reflections were recorded to between 2 and 2.5 m (30 ns) and a number of possible burials were discovered (Figure 10). Although these were not confirmed by intrusive testing methods, they are very similar to burial features seen elsewhere (Conyers 2006b). They are also located in an area where Thomas Shirai, a descendant of the Hawaiian family that once lived here, remembers his grandfather pointing out graves, which date from at least the 1860s and possibly much earlier. Also recognizable at this site is disturbance by earth moving equipment, visible as areas of little or no radar reflection, where sand was removed, homogenized, and then later used as backfill, creating a zone in the GPR profiles where there is no significant radar reflection (Figure 10).

A vacant lot slated for construction in Lā'ie, on O'ahu's North Shore (Figure 3) was used as a test lo-

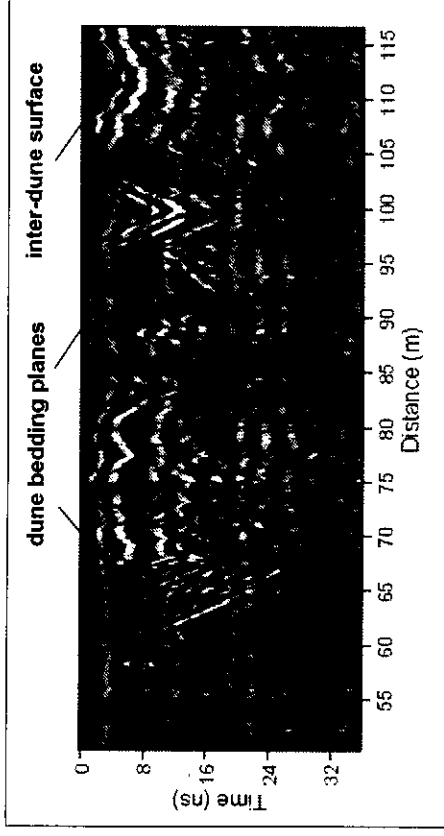


Figure 9. GPR reflection profile collected in active carbonate dunes along the Kāne'ōhe Marine Reserve beach, O'ahu.

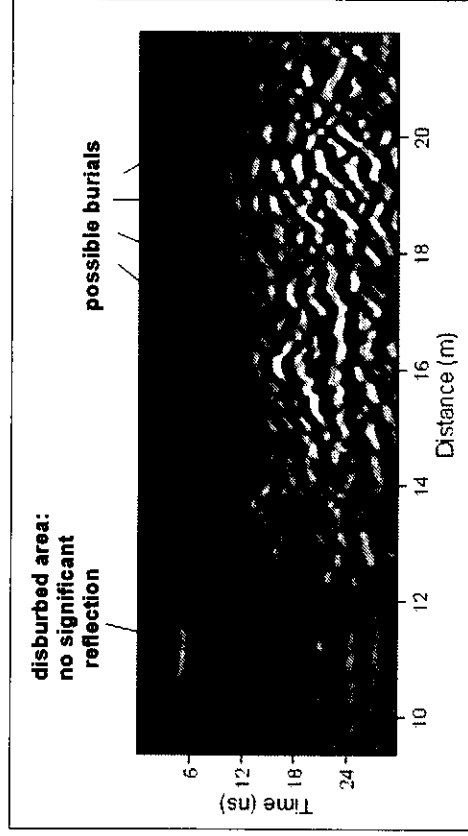


Figure 10. GPR reflection profile from Dillingham Air Field showing possible burials and disturbed area in carbonate sand dunes.

cation to try the GPR method's utility for a common CRM task, cultural resource evaluation. In this area, what appeared to be highly disturbed carbonate sands just landward of a rock breakwater were tested for the presence of burials and also to determine if house floors, middens, or possible hearth features were preserved in the sand. Good reflections were recorded to about 2 m (40 ns) using the 400 MHz antennas and reflection profiles showed a very complex stratigraphy consisting of numerous cut and fill features as well as individual reflections produced from large objects in the ground (Figure 11). The cut and fill features were interpreted as recent ground

disturbances, with objects within them interpreted to be recent trash. Other areas outside of these disturbed zones were noted as containing possible intact cultural features. All areas of interest were noted on maps and rated as to their importance and possible origin. Excavation was allotted only one day by the client, so only representative features seen in the GPR maps and profiles were tested in order to confirm their origin. Excavations by Garcia and Associates personnel in February, 2006 consisted of both shovel tests and 1 x 1 m excavations, which confirmed the interpretation that this area had been heavily disturbed by recent excavations. The objects imaged by GPR within the cut and fill areas were found to be recent metal, wood, and glass debris, with the inclusion of some human and animal bones. While it is likely that human burials were once located in this area, the GPR analysis suggests they had been destroyed by excavation activity. The areas in the GPR profiles with little or no reflection were confirmed to be sterile sand. GPR mapping at this site proved to be an excellent method to quickly evaluate the archaeological potential of an area, and allowed targeting of excavations in specific areas of interest. Unfortunately, at this location the GPR evaluation showed that almost all of the area had been so disturbed by recent activity that little or no potential exists for intact cultural remains.

In general, the carbonate dune areas of Hawai'i provide an excellent medium for GPR analysis. As long as the sand is well above the brackish water table, good radar reflections can be collected to at least 2–2.5 m in most settings. As this type of ground contains a variety of archaeological sites, GPR can be used as a very fast and accurate way to test fairly large areas and to delineate features that can be tested with excavations, if necessary.

Compacted carbonate beachrock or other carbonate material overlain by thin soils have more limited energy penetration than the dunes. This is probably because they have undergone weathering that has transformed some of the carbonate minerals into clay, which appears to somewhat attenuate radar energy. Even in these cases, good reflections were still recorded to about 1–2 m when the ground water was fresh. Where brackish ground water was encountered, radar energy attenuation occurred at a much shallower depth.



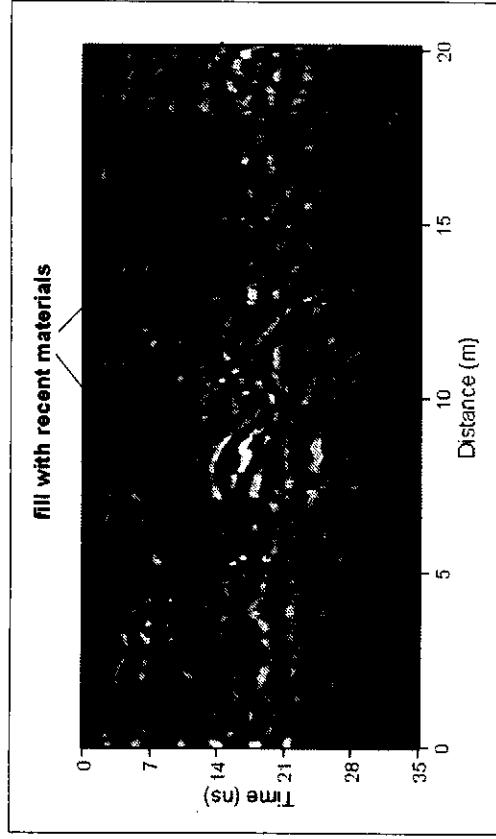


Figure 11. GPR reflection profile in carbonate beach sands, Laie, North Shore, O'ahu. Significant cut and fill features from recent disturbance are visible, which were confirmed by excavations.

#### Weathered Basaltic Soils

As most of the Hawaiian island chain's bedrock is composed of basalt, it is important to understand GPR energy penetration in soils that have formed on this material, as well as energy propagation within the volcanic rock. An understanding of the electrical properties of the weathering products formed from basalt, which can produce the thick reddish-brown clay soils visible throughout the islands, is therefore crucial. Hawaiian basalt is composed of silica, plagioclase feldspar (sodium and calcium aluminum silicates), and iron-magnesium minerals such as magnetite, pyroxene and olivine (Macdonald et al. 1983). The silica in the basalts is mostly stable over time, and its chemical composition affects radar energy very little (Doolittle 2006). The feldspar minerals in basalt, however, will readily weather to a variety of clay minerals depending on environmental conditions, with kaolinite clays formed in the more humid windward areas and allophane, saponite, and montmorillonite clays in the drier leeward areas (Macdonald et al. 1983). The iron and magnesium-rich minerals in the basalt weather to the hydrated iron oxides hematite and limonite, which give many Hawaiian soils their distinctive reddish-brown to yellowish color. In some very wet windward areas, Hawaiian soils containing kaolinite can further weather to bauxite (gibbsite and goethite clays) when

the soils are heavily altered by the leaching action of intense rainfall (Macdonald et al. 1983). In some of the drier leeward areas, calcium carbonate can be an additional basalt weathering product, which produces variegated whitish-red soils. Each of these soil constituents produced on basalt bedrock, in various combinations, will produce surface materials of varying electrical conductivity and magnetic permeability, which can affect the depth to which radar energy will penetrate. When these various materials become water saturated, cations will become mobilized, conducting an electrical current. This chemical property causes these soils to conduct the electrical portion of the electromagnetic wave away, destroying the propagating radar waves.

The most common way to measure the electrical conductivity of soils is by measuring CEC, a common measurement used in determining soil fertility for agriculture (McDonald et al. 2005). The higher the CEC, the greater the electrical conductivity, as measured in units of centimeters of cation change per kilogram. Kaolinite has the lowest CEC of common Hawaiian soils, in the range of 2 to 15 cm/kg, while montmorillonite has the highest (ranging from 80 to 150 cm/kg). The calcium carbonate found in soils in leeward areas will also increase the electrical conductivity when wet, as this mineral constituent can mobilize cations. Therefore, in a basic way, the clay soils formed on basalt in leeward locations will have poorer radar energy propagation, as these electrically conductive soils will destroy most radar energy readily in the ground. As the soils become progressively more weathered because of greater rainfall toward the windward areas, radar energy depth penetration will improve.

As a test of basalt soils on the leeward side of the island, GPR reflection profiles were collected at the National Memorial Cemetery of the Pacific, also called Punchbowl Cemetery (Figure 3), where metal caskets were known to be located at standard depths in the ground. The soil in this area is composed of weathered basalt, with additions of some weathered coral rubble that was imported to level the ground. The ground has been heavily irrigated and fertilized (until a few years ago with iron-rich liquid fertilizer). A number of reflection profiles were collected using the 400 and 270 MHz antennas over known graves. Radar energy was severely attenuated below about

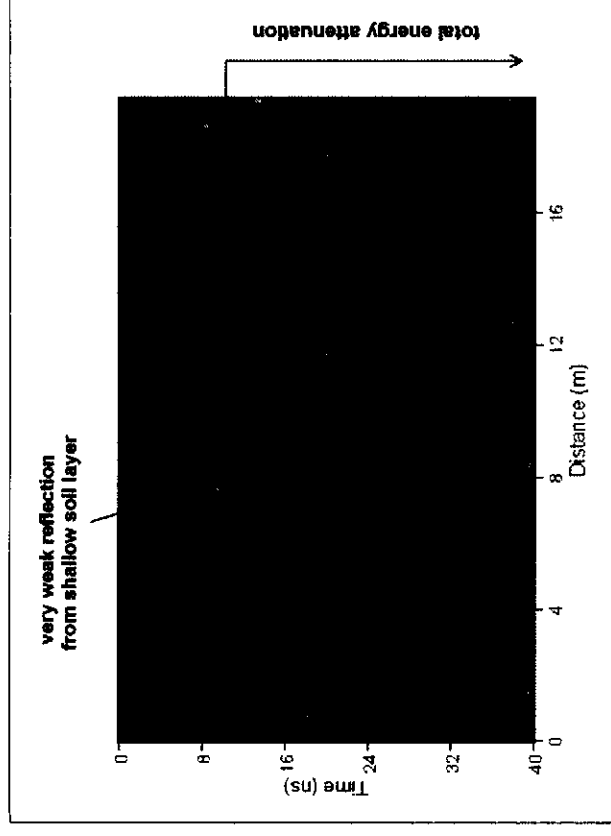


Figure 12. GPR reflection profile from Punchbowl Cemetery, O'ahu. Almost total radar energy attenuation occurred below about 15 nanoseconds (about 40 centimeters in the ground).

10 ns, which is approximately 40 cm in the ground (Figure 12). No coherent reflections were obtained below 20 ns (80 cm) in any of the profiles, and none of the caskets, whose tops were about 120–150 cm below ground surface, were visible. These tests confirm those performed by Sabrina Buck (2003), who reported similar results. Shallow energy attenuation at this location is probably the result of highly conductive clays in the soil, but could also partially result from some magnetic attenuation due to long-term application of iron-rich fertilizer. This high iron content, perhaps from magnetite that had not completely weathered to ferrous oxide minerals in the basaltic fill and possibly from the fertilizer, could have caused the attenuation. Of all the GPR data collected as part of this study, that at Punchbowl showed the most severe attenuation with depth.

While magnetite in Hawaiian soils has generally been considered a limiting GPR factor (Olhoeft 1998), tests in the laboratory suggest that elevated electrical conductivity may play a more important role in tropical soils (Robinson et al. 1994). In these tests, the magnetite by itself did not cause energy attenuation, but when it was crushed and put in a water solution,

higher radar attenuation resulted. This suggests that magnetic permeability might play a very minor role in radar energy attenuation within most Hawaiian rocks, compared to electrical conductivity. It is more likely that the clays in these soils, which consist of higher amounts of montmorillonite with higher electrical conductivity, are producing the high energy attenuation close to the surface.

Tests were conducted in soils formed on basalt parent material at the Schofield Barracks Post Cemetery (Figure 3). This site is in a more windward location than Punchbowl and is in a soil classified as Kunia silty-clay (Foote et al. 1972; Soil Survey Staff 1999). This soil type is composed of dark reddish-brown silty clay with some manganese concretions. While no chemical analysis has been published on the material from Schofield, similar soils in weathered basalts nearby have cation exchange capacities of between 20 and 30 cm/kg, which suggests they contain both kaolinite and montmorillonite clays. Montmorillonite clays are much more electrically conductive than the kaolinitic constituents, and we predicted these soils would produce only moderate radar energy attenuation.

Reflection profiles from the cemetery showed good reflections to about 35 ns, which is about 1.5 m below ground surface after correcting for velocity (Figure 13). Reflection hyperbolas generated from the tops of caskets located at about this depth were visible, with some deeper reflections from other soil discontinuities to depths of about 2 m.

Amplitude slice-maps of a portion of the cemetery where child burials were located (at various depths) were constructed in order to map individual graves and other buried features (Figure 14). Tree roots and sprinkler lines are visible in the shallow slices, while the various deeper slices show the location of the burials as high amplitude reflections. The Schofield Barracks GPR data show that in moderately weathered soils produced on basaltic parent material, good radar energy can penetrate to about 1.5–2 m and good resolution of buried features is possible.

Within the old sugar cane fields just above Hale'iwa, on land owned by the Bishop Estate, a grid of radar data was recorded at the Opa'ula Fire Base (Figure 3) where concrete bunkers were built just after the

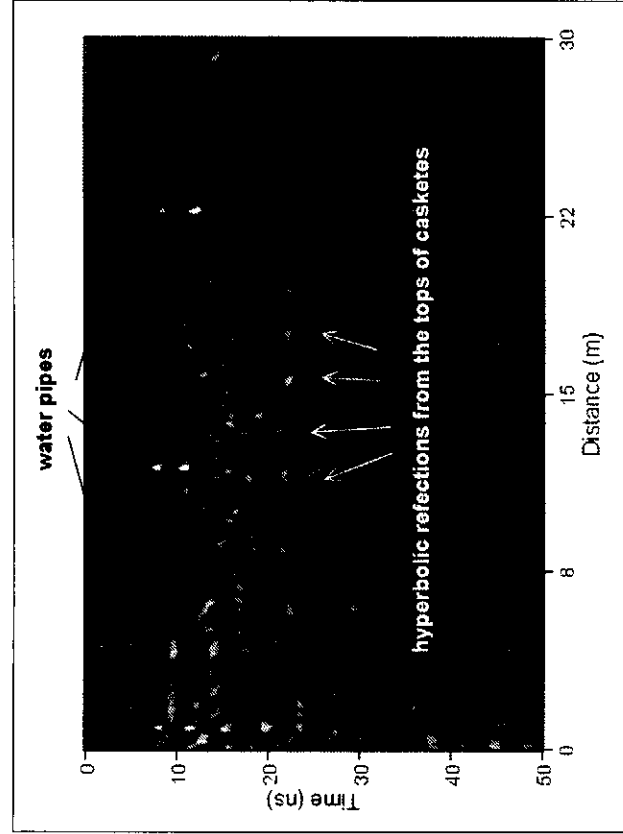


Figure 13. GPR reflection profile from Schofield Barracks Base Cemetery. Good resolution to about 2 meters allowed caskets to be readily identified (only a few are annotated on this figure).

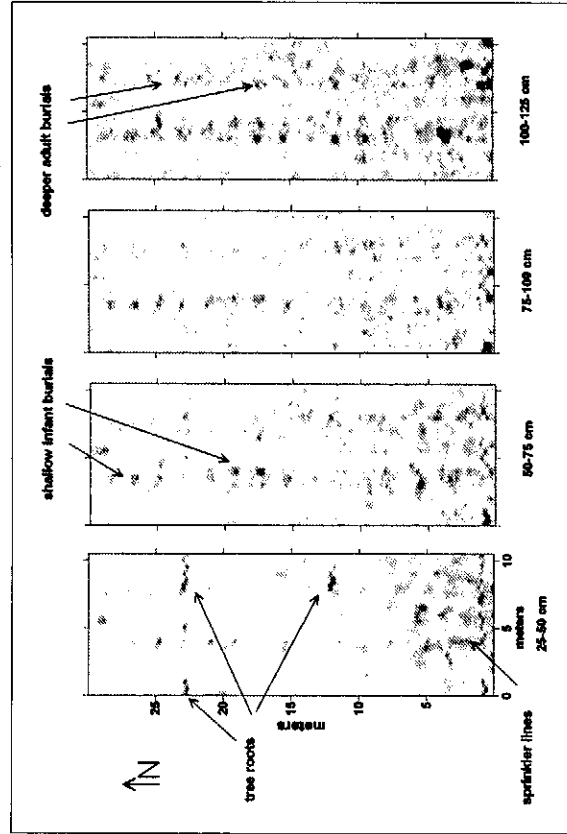


Figure 14. Amplitude slice-maps of graves at various depths, Schofield Barracks, O'ahu.

Pearl Harbor bombings of 1941 (Bennett 1994). In this area there are deeply weathered dark reddish-brown soils similar to those encountered at Schofield Barracks. Both the 400 and 270 MHz antennas were used in this area, and good reflections were recorded to about 40 ns, which is about 2 m in the ground. Energy from both antennas was attenuated below that depth. In this area, the features of interest were located more than 2 m below the ground surface, and the GPR method was not capable of penetrating to that depth. Both frequency antennas transmitted energy that penetrated to about the same depth, indicating that 2 m is about the limit of GPR mapping in these types of soils.

#### Basalt Rock and Rubble

On the flanks of a cinder cone at MCBH on the northeast shore of O'ahu (Figure 3), an attempt was made to map ancient Hawaiian burials that had been encountered during construction of the Pond Road housing project. In this area, about 70 cm of basalt rubble from the nearby cinder cone was deposited on top of a dark brown clay layer of unknown origin and thickness. This layer was visible in a backhoe trench to a depth of 1.3 m. The burials were discovered in the clay layer at about 1 meter depth. A recently buried six-inch diameter plastic pipe (80 cm below surface) was used as a target to test radar penetration in this type of basalt rubble. Both 400 and 270 MHz antennas were used, and the plastic pipe was not visible. Buried objects such as the pipe should be visible in reflection profiles as distinct hyperbolic reflections (Conyers 2004:54).

This test suggests that there is something about recently erupted basaltic cinders that is highly attenuating to radar energy at a very shallow depth. Similar GPR tests conducted in recently erupted basaltic lavas at Craters of the Moon in Idaho indicates that high amounts of titanium and iron in some basaltic ejecta of this sort increases radar attenuation, but only when low frequency antennas below 100 MHz are used (Heggy et al. 2006). That study showed that for most antennas used for archaeological purposes (200 MHz or higher), losses of radar energy with depth was a product of inhomogeneities in the basalt that produced energy scattering, caused by individual cinders, air vugs, or stratigraphic layering. The higher frequency antennas that employ shorter

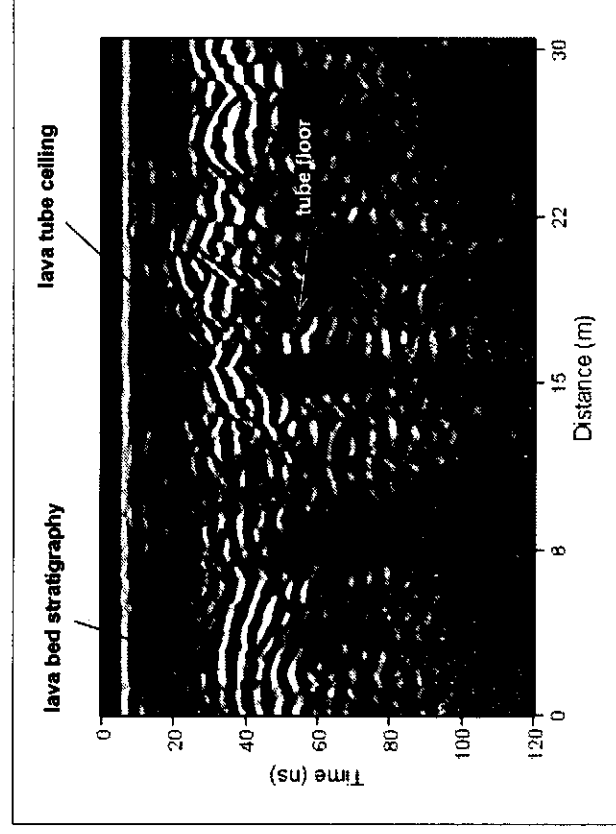


Figure 15. GPR reflection profile of the ceiling and floor of a lava tube, with adjacent lava stratigraphy, Island of Hawai'i.

wavelength radar energy would therefore be more likely scattered by the buried cinders in the ground, and therefore not recorded back at the surface antenna. This might be what caused poor energy penetration at the Kāne'ōhe cinder cone, as the ground was composed of cinders about 5 cm in diameter. However, laboratory measurements of basaltic lavas from Idaho showed that the magnetic permeability of tephra is higher than that of flow rocks because of its higher concentration of magnetite (Heggy et al. 2006). While this mineralogical variable has been noticed in Hawai'i (Olhoeft 1998), it is possible that in cinder cone areas the higher magnetite content of the lava could be playing a significant role in energy attenuation by destroying the magnetic portion of the electromagnetic waves. Other studies question this supposition (Saarenketo 1998), and tend to support the laboratory data of Robinson et al. (1994), suggesting that electrical conductivity variables caused by water and certain clay types are the more important factor in the depth of radar energy penetration.

In tests using the 270 MHz antennas in 5,000-year old basalt flows on the Island of Hawai'i, excellent energy penetration occurred to at least 4 m or more.

At O'oma Phupua'a lava tube, just northwest of the Kona airport, the top and floor of a lava tube were recorded in reflection profiles. The top of the tube is quite visible at 40 ns (Figure 15), which is 2.8 m below ground surface. Volcanic stratigraphy along the margins of the tube is well defined to a depth of about 5 m (60 ns). In this leeward area of Hawai'i, the basalt is mostly unweathered and appears to transmit energy readily to at least 5 or 6 m. The tests performed there are similar to those done by Olhoeft et al. (2000) at Volcanoes National Park on the southern coast of Hawai'i and mimic those from Craters of the Moon, Idaho (Heggy et al. 2006) and Iceland (Cassidy et al. 2004). It is apparent in these tests that fairly fresh lava is a good transmitter of radar energy, and in this case the magnetite and other ferromagnesian minerals do not appear to cause significant radar energy attenuation.

#### Conclusions

Coral sand and carbonate areas of Hawai'i along the coasts are a good medium for ground-penetrating radar mapping of buried archaeological materials and associated stratigraphy. Excellent resolution of buried features, using antennas in the 400 MHz frequency range, occurred to depths of between 1 and 2.5 m in this type of ground. Soils formed on basalt parent material in leeward areas, and in ejecta of recent cinder cones, was a poor medium for GPR due to the scattering effects of the cinders, and possibly the attenuating properties of magnetite in the tephra. In the other more typical reddish brown clay-rich soils found in Hawai'i, energy penetration to about 1.5–2 m was common. Penetration depths were much shallower in these soils in leeward areas, likely due to the electrically conductive clay types found in those environmental conditions. Penetration depth appears to increase in more windward locations where the higher conductivity clays in the soils have undergone alteration to less conductive clay minerals. This depth of radar energy penetration was the case at all tests except the recent cinder cone on the windward side where radar energy penetration was severely limited due to the dispersive nature of the cinders. In general, depth penetration to greater than about 2 m is not expected in weathered clay soils anywhere on O'ahu. This depth, how-

ever, is more than deep enough for the mapping of most archaeological sites found in this region of Hawaii. Relatively recent basalt flows on the island of Hawaii allowed energy penetration to at least 5–6 m, which is a depth suitable for mapping near-surface lava tubes.

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#### References Cited

- Bennett, J. D. 1994. Site Survey: Battery Carroll C. Riggs, Opaenua Ranch, O'ahu. In *Batteries Brodie & Opaenua (8-Inch 55 Caliber MKIX Naval Mounds) Saratoga Gun Group, North Shore, Oahu, T.H. Compiled for the Coast Defense Study Group (CSSG) and the Council of America's Military Past (CAMP)* by J.D. Bennett and Scarp Associates.
- Buck, S. C. 2003. Searching for Graves Using Geophysical Technology: Field Tests with Ground-penetrating Radar, Magnetometry and Electrical Resistivity. *Journal of Forensic Science* 48 (1):1–7.
- Cassidy, N. J., Russell, A. J., Pringle, J. K. and J. L. Carrivick. 2004. GPR derived architecture of large scale Icelandic Jokulhlaup deposits, Northeast Iceland. In *Proceedings of the 10th International Conference on Ground-penetrating Radar*, Delft The Netherlands June 31–24, edited by Evert Slob, Alex Yarovoy and Jan Rhebergen, Delft University of Technology, pp. 581–584.
- Conyers, L. B. 2004. *Ground-penetrating Radar for Archaeology*. Altamira Press, Walnut Creek, California.
- Conyers L. B. 2005. GPR Software Programs: [http://www.du.edu/~lconyers/SERDP/software\\_downloads.htm](http://www.du.edu/~lconyers/SERDP/software_downloads.htm).
- Conyers, L. B. 2006a. Ground-penetrating Radar. In *Remote Sensing in Archaeology*, edited by Jay K. Johnson, The University of Alabama Press, Tuscaloosa, Alabama, pp. 131–160.
- Conyers, L. B. 2006b. Ground-penetrating radar techniques to discover and map historic graves. *Historical Archaeology*, v 40, n. 3, pp. 64–73.
- Conyers, L. B. and J. E. Lucius. 1996. Velocity analysis in archaeological ground-penetrating radar studies. *Archaeological Prospection*, v. 3, pp. 312–333.
- Conyers, L. B. and T. Osburn. 2006. GPR Mapping to Test Anthropological Hypotheses: A Study from Comb Wash, Utah, American Southwest. In *Proceedings of the 11th International Conference on Ground-penetrating Radar*, Columbus Ohio, June 19–21, 2006, edited by Jeffrey J. Daniel, pp. 1–8.

- Doolittle, J. A. 2006. Ground-Penetrating Radar Soil Suitability Maps of the Conterminous United States. U.S. Department of Agriculture Natural Resources Conservation Service, <http://soils.usda.gov/survey/geography/maps/GPR/index.html>.
- Doolittle, J. A. and M. E. Collins. 1995. Use of soil information to determine application of ground-penetrating radar. *Journal of Applied Geophysics*, 33:101–108.
- Foote, D. E., Hill, E., Nakamura, S. and F. Stevens. 1972. Soil Survey of the Islands of Kauai, O'ahu, Maui, Molokai and Lanai, State of Hawaii. U.S. Department of Agriculture Soil Conservation Service. In cooperation with the University of Hawaii Agricultural Experiment Station, Honolulu, Hawaii.
- Gaffney, C. and J. Gater. 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Tempus Publishing, Stroud, Gloucestershire, England.
- Grant, J. A. and P. H. Schultz. 1994. Erosion of ejecta at Meteor Crater: Constraints from ground penetrating radar. 789–803 pp. In: *Proceedings Fifth International Conference on Ground-Penetrating Radar*. Waterloo Centre for Groundwater Research and the Canadian Geotechnical Society. June 12–14, 1994, Kirchner, Ontario, Canada.
- Grün, R. E. 1968. *Clay Mineralogy, 2nd Edition*. McGraw-Hill, New York.
- Hammatt, H. H. 2005. *Archaeological Literature Review and Field Inspection of the Proposed Kaiwo Drive Multi-Family Development in Waikiki, Kona District, Island of Oahu*. Draft copy prepared for Kusao & Kurahashi, Inc. by Cultural Surveys Hawaii, Inc., Kailua, Hawaii.
- Heggy, E., Clifford, S. M., Grimm, R. E., Dinwidie, C. L., Wyrick, D. Y. and B. E. Hill. 2006. Ground-penetrating radar sounding in mafic lava: Assessing attenuation and scattering losses in Mars-analog volcanic terrains. *Journal of Geophysical Research*, Volume III E06S04: pp. 1–16.
- Johnson, J. K. 2006. A comparative guide to applications. In *Remote Sensing in Archaeology*, edited by Jay K. Johnson, The University of Alabama Press, Tuscaloosa, Alabama, pp. 305–320.

- Kam, W. 1986. *Memorandum: Investigation of Discovery of Human Skeletal Remains Bellows AFS, Koolapoko, Oahu*. Prepared by the State of Hawaii, Department of Land and Natural Resources, Honolulu, Hawaii.
- Kvamme, K. L. 2003. Geophysical surveys as landscape archaeology. *American Antiquity*, v. 63, n. 3, pp. 435–457.
- Lucius, J. E. and M. H. Powers. 2002. GPR data processing computer software for the P.C. U.S.G.S. Open File Report 02-116. U.S. Department of the Interior, U.S. Geological Survey, Denver, Colorado, USA.
- Macdonald, A., Abbott, A. T., and F. L. Peterson. 1983. *Volcanoes in the Sea: The Geology of Hawaii*. University of Hawaii Press, Honolulu
- McDonald, L. M., Evangelou, V. P. and M. A. Chappel. 2005. Cation exchange, in *Encyclopedia of Soils in the Environment*, edited by Daniel Hillel. Elsevier Academic Press, Amsterdam, vol. 1, pp. 180–188.
- Miyamoto, H., Haruyama, J., Kobayashi, T., Suzuki, K., Okada, Y., Hishibori, T., Showman, A., Adam, P., Lorenz, R., Mogi, K., Crown, D. A., Rodriguez, J. A. P., Rokugawa, S., Tokunaga, T., and K. Masumoto. 2005. Mapping the structure and depth of lava tubes using ground penetrating radar. *Geophysical Research Letters*, v. 32, L21316, pp. 1–5.
- Olhoeft, G. R. 1998. Electrical, magnetic and geometric properties that determine ground penetrating radar performance. In *Proceedings of GPR 98, 7th International Conference on Ground Penetrating Radar*, edited by D.A. Noon, G. F. Stickley and D. Longstaff. SPIE International Society of Optical Engineering, 4084. pp. 482–487.
- Olhoeft, G. R., Sinex, D. B., Sander, K. A., Lagmanon, M. M., Stillman, D. E., Lewis, S., Clark, B. T., Wallin, E. L. Kaunahikaua, J. P. 2000. Hot and cold lava tube characterization with ground penetrating radar. In *Proceedings of SPIE, Eighth International Conference on Ground Penetrating Radar*, edited by David A. Noon, Glen F. Stickley and Dennis Longstaff, v. 4084, pp. 482–487.



- Putzi, J. L. and T. S. Dye. 2005. *Archaeological Monitoring Report for Replace Military Family Housing Projects Phase I at Hickam Air Force Base and Belmou Air Force Station, Hawaii*. Prepared for Rim Architects by T. S. Dye & Colleagues, Archaeologists, Inc., Honolulu, Hawaii.
- Reynolds, J. M. 1998. *An Introduction to Applied and Environmental Geophysics*. Wiley, New York.
- Robinson, D. A., Bell, J. P. and C. H. Batchelor. 1994. Influence of Iron Minerals on the determination of soil water content using dielectric techniques. *Journal of Hydrology*, v. 161, pp. 169-180.
- Saarenketo, T. 1998. Electrical properties of water in clay and silty soils. *Journal of Applied Geophysics*, v. 40, pp. 73-88.

- Schulze, D. G. 2005. Clay minerals. In *Encyclopedia of Soils in the Environment*, edited by Daniel Hillel. Elsevier Academic Press, Amsterdam, v. 1, pp. 246-254.
- Soil Survey Staff. 1999. *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys 2nd Edition*. US Department of Agriculture—Natural Resources Conservation Service, Agriculture Handbook No. 436, US Government Printing Office, Washington, DC.
- Vehara, G. 2005. Volcanic Soils. In *Encyclopedia of Soils in the Environment*, edited by Daniel Hillel. Elsevier Academic Press, Amsterdam, v. 4, pp. 225-232.

## Rights, Rites, and Riots: Values of Resources and Research in Hawaiian Archaeology

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### Introduction

As in many regions, Hawaiian archaeological resources are becoming increasingly recognized as valuable by a variety of stake-holders, yet the perceived value of archaeological research is somehow out-ranked by other potential values of the same resources. Artifacts, sites, and other resources are accepted as important for cultural meaning, general appreciation, and responsible management. Potential scientific value is generally recognized, but it is not always understood to be significant. Meanwhile, the practice of archaeology is viewed as a costly nuisance, an unwanted intrusion into the past, and a self-serving trivial hobby. Clearly, archaeologists need to improve the perceived value of their research as a significant and desirable contribution.

In the strictest sense, the archaeological value of a resource equals its potential to generate research data, but other stake-holders have different opinions about this largely misunderstood value relative to other considerations. Archaeological research constitutes only one of many possible values of any given resource (Carver 1996; Darvill 1995; Mathers et al. 2004). An abandoned site (for example, a set of mounds in the Kona Field System) may be viewed as less valuable than an intended housing complex, roadway, airport, industrial factory, agricultural field, or other development. A museum collection (such as the Forbes Cave assemblage), ancient monument (such as Pu'u o Mahuka Heiau), a geographically or culturally defined landscape (such as Waimea Valley of O'ahu Island), or other resource may be seen as important for traditional cultural practitioners or for members of a community-based group, but the role of archaeologists in learning new information is often disregarded. Nonetheless, these examples are potentially valuable sources of