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Application of Ground-Penetrating Radar at McMurdo Station, Antarctica

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ABSTRACT

Argonne National Laboratory initiated a site investigation program at McMurdo Station, Antarctica, to characterize environmental contamination. The performance and usefulness of ground-penetrating radar (GPR) was evaluated under antarctic conditions during the initial site investigation in January 1991. Peliminary surveys were successful in defining the contact between reworked pyroclastic material and the prefill, undisturbed pyroclastics and basalts at some sites. Interference from radio traffic at McMurdo Station was not observed, but interference was a problem in work with unshielded antennas near buildings. In general, the results of this field test suggest that high-quality, high-resolution, continuous subsurface profiles can be produced with GPR over most of McMurdo Station.

INTRODUCTION

The National Science Foundation, manager of the United States Antarctic Program (USAP), is conducting a multiyear environmental quality program at McMurdo Station and other antarctic bases. As part of this program, Argonne National Laboratory has initiated a multiyear site investigation at McMurdo Station to characterize environmental contamination that may be present and to develop possible remedial strategies. The geology, climate, and logistical constraints at McMurdo Station presented unique technical challenges. Ground-penetrating radar was tested at McMurdo Station during January 1991 to evaluate the equipment and determine its potential applications and limitations under antarctic conditions.

DESCRIPTION OF STUDY AREA

Background

McMurdo Station was established during the International Geophysical Year of 1956 to support scientific research on the antarctic continent. The station was managed and operated by the U.S. Navy from 1956 to 1970, when administration of the USAP was turned over to the National Science Foundation. Large volumes of petroleum fuels and other potentially hazardous materials are stored at McMurdo Station, the primary logistics support and resupply center for USAP continental operations. With approximately 100 structures and a summer population approaching 1,200 people, McMurdo Station is the largest permanent facility on the antarctic continent.

Location and Climate

McMurdo Station is located on the southern tip of Hut Point Peninsula on Ross Island, Antarctica, at 77°51' south latitude and 166°39' east longitude (Figure 1). The Hut Point Peninsula is a seven-mile-long extension of the lower slopes of Mt. Erebus, an active volcano that reaches an elevation of over 13,000 ft. Ross Island lies in the Ross Sea and is located about 40 miles from the

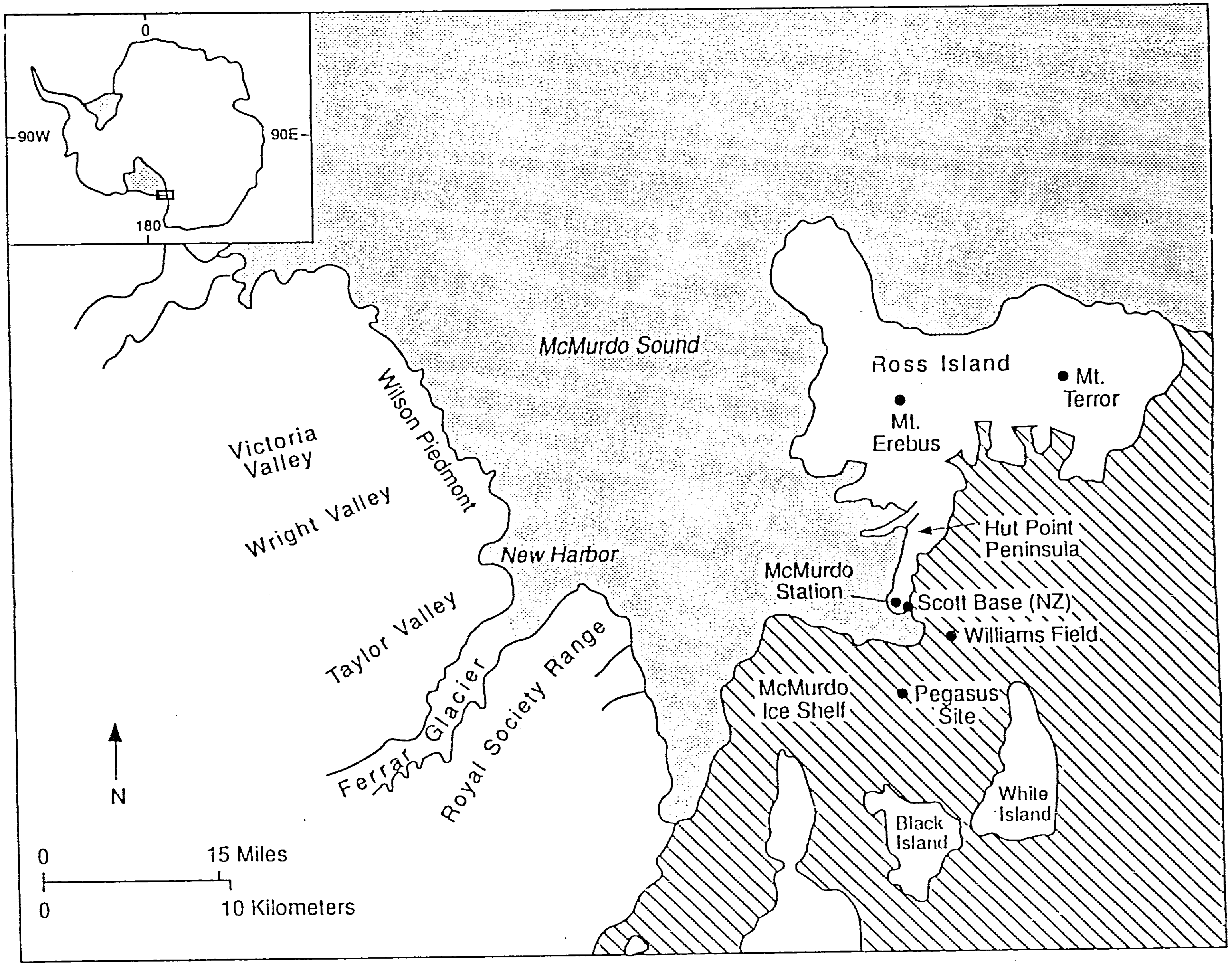

Figure 1 Location Map of McMurdo Station, Ross Island, Antarctica

antarctic continent. It is separated from the coast of Victoria Land by McMurdo Sound.

Average daily temperatures at McMurdo Station remain below freezing throughout the year. Mean annual temperatures recorded by the Naval Oceanography Command Detachment (NOCD, 1988) between 1956 and 1979 ranged from -2.1°F to 4.3°F. The austral summer season begins in December and ends in early February. During January, the warmest month, temperatures sometimes climb above freezing (NOAA, 1983). The coldest temperatures are generally recorded in August, when temperatures get as low as -48°F (NOAA, 1983). Precipitation at McMurdo Station is always in the form of snowfall. Between 1956 and 1979 the mean annual precipitation was 7.7 in. or about 77 in. of snow (NOAA, 1983). Most of the snow falls during the winter season. During the summer months most of the snow melts, and McMurdo Station is typically free of snow cover during January and February.

Geology

Surface materials at McMurdo Station are poorly sorted pyroclastics deposited during periods of volcanic activity that occurred between 0.4 and 1.2 million years ago (Kyle and Treves,1974). The angular vesicular fragments that make up this pyroclastic deposit range in size from silt to boulders. These surface materials have been reworked over time by glacial and fluvial processes. Human activities in and around McMurdo Station have further altered the distribution and thickness of these surface rocks. The thickness of these deposits at McMurdo Station probably ranges from a few inches to 50 ft. Pyroclastics at McMurdo can be divided into three distinct units on the basis of temperature and water/ice content. These three physical units are the active layer, dry (no ice) permafrost, and ice-rich permafrost. Although all three units are composed of the same lithologic material, each has distinct physical characteristics with respect to soil moisture, porosity, and pearmeability.

The active layer at McMurdo is generally in the upper 1-2 ft. of the pyroclastic materials (Mayo, 1990). This surface layer freezes each winter and thaws each summer. The active layer is generally dry because of high evaporation rates, but near stream channels and on slopes below ice or snow patches this layer becomes wet. When the wet areas of the active layer freeze at the end of the summer, they become ice cemented. However, the upper few inches dry out during the winter and spring because of ablation of the ice cement. During the summer, the permeability of the entire active layer is very high, like that of a sandy gravel. During the winter, the dry areas of the active layer remain highly permeable, while the ice-cemented areas become virtually impermeable.

Dry permafrost remains permanently below freezing, but contains insufficient ice to harden or cement it. These "dry" zones in the permafrost are highly pervious. Areas at McMurdo where dry permafrost is most likely to be found are (1) in fill placed during construction, (2) where meltwater is absent (i.e., in windblown areas where snow is removed by erosion and sublimation), and (3) where dry winds ventilate porous ground and can sublimate ground ice (Mayo, 1990). At McMurdo Station, the majority of dry permafrost is probably associated with materials placed or reworked during construction activities. Research by Campbell et al. 1990 showed that ice content in disturbed materials were much lower than in undisturbed materials, even after several decades. There are no reliable surface expressions that can be used to distinguish between dry and ice-rich permafrost zones, and the vertical extent of dry permafrost at McMurdo Station is not known.

Ice-rich permafrost is permanently frozen material in which all of the interstices between the solids are filled with ice. This material may serve as a barrier to downward fluid migration. The water source for this ice comes from snowmelt, which is negligible in the short term but over geologic time is sufficient to cement the pyroclastic materials into an impermeable layer. The places where ice-rich permafrost is most likely to be found are (1) areas of the station undisturbed by construction, (2) topographically low areas that become wet each summer, and (3) areas shielded from winds that can sublimate ground ice.

Bedrock at McMurdo is permanently frozen and consists primarily of flow basalts (Kyle and Treves, 1974). Ice typically found in the joints and fractures of the basalts results in very low permeabilities. Drilling fluid losses were reported in the basalt during the Dry Valleys Drilling Project (Kyle and Treves, 1974). These losses indicate that some voids in the basalt are not ice filled.

METHODS OF INVESTIGATION

Theory of Ground-Penetrating Radar

Ground-penetrating radar uses high-frequency radio waves to aquire subsurface profiles. From a small antenna that is moved slowly across the ground, energy is radiated downward into the subsurface, then reflected back to the receiving antenna. The signals recorded at the receiver provide a map or a cross section of the subsurface that is similar in appearance to a seismic reflection record. Variations in response are caused by radar wave reflections from interfaces of materials having different electrical properties. The depth of penetration is highly site-specific, being dependent on properties such as water content, amount of clay, and the amount of salts in solution.

Although the shallow subsurface (0-50 ft) at McMurdo Station is composed mostly of a single geologic material (brecciated pyroclastics), the difference in dielectric constants (E_r) between air ($E_r = 1$) and ice ($E_r = 4$) makes it possible to differentiate dry permafrost from ice-rich permafrost. This distinction will be important in mapping possible contaminant migration pathways and accumulation points.

Equipment and Methodology

The GPR system tested in this effort was manufactured by Geophysical Survey Systems, Inc. (GSSI). The model SIR-3 system was powered by a 12-volt direct current battery in the transport vehicle. Radar antenna frequencies were chosen to provide an acceptable compromise between high resolution and deep penetration. Transmission frequencies employed were 80 MHz, 300 MHz, and 500 MHz (megahertz). The graphic recorder used with this equipment was an ADTEK Model SR8000 line-scanning graphic recorder.

The central unit/graphic recorder was located in the transport vehicle. Antennas were equipped with wheels or skids and were towed by hand at approximately 50 ft/min. The transport vehicle was parked as far as possible from the radar traverse. The location of the closest pass to the vehicle was marked on the graphic recording so that the effect, if any, on the radar record could be determined. The electromagnetic wave velocity for compacted fill material was calculated at a culvert beneath Hut Point Road, adjacent to Building 183. An approximate velocity of 3 ns/ft was calculated by using the known depth to the culvert and the two-way travel time recorded. Velocities in the undisturbed materials where depth to reflectors could not be determined from positive correlation were assumed, for this test program, to be approximately the same as for the fill material. This assumption allowed a single depth scale to be used in interpreting the radar record.

FIELD RESULTS

Radar traverses were run at five locations with variable success (Figure 2). The 300-MHz and 500-MHz antennas were used at locations where the 80-MHz antenna did not perform well and at locations where greater resolution was desired. A summary of the results at each location follows.

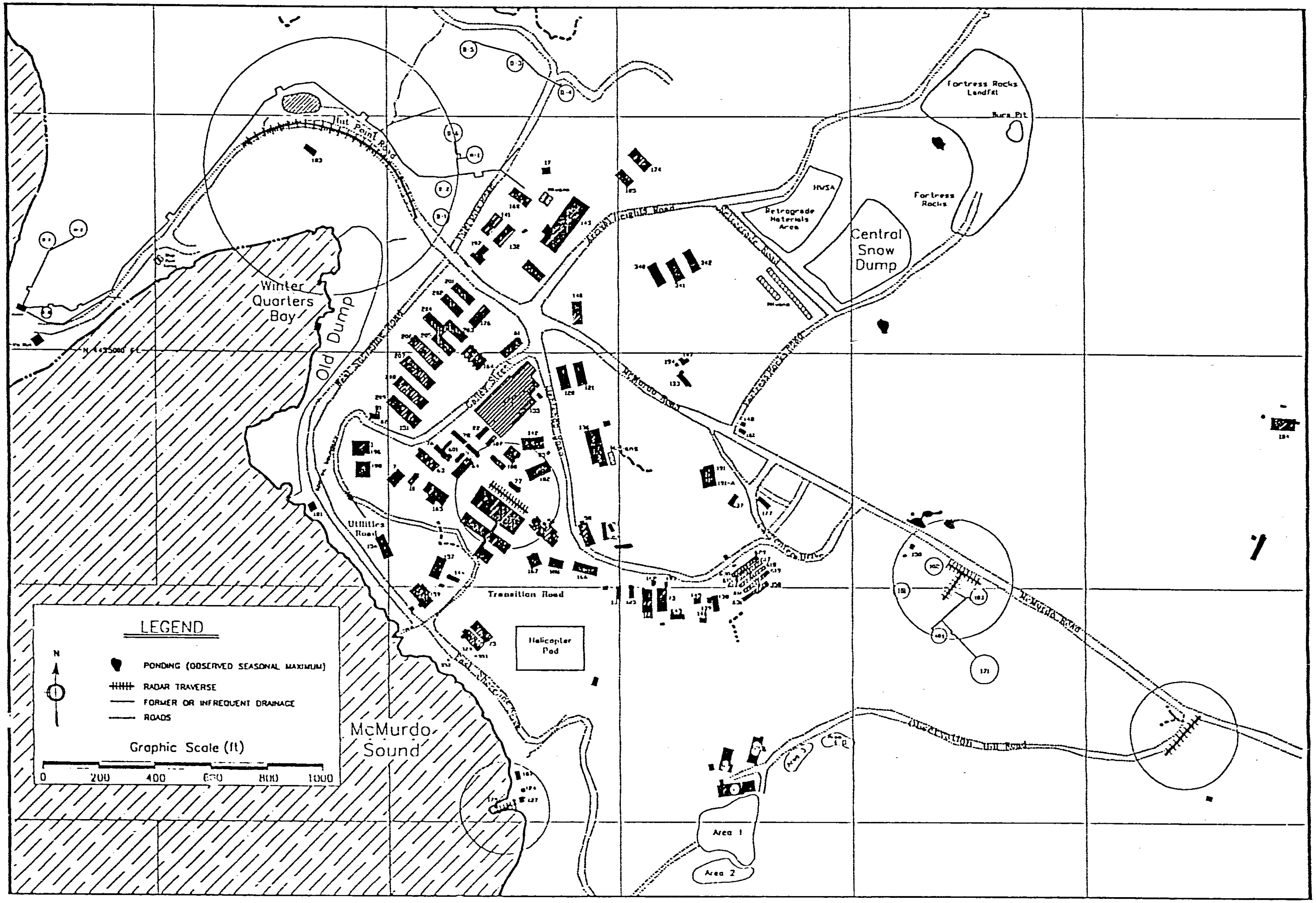

FIGURE 2 Location of Ground-Penetrating Radar Traverses at McMurdo Station

Hut Point Road

The first radar record (Figure 3) from Hut Point Road shows the characteristic hyperbola of a buried culvert at a measured depth of 4 ft. A second reflection in the radar record to the right of the culvert was caused by the antenna's pass over the antenna cable. The remainder of the reflection configuration of this radar record is roughly horizontal, as would be expected for graded roadbed materials.

The second radar record (Figure 4) from Hut Point Road shows a hummocky to chaotic reflection configuration and a few rather steeply dipping reflectors that are smooth and continuous. The hummocky/chaotic areas are interpreted as pyroclastic fill and rubble that was randomly dumped. Near-surface reflectors are more parallel, as if they are fine materials that have been graded to form a smooth roadbed. The nature of the dipping reflectors is unclear. Measurements made on the fill slope showed the fill to be approximately 40 ft thick at the 150-ft mark of the radar record. This result suggests that the dipping reflector at that point is contained entirely within the fill. The same is true for the dipping reflector at the 400-ft mark. These reflectors might represent previous road surfaces that appear to be much steeper than they actually were because of the vertical exaggeration of the radar record. Repeat traverses with the same anrenna produced almost identical radar records.

Observation Hill Road

The radar record (Figure 5) from the foot of Observation Hill Road has a distinct dipping reflector that is interpreted to be the bedrock surface upon which fill was placed to bridge the valley. The slope of the reflector coincides closely with the slope of Observation Hill. Therefore, it is surmised that this reflector is the former surface profile of Observation Hill. Zones with no reflectors are interpreted as ice pockets. Some ice was clearly seen outcropping on the fill slope beneath the roadbed. The fill material contains some metallic and/or wood debris. The hyperbolas at 6-9 ft are interpreted as debris. A drum was seen protruding from the west slope face of the fill. A repeat traverse with the same antenna produced an identical radar record.

Tank Farm 2

Radar traverses were run at several locations in Tank Farm 2. These attempts were unsuccessful because most of the energy was attenuated in the upper 6 ft. The attenuation may have been due to the presence of near-surface water and/or fuel. Areas of apparently deeper penetration were interpreted as antenna ringing.

Intake Jetty

Radar traverses were run near the end of the intake jetty in an attempt to record the intake pipes located approximately 50 ft below the surface of the jetty. These attempts were unsuccessful because the radar records showed abrupt attenuation of energy at approximately sea level. The high conductivity of the seawater

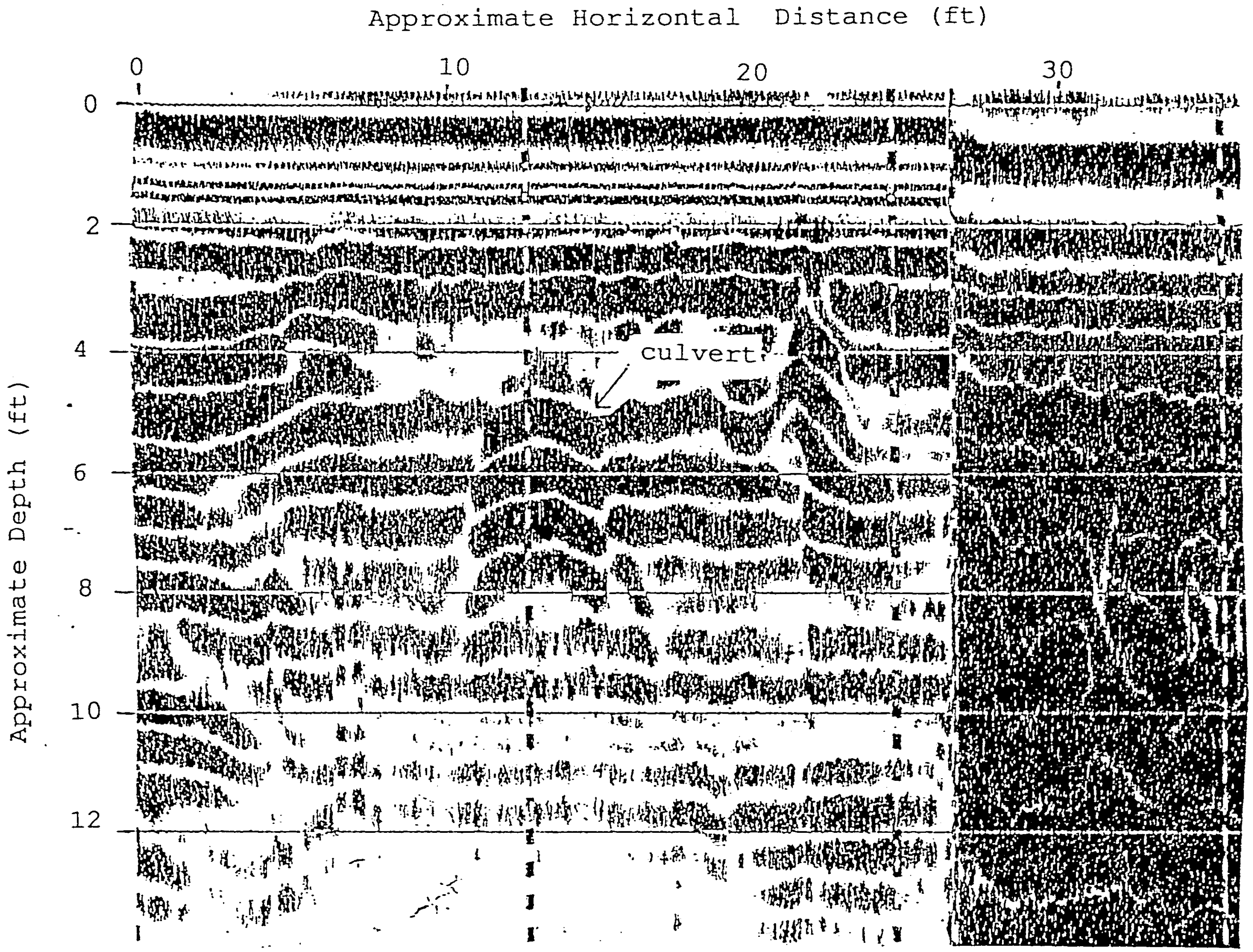

Figure 3. Radar Record from Hut Point Road Showing a Buried Culvert (300 Mhz antenna, range 100 ns.)

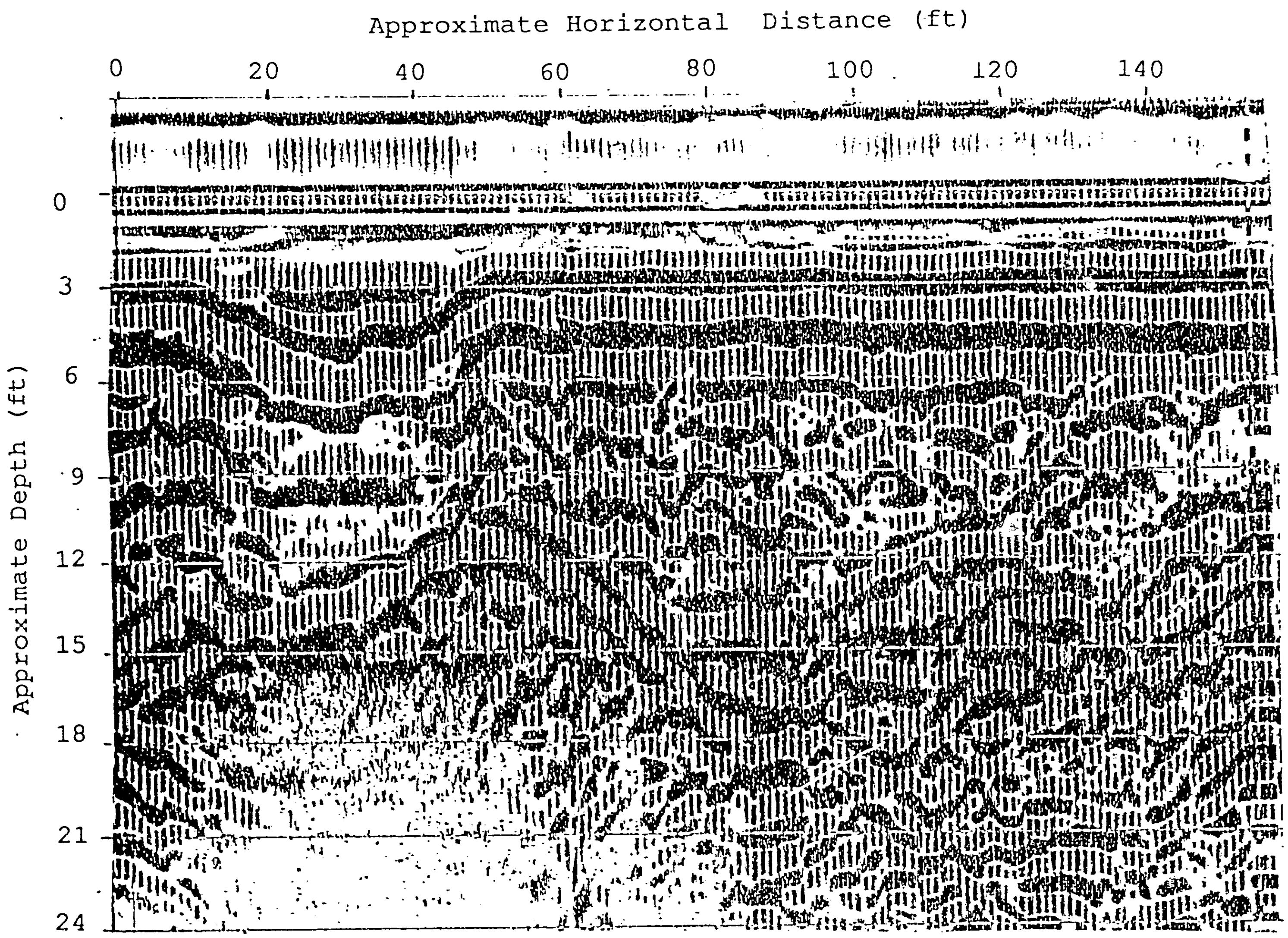

Figure 4. Radar Record from Hut Point Road Showing Engineering Fill Placed to Bridge Valley (80 Mhz antenna, range 200 ns.).

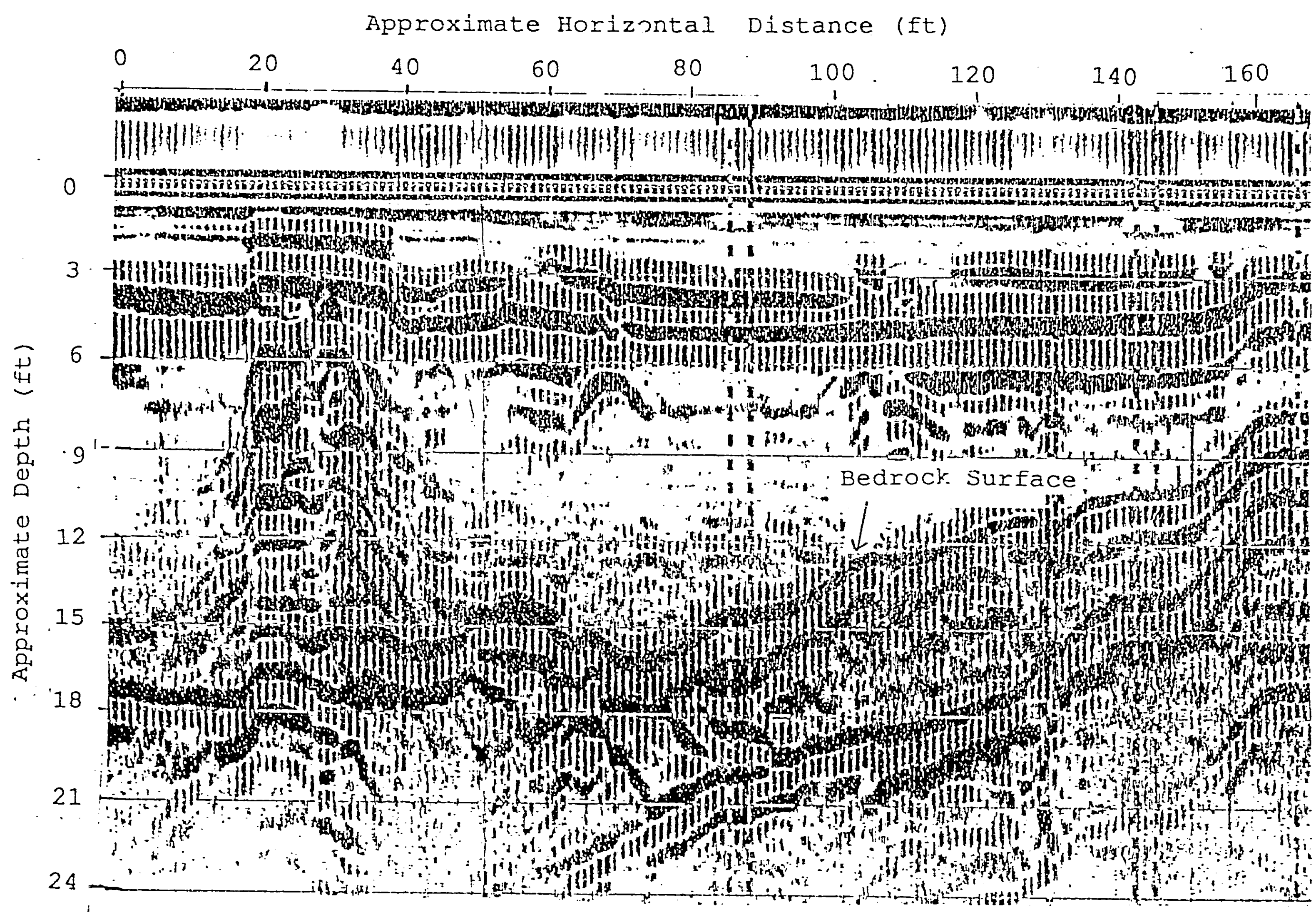

Figure 5. Radar Record from Observation Hill Road Showing Bedrock Surface Beneath Engineering Fill (80 Mhz antenna, range 200 ns.).

apparently caused rapid attenuation of the electromagnetic energy below the water line.

Downtown McMurdo

A radar traverse was run parallel to the front of the New Science Building in an attempt to determine the building's effects on the radar performance. The traverse was run with the 80-MHz unshielded antenna approximately 20 ft from the building. The radar record showed only noise. The plan had been to repeat traverses at greater distances from the building until the effect of the building dropped off. Unfortunately, recorder problems prevented any additional radar work from being performed.

CONCLUSIONS

In general, the results of this field test suggest that high-quality, high-resolution, continuous subsurface profiles can be produced with GPR at McMurdo Station. With the 80-Mhz antenna, good penetration was possible to depths of 30 ft, and the contact between pyroclastic fill material and the prefill natural surface could be defined. The 300- and 500-Mhz antennas will be useful for defining the configuration of the active layer and for working close to structures, but penetration with those antennas was less than 15 feet. The GPR was not adversely affected by austral summer weather conditions if the recorder is sheltered, and it was not succeptable to interference from radio traffic at McMurdo.

ACKNOWLEDGMENT

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