File
Doolittle

United States Department of Agriculture | Soil Conservation Service | 160 East 7th Street Chester, PA 19013-6092

Subject: Ground-Penetrating Radar-
Legacy Project

Date: 17 February 1993

To: Dr. Robert Hommon
Archaeologist
Facilities Planning Department
PACNAVFACENGCOM CODE 233
Pearl Harbor, Hawaii 96860-7300

Purpose of Study:
The purpose of this study was to assess the suitability of using ground-penetrating radar (GPR) techniques for the non-invasive detection of subsurface human burials and archaeological resources in areas of Hawaii with coarse-textured soil materials.

Principal Participants:
Jim Doolittle, Soil Specialist, SCS, NSSC, Chester, PA
Scott Henderson, Environmental Facilities Dept., MCAS Kaneohe Bay, HA
Tirzo Gonzales, Senior Archaeologist, Advance Sciences Inc. San Diego, CA
Scott Williams, Senior Archaeologist, Ogden Environmental and Energy Services, Honolulu, HA
Loren Zulick, Archaeologist, Ogden Environmental and Energy Services, Honolulu, HA

Activities:
I arrived on Kauai on 10 January 1993. Field studies were conducted at the Pacific Missile Range Facility (PMRF) during the period of 11 to 15 January 1993. AT PMRF, two sites were surveyed: a grave site and the Niholi Archaeological Site. Equipment was packed and shipped to Oahu on 15 January. Field sites were reviewed and equipment unpacked at the Marine Corp Air Station (MCAS), Kaneohe Bay, on 18 January 1993. Field studies were completed at two sites (Pyramid Rock Beach and Fort Hase Cove) within MCAS, Kaneohe Bay, on 19 and 20 January 1993. Field studies were completed on a section of Waimanalo Bay within Bellows Air Force Base on 21 January 1993. Equipment was packed and picked up for assignments on Kahoolawe on 22 January 1993. Scott Williams and I reviewed field work and prepared plots of study sites on 22 January 1993.

Equipment:
The radar units used in this study were the Subsurface Interface Radar (SIR) System-8 and System-3 manufactured by Geophysical Survey Systems, Inc. The SIR System-8 consists of the Model 4800

control unit, the ADTEK SR 8004H graphic recorder, the ADTEK DT 6000 digital tape recorder, a power distribution unit, a 30 meter transmission cable and antennas. Because of component failures within the ADTEK DT 6000 tape recorder, a Model 38 video display unit with a SONY model TCD-D3 digital tape-corder had to be used.

The ADTEK SR 8004H graphic recorder malfunctioned during field work at PMRF on 14 January. A SIR System-3 unit was shipped from a SCS field office in Middleboro, Massachusetts, to the office of Ogden Environmental and Energy Service on 14 January. The unit arrived on 18 January. All field studies on Oahu was completed with the SIR System-3 unit. The SIR System-3 consists of the Model PR-8300 profiling recorder. The systems were powered by a 12-volt vehicular battery.

A Model 3110 (120 mHz) and Model 3102 (500 mHz) antennas were used in the field studies. A Model 705DA transceiver was used with the Model 3110 antenna.

Results:
Results from this study have further demonstrated the utility of using ground-penetrating radar for archaeological investigations in most areas of coarse-textured soils that fringe the Hawaiian Islands. In most areas of these soils, present GPR systems provide highly resolved subsurface profiles with adequate depths of observation for most archaeological and many engineering applications. Generally, computer processing of radar profiles to enhance the imagery is unnecessary and unwarranted.

This study further demonstrated the capabilities of GPR to detect anomalies in coarse-textured soils. With only one exception, anomalies detected with GPR were unearthed at inferred locations and anticipated depths. However, at most sites, interpretation and identification of cultural features were complicated by a large number of undesired reflections from modern cultural debris. This study emphasized the need to verify radar interpretations in the field.

This study demonstrated the need for an adequate assessment of soil, terrain, and cultural features at sites prior to recommending the use of GPR. As a pre-survey tool, the ability of GPR to rapidly reconnoiter large areas and locate potentially hazardous features was demonstrated at the Niholi Site at PMRF.

Results emphasized that the choice of grid interval(s) and survey design(s) are dependent on the size of the survey area, features being identified, desired detection probability, desired position accuracy, and time and resources available.

Results from this study confirm the advantages of conducting surveys along orthogonal grid lines. Results suggest that orthogonal traverses are more informative than traverses conducted in only one direction and at a slightly closer intervals. Unless traverses are conducted along orthogonal grid lines, linear features, such as utility lines or foundation walls, may be overlooked by even the most intensive survey. Regardless of survey design, the number of anomalies detected and site coverage decreases with widening of the grid interval.

Contracts for GPR surveys should specify the proportion of the area to be profiled and the number or proportion of detect anomalies that should be verified through excavation pits.

Recommendations:

Within the Hawaiian Islands, in areas of coarse textured soils, the use of ground-penetrating radar should become an accepted and standardized technique for archaeological, engineering, and environmental site assessments.

Considering the amount of coarse-textured soils under its authority, the Pacific Naval Facilities Engineering Command should review the merits and cost-effectiveness of purchasing a GPR System.

James A. Doolittle
Soil Specialist

cc:
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The enclosed five draft report copies are summitted in accordance with item a.(6), terms of agreement for Interagency Service Agreement between the Department of Agriculture, Soil Conservation Service, and the Department of the Navy, Pacific Division, Naval Facilities Engineering Command.

All radar profiles are in my possession and will be forwarded to you following the Navy review of the draft report and my completion of the final project report.

With kind regards.

James A. Doolittle
Soil Specialist

cc:
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GROUND-PENETRATING RADAR LEGACY PROJECT
DETECTION OF BURIED CULTURAL FEATURES IN AREAS OF COARSE-TEXTURED SOILS ON KAUAI AND OAHU, HAWAII

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ABSTRACT

Ground-penetrating radar (GPR) techniques are being more frequently used to aid reconnaissance and pre-excavation surveys at archaeological sites. A non-invasive, geophysical tool, GPR can provide continuous, high resolution graphic profiles of the subsurface. Ground-penetrating radar is a rapid, cost effective, and nondestructive method for identification and location analyses. Ground-penetrating radar can be used to facilitate excavation strategies, provide greater areal coverage per unit time and cost, minimize the number of unsuccessful exploratory excavations, and reduce unnecessary or unproductive expenditures of time and effort.

Compared with other geophysical techniques, GPR provides the highly resolved images of subsurface features. However, results of radar surveys are site specific and interpreter dependent. Because it does not perform equally well in all soils, GPR is an imperfect tool. Soils having high electrical conductivities are essentially radar opaque and the use of GPR in these soils is inappropriate. Interpretations depend on the experience of the operator, quantity and complexity of soil or geologic features, amount and quality of independent observation data, and the system and antennas used.

The purpose of this study was to assess the applicability of GPR techniques for the non-invasive detection of subsurface human burials and archaeological resources in Hawaii. The focus of this study was to assess the utility of GPR in areas of coarse-textured soil materials. The objective of this study was to assess the suitability of GPR as an archaeological tool.

Ground-penetrating radar is highly suited to archaeological investigations in most areas of coarse-textured soils that fringe the Hawaiian Islands. In most areas of these soils, present GPR systems provide highly resolved subsurface profiles with adequate depths of observation for most archaeological and many engineering applications. Generally, computer processing of radar profiles to enhance the imagery is unnecessary and unwarranted.

This study further demonstrated the capabilities of GPR to detect anomalies in coarse-textured soils. With one exception, anomalies detected with GPR were unearthed at inferred locations and anticipated depths. However, at most sites, interpretation and identification of pre-historic or early Hawaiian cultural features were complicated by an inordinate number of undesired reflections from modern cultural debris. The need to verify radar interpretations in the field is stressed. Survey requirements should specify that a representative number or

proportion of the anomalies detect with GPR be observed in excavation pits.

This study demonstrated the need for an adequate assessment of soil, terrain, and cultural features at sites prior to recommending the use of GPR. As a pre-survey tool, the ability of GPR to rapidly reconnoiter large areas and locate potentially hazardous features was demonstrated at the Niholi Site at PMRF.

Results emphasized that the choice of grid interval(s) and survey design(s) are dependent on the size of the survey area, features being identified, desired detection probability, desired position accuracy, and time and resources available. Survey requirements should specify the proportion of the area that should be profiled.

Results from this study confirm the advantages of conducting surveys along orthogonal grid lines. Results suggest that multiple orthogonal traverses are more informative than traverses conducted in only one direction and at a slightly closer intervals. Unless traverses are conducted along orthogonal grid lines, linear features, such as utility lines or foundation walls, may be overlooked by even the most intensive survey. Regardless of the survey method used, the number of anomalies detected and site coverage decreases with widening of the grid interval.

INTRODUCTION

Archaeologists are using ground-penetrating radar to facilitate excavation strategies, decrease field time and costs, and locate buried artifacts and archaeological features. Ground-penetrating radar compliments traditional methods of archaeological investigation. Compared with traditional methods, GPR techniques are faster, provide greater areal coverage per unit time and cost, increased confidence in site assessments, and are non-destructive.

Studies have documented the use of GPR to locate buried cultural features in many areas of the world (Batey, 1987; Berg and Bruch, 1982; Bevan, 1977, 1984a and 1984b; Bevan and Kenyon, 1975; Bevan et al., 1984; Bruzewicz et al., 1986; Cole, 1988; Dolphin and Yetter, 1985; Doolittle, 1988; Doolittle and Miller, 1991, Gibson, 1989; Grossman, 1979; Imai et al., 1987; Kenyon, 1977; Parrington, 1979; Sakayama et al., 1988; Vaughan, 1986; Vickers and Dolphin, 1975; Vickers et al., 1976; and Weymouth and Bevan, 1983). Recently, GPR technology has been used by forensic scientists for crime scene investigations (Davenport et al., 1988, 1990; Hoving, 1986; and Strongman 1992). Archaeological studies have been conducted with GPR on several of the Hawaiian Islands (Doolittle, 1990 and 1992). These studies document the efficiency of using GPR to facilitate excavation strategies, locate buried features, and aid site interpretations.

GROUND-PENETRATING RADAR

Ground-penetrating radar is an impulse radar system designed for shallow, subsurface investigations. This system operates by transmitting short pulses of electromagnetic energy into the ground from an antenna. Each pulse consists of a spectrum of frequencies distributed around the center frequency of the transmitting antenna. Whenever a pulse contacts an interface separating layers of differing electromagnetic properties, a portion of the energy is reflected back to the receiving antenna. The receiving unit amplifies and samples the reflected energy and converts it into a similarly shaped waveform in a lower frequency range. The processed reflected waveforms are displayed on a graphic recorder or are recorded on magnetic tape for future playback or processing.

The radar units used in this study were the Subsurface Interface Radar (SIR) System-8 and System-3 manufactured by Geophysical Survey Systems, Inc. [1]. The SIR System-8 consists of the Model

1. Use of trade names in this report is for identification purposes only and does not constitute endorsement by the authors or their institutions.

4800 control unit, the ADTEK SR 8004H graphic recorder, the ADTEK DT 6000 digital tape recorder, a power distribution unit, a 30 meter transmission cable and antennas. Because of component failures within the ADTEK DT 6000 tape recorder, a Model 38 video display unit with a SONY model TCD-D3 digital tape-corder was used. The SIR System-3 consists of the Model PR-8300 profiling recorder. The systems were powered by a 12-volt vehicular battery. The use and operation of GPR have been discussed by Morey (1974), Doolittle (1987), and Daniels and others (1988).

A Model 3110 (120 mHz) and Model 3102 (500 mHz) antennas were used in the field studies reported in this paper. A Model 705DA transceiver was used with the Model 3110 antenna. The lower frequency 120 mHz antenna has greater powers of radiation, longer pulse widths, and emits signals that are less rapidly attenuated by earthen materials than signals emitted from the higher frequency, 500 mHz antenna. The 500 mHz antenna is smaller, provides better depth and lateral resolution of subsurface features, but in most medium and fine textured soils, its performance and depth of observation are severely restricted. Along each traverse line, these relatively light-weight antennas were hand-towed or pulled behind a vehicle at an average speed of about 1.8 km h^{-1}.

The system radiates a conical beam and scans a footprint area beneath each antenna. The footprint area is considered circular and can be approximated by the formula:

$$2 \sin^{-1} (1/e),$$

where e is the dielectric constant of the scanned materials (Kovacs, 1991). At the time of this survey, an apparent dielectric constant of 8.0 was determined for areas of Jaucas soils. In this medium, the calculated beam-width for the antennas would be 14°. The estimated beam diameter would be about 12 and 25 cm at depths of 50 and 100 cm, respectively. It is important to stress that both antennas (500 and 120 mHz) will vertically profile columns of soil having similar horizontal dimensions. Often, field investigators have mistakenly believed that the physically larger 120 mHz antenna scans a larger footprint area than the smaller 500 mHz antenna.

Compared with other geophysical techniques, GPR provides the highest resolution of subsurface features. However, results of radar surveys are site specific and interpreter dependent. Interpretations depend on the experience of the operator, complexity of soil or geologic conditions, quantity and quality of independent observation data, and the system and antennas used. In many terrains, unless mounted in a suitable vehicle, the equipment is heavy and cumbersome to move and operate. In some areas, conductive soil conditions limit its profiling depth and applicability. Ground-penetrating radar is best suited for shallow (3 to 10 meters) investigations in electrically resistive mediums (i.e. dry, sandy soils).

SOIL FACTORS WHICH INFLUENCE GPR APPLICATIONS

When assessing the appropriateness of using GPR, a major consideration is signal attenuation at the desired antenna operating frequency (Daniels et al., 1988). The maximum depth of investigation decreases rapidly with increasing antenna frequency. High frequency antennas (>500 mHz) can provide well resolved images of shallow features in soils having low conductivity. In soil having high conductivity, levels of signal attenuation become prohibitive to GPR systems (Daniels et al., 1988). In these soils, low frequency antenna can be used to improve the depth of investigation. However, as lower frequency antennas are used to achieve the desired depth of investigation, the resolution of subsurface features is often reduced and smaller features are more likely to be overlooked.

The maximum depth of investigation is, to a large degree, determined by the conductivity of the soil. Soils having high conductivities rapidly dissipate the radar's energy and restrict investigation depths. The principal factors influencing the conductivity of soils to electromagnetic radiation are: (i) degree of water saturation, (ii) amount and type of salts in solution, and (iii) the amount and type of clay.

Generally, soils have lower signal attenuation when dry than when wet. As the water-filled porosity is increased, the rate of signal attenuation is amplified and the investigation depth of the radar is reduced. Even in arid and semi-arid environments, small amounts of moisture in the soil can significantly increase the rate of signal attenuation (Dolphin and Beaty, 1982; Dolphin and Yetter, 1985; Vickers et al., 1976). In the Hawaiian Islands, most areas of coarse-textured soils are excessively drained, seasonally dry, and have water tables at depths greater than 1.5 m.

Electrical conductivity is directly related to the concentration of dissolved salts in the soil solution. The concentration of ions in the soil solution is dependent upon the clay minerals present, the pH of the soil solution, the degree of water filled porosity, the nature of the ions in solution, and the relative proportion of ions on exchange sites. In general, soluble salts are more thoroughly leached from soils in humid than in arid or semi-arid areas. In semi-arid and arid areas, soluble salts of potassium and sodium and less soluble carbonates of calcium and magnesium are more likely to accumulate in the upper parts of soil profiles and produce high attenuation rates. High rates of signal attenuation and restricted profiling depths caused by high concentrations of dissolved carbonates within soil profiles were reported in studies conducted by Batey (1987), Doolittle (1988), and Grossman (1979). In some coastal areas of the Hawaiian Islands where the ground water is brackish and the water table is close to the surface, soluble salts accumulate in the soil profile (Doolittle, 1990). In these areas, present radar system can not profile below the water table.

The investigation depth of GPR increases as the clay content decreases or the proportion of low activity clays increases. Daniels and others (1988) observed a reduction in investigation depths from 5 meters (with a 1 gHz antenna) in sandy soils to 2 meters (with a 100 mHz antenna) in clayey soils. Ions absorbed on clay particles undergo exchange reactions with ions in the soil solution and contribute to the electrical conductivity of the soil. Smectite and vermiculite clays have higher cation-exchange capacities than kaolinite, gibbsite and goethite clays, and under similar soil moisture conditions, are more conductive. Signal attenuation and restricted profiling depths caused by relatively high clay contents were observed in archaeological investigations conducted by Batey (1987), Dolphin and Yetter (1985), Doolittle (1988), Gibson (1989), Vaughan (1986), and Vickers et al. (1976). Many moderately-fine and fine textured soils on the Hawaiian Islands are highly weathered and dominated by kaolinite, gibbsite, and other low-activity clay minerals. In these soils, depths of investigation range from 0.5 to about 3 meters with the 120 mHz antenna (Doolittle, 1990).

Under unfavorable conditions (wet, calcareous, clayey soils), the maximum profiling depth of the GPR is less than 0.5 meters. In addition, as low frequency antennas are required to achieve these profiling depths, resolution of subsurface features is often very poor. However, under resistive conditions (dry, coarse-textured soils), profiling depths of 5 to 35 meters have been achieved with the lower frequency antennas and 3 to 6 meters with the higher frequency antennas.

This study was restricted to areas of coarse-textured soils on the Islands of Kauai and Oahu. Areas of coarse-textured soils fringe many areas of the Hawaiian Islands. Earlier studies (Doolittle, 1990 and 1992) indicated the utility of using GPR for archaeological investigations in these soils. However, not all areas of coarse-textured soils are suited to GPR. Beach areas, which are influenced by tides or shallow water tables, are poorly suited to GPR applications because of the high concentrations of soluble salts. Steep and often unstable terrain conditions makes the profiling of dunes with GPR difficult and detrimental to colonizing plants.

Many areas of coarse-textured soils adjacent to beaches and dune areas are well suited to GPR. These very deep (> 1.5 m), excessively drained, coarse-textured soils have formed in stabilized coral deposits. Typically, these deposits are on long, narrow, area that parallel shorelines. These soils belong to the carbonatic, isohyperthermic Typic Ustipsamments family. Areas of these soils receive 10 to 40 inches of rain annually. Mean annual soil temperature is about $75^{\circ}F$. Because of the rapid infiltration rates and high hydraulic conductivities, these coarse-textured soils are generally dry for 90 or more cumulative days each year.

DETECTION OF BURIED CULTURAL FEATURES WITH GPR

Even with favorable site conditions (i.e. dry, coarse-textured soils) the detection of a buried cultural features with the GPR can not be guaranteed. The detection of buried cultural features is affected by (i) the electromagnetic gradient existing between a cultural feature and the soil, (ii) the size, shape, and orientation of the buried cultural feature, and (iii) the presence of scattering bodies within the soil (Vickers et al., 1976).

The amount of energy reflected back to an antenna by an interface is a function of the dielectric gradient existing between the two mediums. The greater or more abrupt the difference in dielectric properties, the greater the amount of energy reflected back to the antenna, and the more intense will be the amplitude of the image recorded on the radar profile. Buried cultural features with dielectric properties similar to the surrounding soil matrix are poor reflectors of electromagnetic energy and are difficult to discern on radar profiles (Doolittle, 1988; Gibson, 1989; Vaughan, 1986).

Most buried cultural features and layers contrast with the soil matrix. However, with the passage of time, buried cultural features decay or weather and can become less electrically contrasting with the surrounding soil matrix. For burials, the degree of preservation is dependent on both extrinsic and intrinsic factors. Intrinsic factors include the shape, size, density and chemistry of the cultural feature. For human burials, intrinsic factors are often dependent upon the genetic age and health of the deceased as well as length of burial (Killam, 1990). Extrinsic factors influencing the degree of preservation include time, soil type, moisture content, temperature, flora and fauna (Killam, 1990). Corpses deteriorate more rapidly in highly acidic soils than in neutral or alkaline soils (Mellett, 1992). Rodriquez and Bass (1985) noted a direct correlation between rates of decomposition or preservation and soil type, soil temperature, or depth of burial.

The size, orientation, and depth to an anomaly affects detection. Large objects reflect more energy and are easier to detect than small objects. Small, shallowly-buried features will be missed, unless located directly beneath the aperture of the radar antenna. With GPR surveys covering extensive areas, the detection of most small cultural features is considered fortuitous. The detection of a corpse reported by Mellett (1992) is an example of a fortuitous detection. Small, deeply buried cultural features are often more difficult to discern on radar profiles. In many soils, signal attenuation limits observation depths. In addition, the reflective power of an object decreases proportional to the fourth power of the distance to the object (Bevan and Kenyon, 1975).

Large, electrically contrasting features reflect more energy and are easier to detect than small, less contrasting features. Foundation walls of a large buried structure are more likely to be detected than a small, isolated artifact. Bevan (1991) noted that it is more likely that GPR will detect the disturbed soil within a grave shaft, a partially or totally intact coffin, or the chemically altered soil materials which directly surrounds a burial rather than the bones themselves. Killam (1990) believes that most bones are too small and not directly detectable with GPR. This author noted that the disruption of soil horizons makes most graves and some cultural features detectable. However, in soils that lack contrasting horizons or geologic strata, the detection of a grave shafts is more improbable. In addition, with the passage of time, the signs of disturbances are erased by natural soil-forming processes.

Commonly, in prehistoric burials on the Hawaiian Islands, bodies were interred in a "flexed" or fetal position. Though this procedure reduces the lateral extent and the probability of locating a burial with a single pass of the antenna, it increases the likelihood of detection provided the antenna passed directly over the burial site. If an antenna passes directly over a flexed burial, the concentration of bones should increase the probability of detection.

IDENTIFICATION OF BURIED CULTURAL FEATURES ON RADAR PROFILES

The identification of a subsurface reflector is based on knowledge, experience, and inferences. The identification of subsurface anomalies depends on local soil conditions, and the depth, geometry, and composition of the feature (Mellett, 1992).

In highly attenuating soils, profiling depths are restricted and many subsurface features are not directly sensed with GPR. Under highly attenuating conditions, the location and identification of buried cultural features are frequently inferred from bowed, disrupted, or disturbed soils horizons. At many sites, the most distinctive feature of a grave is the disturbed soil materials which fill and cover the grave shaft (Bevan, 1991). However, caution must be exercised as a number of artificial and natural processes can produce disturbed soil conditions.

Cultural features are difficult to distinguish in soils having numerous rock fragments, tree roots, animal burrows, modern cultural features, or stratified or segmented soil layers. These scattering bodies produce undesired subsurface reflections which complicate radar imagery and mask the presence of buried cultural features. Under such conditions, "desired" cultural features can be indistinguishable from the background clutter. In soils having numerous scattering bodies, results from GPR survey often provide little meaningful information to supplement random sampling procedures (Bruzewicz et al., 1986). The identification of buried cultural features was complicated by scattering bodies in radar surveys conducted by Bevan (1991), Dolphin and Yetter (1985), Doolittle (1988), and Vaughan (1986).

The size, orientation, and depth to buried features affect their discernment with GPR. The size and shape of a subsurface anomaly may suggest its identity. Subsurface anomalies that are narrow and linear may, depending on their dimensions, suggest a buried utility line, road, foundation wall, or burial. Burials may range in depth from shallow (<50 cm) to very deep (>150 cm). Burials may be uniformly spaced or aligned in a particular direction. Bartel (1982) observed burials aligned with the orientation of the solar traverses. Multiple cultural layers or stacked burials have been inferred (Doolittle, 1990; Mellett, 1992). Multiple, randomly spaced, subsurface anomalies occurring at a common depth may suggest cultural features from a unique period of occupation history. In instances where features are small, randomly distributed, non-aligned, and/or variable in depth, positive identification can not be assured from radar interpretations and a greater number of observation pits are often required to verify interpretations.

In several studies, subsurface anomalies have been identified as cultural features or burials based on above-ground conditions. This often occurs in highly attenuating mediums where GPR is severely depth restricted. In these mediums, GPR provides meager and often poorly resolved subsurface information. Lacking adequate subsurface information, interpretations are more likely to be made on the basis of conspicuous surface features rather than from imagery appearing on radar profiles. Foundation walls which are not deeply buried can produce low, linear ridges. Soil materials used to fill a grave shaft or excavation often settle, leaving an obvious depression. In some areas, burials are outlined with borders of rock fragments or other objects. In these examples, unless the GPR provided supplementary, subsurface information, its use should be viewed with deep skepticism.

In the search for buried cultural features with GPR, success is never guaranteed. Even under ideal site and soil conditions, buried cultural features will be missed with GPR. The usefulness of GPR for site assessment purposes depends on the amount of uncertainty or omission that is acceptable.

SURVEY PROCEDURES

The most accepted and perhaps efficient procedure to detect and chart the location of buried cultural features with GPR is to establish a grid across the survey area. Generally, rectangular grids are preferred, though Bevan (1977), in a survey of military earthworks, described a grid consisting of lines radiating outwards from a fortification like spokes of a wheel. Berg and Bruch (1982) described the use of "wildcat" surveys. These surveys consist of random traverses. Wildcat surveys provide an effective method to quickly reconnoiter large areas for prominent archaeological features or to locate sub-areas with higher concentrations or clusters of cultural features which may indicate archaeological sites. Most GPR surveys are conducted using multiple traverses along parallel and/or orthogonal grid lines (Hoving, 1986; Bevan, 1991). However, the comparative advantages of conducting radar traverses in one or two directions has not been adequately assessed.

Grid dimensions are often dictated by the size and shape of the survey area, terrain conditions, and/or of above-ground cultural features. Generally, as most radar units are cumbersome to operate, deeply dissected, steep, bouldery, or densely vegetated terrains are avoided. Buildings, foundation walls, utility lines, fences and other above-ground features restrict the extent of radar surveys.

Grid interval is a compromise among the purpose of the survey, size of the area to be surveyed, features being identified, available time, desired detection probability, and desired position accuracy. For reconnaissance surveys, large grid intervals (5 to 10 meters) are often used to define the general locations of larger subsurface anomaly or clusters of smaller point anomalies, and to assess their relative density per unit area or general site attributes. Larger grid intervals or traverse spacings have been used for reconnaissance surveys designed to expeditiously cover extensive areas in search of burial sites (Hall, 1992). Once the general locations of anomaly clusters have been defined, smaller grid intervals can be used to more precisely chart the location, spatial extent, and identity of subsurface anomalies. Regardless of the interval used, it is recommended that search areas be subdivided into sections that can covered in a days effort (Killam, 1990).

Studies have used 1.0 to 3.0 meters to locate buried hearths and foundation walls (Batey, 1987; Bevan et al., 1984; Doolittle, 1988; Fischer et al. 1980; and Grossman, 1979), and 5.0 to 10.0 meters to define the general location of buried dwellings (Imai et al., 1987; Vickers et al., 1976; and Weymouth and Bevan, 1983). To detect burials within designated or confined areas, grid intervals have ranged from 15 to 150 cm (Bevan, 1991; Hoving, 1986; Mellett, 1992; Strongman, 1992; Unterberger, 1992; and Vaughan, 1986). The smaller grid intervals are required to detect smaller burials of infants or cremation urns (Unterberger, 1992). Even when closely spaced grid intervals (50 cm) and relatively high frequency antennas (500 mHz) are used, some buried cultural features will be overlooked (Doolittle, 1990).

Survey procedure involves moving the radar antenna along traverse or grid lines at a reasonably constant rate. As the antenna passes each reference point, the operator records the position by impressing a dashed, vertical line on the radar profile. The dashed, vertical lines help to locate subsurface features along the grid lines (see Fig. 1).

Results from radar survey are displayed on graphic profiles. These profiles should be annotated (with site, traverse line, fiducial marks, distance, and directional information) and interpreted in the field. Interpretations are frequently transferred to plots or maps of the site (Heimmer, 1992). Two-dimensional plots charting the locations of the recognized anomalies are useful for determining the spatial distribution, patterns, and boundaries of areas containing buried cultural features. Prior to the completion of a radar survey, a prescribed number of interpreted subsurface features should be verified in the field.

INTERPRETING RADAR PROFILES

The graphic recorder uses a variable gray scale to display the reflected waveforms. A graphic profile is developed as electrosensitive paper is moved under the revolving styli of the graphic recorder. The intensity of an image is dependent upon the amplitude of the reflected signals.

Figure 1 is an example of a graphic profile. The horizontal scale represents units of distance traveled along an antenna traverse. This scale is dependent upon the speed of antenna advance along a traverse line and the rate of paper advance through the graphic recorder. The vertical scale is a time or depth scale which is based on the velocity of signal propagation. The evenly spaced horizontal lines are scale lines. Scale lines provide reference lines for relative depth measurements.

In Figure 1, the dashed vertical lines are reference markers inserted on the graphic profile by the operator to indicate known antenna positions or observation points along traverses. On most radar profiles, though the actual distances are uniform, the spacing between grid intersect appears to be variable. Inconsistent spacings of grid intersects on radar profiles are caused by non-uniform speeds of antenna advance across the ground surface and/or failures of the operator to impress the marker as the antenna passes referenced locations. While conducting most GPR surveys, it is difficult to maintain a constant speed of advance over the ground. Electrical devices are available which will automatically impress marks on radar profiles at preset distances. These devices can be attached to survey wheels or odometers on vehicles. In addition, processing techniques are available to "normalize" the distances between grid intersects.

However, this procedure assumes uniform speeds between the marked grid intersects.

The four basic components of a radar profile have been identified in Figure 1. These components are the start of scan pulse (A), inherent system noise (B), surface image (C), and subsurface interface images (D). Each of these components, with the exception of the start of scan pulse, is generally displayed as a group of dark bands. The number of bands can be limited by high rates of signal attenuation or superposed signals. These bands limit the ability of GPR to discriminate closely spaced interfaces. The dark bands occur at both positive and negative signal amplitudes. The narrow white band(s) separating the darker bands represent the neutral or zero crossing between positive and negative signal amplitudes.

The start of scan image (see A in Fig. 1) results from direct feed-through of transmitted pulses into the receiver section of the antenna. Though a source of unwanted clutter, the start of scan pulse is often used as a time reference line.

Reflections unique to each of the system's antennas are the first series of multiple bands on graphic profiles. Generally the width of these bands increases with decreasing antenna frequency or signal filtration. These reflection (see B in Fig. 1) are a source of unwanted noise on graphic profiles.

The surface image (see C in Fig. 1) represents the ground surface. Below the image of the surface reflection are images from subsurface interfaces (see D in Fig. 1). Interfaces can be categorized as being either plane or point reflectors. Most soil horizons, buried cultural layers, geologic strata appear as a series of continuous, parallel bands similar to those appearing in the left-hand portion of Figure 1. Features that produce these reflections are referred to as "plane reflectors." Small objects such as rocks, roots, or buried cultural features will produce a hyperbolic pattern similar to those appearing in the right-hand portion of Figure 1. Features that produce these reflections are referred to as "point reflectors." In this paper, point reflectors may be referred to as "point anomalies."

The GPR is a time scaled system. This system measures the time that it takes for electromagnetic energy to travel from the antenna to an interface (e.g. buried cultural feature, soil horizon) and back. In order to convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationship among depth (d), two-way, pulse travel time (t), and velocity of propagation (v) are described by the following relationship:

$$v = 2d/t$$

The velocity of propagation is primarily effected by the dielectric constant (e) of the profiled material(s) according to the equation:

$$e = (c/v)^2$$

where c is the velocity of propagation in a vacuum (3×10^8m/s). The amount and physical state (temperature) of water has the greatest effect on the dielectric constant. Tabled values are available that approximate the dielectric constant and velocity of propagation through some materials. However, as discussed by Daniels and others (1988), the determination of these values is largely experimental.

Generally, for most archaeological investigations, observation pits are used to verify interpretations and confirm the depths to known reflectors. These data are used to determine the depth scale.

DETECTION OF BURIED CULTURAL FEATURES IN AREAS OF COARSE-TEXTURED SOILS ON KAUAI AND OAHU, HAWAII

The purpose of this study was to assess the applicability of GPR techniques for the non-invasive detection of subsurface human burials and archaeological resources in Hawaii. The focus of this study was to assess the utility of GPR on areas of sand deposits and coarse-textured soils. The objective of this study was to assess the suitability of GPR as an archaeological tool, not to retrieve or analyze archaeological resources. As a consequence, site disturbance was kept to a minimum. Some areas were purposely excluded from the study because of adverse vegetation, slope, or other terrain conditions. Had the need existed, all excluded areas could have been surveyed. However, site preparation (removal of vegetation) would have been time consuming.

Along many coastal areas of the Hawaiian Islands, native Hawaiian burials and archaeological resources are known to occur. In some of these areas, coarse-textured soils provide a highly suitable environment for the use of GPR techniques. In these soils, rates of signal attenuation are low and depths of observation are generally greater than 2 meters. These soils generally occur on narrow coastal fringes or along restricted drainageways, and are limited in extent. In addition, not all areas of coarse-textured soils or deposits are equally suited to GPR investigations. The most suitable soils for GPR are members of the coarse-textured Jaucas and Mokuleia series. Jaucas is a member of the carbonatic, isohyperthermic Typic Ustipsamments family; Mokuleia is a member of the sandy, carbonatic, isohyperthermic Entic Haplustolls family. In some areas of Mokuleia, finer-textured layers of alluvium restrict the observation depth of GPR.

This study was restricted to areas of Jaucas soils and beaches on the Islands of Kauai and Oahu. According to Foote and others (1972), Jaucas soils occur on about 4000 acres of Kauai (1.1 percent of area) and 4800 acres of Oahu (1.2 percent of area). On each island, areas of beaches and dune land provide additional areas suitable for GPR. However, because of high salt concentrations, not all beach areas are suited to GPR. Dune lands are environmental sensitive areas and some are unsuited to GPR because of relatively steep slopes. Table 1 lists, for Kauai and Oahu, the approximate acreage of soils considered suitable for GPR.

Table 1

Approximate Acreage of Soils Considered Suitable for GPR on Kauai and Oahu

(from Foote, et al., 1972)

Soil Map Unit	Kauai	Oahu
Jaucas sand, 0 to 15 percent slopes	----	4,795
Jaucas loamy fine sand, 0 to 8 percent slopes	3,562	----
Jaucas loamy fine sand, dark variant, 0 to 8 percent slopes	377	----
Mokuleia fine sandy loam	1,639	
Beaches	741	1,772
Dune land	638	----
total acreage	6,957	6,567

This report summarizes the results of field studies conducted on Kauai and Oahu during the period of 10 to 22 January 1993. Field studies were completed at the Pacific Missile Range Facility on Kauai, and at the Kaneohe Bay Marine Corps Air Station and Bellows Air Force Base on Oahu.

PACIFIC MISSILE RANGE FACILITY (PMRF), KAUAI

Grave Site near Building 389

Initial field work was directed towards a site within PMRF that was known to contain four graves. The graves had been detected during excavations for utility lines. As the site contained four known burials, the purpose of the survey was to assess the capabilities of GPR technique to detect these burials. In addition, results would help to document the location of other anomalies and subsurface features within the site. The survey was designed to test different antennas and sampling designs and intensities.

A 20 by 13 meter, rectangular grid was established across the site. A transit was used to establish grid corners. The grid interval was 1 meter. Survey flags were inserted in the ground at one meter intervals and at each of the 294 grid intersects. The locations of the four known burials within the site were identified prior to the GPR survey.

Soil maps (Foote et al., 1972) revealed that the Grave Site was located in an area of Jaucas loamy fine sand, 0 to 8 percent slopes. This coarse-textured soil is relatively resistive and provides a favorable environment for GPR applications. Within the site, slopes were level (< 1 percent).

Calibration trials were completed with the SIR System-8 and the 120 mHz and 500 mHz antennas. A scanning time of 60 nanoseconds (ns) and a scanning rate of 25.6 scans/sec were used in these trials and in all subsequent field work on Kauai. Because of the sensitive nature of this site, no ground-truth observations were made.

The depth of observation was estimated from the depth to a known utility line located along the eastern boundary of the study site. This utility line was buried at a depth of about 40 centimeters and was clearly resolved on most radar profiles. With a two-way, scanning time of 60 ns and using the 120 mHz antenna, the estimated depth of investigation was 3.21 meters. This estimate assumes a velocity of propagation of 0.107 m/ns.

At the time of this survey, the estimated dielectric constant for Jaucas soils was 8.0. Although this survey was conducted with an investigation depth of about 3.2 meters, deeper depths of investigation could have been achieved in many areas of this soil with either the 120 mHz or 500 mHz antenna. Deeper depths of investigation were not contemplated as the desired targets (buried cultural features) were buried principally within the upper 1.5 meter of the soil profile. Had deeper depths of investigation been attempted, the resolution and clarity of many shallow and moderately deep subsurface features would have been sacrificed.

During calibration trials, multiple traverses were conducted with both the 120 mHz and 500 mHz antennas. Figure 2 compares the profiles of the 120 mHz (A) and 500 mHz (B) antennas along a portion of the same grid line. In Figure 2, the vertical scales are time scales (in nanoseconds) and the horizontal scales are distance scales (in meters). The distance between the dashed, vertical lines is 1 m.

Similar strata (designated "1" and "2") have been identified in each figure. These strata represent the internal bedding structure of former dunes. In the lower, left-hand portion of Figure 2B, signals from the 500 mHz antenna have been attenuated, resulting in faint reflected signals below a depth of about 35 ns or about 1.9 m. As this portion of the traverse was nearest the coast, higher concentrations of soluble salts in the lower part of soil profiles were assumed to be responsible for the high attenuation and restricted profiling depths.

Informal procedures for field operations recommend, if more than one antenna are available, to use the antenna with the highest frequency that attains the desired depth of investigation. Higher frequency antennas provide better horizontal and vertical resolution of subsurface features. Resolution is defined as the ability to discern closely spaced interfaces.

Both antennas provided adequate depths of observation. Both antennas discerned planar features such as soil horizons and geologic strata. However, resolution was higher with the 500 mHz than with the 120 mHz antenna. In Figure 2, the 500 mHz antenna discerned multiple, finely stratified layers in areas where the 120 mHz antenna distinguish only the coarser stratifications. Furthermore, compared with the 120 mHz antenna, the 500 mHz antenna defined a greater number of segmented soil layers and features. These features were believed to have included coral fragments, roots, and small cultural features. However, the large numbers of soil layers and features discerned with the 500 mHz antenna produced undesired reflections which obscured the detection and identification of reflections from desired targets, and complicated interpretations.

At this site, the 500 mHz antenna did not adequately differentiate known burials and buried cultural features from soil horizons and geologic strata. With the 500 mHz antenna, some reflectors, evident with the 120 mHz antenna, were not apparent, and interpretations were less straightforward and more "interpretative." In Figure 2A, with the 120 mHz antenna, the locations of two metallic reflectors, possibly buried pipes, are apparent and have been labelled (see "A" and "B" in Fig. 2A). Metallic reflectors are identified by the reverberated echoes that they produce on radar profiles. These reverberations repeat vertically down the radar profiles. Radar profiles collected with the 120 mHz antenna contained less information, but more clearly disclosed the location and identity of buried metallic reflectors and utility lines.

The use of the lower frequency, 120 mHz antenna was preferred by the operator and field archaeologist. This preference was prompted by the relative ease of interpretations rather than by any concerns for higher resolution of subsurface features. Had the objectives of this study included a detailed stratigraphic investigation of the site, the 500 mHz antenna would have undoubtedly been a more suitable selection. All further GPR field studies at the Pacific Missile Range Facility were conducted with the 120 mHz antenna.

Figure 3 is a representative radar profile from the Grave Site. This profile was obtained with the 120 mHz antenna along north-south traverse number 13 (see Fig. 6). In Figure 3, the vertical scale is a time scale (in nanoseconds) and the horizontal scale is a distance scale (in meters). The distance between the dashed, vertical lines is 1 m.

In Figure 3, a known burial site is located near "A." The location of this burial (below the 5 m mark) was partially masked by soil horizons. The disruption of soil horizons to the upper-right and a distinct point reflector to the lower-right of "A" may represent the grave shaft and the burial. However, the burial may no-longer be a good reflector. The integrity of the grave site was disturbed by excavations for a utility line and some cultural features within the burial may have been destroyed or scattered during excavation. A second point reflector has been identified above "B." In Figure 3, the location of two metallic reflectors, possibly buried pipes, have been labelled "P."

The GPR survey of the Grave Site was completed by towing the 120 mHz antenna along each grid line. Traverses were completed in both north-south (21 lines) and east-west (14 lines) directions. As the antenna past each grid intersect, the operator recorded the position by impressing a dashed, vertical line on the radar profile.

The operator attempted to maintain a constant speed of advance along each traverse line and to record the position of each intersect as the antenna drew abreast of the survey flags. Slight spatial discrepancies were immediately noted in the field. Though slight, these incongruities affected the proper location of most subsurface anomalies charted on the two-dimensional plots. On each of the enclosed two-dimensional plots, no adjustments have been made in the location of detected subsurface anomalies from their estimated positions.

The center of the antenna was taken as the point of observation. Generally, for the 120 and 500 mHz antennas, this position tracked about 50 and 15 cm away from the actual grid intersect, respectively. On radar profiles, the positions of anomalies discovered between grid intersects were estimated, assuming a constant speed of advance, at a proportional ground distance. As the antenna radiates energy into the subsurface in a conical fashion, buried anomalies on either side of the center of the radar tract may have been detected.

Figure 4 is a two-dimensional plot of the point anomalies detected within the Grave Site near Building 389. The actual Grave Site is bounded by a low, chain fence which is shown on all of the enclosed plots from this site. The survey area extended beyond the chain fence. The data plotted in Figure 4 were compiled from radar traverses spaced at one meter intervals and conducted along orthogonal grid lines. The locations of the detected anomalies are indicated by dark circles. The locations of the four known burials are indicated with star symbols. Several of the more closely-spaced anomalies probably represent the same feature. Frequently on orthogonal traverses, anomalies located near the crossing points and detected on two radar traverses will, if uncorrected, plot at two slightly different positions.

Figure 4 contains 97 point anomalies. This plot provides the most detailed information of the site. The locations of three utility lines are evident along the east (first 4 meters of north-south line 1, and along north-south line 3) and the south (line extending from southwest corner to the aforementioned utility lines along eastern border) margins of the site. However, a fourth, known utility line, which extends diagonally (NNE to SSW) across the site, is difficult to detect because of the large number subsurface anomalies in the west and northwest portions of the study site. Measurement errors and non-uniform speeds of antenna advance has resulted in the apparent non-alignment of point anomalies from these utility lines.

No burials could be inferred directly from interpretation of the radar profiles. Interpretations of potential burials were complicated by the lack of characteristic graphic signatures from the known grave sites, superimposed reflections from utility lines masking reflections from the know grave sites, and the large number of subsurface point anomalies within the site.

The site contains a large number of randomly spaced point anomalies. The site has been heavily disturbed by the installation of four utility lines and a utility pad (see northeast corner of Fig. 4). The most probable locations for additional burials appeared to be in the west and northwest portions of the study site where a significant number of randomly spaced anomalies occur.

Figure 5 and 6 are two dimensional plots of subsurface anomalies prepared from data collected with the GPR along parallel grid lines spaced at a one meter interval. Figure 5 represents the information collected along the east-west grid lines. Figure 6 represents the data collected along the north-south grid lines. These figures contain a similar number of point anomalies (Figure 5, 52; Figure 6, 49).

It is apparent from figures 5 and 6 that the detection of buried linear features such as utility lines or foundation walls requires these features to be crossed by the antenna. In addition, in order to be inferred, linear features must be crossed by a sufficient number of traverses. In Figure 5, the utility line along the southern margin of the study area was missed because the radar did not pass over it. However, sufficient data was available to infer the presence of the two utility lines along the eastern and southeastern portions of the study site. In Figure 6, the east-west trending utility line near the southern boundary of the site is evident, but insufficient data is available to infer the presence of the two lines along the eastern and southeastern portion of the study site. In both figures, a diagonal pattern (trend is NNE to SSW) of point anomalies is evident in the northwest portion of the site. However, these anomalies are too numerous and nonaligned for a utility line to be identified. In these figures, the large number of randomly spaced point anomalies in the north and western portions of these plots has masked the presence of this utility line.

Figure 7 is a two dimensional plot of subsurface anomalies prepared from data collected along orthogonal grid lines spaced at a two meter interval. This figure contains 54 point anomalies. Compared with orthogonal traverses conducted at a one meter interval, orthogonal traverses conducted at a two meter interval required less field time, covered 11 % less area, and detected 44 % fewer anomalies. Undoubtedly, the one meter interval provides more information. However, neither interval disclosed the locations of all subsurface anomalies. Even with a grid interval of less than 50 cm some anomalies would be overlooked or misinterpreted. If an objective of a GPR survey is to delineate the general locations of areas suspected of containing clusters of subsurface anomalies, then interpretations derived from both intensities of survey (1 and 2 meter intervals) are comparable.

Figure 8 and 9 are two dimensional plots of subsurface anomalies prepared from data collected along parallel grid lines spaced at a two meter interval. Figure 8 represents information collected along the east-west grid lines. Figure 9 represents the data collected along the north-south grid lines. These figures contain a similar number of point anomalies (Figure 8, 33; Figure 9, 25).

The data was manipulated to analyze the relationships among grid intensity or interval, site coverage, and the amount of anomalies detected. The results are summarized in Table 2. The tabulation is based on the number and lengths of GPR traverses and assumes that the antenna scans a 12 cm wide foot-print area at a depth of 50 cm below the surface. Duplicate areas scanned on orthogonal traverses were deleted from tabulations.

TABLE 2

Radar Grid Intensity and Point Anomalies Detected with 120 mHz Antenna at the Grave Site near Building 389

Grid Interval	Directions	Coverage	Anomalies
1 meter	2	24%	97
1 meter	1 (E-W)	13%	52
1 meter	1 (N-S)	13%	49
2 meters	2	13%	54
2 meters	1 (E-W)	6%	33
2 meters	1 (N-S)	7%	25

Grid interval represents a compromise among the purpose of the survey, availability of time and resources, features being detected, local terrain conditions, and the desired detection probability. It is apparent from the data in Table 2 that conducting traverses along orthogonal grid lines yields more information than conducting traverses along parallel grid lines alone. Regardless of the survey method used, the number of anomalies detected and site coverage decreases with widening of the grid interval.

The results of this investigation suggest that addition point anomalies, possibly burials, are clustered in the west and northwest portion of the site. The site has a long and complicated history of use. Cultural features from several periods may be present. Within this site, the large number of subsurface anomalies has stymied some interpretations. Where known to exist, some burials were either not detected or partially masked by adjoining subsurface features. The burials did not provide distinct or unambiguous graphic signatures which would have enabled their identification. The locations of the four buried utility lines were compared with official records and confirmed on radar profiles and plots. This study found that unless traverses are conducted in more than one direction, some features may be overlooked by even the most intensive survey. Also, to detect the presences of linear features, these objects must be cross by the antenna on at least 3 to 4 closely-spaced traverses. Detection of linear features is facilitated when reflections are aligned and not masked by reflections from other subsurface features. Results suggest that orthogonal traverses are more informative than traverses conducted in only one direction and at a slightly closer intervals.

<u>Niholi Archaeological Site</u>
The site was located on a gently sloping, east-facing backslope area to a beach scarp (see Figure 10). The Pacific Ocean was located to the west of the study site. Erosion had exposed several imu's and dark-colored cultural layers along the summit and shoulder slopes of the beach scarp. The study site was in an area of Jaucas loamy fine sand, 0 to 8 percent slopes. Although the study site has relatively low relief (@ 1.6 m), several small, shallow gullies extended inland from the beach scarp.

An irregularly shaped, rectangular grid was established across the study site (see Figure 10). Areas containing gullies were not surveyed. A densely vegetated area in the southeast portion of the study site was excluded from the survey. The maximum dimensions of the grid were 135 by 30 meters. The grid interval was 5 meters. Survey flags were inserted in the ground at each grid intersect. A transit was used to establish grid corners and to determine surface elevations at each of the 151 grid intersects. The lowest point in the grid was used as datum.

Calibration trials were completed with the SIR System-8 and the 120 mHz and 500 mHz antennas. A scanning time of 60 ns and a scanning rate of 25.6 scans/sec were used in these trials and in all subsequent field work at this site. Following field calibration trials, the survey was conducted with the 120 mHz antenna. It was felt that the 120 mHz antenna provided more interpretable and less complicated graphic profiles.

Figure 11 is a two-dimensional plot of the anomalies detected within the site. This plot has been prepared from data collected along orthogonal traverses spaced at five meter intervals. The locations of the detected anomalies are indicated by dark circles. Following the GPR survey, the identity of four anomalies were verified in small observation pits. The locations of the four pits are indicated with star symbols.

Figure 11 contains 162 point anomalies. Considering the relatively coarse grid interval used at this site, the number of detected anomalies was considered most astonishing. The anomalies appear to be most concentrated within 15 m of the beach scarp (west). The number of detected anomalies decrease towards the north and east. Many of the anomalies appear to form linear features. However this pattern is, in part, an aberration produced by the glut of point anomalies, limited GPR traverses, and relatively coarse grid interval used.

Figure 12 is a representative radar profile from the Niholi Site. This profile was obtained along east-west traverse number 125 (see Figure 11). In Figure 11, three of the six anomalies which appear to be located along east - west grid line 125 were detected on north - south traverses. In Figure 12, the vertical scale is a time scale (in nanoseconds). The estimated velocity of propagation was 0.107 m/ns. The horizontal scale is a distance scale (in meters). The distance between the dashed, vertical lines is 5 m.

Compared with the Grave Site, radar profiles from the Niholi Site contained fewer subsurface soil and geologic stratifications. Within the Niholi Site, the lack of subsurface reflections may be related to higher signal attenuation or the absence of well-expressed stratifications within the sand deposits. The Niholi Site is located closer to the ocean and the influence of salt water.

In Figure 12, three subsurface point anomalies have been identified. Two of these anomalies, "A" and "B", were ground-truthed. The anomaly labeled "A" was an imu buried at a depth of 38 cm. The imu consisted of sandstone and vesicular basalt rock fragments with charcoal. With the 120 mHz antenna, these rock fragments produced a single reflection. The anomaly that produced the reflection at "B" was not uncovered during test excavations. This anomaly was more deeply buried (@ 1.1 m) and probably more removed than expected from the radar traverse and the point of observation.

Successive radar profiles from the Niholi Site revealed the presence of two prominent, linear features (see Figure 11). Each of these features disrupted the natural soil continuum, and contained distinct and often repeatable assemblages of subsurface reflectors. The features included segmented and inclined plane reflectors, and prominent point reflectors.

Reflections from these two prominent, linear features are displayed in Figure 13. Figure 13 is a radar profile obtained along east-west grid line number 70 (see Fig. 11). In Figure 13, the vertical scale is a time scale (in nanoseconds). The estimated velocity of propagation was 0.107 m/ns. The horizontal scale is a distance scale (in meters). The distance between the dashed, vertical lines is 5 m.

The eastern-most feature was larger (about 4 by 40 m), appeared to contain truncated and disturbed soil horizons (see "A" in Fig. 13) and several point anomalies buried at different depths. This feature was interpreted as a probable landfill. This interpretation was latter confirmed by members of the Public Works Department of the Pacific Missile Range Facility. As this landfill was unknown to the investigators prior to field work and radar interpretations, the survey documented a potentially hazardous feature that should have been known and avoided by archaeologists conducting exploratory excavations.

The western-most feature was narrower and consisted of a conspicuous and repeatable graphic signature (see "C" in Fig. 13). The unique graphic signature from this feature consisted of a central point reflector bracketed by two short, inclined plane reflectors. The identity of this feature, a small-gage railway, was disclosed in two observation pits (see Fig. 11) The rails were narrow and spaced about 50 cm apart. The tracks were buried beneath 20 to 45 cm of recent, wind-blown sand deposits. This railway extended about 40 meters across the site. The presence of this feature was unknown to members of the Public Works Department and indicated that the site was more intensively disturbed than previously anticipated.

In addition to the reflections from the railway (C) and the landfill (A), three additional point anomalies are identified in Figure 13. These anomalies vary in depth from about 55 to 170 cm. With the exception of the railway, none of these anomalies were observed through excavation pits. The right-hand portion of Figure 13 is higher-lying, better drained, and contains fairly well-expressed subsurface stratifications. The left-hand portion of Figure 13 is lower-lying, closer to the water table, and lacks subsurface stratifications. The lack of subsurface stratifications in lower-lying areas may be the result of higher concentrations of soluble salts in the soil profiles.

The radar survey of the Niholi Site helped to confirm a rich and prolonged occupational history. Four anomalies were verified in small pits using traditional archaeological methods. Three of the four anomalies were unearthed. One of the confirmed anomalies was imu's. Two of the confirmed anomalies were tracks from a small railway. Interpretation of the radar profiles from the Niholi Site disclosed a potentially hazardous abandoned landfill.

MARINE CORPS AIR STATION KANEOHE BAY, OAHU:

Pyramid Rock Beach

The site was located on an east-facing beach area immediately south of Pyramid Rock. The study site was located on beach deposits which are washed and rewashed by storm waves. The site had been mapped as beaches by Foote and others (1972). The study site supports little or no vegetation. Figure 14 is a contour map of the study areas. In Figure 14, north is to the right. The area has relatively low relief (@ 155 cm).

An irregularly shaped, rectangular grid was established across the study site (see Figure 14). The maximum dimensions of the grid were 150 by 25 meters. The grid interval was 5 meters. Survey flags were inserted in the ground at each grid intersect. A transit was used to establish grid corners and to determine surface elevations at each of the 146 grid intersects. Mean sea level was used as datum. In Figure 14, two areas were excluded from the survey because of a thick mat of naupaka or steep slopes.

Calibration trials were completed with the SIR System-3 and the 120 and 500 mHz antennas. A scanning time of 60 ns and a scanning rate of 25.6 scans/sec were used in these trials and in all subsequent field work. Field work was conducted with the 120 mHz antenna.

Figure 15 is a two-dimensional plot of the Pyramid Rock Beach Site. This plot has been prepared from transit and GPR data. The GPR data was collected along orthogonal grid lines spaced at five meter intervals. The locations of 14 detected subsurface anomalies are indicated by dark circles.

A dash line has been used in Figure 15 to indicate the area of recent (and temporary) beach deposits. This area consists recently deposited and storm reworked sands. It supports no vegetation. The sand deposits within this area were highly attenuating to radar signals. These deposits contain high concentrations of soluble salts which severely limit the depth of investigation (< 10 cm). In this and similar low-lying areas of recently deposited beach sands, the performance of both antenna was very poor and the use of GPR techniques appears to be inappropriate.

Figure 15 contains only 14 point anomalies. Compared with the Niholi Archaeological Site on Kauai, the Pyramid Rock Beach Site appears to contain relatively few anomalies. In addition, most (12 of 14) anomalies were weakly expressed and selection was highly interpretative. Interpretations are undoubtedly biased. Often, in areas where there are few or only weakly expressed subsurface features, an interpreter will select those features which provide the most anomalous graphic signatures. In areas where there are more numerous and/or better expressed subsurface features (the Niholi Site), weakly expressed anomalies, such as many of those detected from the Pyramid Rock Beach Site, are generally ignored in the primary phases of interpretations. Though the fourteen features identified at Pyramid Rock Beach Site represent point anomalies, they were not considered by the interpreter to represents the "best choice" for buried cultural anomalies. With experience and ground-truthing, the selection process can be improved.

Following the GPR survey, the identity of one, well-expressed anomaly was disclosed in a small observation pit. The anomaly was a refilled pit containing modern wastes. As this site is actively used by surfers and sun bathers, the likelihood is great that most of the fourteen anomalies detected at this site represent modern wastes.

The Pyramid Rock Beach Site consists of fairly recent beach deposits. Considering the size of the survey site, exceeding few anomalies were detected and most were suspected of being modern cultural debris and wastes. It is considered unlikely that the site contains any cultural features of significance.

<u>Fort Hase Beach</u>
This site was located on an east-facing portion of the beach immediately south of Fort Hase Cove. The area had been mapped as Jaucas sand, 0 to 15 percent slopes, by Foote and others (1972). The study site supports very little vegetation. Near the shoreline, in areas immediately east of the study site, coral limestone was exposed at the surface.

A rectangular grid was established across the study site (see Figure 16). The dimensions of the grid were 40 by 24 meters. The grid interval was 2 meters. Survey flags were inserted in the ground at each of the 273 grid intersects. A transit was used to establish grid corners.

Calibration trials were completed with the SIR System-3 and the 500 mHz antenna. At this site, because of the relative absence of near-surface reflections, the 500 mHz antenna was used. Generally, radar profiles from this site contained few near surface plane or point reflectors and were relatively easy to interpret. The 500 mHz antenna provided the desired depth of investigation and exceptionally high resolution of subsurface features including stratifications within the coral limestone. A scanning time of 60 ns and a scanning rate of 25.6 scans/sec were used in these trials and in all subsequent field work.

Figure 16 is a plot of the point anomalies detected with the Fort Hase Beach Site. This plot has been prepared from data collected along orthogonal grid lines spaced at two meter intervals. In Figure 16, the locations of the 65 detected subsurface anomalies have been indicated with dark circles. These point anomalies are distributed throughout the study site.

The radar signal was rapidly attenuated in two irregularly-shaped areas near the shoreline. Presumably, high concentrations of soluble salt within these deposits limited profiling to depths of less than 10 cm. The location and extent of these two relatively saline areas have been outlined with a dashed line in each of the plots from this site.

Following the GPR survey, four anomalies were excavated and verified. Three of the four anomalies represented natural features (rock, buried A horizon, cemented root channels). The fourth anomaly was a buried wire. All anomalies were buried at the anticipated depths. One anomaly, a small, vertically orientated, cemented root channel, produced an exceptionally strong radar reflections. The reflections from these narrow, cylindrical, cemented root channels produced reverberations similar to those induced by metallic objects.

The data was manipulated to analyze the relationships among grid intensity or interval, site coverage, and the amount of anomalies detected. The results are summarized in Table 3. Coverage is based on the grid interval, the number of orthogonal traverses and the assumption that the antenna scans a 12 cm wide foot-print area at a depth of 50 cm. Duplicate areas scanned beneath intersects were deleted from tabulations.

Grid interval represents a compromise among the purpose of the survey, availability of time and resources, features being detected, local terrain conditions, and the desired detection probability. At the Fort Hase Beach Site, the number of anomalies detected and the area covered decreased with increasing grid intervals. The most significant decline in the number of point anomalies detected occurred when the grid interval was expanded from 2 (see Figure 16) to 4 (see Figure 17) meters. Differences in the number of anomalies detected among the coarser grid intervals of 4, 6, and 10 meters, do not appear to be significant.

Figures 17, 18, and 19 are plots prepared from data collected with 4, 6 and 10 meter intervals, respectively. In each of these plots, multiple traverses were conducted along orthogonal grid lines. All of these figures indicate a greater prevalence of detected anomalies in the southern portion of the study area.

TABLE 3

Radar Grid Intensity and Point Anomalies Detected with 500 mHz Antenna at Fort Hase Beach Site

Grid Interval	Coverage	Anomalies
2 meters	12%	65
4 meters	7%	29
6 meters	4%	21
10 meters	3%	16

Fort Hase Beach Site represented a heavily disturbed (both natural and artificial) area. Based on the radar survey, the probability of noteworthy buried cultural features existing at this site is considered exceeding low.

WAIMANALO BAY - BELLOWS AIR FORCE BASE

A site was selected in an sparsely wooded area immediately west of a portion of the beach on Waimanalo Bay. The area had been mapped as Jaucas sand, 0 to 15 percent slopes by Foote and others (1972). Figure 20 is a topographic map of the study site. The beach is located immediately east of the study site. The site has relatively low relief (@ 125 cm). Mean sea level was used as datum.

Traditionally, archaeologists make judgements as to where archaeological sites or cultural features will be found within a survey site. While no portion of the survey site should be excluded from visual inspection or coverage, obscured subsurface features can only be exposed in a limited number of excavation pits or trenches. Archaeologists assesses the significance or insignificance of various areas within a survey site and select the locations for excavation pits and trenches. A study was conducted at the Waimanalo Site to compare the number and distribution of anomalies that would be detected along randomly spaced traverse lines and systematically spaced grid lines.

Traverses are used to quickly reconnoiter areas for large subsurface features or to locate concentrations or clusters of smaller cultural features. The location of traverse lines reflects the knowledge, experiences, and biases of the field archaeologist.

Three randomly-spaced traverse lines were established within a 30 by 50 meter survey site. The traverses were orientated with a compass and identified as lines A, B, and C (see Figure 21). Traverse were either 30 or 40 meters in length with survey flags inserted in the ground at 5 meter intervals. Normally, these traverse lines would have been excavated with a backhoe. Unlike the backhoe trenches, GPR is a non-invasive technique and the need for excavations can be kept to a minimum.

Calibration trials were completed with the SIR System-3 and the 120 mHz and 500 mHz antennas. A scanning time of 100 and 60 ns were used with the 120 mHz and 500 mHz antennas, respectively. The scanning rate was 25.6 scans/sec. Field work was conducted with the 120 mHz antenna. Once again, it was felt that the 120 mHz antenna provided less complicated and more interpretable profiles.

Representative radar profiles from traverse line C and east - west grid line 30 are shown in Figure 22. The traverse line was conducted with the 500 mHz antenna (Fig. 22A); the grid line with the 120 mHz antenna (Fig. 22B). The first portion (0 - 30 m) of each radar profile passed over the same surface area. The radar profiles are reversed as traverses were conducted in opposite directions. The grid line was 10 meters longer than the random traverse line. This difference proved significant as the longer grid line passed over and detected a refilled trench (see "A" in Fig. 22B).

Improved resolution and a greater number of shallow, subsurface point reflectors were observed with the 500 mHz antenna. However, a large number of the point anomalies detected with the 500 mHz antenna were believed to be roots from nearby trees. The 500 mHz antenna did not discriminate metallic from non-metallic reflectors. With the 120 mHz antenna, metallic objects displayed the characteristic reverberated reflected signals (see A, B, D, E, and F in Fig. 22B). The improved resolution of the 500 mHz antenna permitted the observation of closely-spaced and perhaps more subtle variations in soil horizons and geologic strata.

The radar survey of the three traverse lines were completed in less than 10 minutes and the entire survey in less than one hour. Figures 21 and 23 are plots of the study site showing the location of the traverse lines and the anomalies detected along the traverse lines (Fig. 21) and the grid lines (Fig. 23).

In figure 21 an 23, the locations of 16 tree and stumps have been plotted. Knowledge of the locations of these features aided radar interpretations. Tree roots produce undesired reflections on radar profiles. Reflections from tree roots can mask the presence of buried cultural features and complicate interpretations (Barker and Doolittle, 1992). On radar profiles, tree roots most commonly appear as point anomalies. Based on their proximity to tree, a large number of these point anomalies were discounted as representing buried cultural features. It was assumed that point anomalies occurring within 1.5 meters of a tree represented roots.

Twenty-four anomalies were identified along the three traverses (see Figure 21). In Figure 21, the locations of these anomalies are indicated by dark circles. Excavations were carried-out to verify the nature of two of these anomalies. The anomalies were identified as a cluster of buried wires and a shredded aluminum can. An area of disturbed soils containing metallic reflectors was inferred from the radar profile of traverse "B." In Figure 21, the location of the area of disturbed soil has been enclosed in a small rectangle. As a bath house and water fountains were adjacent to the study site, it was assumed that the radar had detected a refilled trench containing possibly two buried water pipe.

A rectangular grid was established across the study site for the purpose of comparing a relatively coarse grid with the random traverses. The grid interval was 10 meters. A transit was used to establish grid corners and to determine surface elevations at each of the grid intersects. Survey flags were inserted in the ground at each of the 24 grid intersects.

Figure 23 is a two-dimensional plot of the anomalies detected along grid lines at the Waimanola Bay Site. This plot has been prepared from transit and GPR data. The GPR data was collected along orthogonal grid lines spaced at 10 meter intervals. In Figure 23, the locations of 68 detected subsurface point anomalies are indicated by dark circles.

The grid survey disclosed that the area of disturbed soil located by the random traverses was not a water pipe line, but more likely a buried trash disposal trench. As this feature was observed in only one of the grid line, it was considered too limited in extent to be a buried utility line. To confirm this interpretation, a test excavation was conducted in the area of disturbed soil conditions. At a depth of about 80 cm, trash was found in the test pit. Once again, observations were required to verify interpretations.

A smaller 10 by 10 meter grid was established to determine the extent of the refilled pit or trench which contained the trash. A 2 meter interval was used and traverses were conducted along orthogonal grid lines. The location of this grid within the study site is shown in Figure 23. Figure 24 is a two-dimensional plot of the anomalies detected within the detailed grid. Anomalies were concentrated in the north-central portion of the detailed grid area. In Figure 24, the trench extends from approximately the tip of "N" in a southwest direction into the grid area. The trench appears to be less than 2.5 m long.

Although there was a high concentration of anomalies within this site, few are believed to be of significance. Observations confirmed the presence and nature of three of the 68 anomalies. On the basis of these limited ground-truth observations and following an appraisal of the site by a qualified archaeologists, it was felt that most of the anomalies occurring at this site represent either roots or modern cultural debris.

CONCLUSIONS

The use of ground-penetrating radar for archaeological investigations is in an active stage of growth and development. This trend has been accelerated by growing commercialization and familiarity with the GPR's applicability to archaeological investigations. However, the use of GPR techniques has been limited because of (i) limited knowledge of its performance in various media and geographic locations, (ii) rapid rates of signal attenuation and restricted profiling depth in certain media, and (iii) results which are often dependent upon the skills and experience of the operator. Ground-penetrating radar is an imperfect geophysical technique that compliment but does not replace traditional archaeological methods. Results from GPR investigations are often tentative and incomplete until interpretations are confirmed by traditional archaeological methods.

Ground-penetrating radar techniques can be used to facilitate excavation strategies, to provide greater areal coverage per unit time and cost, to minimize the number of unsuccessful exploratory excavations, and to reduce unnecessary or unproductive expenditures of time and effort. Under suitable soil conditions (dry, coarse-textured soils), GPR can provide highly resolved reflective images of the subsurface to the desired depths of most archaeological investigations.

As a pre-survey tool, the ability of GPR to rapidly reconnoiter an area and locate potentially hazardous utility lines or waste disposal areas was demonstrated at the Niholi Site at PMRF.

Ground-penetrating radar survey should be designed to cover a prescribed proportion of a site. The selected grid interval(s) and survey design(s) are dependent on the proportion of the survey area to be covered, and the time and resources available. Investigators should be required to verify a number of detected anomalies in the field. A statement should be made as to the nature of the anomalies observed, the proportion representing "desired" cultural features, and the spatial extent or distribution of desired and undesired reflections within the study area.

Typically, in dry, coarse-textured soils, expensive and time-consuming processing of the radar imagery is not required. This study was purposely conducted on the most favorable soils for GPR applications in the Hawaiian Islands. In areas of moderately-fine and fine textured soils, results will be more restricted and interpretative, and computer processing of digitally recorded radar data may be necessary to resolve subsurface imagery or extend the depth of investigation. Presently, fine-tuning of the radar in the field to achieve optimal imagery is considered more critical to successful interpretations than any post-processing technique. Processing is "glitzy," "high-tech," but improved results can not be insured with existing processing techniques. Existing techniques are mostly cosmetic.

This study has demonstrated the need for an adequate assessment of soil, terrain, and cultural features at a site prior to recommending the use of GPR. Beaches are composed of coarse-textured materials and are generally assumed to be appropriate and accessible to GPR. However, reworked or rewashed beach areas contain high concentrations of soluble salts. High concentrations of soluble salts restrict the use of GPR techniques. This study has demonstrated that many beach areas contain an excessive amount of recent, buried cultural rubbish. Though this debris is discernible with GPR, it creates a prohibitive number of point reflectors. An inordinate number of undesired reflections compound interpretations and increase the need for additional observation pits. Dune areas were avoided in this study. Vegetation stabilizing many dunes are extremely sensitive and do not tolerate being run over by the radar equipment. In addition, many dunes have steep slopes which can be exhausting to survey. Areas of dense vegetation, unless trimmed, are inaccessible to GPR. The study at Bellows Air Force Base demonstrated the need to chart the locations of trees, assess the distribution of roots, and to modify radar interpretations to these patterns.

The identity of several anomalies were verified in excavated pits. At the time of the excavations depths to anomalies were approximated. Most anomalies were estimated to occur between depths of 40 to 80 cm. All but one anomaly occurred within these depths; the one exception was the lone anomaly which was undetected. This anomaly was assumed to be at a depth of about 1.2 meters. It was felt that the small excavation pit missed this anomaly.

This study further demonstrated the capabilities of ground-penetrating radar to detect small anomalies in coarse-textured soils. Generally, large, linear features are easy to detect and identify with GPR. Small, point anomalies are easily overlooked and difficult to identify with GPR. These anomalies are detected only if the antenna pass directly over or very close to the buried feature. The strength of the reflected signal will depend upon the presence of additional reflectors in the soil, the orientation, depth, and composition of the anomaly, and whether or not the antenna past directly over the anomaly.
It is doubtful whether anyone could every assure that "all" small point anomalies have been detected with GPR. Errors of omission exist in most survey.

This study demonstrated that unless traverses are conducted in more than one direction, some features may be overlooked by even the most intensive survey. Also, to detect the presences of linear features, these objects must be cross by the antenna on at least 3 to 4 closely-spaced traverses. In addition, the imagery of these linear features should be aligned and free from interference from other anomalies or subsurface soil features. Results suggest that orthogonal traverses are more informative than traverses conducted in only one direction and at a slightly closer intervals.

Results emphasized that the choice of grid interval(s) and survey design(s) are dependent on the size of the survey area, features being identified, desired detection probability, desired position accuracy, and time and resources available. Survey requirements should specify the proportion of the area that should be profiled.

Results from this study confirm the advantages of conducting surveys along orthogonal grid lines. Results suggest that multiple orthogonal traverses are more informative than traverses conducted in only one direction and at a slightly closer intervals. Unless traverses are conducted along orthogonal grid lines, linear features, such as utility lines or foundation walls, may be overlooked by even the most intensive survey. Regardless of the survey method used, the number of anomalies detected and site coverage decreases with widening of the grid interval.

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Figure 15. Plot of point anomalies detected within the Pyramid Rock Beach Site using a five meter interval with traverses conducted along orthogonal grid lines. High attenuation limited effectiveness of GPR in areas of recent beach deposits (area enclosed by dashed line).

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Figure 22. Radar profiles from Waimanalo Bay Site. Profiles were collected with the 500 mHz (A) and the 120 mHz (B) antennas along similar traverse lines.

Figure 23. Plot of point anomalies detected within the Waimanalo Bay Site, Bellows Air Force Base, using a ten meter interval with traverses conducted along orthogonal grid lines.

Figure 24. Plot of point anomalies detected within section of the Waimanalo Bay Site, Bellows Air Force Base, using a two meter interval with traverses conducted along orthogonal grid lines.

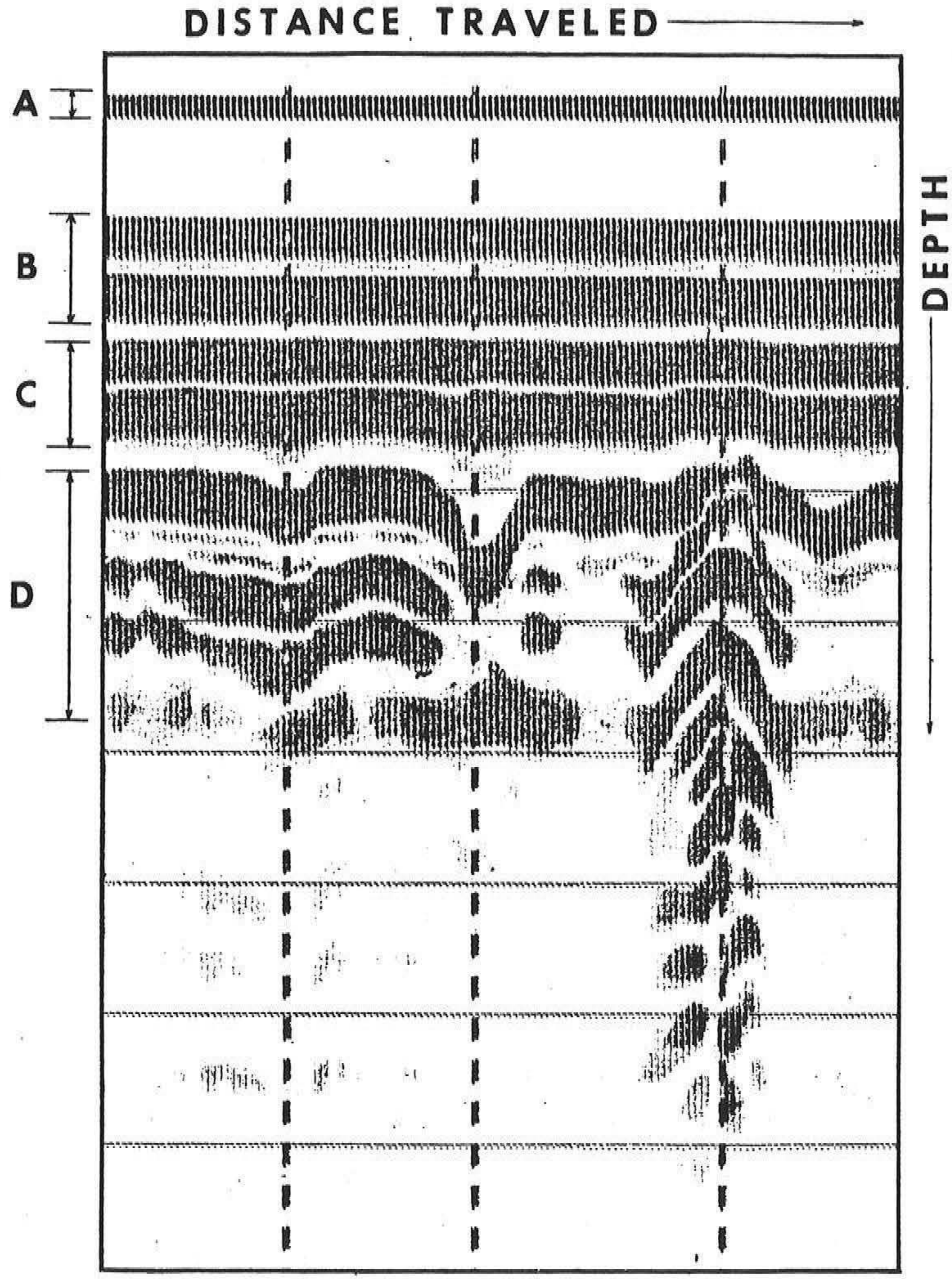
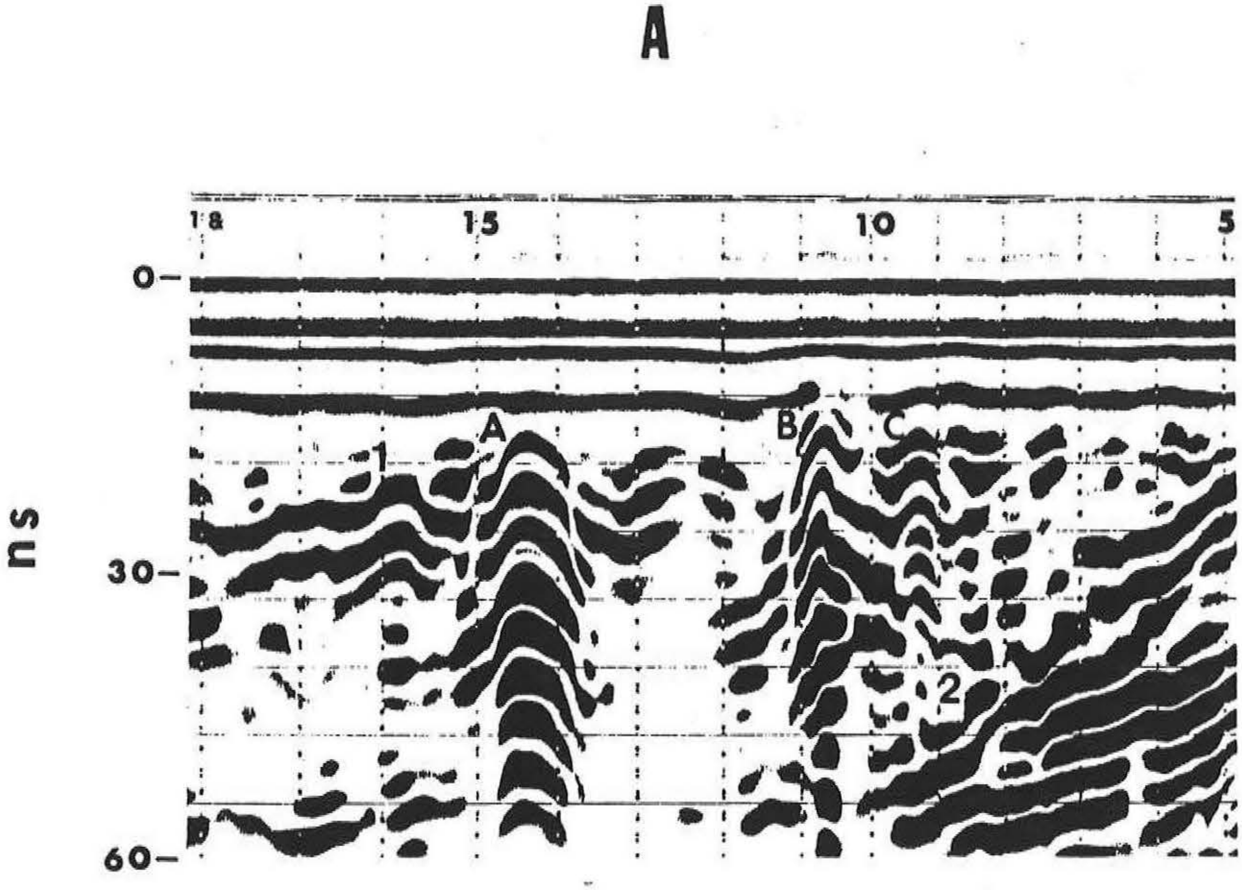


FIG. 1

A GRAPHIC PROFILE

FIGURE 2



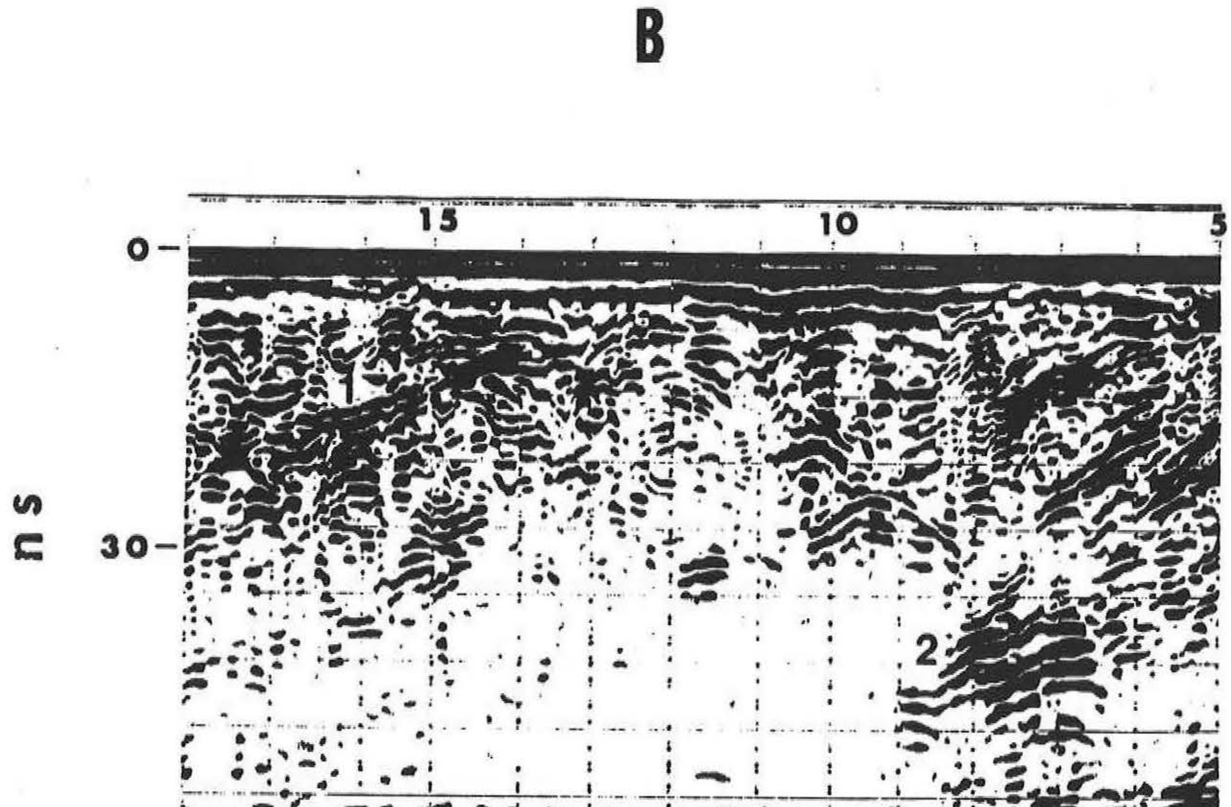


FIGURE 3

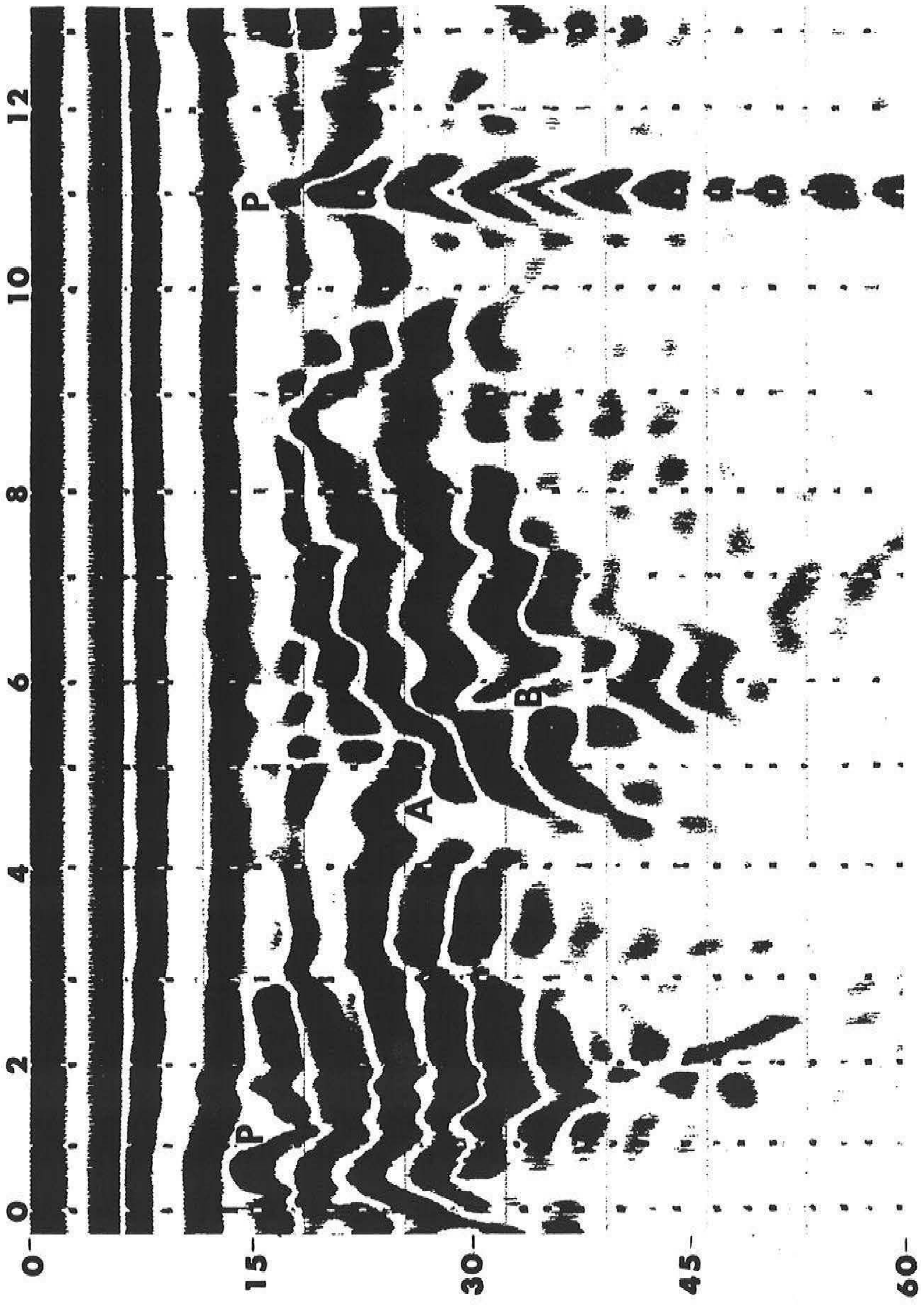
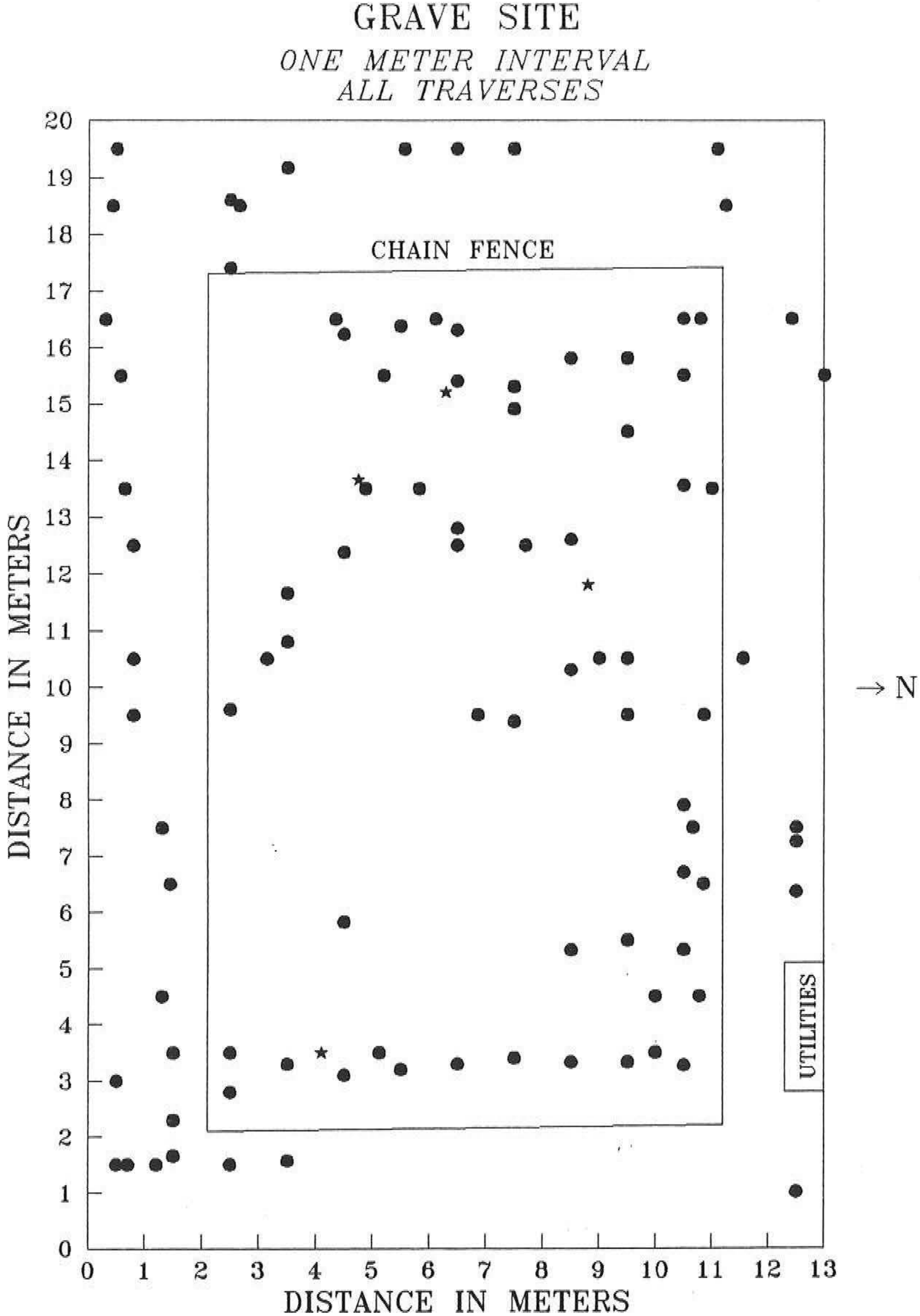


FIGURE 4


GRAVE SITE
ONE METER INTERVAL
ALL TRAVERSES
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UTILITIES
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DISTANCE IN METERS
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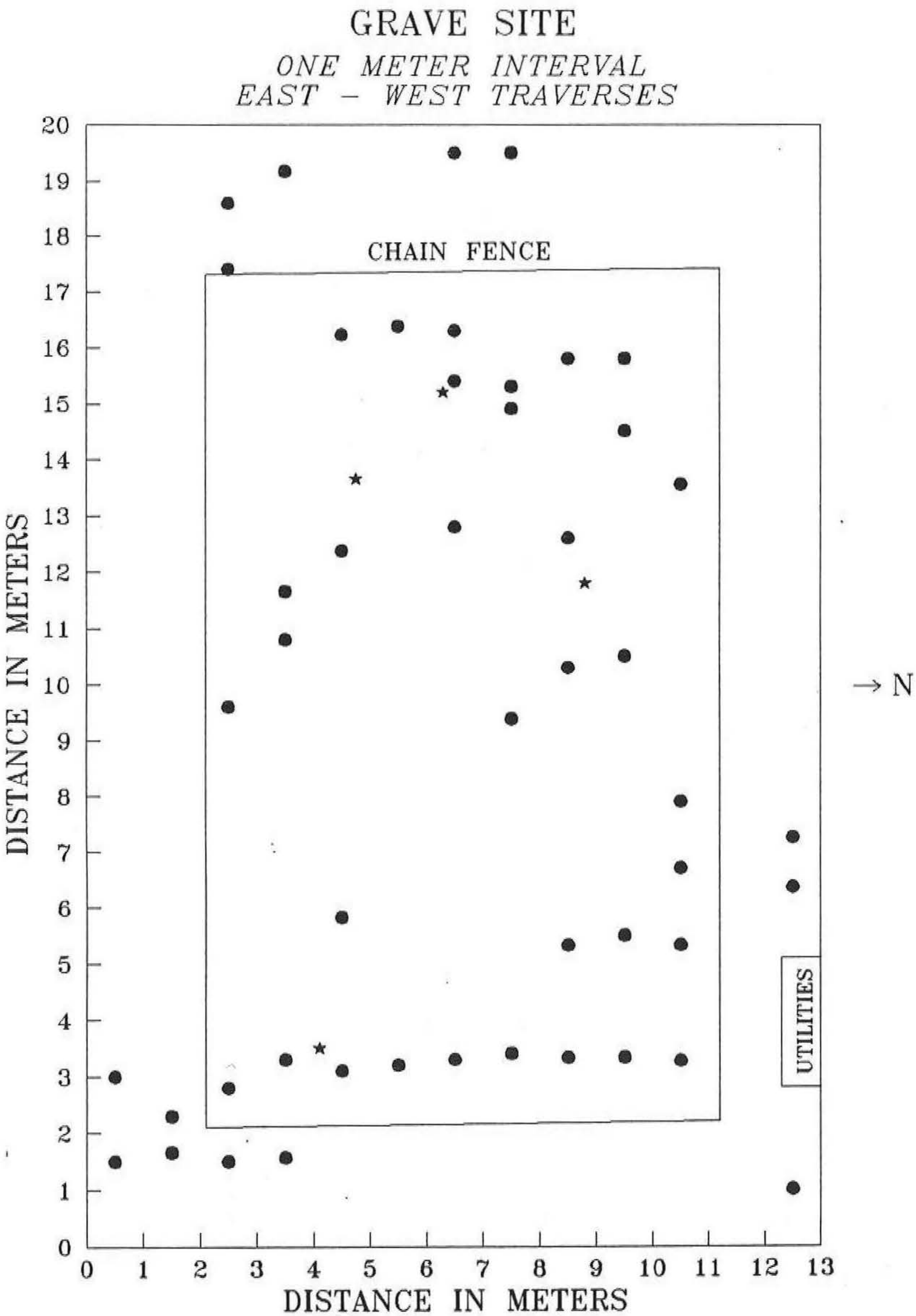
FIGURE 5


GRAVE SITE
ONE METER INTERVAL
EAST - WEST TRAVERSES
CHAIN FENCE
UTILITIES
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DISTANCE IN METERS
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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

FIGURE 6

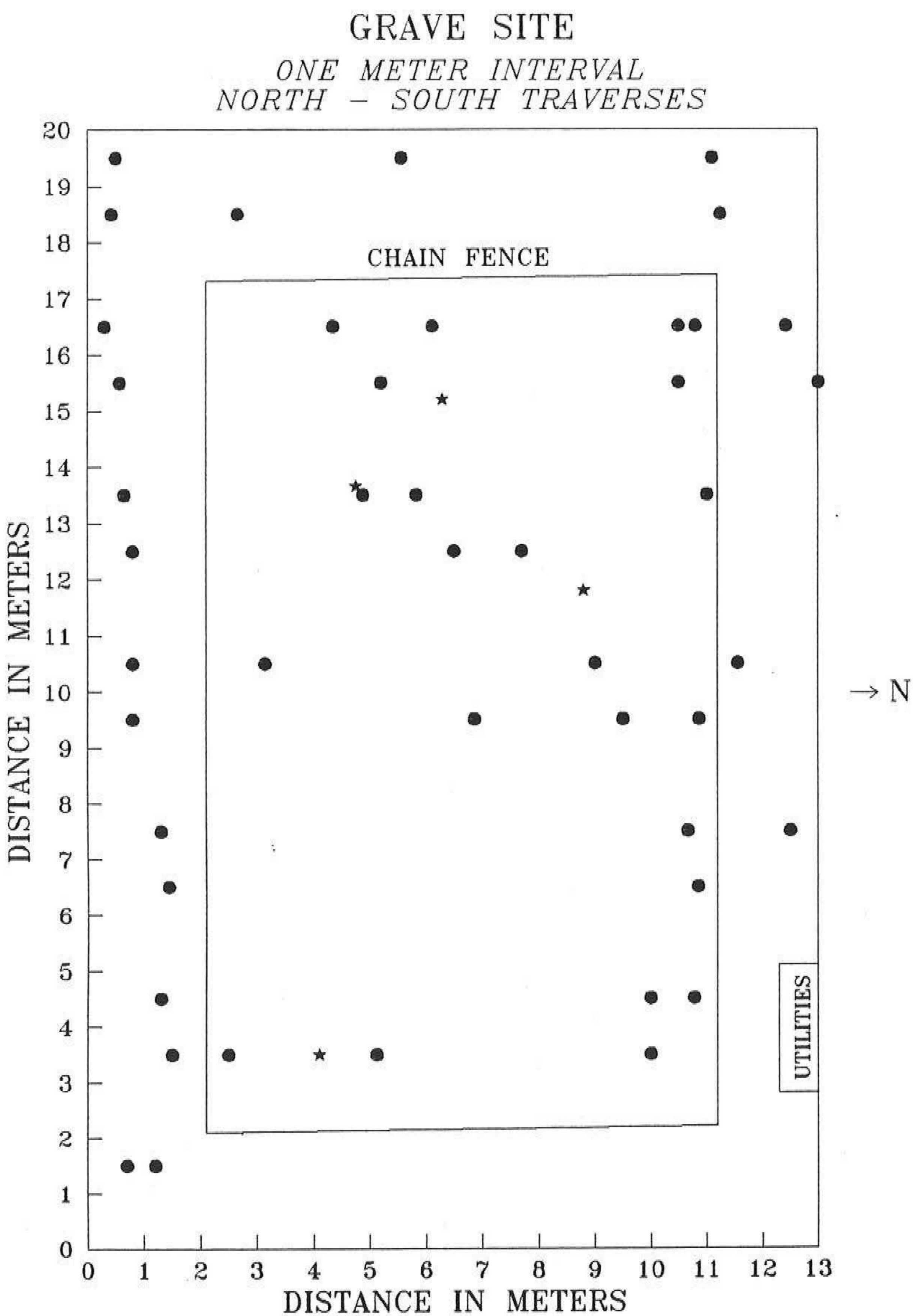
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FIGURE 7

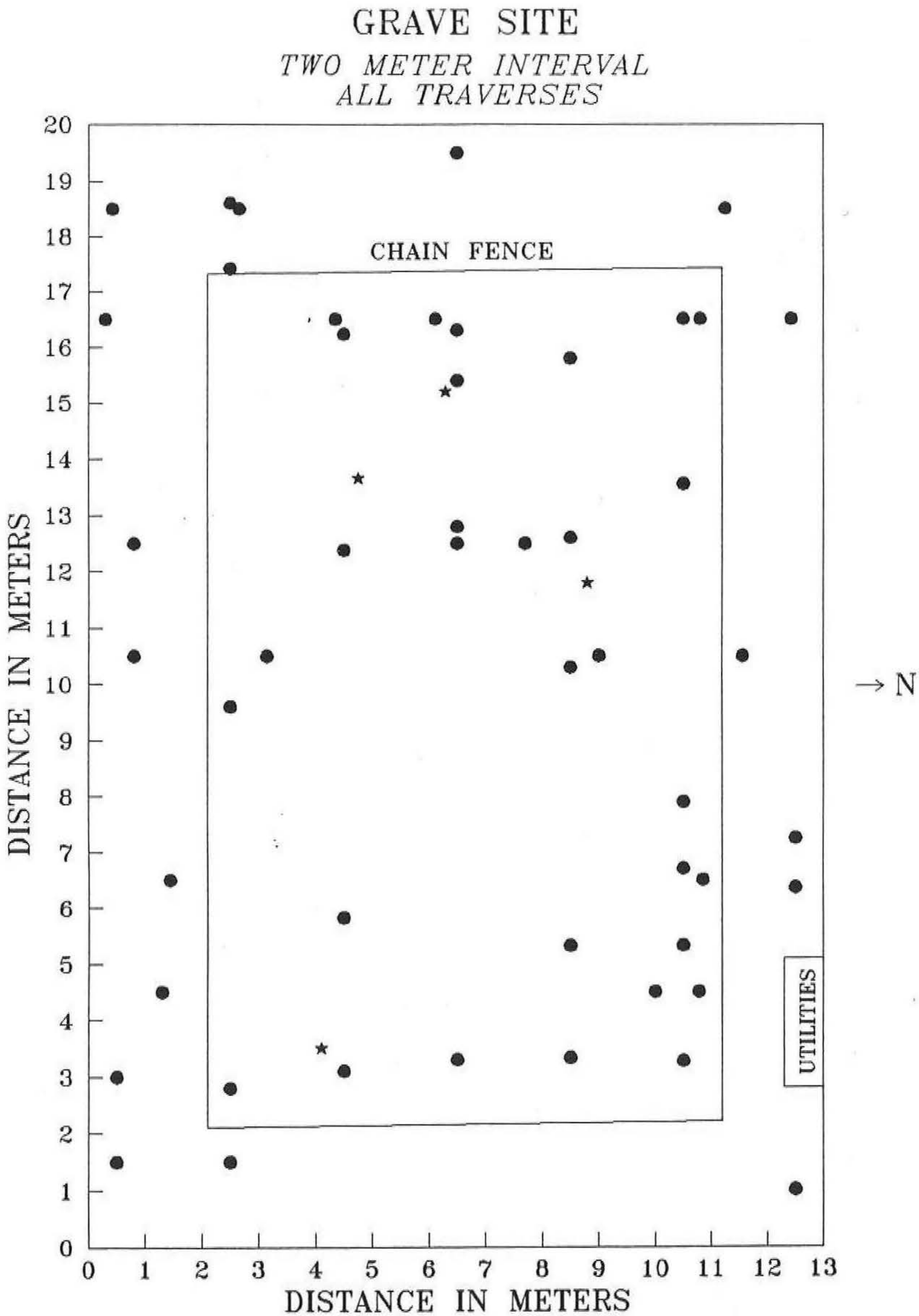
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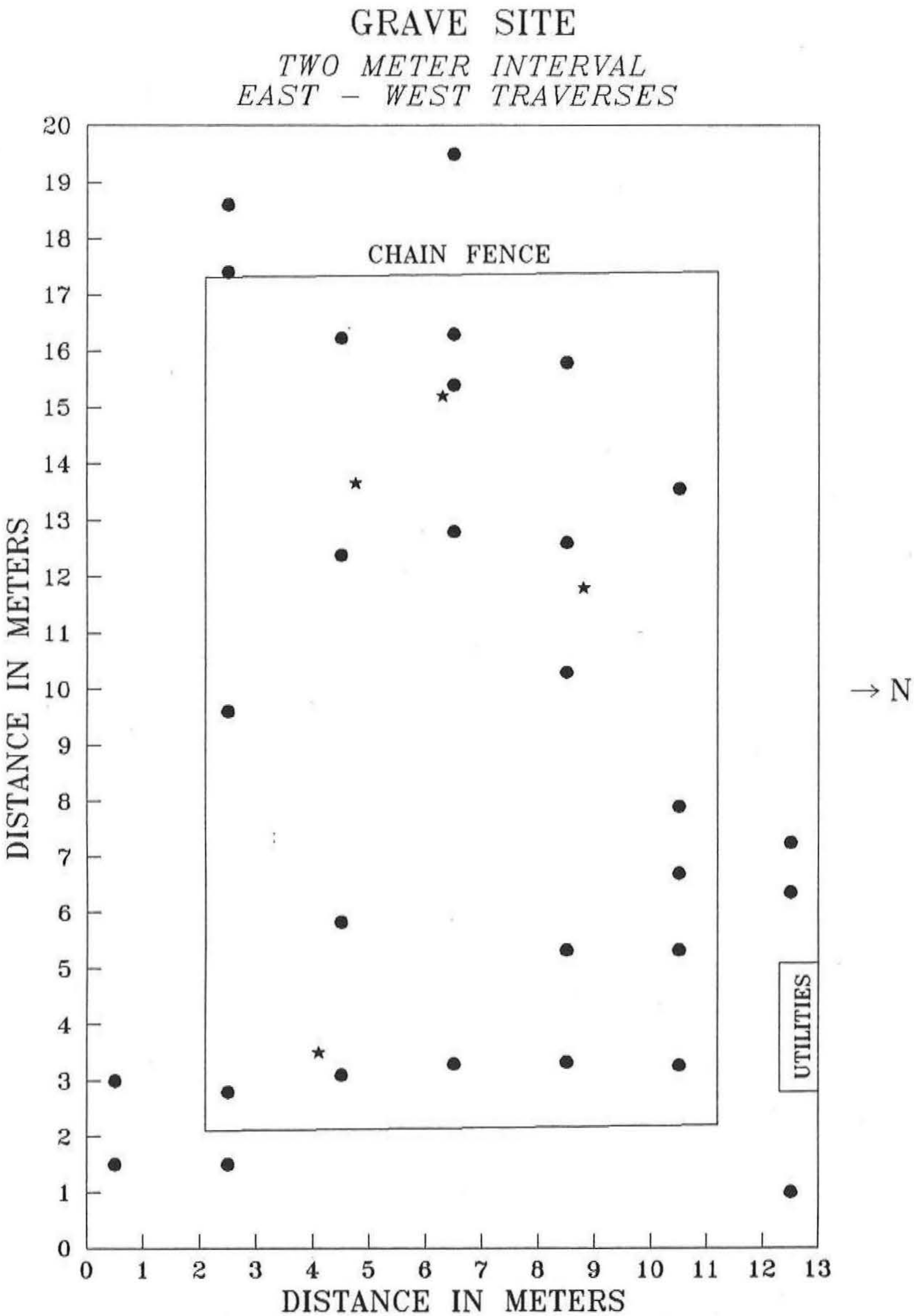
FIGURE 8


GRAVE SITE
TWO METER INTERVAL
EAST - WEST TRAVERSES
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UTILITIES
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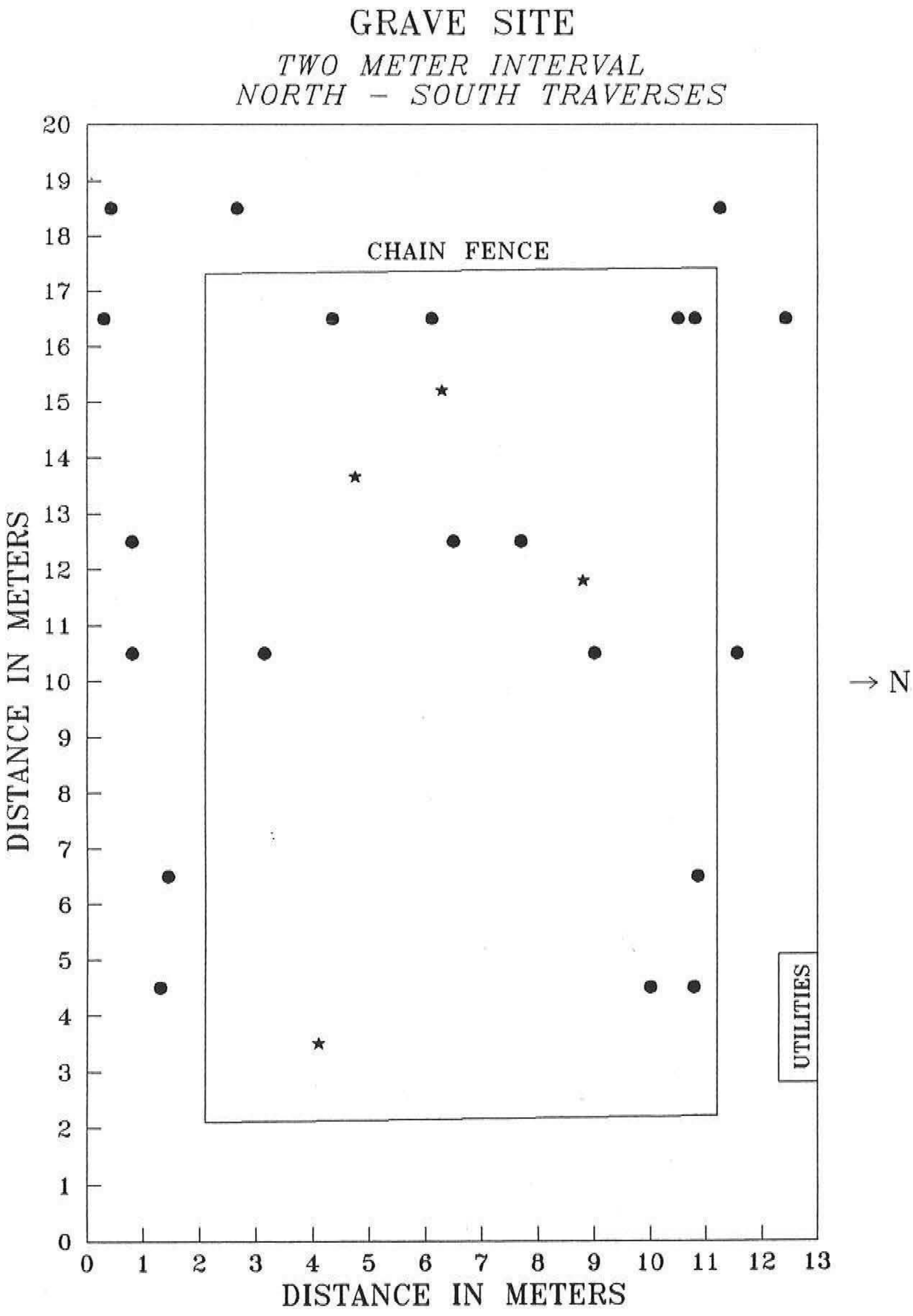
FIGURE 9


GRAVE SITE
TWO METER INTERVAL
NORTH - SOUTH TRAVERSES
CHAIN FENCE
UTILITIES
→ N
DISTANCE IN METERS
DISTANCE IN METERS
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NIHOLI ARCHAEOLOGICAL SITE

CONTOUR INTERVAL = 0.20 M

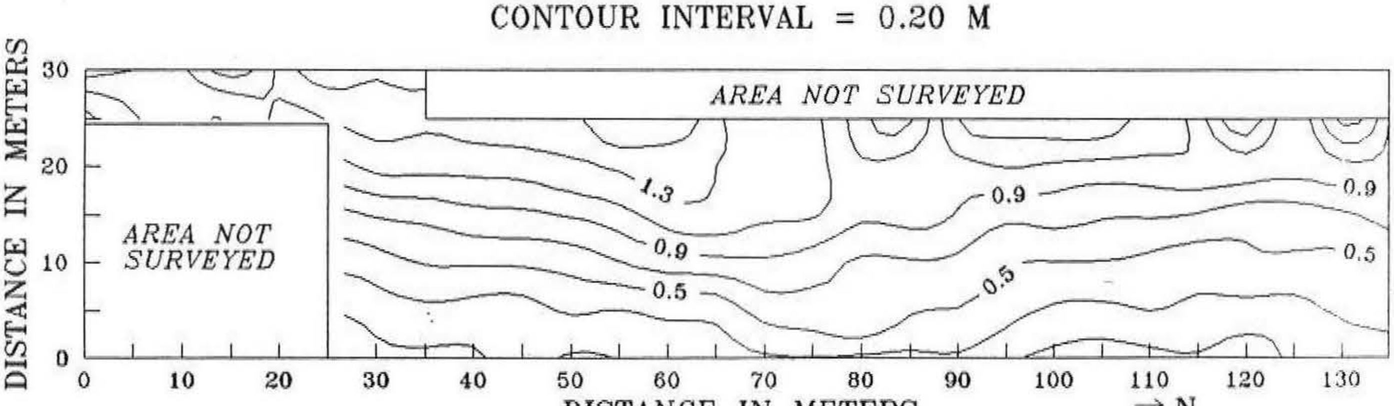
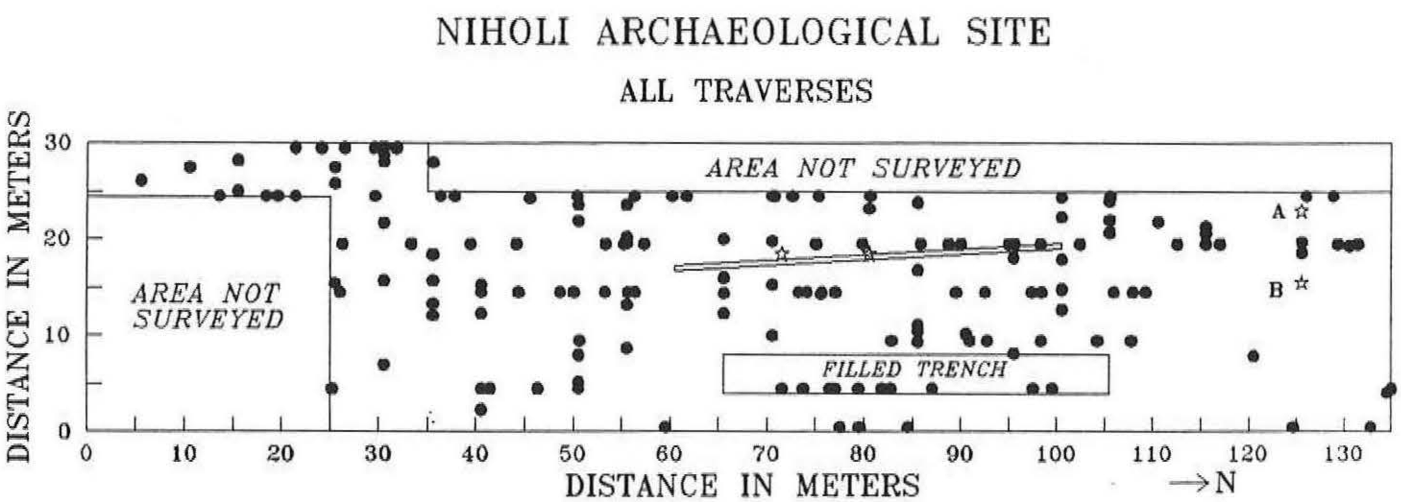


FIGURE 11



NIHOLI ARCHAEOLOGICAL SITE
ALL TRAVERSES
AREA NOT SURVEYED
AREA NOT SURVEYED
FILLED TRENCH
A
B
DISTANCE IN METERS
0
10
20
30
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50
60
70
80
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100
110
120
130
DISTANCE IN METERS
→N

FIGURE 12

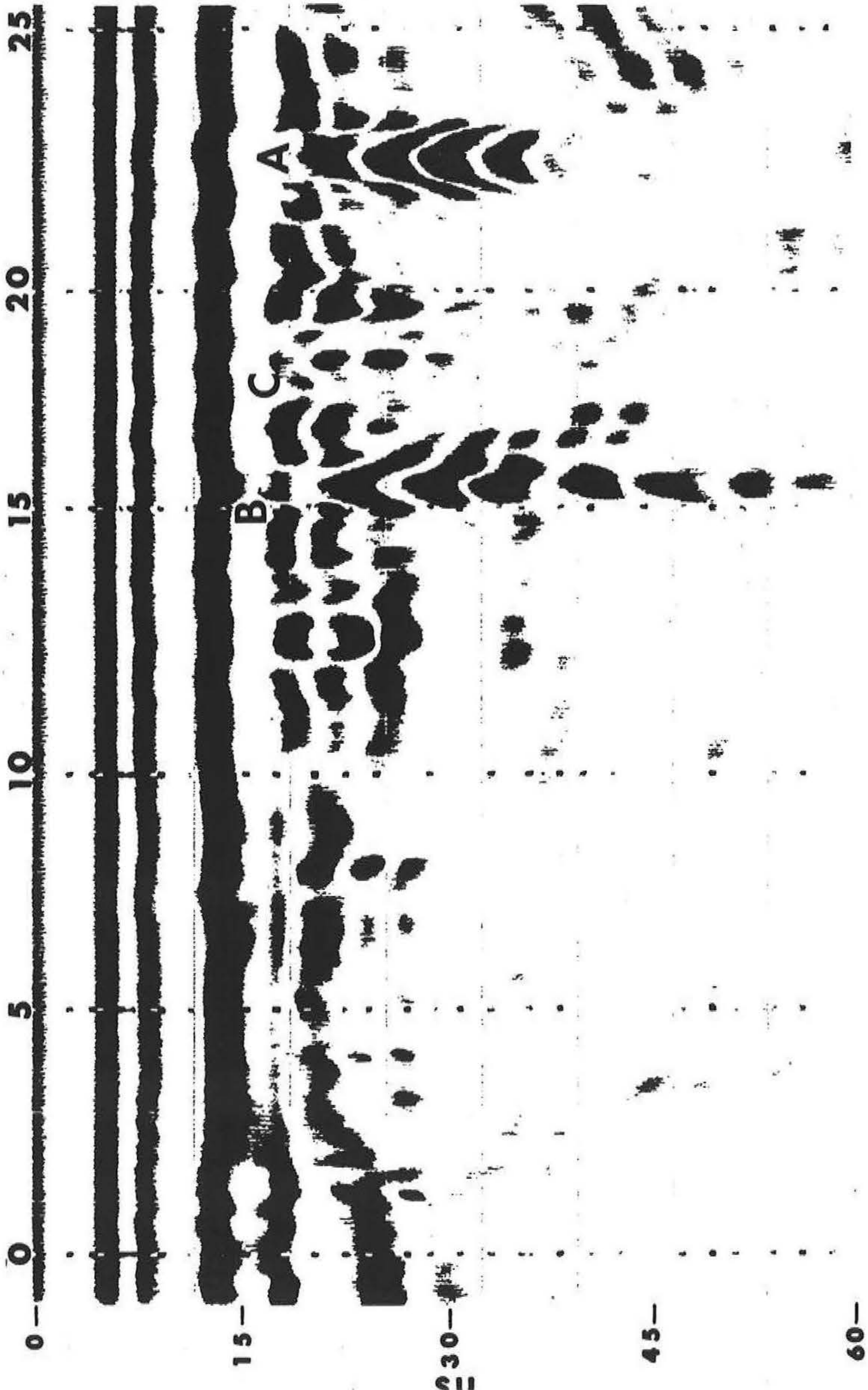


FIGURE 13

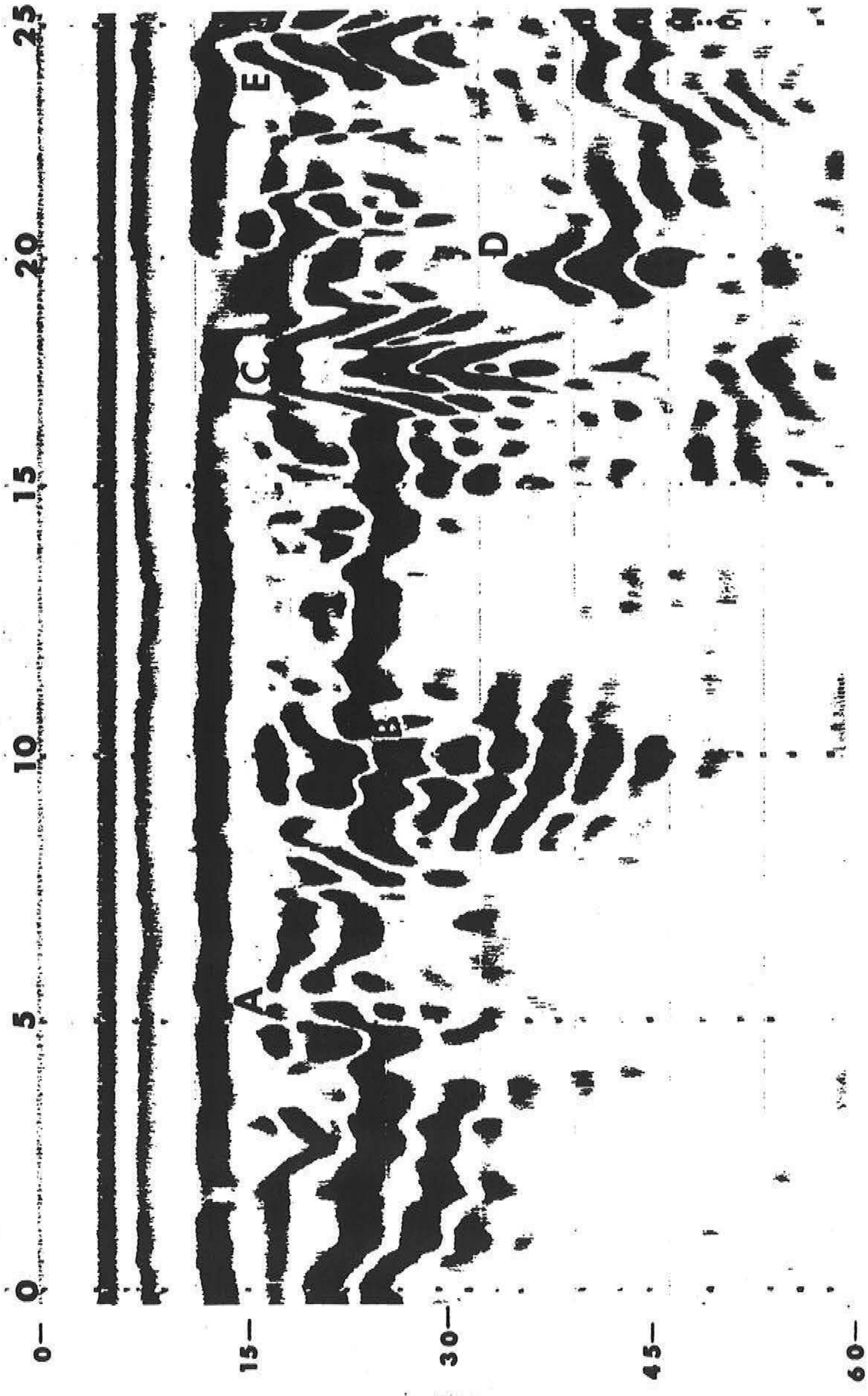
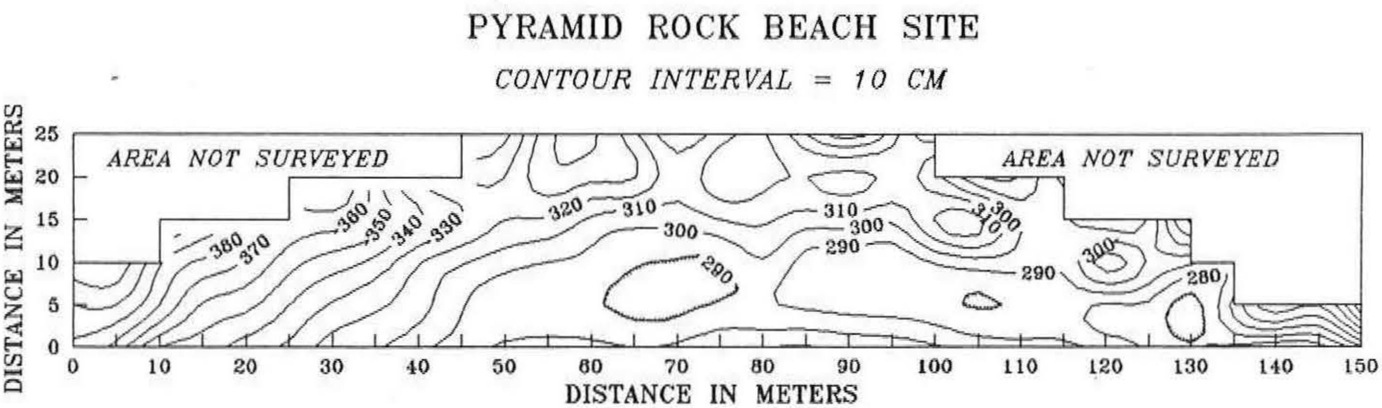


FIGURE 14



PYRAMID ROCK BEACH SITE
CONTOUR INTERVAL = 10 CM
AREA NOT SURVEYED
AREA NOT SURVEYED
DISTANCE IN METERS
DISTANCE IN METERS

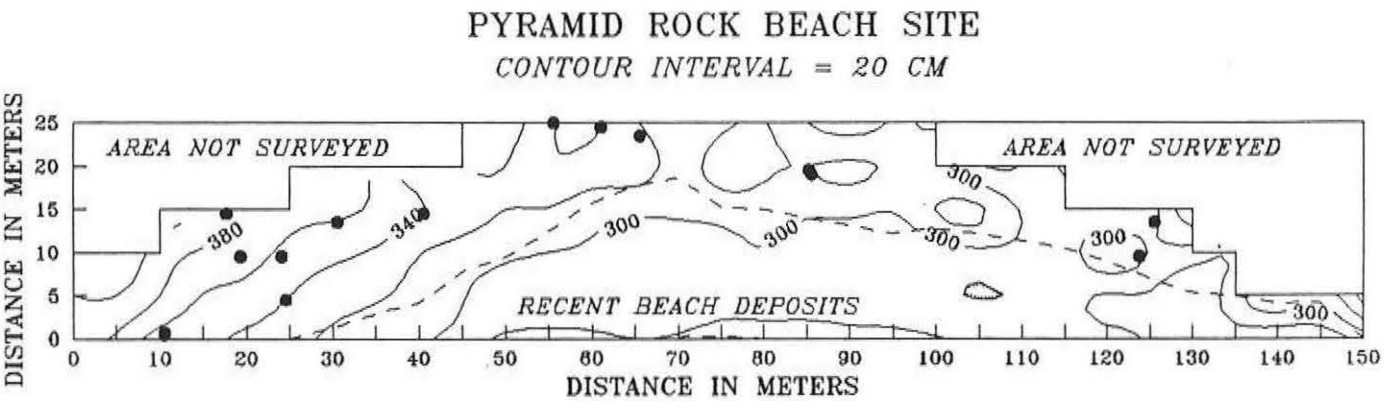
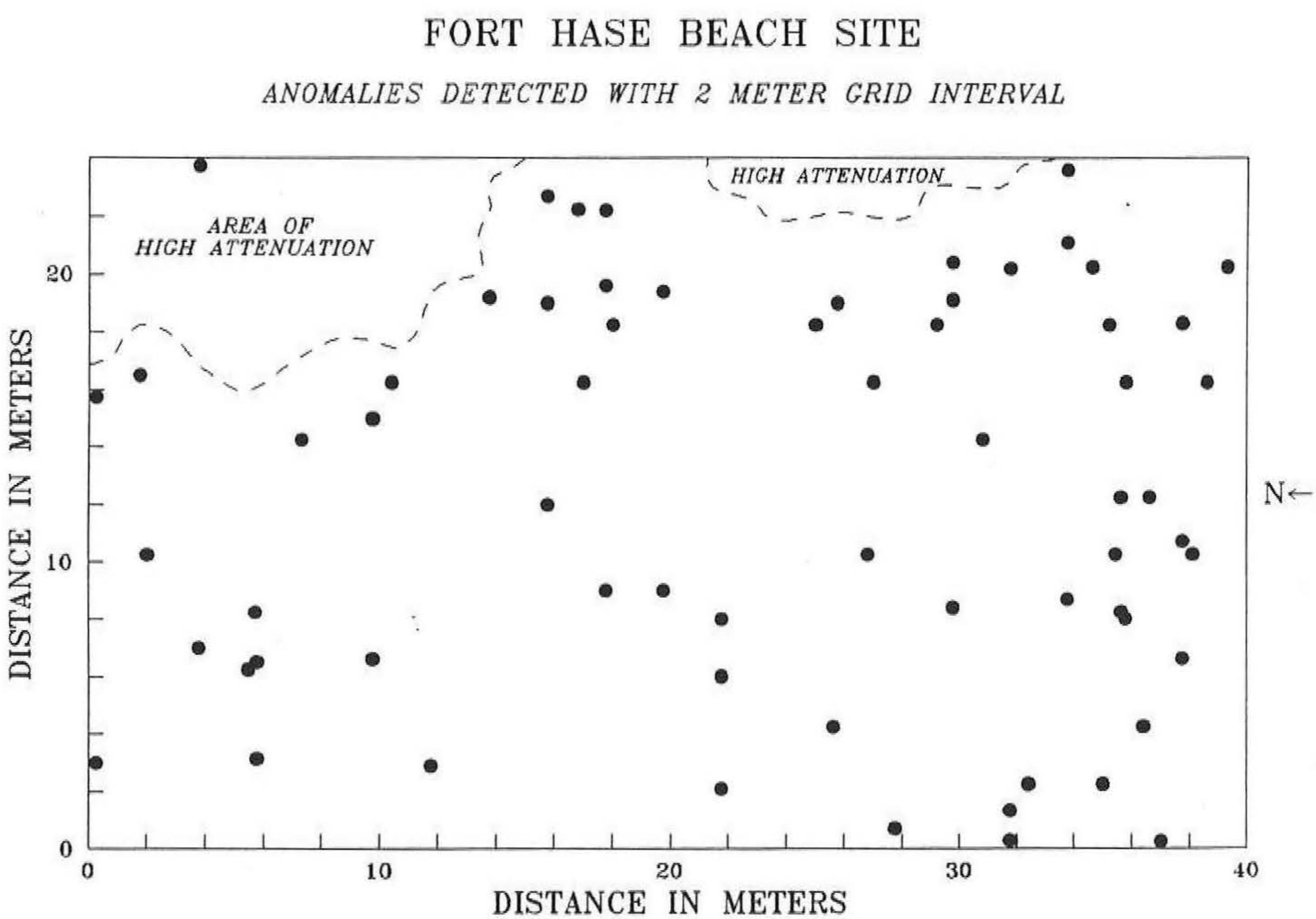
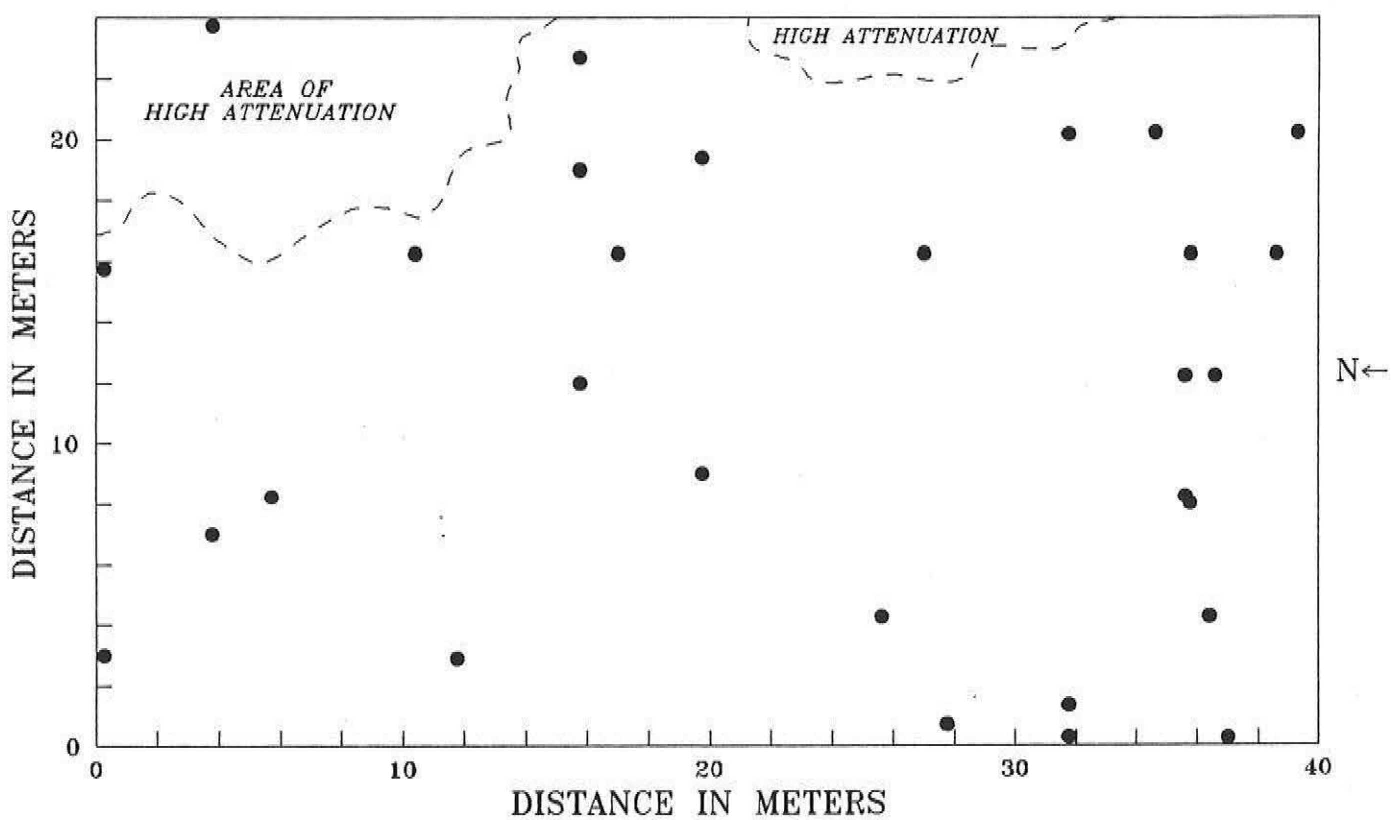

PYRAMID ROCK BEACH SITE
CONTOUR INTERVAL = 20 CM
AREA NOT SURVEYED
AREA NOT SURVEYED
RECENT BEACH DEPOSITS
380
340
300
DISTANCE IN METERS
DISTANCE IN METERS

FIGURE 16


FORT HASE BEACH SITE
ANOMALIES DETECTED WITH 2 METER GRID INTERVAL
AREA OF
HIGH ATTENUATION
HIGH ATTENUATION
DISTANCE IN METERS
0
10
20
30
40
DISTANCE IN METERS
N←

FORT HASE BEACH SITE

ANOMALIES DETECTED WITH 4 METER GRID INTERVAL



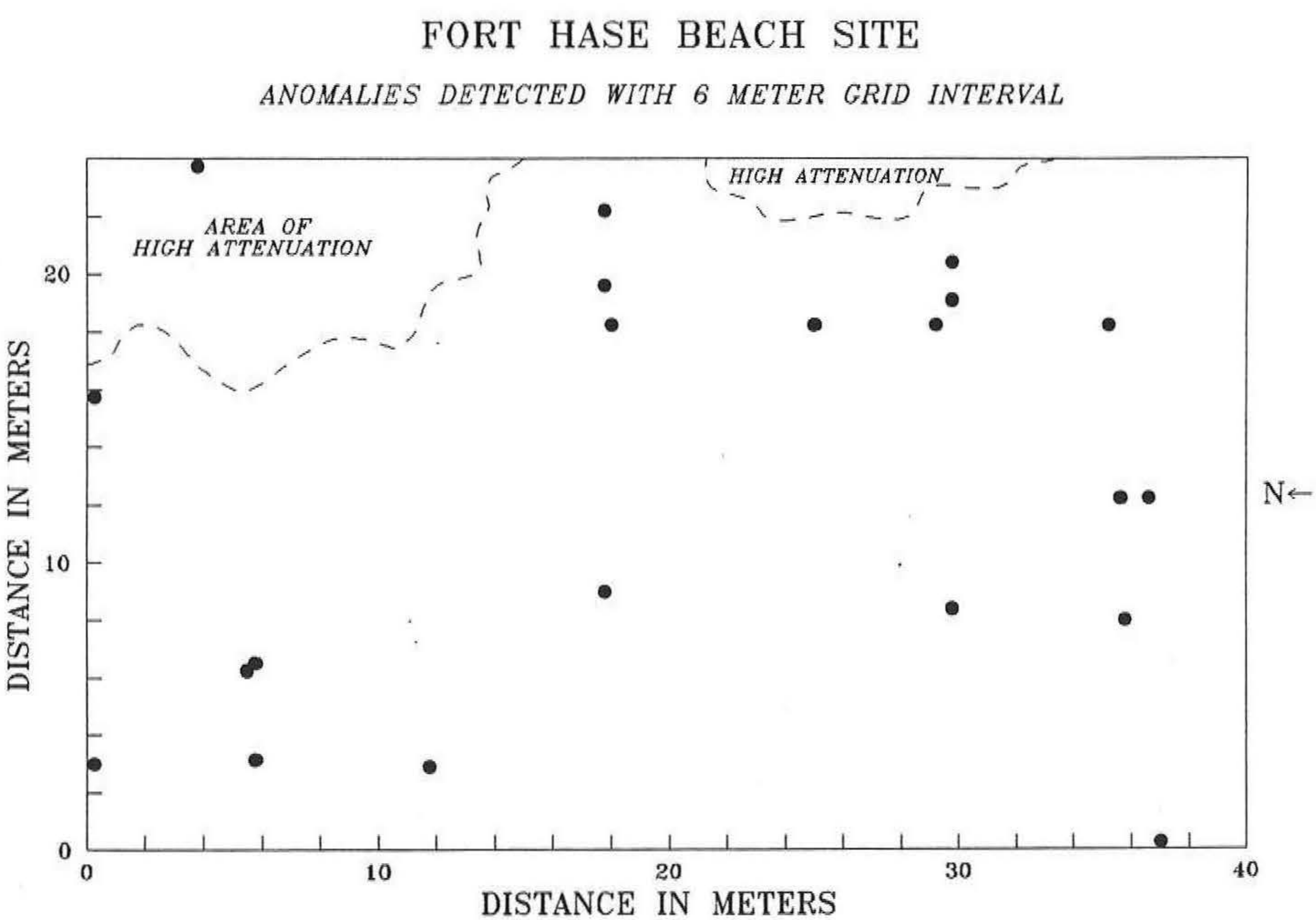

FORT HASE BEACH SITE
ANOMALIES DETECTED WITH 6 METER GRID INTERVAL
AREA OF
HIGH ATTENUATION
HIGH ATTENUATION
DISTANCE IN METERS
DISTANCE IN METERS
0
10
20
30
40
N←

FIGURE 19

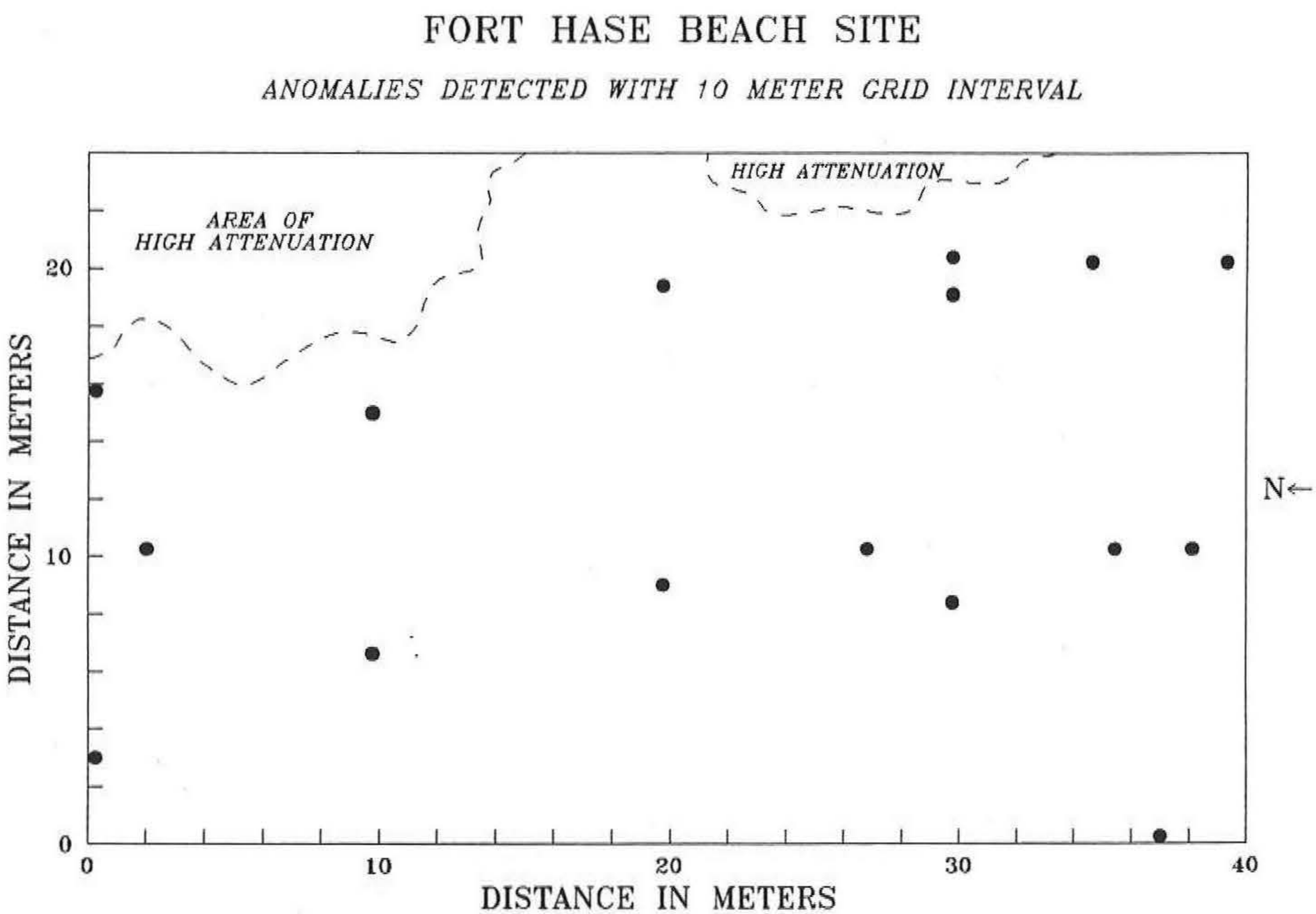
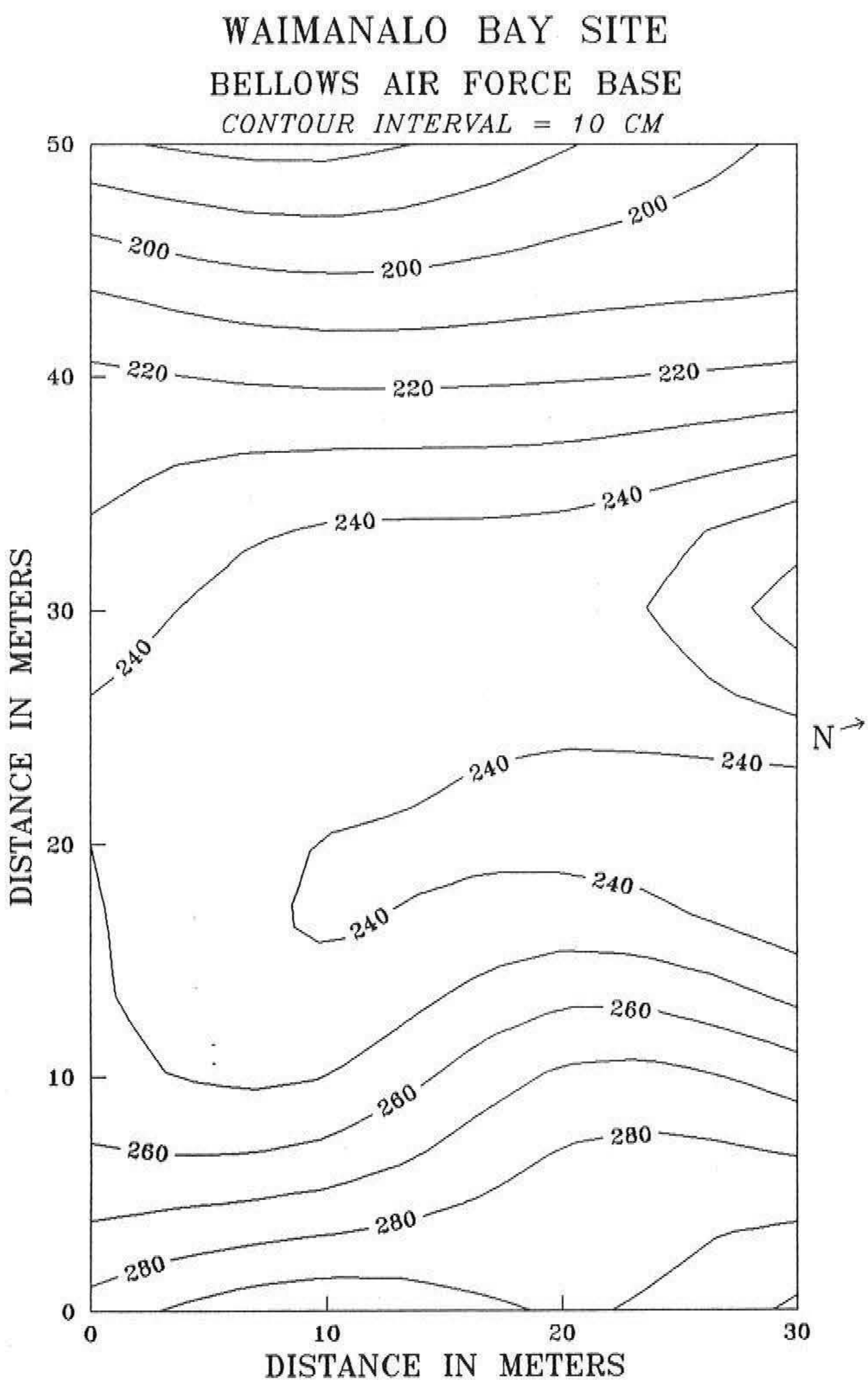

FORT HASE BEACH SITE
ANOMALIES DETECTED WITH 10 METER GRID INTERVAL
AREA OF
HIGH ATTENUATION
HIGH ATTENUATION
DISTANCE IN METERS
DISTANCE IN METERS
0
10
20
30
40
0
10
20
N←

FIGURE 20


WAIMANALO BAY SITE
BELLOWS AIR FORCE BASE
CONTOUR INTERVAL = 10 CM
DISTANCE IN METERS
DISTANCE IN METERS
N
0
10
20
30
40
50
0
10
20
30
200
200
200
220
220
220
240
240
240
240
240
240
240
260
260
260
280
280
280

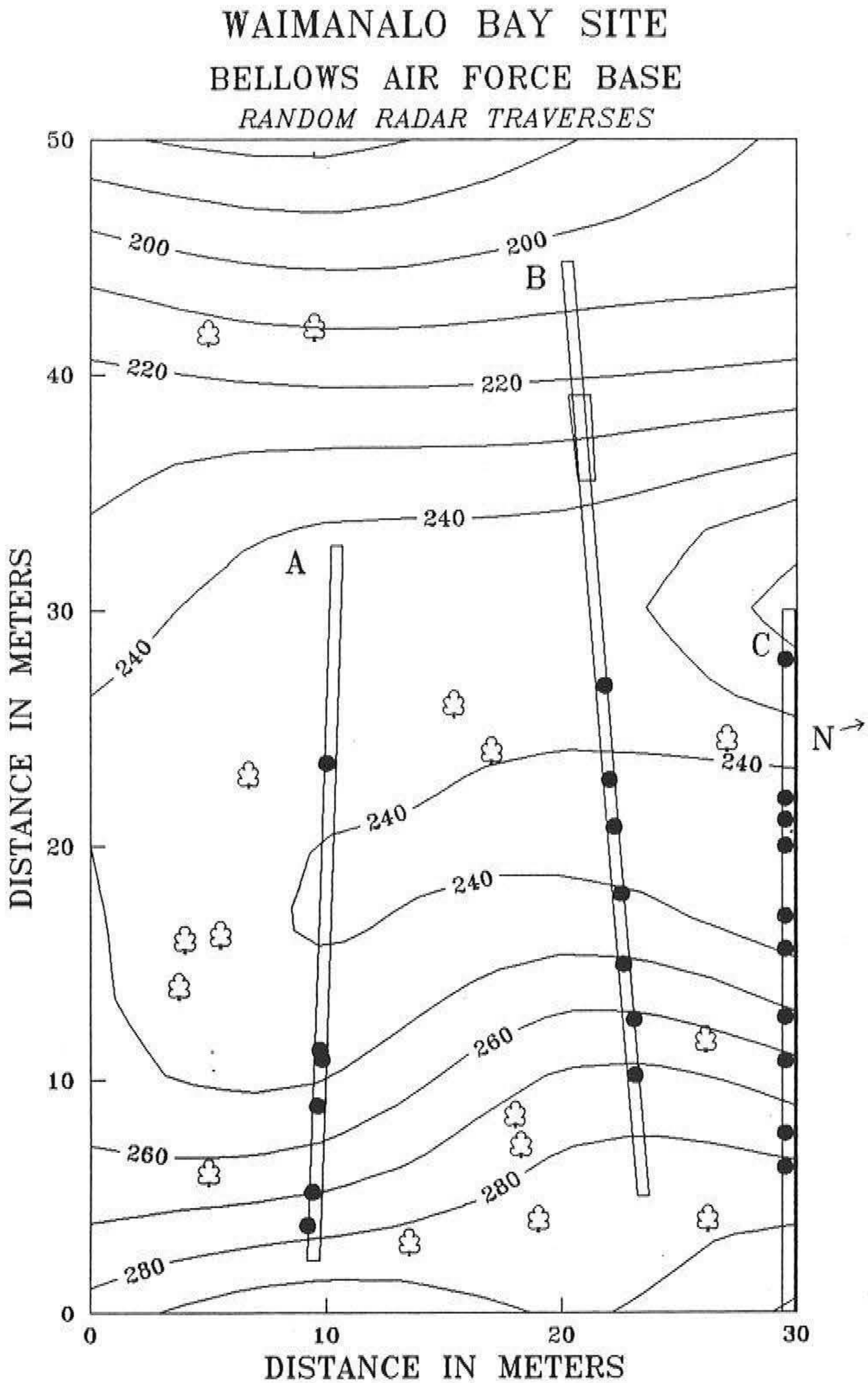
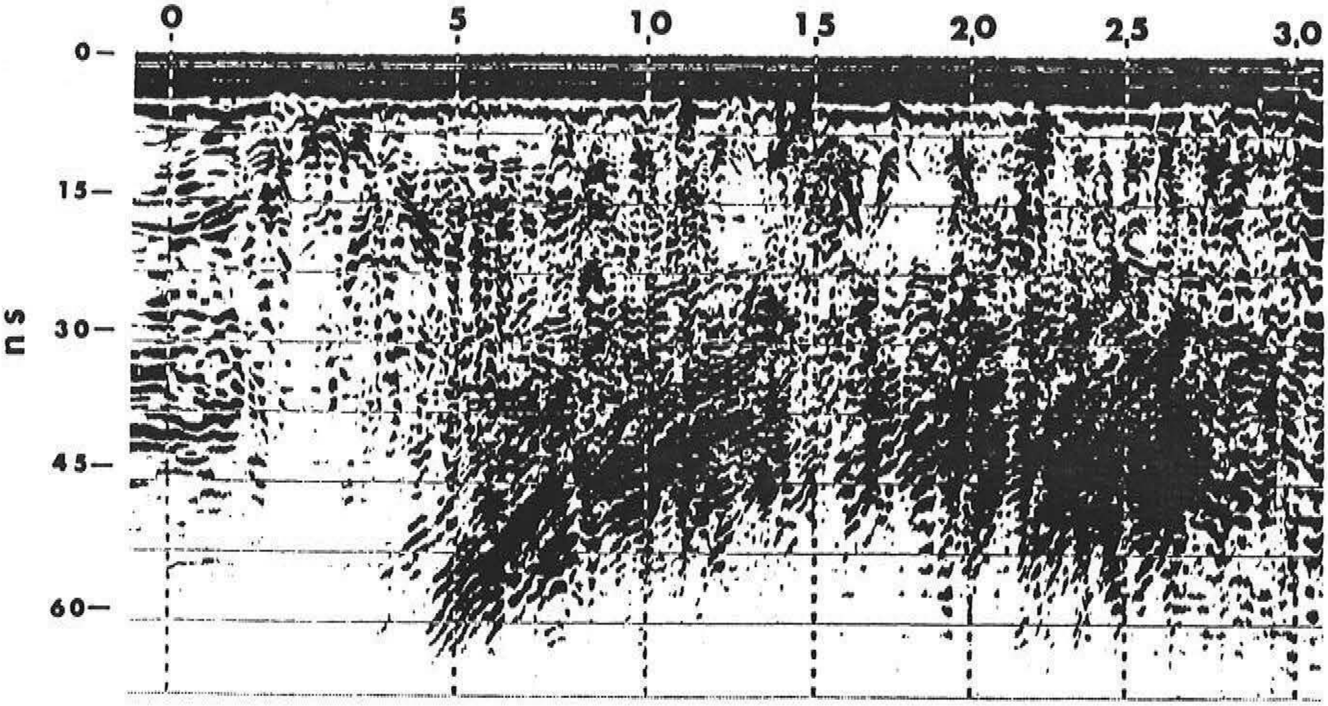

WAIMANALO BAY SITE
BELLOWS AIR FORCE BASE
RANDOM RADAR TRAVERSES
DISTANCE IN METERS
DISTANCE IN METERS
0
10
20
30
40
50
0
10
20
30
200
200
220
220
240
240
240
240
240
260
260
280
280
A
B
C
N

FIGURE 22

A


0 5 10 15 20 25 30
0
15
30
45
60
ns

B

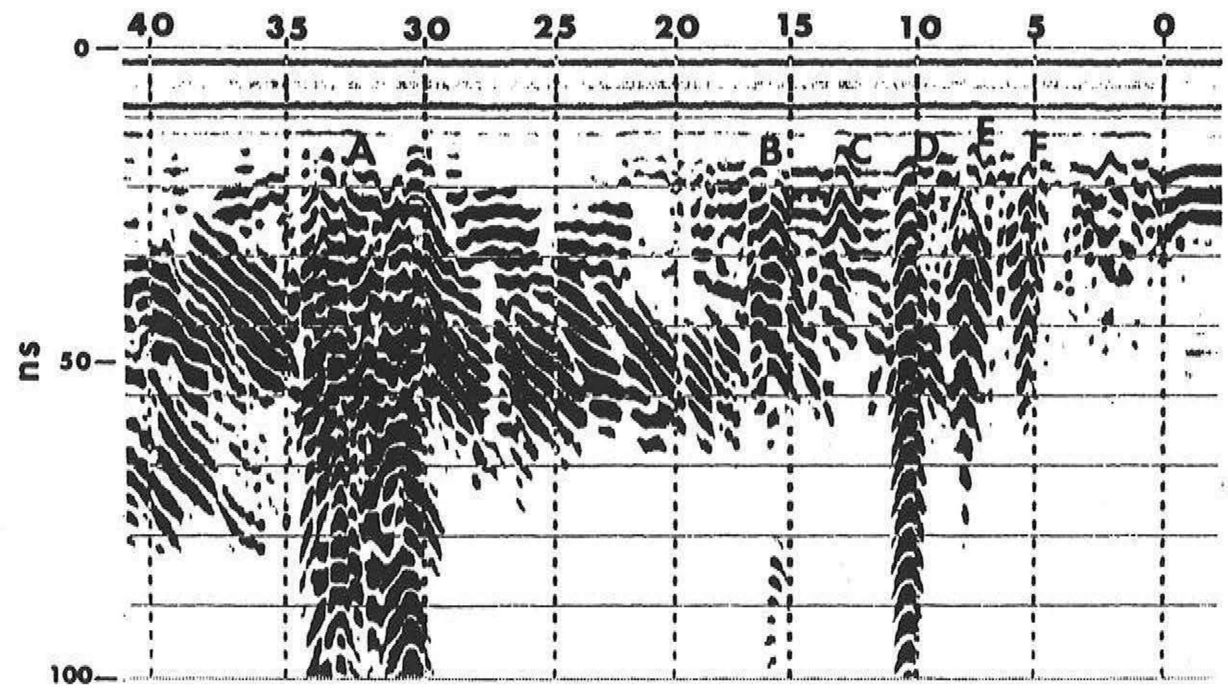
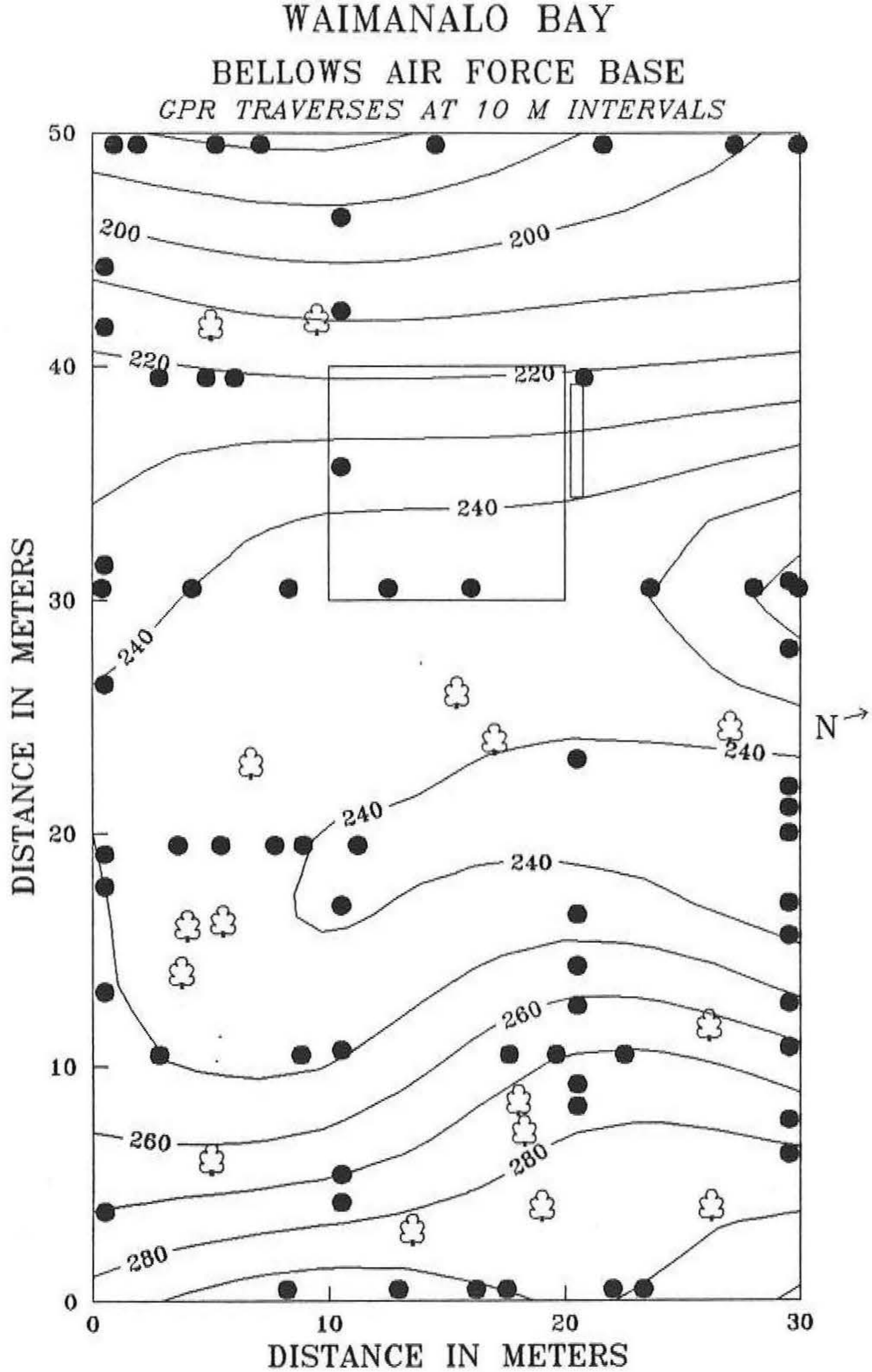
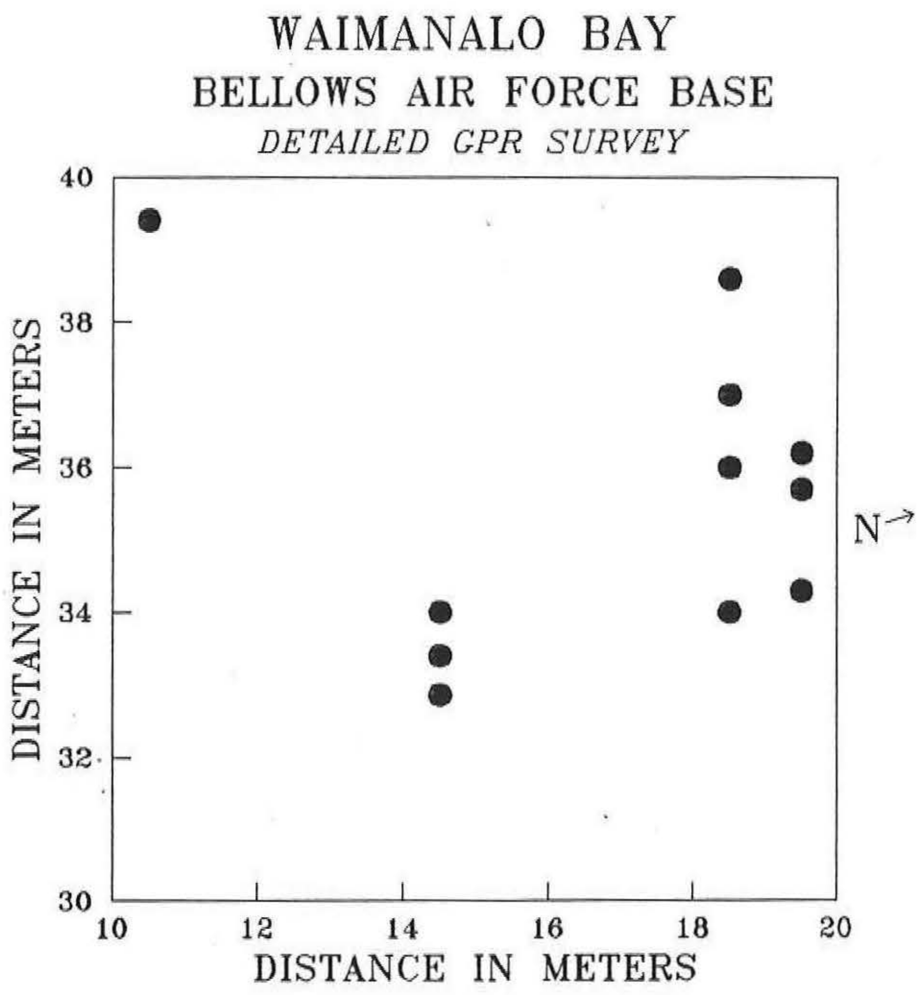

40 35 30 25 20 15 10 5 0
A B C D E F
0
50
100
ns

FIGURE 23



WAIMANALO BAY
BELLOWS AIR FORCE BASE
GPR TRAVERSES AT 10 M INTERVALS
DISTANCE IN METERS
DISTANCE IN METERS
N
200
200
220
220
240
240
240
240
240
260
260
280
280
0
10
20
30
40
50
0
10
20
30


WAIMANALO BAY
BELLOWS AIR FORCE BASE
DETAILED GPR SURVEY
40
38
36
34
32
30
10
12
14
16
18
20
DISTANCE IN METERS
DISTANCE IN METERS
N→