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Subject: SOI – Ground-penetrating radar study of Gelisols, Barrow, Alaska **Date:** 29 June 1999

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Purpose:
To assess the suitability of ground-penetrating radar (GPR) for delineating soils and soils features in areas of permafrost.

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Activities:
All field activities were completed on 10 to 14 May 1999.

Equipment:
The radar unit is the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.[1] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 12-volt battery powers the system. This unit is backpack portable and, with an antenna, requires two people to operate. As high resolution of subsurface features occurring at shallow depths was required, a model 5103 (400 mHz) antenna was used in this study. The scanning time was either 30 to 40 nanoseconds (ns); the scanning rate was 32 scan/second. Selected radar profiles were processed through the WINRAD software package [1].

Study Area:
The study area is located within the Barrow Environmental Observatory (BEO), near Barrow, Alaska. The mean annual temperature is about –12.6°C (Brown, 1967). Perennially frozen soils form a continuous blanket over the study area and most of the Arctic Coastal Plain. At Barrow, the thickness of perennial frozen sediments is greater than 300 meters (Brown

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

and Johnson, 1965). The depth of seasonal thaw varies from year to year. Over a period of five years, Brown (1967) observed an average thaw depth of about 38-cm with a range of 33 to 43 cm.

Figure 1 shows the relative topography of the study area. Relief is about 1.6 m. A noticeable ridgeline extends across the study area. Differential thawing, deformation and heaving of soil materials have produced polygonal ground patterns (Brown and Sellmann, 1973). These frost features consist of bare to partially vegetated scars and vegetated domes and hummocks separated by shallow, interconnected troughs (Brown and Johnson, 1965). The troughs outline the polygons and are underlain by massive ice wedges. Troughs have widths of 2 to 3 m. However, not all ice wedges are so easily predicted. Some deeper, buried wedges and smaller, newly formed wedges lack surface expression (Arcone et al., 1982)

Major soils that have been reported in the BEO include Upland Tundra, Meadow Tundra, and Arctic Brown (Brown, 1967). Upland Tundra occurs on domes and hummocks; Meadow Tundra occurs in the troughs of polygonal ground patterns (Brown, 1967). Arctic Brown soils occur on the higher-lying ridge, which is composed of coarser-textured soil materials. Cryoturbation results in the mixing, disruption and displacement of soil horizons and textural layers (Tarnocai, 1973). Cryoturbation also removes organic materials from surface layers and deposits them along the permafrost table (Mackay et al., 1961). Typically, a thin (0 to 18 cm) organic mat overlays the mineral soil. The mineral soil materials are predominantly silt loam.

Soils contain a large volume of ice as films, lenses, massive layers and large ice wedges. Within the Barrow area, the upper several meters contain about 60 to 70 percent segregated ice by volume (Sellmann and Brown, 1973). Brown (1967) described a typical Meadow Tundra soil profile as having varying concentrations and forms of stratified ice segregations and lenses. Finer ice lenses often occur in the upper part of the mineral soil profile as a result of relatively rapid rates of freezing from the top down (Brown, 1967). In the lower part of the mineral soil profile, the presence of thick (5 to 10 cm) horizontal ice lenses reflects the migration and freezing of soil water from the permafrost table up (Brown, 1967).

While not observed, the dominant vegetation within the study area consists of low, wet tundra (Sellmann and Brown, 1973). Dominant species include sedge (Carxe aquatilis), grass (Dupontia fisheri), and cotton grass (Eriophorum scheuchzeri and Eriophorum angustifolium) (Brown and Johnson, 1965).

Field Methods:

Fieldwork was carried out in early May, when the active layer was still frozen. At Barrow, this time of the year offered the most favorable temperatures and soil conditions for GPR operations. Active layers inhibit the penetration of radar signals. In thawed medium and fine textured sediments, radar signals are severely attenuated (Arcone and Delaney, 1982). Adsorptive losses (high moisture contents) within the active layer and reflective losses (variable ice and water contents) within the upper part of the permafrost attenuate radar signals. Lawson and others (1998) observed that radar signals suffered less attenuation where the active layer was thin or nonexistent and the permafrost was very close to the soil surface.

At the time of the survey, the study area was covered by a mantle of snow that ranged in thickness from 0 to more than 150 cm. Snow cover provided easier access to the study area with GPR and coring equipment. While this study was being carried out daytime temperatures ranged from about 10 to 35° F. The antenna was towed behind a snowmobile or dragged by hand along three 1000-m traverse lines (see Figure 1). Along each traverse line, survey flags were inserted in the snow at an interval of about 10-m. These radar records were reviewed and more intensive radar investigations were conducted along selected portions of each traverse line. For these detailed investigations, survey flags were inserted in the snow at an interval of about 1-m.

Soil data were obtained from thirteen cores collected at specific points along radar traverse lines. Small diameter (6 cm) cores were obtained to depths of about 58 to 100 cm with an *Eager-Beaver* drill. Samples were collected by soil horizons and analyzed for moisture content, bulk density, and texture. Core data were compared with radar reflections to scale the radar profiles and verify interpretations.

Background:

Ground-penetrating radar (GPR) is an impulse radar designed for shallow subsurface investigations. It has been used extensively in areas of permafrost. Areas of permafrost have electrical properties that are favorable to the operation of GPR. Scott and other (1990) observed that as the temperature drops below 0°C, the conductivity, dielectric permittivity and loss tangent decrease, while the velocity of propagation increases. As water freezes in soils, signal attenuation decreases and penetration depth increases. However, as the amount of ice increases in soils, the contrast in electromagnetic properties between frozen soil layers decreases and the detection of some soil horizons and stratigraphic features with GPR is reduced.

The suitability of GPR is dependent on the specific application, depth of interest, and soil type. High rates of signal attenuation limited the effectiveness of GPR in frozen silts and clays (Annan and Davis, 1977, Arcone et al., 1998, Davis et al., 1976). Rates of signal attenuation are lower, depths of observation are greater, and results of GPR surveys are more favorable in areas of coarse textured soil materials.

In areas of permafrost, because of the strong contrast in dielectric permittivity between unfrozen and frozen materials, GPR has been extensively used to detect boundaries separating materials containing varying amounts of liquid and frozen water. Ground-penetrating radar has been used to measure dielectric permittivity of frozen sediments (Annan et al., 1975, Annan and Davis, 1976, Davis et al., 1976, Arcone and Delaney 1982, 1984, 1889, Arcone et al., 1982). It has been used to identify and map areas of massive ground-ice (Arcone et al., 1982, Dallimore and Davis, 1987, Kovacs and Morey, 1979, 1985, Robinson et al., 1993, Scott et al., 1990). Ground-penetrating radar has also been used to locate unfrozen aquifers and profile depths to groundwater beneath perennial frozen sediments within areas of discontinuous permafrost (Arcone et al., 1998, Lawson et al., 1998). In addition, GPR has also been used to study spatial and temporal variations in the thickness of the active layer (Annan and Davis 1978, Doolittle et al., 1990, 1992, Pilon et al., 1979, 1985, Wong et al., 1977).

Calibration:

Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (i.e., soil horizon, stratigraphic layer) and back. In this study, two-way travel times to reflections appearing on radar profiles were compared with measured depths to soil horizons observed in soil cores. Depths to soil horizons observed in cores were used to verify radar interpretations, estimate pulse propagation velocities, and establish a depth scale for the radar profiles.

The relationships among depth (d), two-way, pulse travel time (t) and velocity of propagation (v), are described in the following equation (after Morey, 1974):

$$d = vt/2 \qquad [1]$$

The velocity of propagation is inversely related to the bulk dielectric permittivity of the profiled material according to the equation:

$$e = (c/v)^2 \qquad [2]$$

where e is the bulk dielectric permittivity and c is the velocity of propagation in a vacuum (0.3 m/ns).

Initially, the identity and depth to subsurface reflections observed on radar profile were unknown. Preliminary interpretations were conducted over ice wedges because of their distinct hyperbolic reflections (see Figure 2). At three coring sites, depths to permanently frozen water layers (Wf horizon) were compared with the two-way travel time to these subsurface reflectors. Initial estimates of the propagation velocity ranged from 0.04 to 0.06 m/ns. These velocities were too slow for frozen silts, but were comparable to propagation velocities obtained in saturated, unfrozen silts (dielectric permittivity of 30 to 56). In frozen, predominantly silty sediments, the estimated velocity of propagation should range from 0.10 to 0.15 m/ns and the dielectric permittivity ranged from 3.9 to 9.1 (Arcone, 1984).

Based on these first interpretations, it was obvious that the wrong reflections had been selected. In order to approximate the referenced propagation velocity for frozen silts, reflections from the tops of the ice wedges needed to occur at shallower soil depths and at shorter time intervals. Arcone and others (1982) noted that, ice wedges produce conspicuous superimposed hyperbolic reflections. These researchers observed that these apparent reflections do not necessarily represent or indicate the actual tops of ice wedges. The true tops of ice wedges often occur at shallower depths where they are masked by reflections from overlying reflectors.

The most conspicuous subsurface soil horizons observed in soil cores were the Oe, Oe/Cg, and Wf horizons. These horizons contrast in either organic matter or ice contents with adjacent or enclosing horizons. At the upper interface or boundary of these horizons, the contrast in electromagnetic properties (with the overlying horizon) was considered sufficiently abrupt and contrasting to produce a discernible reflection on radar profiles. Measured depths to these horizons ranged from 18 to 95 cm.

Several planar reflections were identifiable in the upper part of radar profiles. These reflectors were interpreted to be the interfaces separating the snow and ground surface, the Cg and Oe/Cg horizons, and the permafrost table. In places, these

reflectors were partially obscured by superimposed reflections from overlying soil horizons. In other places, chaotic patterns or multiple diverging, converging, or overlapping reflections reduced confidence in interpretations. On radar profiles, the permafrost table appears as a continuous, low amplitude, planar reflector. The low amplitude reflections from the permafrost table were often punctuated by higher amplitude, point reflectors. The point reflectors were assumed to be ice lenses or the tops of ice wedges. A discontinuous planar reflector with low to medium amplitudes often occurred above the reflection from the presumed permafrost table. This reflector was believed to represent layers of organic matter accumulation (Oe or Oe/Cg horizon).

At seven observation points, the measured depths to these soil features were compared with the two-way travel time to the interpreted reflectors. A strong relationship (r^2 ranged from 0.97) was found to exist between the two-way travel time to these reflectors and the measured depth to the observed soil horizons. Because of variations in soils and soil properties, the velocity of propagation was variable among the coring sites. Based on estimates made at each of the seven coring sites, the velocity of propagation averaged 0.1353 m/nanoseconds (ns) and ranged from 0.1077 to 0.1723 m/ns through the frozen soil. Based on these propagation velocities and equation [2], the bulk dielectric permittivity was estimated to range from 3.0 to 7.8. This range is comparable with the range in dielectric permittivity obtain by Arcone (1984).

Interpretation of Radar Profiles:
Figures 2 and 3 are representative radar profile from the study area. Figure 2 is representative of a detailed survey conducted at a slow speed of advance (about 0.5 km/hr). Figure 3 is representative of a survey conducted at a walking pace (about 6 km/hr). In each profile, the horizontal scale represents units of distance and is expressed in meters. The short vertical lines at the top of the radar profiles represents equally spaced flagged observation points. In Figure 2, the distance between observation points is 1 meter. Observation points are numbered 0 to 19. In Figure 3, the distance between observation points is 10 meter. Observation points are numbered 0 to 90. In each profile, the vertical scale is a depth scale expressed in meters. The vertical scale is about 2.7 m and is based on the two-way pulse travel time, the average velocity of propagation (0.1353 m/ns), and equation [1].

The radar profiles shown in figures 2 and 3 have been processed through the WINRAD software package. Processing was limited to signal stacking, horizontal high pass filtering, color transforms, range gain, and distance normalization. Signal stacking averages several scans and presents the results as a signal trace. Stacking helps to remove unwanted background noise. Horizontal high pass filters were used to remove horizontal bands of noise in the data. As the raw data contained a large number of low amplitude reflections, color transforms and range gain were used to enhance these reflections. Color transforms resulted in the enhancement of low amplitude reflections with only a minimal effect on high amplitude reflections. Range gain was used to increase the amplitude of both low and high amplitude reflections. Distance normalization corrects for variation in survey speed by stretching and skipping scans between the observation points. Distance normalization provides a constant horizontal scale.

In both figures, the two, continuous horizontal bands at the top of the radar profile represent the snow surface. The discontinuous, high amplitude reflections immediately below these bands represent the snow/ground surface interface. These reflections appear discontinuous as they are partially obscured by reflections from the snow surface. In areas where the snow cover is less than about 20 cm, reflections from the soil surface are masked by the reflections from the snow surface. In both figures, the soil surface has been highlighted with a dark line.

The two illustrated radar profiles are believed to have traverse polygonal ground patterns. In Figure 2, it is believed that the radar traversed a hummock or dome between observation points 4 and 11. The snow cover appears to be thinner across this surface suggesting a slightly higher-lying and more wind-swept surface. Compared with other portions of this radar profile (Figure 2), reflections are considerably weaker below the hummock or dome. The low amplitudes of these reflections suggest greater attenuation and increased conductivity; factors that can be attributed to a greater unfrozen water content (adsorbed water) beneath the mounds. The amplitude of subsurface reflections appears to increases on either side of the hummock where ice wedges commonly occur.

The most conspicuous subsurface reflectors on the radar profiles were massive ice wedges. In Figure 2, two massive ice features produce high amplitude, multiple reflections that are centered below observation points 2 and 14 at depths ranging from about 0.75 to 1.4 m. These ice wedges produce diverse and exceedingly complex reflections. Large ice masses provide high amplitude, easily identifiable hyperbolic reflections and reverberations on radar profiles. The hyperbolic reflection is caused by the antenna's wide arc of radiation and signal diffraction.

Depths to ice masses were used to identify the permafrost table. As ice masses do not extend into the active layer, the depth to these reflections provided an indication as to the identity of the permafrost table's reflection. The permafrost table has

been highlighted and labeled in Figure 2. Because of seasonal thawing, water migrates and accumulates at the permafrost table. The permafrost table is detectable because of its greater ice content. The permafrost table contrasts with overlying horizons in ice and moisture contents. In Figure 2, reflections from the permafrost table consist of two continuous, low amplitude, horizontal bands. In Figure 2, the permafrost table occurs at an average depth of about 42 cm with a range of about 30 to 51 cm. The permafrost table can be traced laterally across this figure. Several higher amplitude point reflectors punctuate the low amplitude reflections from the permafrost table. These point reflectors are believed to be the tops of ice lenses or wedges. In Figure 2, eight, high amplitude point reflectors that occur within the reflection from the permafrost table have been identified ("^").

Some lower-lying interfaces were difficult to identify and trace laterally because of multiple reflections (reverberations) from over-lying reflectors. These overlying reflectors produced unwanted clutter on radar profiles and obscured some subsurface reflectors. This was most noticeable where the "ringing" from point anomalies (i.e., ice wedges, ice lenses) partially mask or distort reflections from deeper-lying reflectors. In Figure 2, unwanted clutter partially masks an unidentified subsurface layer that can be traced across the radar profile between depths of 0.9 and 1.0 m.

The large number of point reflectors in the lower part of the soil profile is attributed to the presence of ice lenses. High concentrations of ice lenses in fine-grained sediments are known to produce chaotic radar reflection patterns (Moorman et al., 1994). The composite pattern of these reflectors provides a characteristic graphic signature for permafrost. In Figure 2, the chaotic pattern of the permafrost contrast with the more linear pattern above the permafrost table.

In Figure 2, soil cores were collected at observation points 0, 4, 10, and 14. Soil horizons were mixed and disrupted by cryoturbation and were exceedingly variable over short distances. As a result, most reflections were discontinuous and unclear to poorly expressed on radar profiles. Table 1 lists the depths to major subsurface horizons observed at each observation point. Examined soil profiles showed the effects of cryoturbation and contained buried peat layers. Soils were classified as being members of the Glacic Umbrorthels (#0), Glacic Aquorthels (#4), Typic Aquiturbels (#10), and Glacic Aquiturbels (#14) soil taxonomic subgroups (Soil Survey Staff, 1998).

Table 1
Brief Profile Description
of Cored Soil Samples
(all depths are in cm)

	Cores			
Horizon	**0**	**4**	**10**	**14**
Oe	0-8	0-9	0-7	0-14
A	8-22	----	----	----
Cg	22-43	----	7-18	14-34
Oe/Cg	----	9-26	18-65	34-45
Oe2	----	26-34	----	----
Cg/Oe	----	----	65-84	----
Wf	43-77	34-62	----	45-77

The radar profile shown in Figure 3 was collected at a faster speed of advance than the radar profile shown in Figure 2. In Figure 3, only the soil surface, permafrost table and several ice wedges are apparent and can be interpreted with some degree of confidence. However, the reflection of the permafrost table is partially obscured by reflections from overlying soil horizons. Comparing these two figures, Figure 3 appears to contain fewer subsurface reflections. In addition, though each profile was collected with the same settings and was similarly processed, the subsurface reflections seen in Figure 3 have lower signal amplitudes. The dissimilarity in the amount of subsurface information provided in each figure is directly related to the speed at which each traverse was conducted. Slower speeds of advance provide a greater number of scans per unit distance travel and a greater clarity of subsurface reflectors.

Discussion:
Ground-penetrating radar can provide a wealth of interpretive information. In most soil investigations, a small number of orderly arranged, continuous, and contrasting soil horizons simplifies radar interpretations and drastically reduces the number of cores required to verify interpretations. Radar interpretations are more obscured in areas of Gelisols. Areas of

cryoturbated soils are generally unfavorable for the interpretation of radar data. Because of cryoturbation, soil horizons are often closely spaced, mixed and discontinuous. Interpretation errors often occur where two or more interfaces are close together. In some instances a reflector can appear to splits into two interfaces. In other instances, two closely spaced reflectors can appear to merge into one reflector. In these cases, interpretations are considered less reliable. Additional coring is often required to allay the uncertainty and confirm interpretations.

Cryoturbated soil horizons produced low amplitude, discontinuous, and poorly expressed reflections. Because of their disrupted and mixed nature, some soil horizons will be undetectable on radar profiles. Other horizons that lack sufficient contrast in electrical properties are also indiscernible on radar profiles.

Cryoturbated soil horizons are best expressed on radar profiles when more scans can be collected per unit of time or distance traveled. In this survey, the scan rate was 32 scans/second. On the SIR System-2 GPR, this could be increased to a maximum of 62 scans/second. At least 20 scans are necessary to resolve an object. The detection of some subsurface features can be increased by increasing the number of scans per second or by decreasing the speed of antenna advance. In areas of permafrost, more detailed and relevant soil information may be obtained by collecting radar data at slower speeds of advance, using scan rates of 62 scans/seconds, or higher frequency antennas (900 mHz).

Greater control can be achieved by conducting shorter radar traverses with multiple observation cores to verify interpretations. The degree of interpretative uncertainty increases as the length of radar traverses and the distance between core observations increase. Ground-truth verification is required to confirm the identity and depth to subsurface reflectors. Without these observations false interpretations and unreasonable expectations for GPR can be made. In the absence of sufficient soil coring the identity and depths to most interfaces would be speculative. Even with coring data some uncertainty exist in all interpretations.

At Barrow, GPR provided adequate observation depths and detected a large number of subsurface reflectors. The permafrost table, ice wedges, and some layers of organic enrichment (buried Oe and Oe/c1 horizons) can be identified on radar profiles. Some soil features were inferred based on changes in reflector patterns.

Results from this study do not presently support the use of GPR for the determination of soil taxonomic composition. More data needs to be collected in different areas and soil types, using a greater range of antenna frequencies and/or increased scanning rates before a more definitive statement on the practicality of using GPR for soil investigations in areas of Gelisols can be made.

Reflectors within the permafrost include strata of different grain size, composition, or ice volume. Multiple subsurface reflections often produce complicated radar profiles that are difficult to interpret. Subsurface reflectors can be so numerous, discontinuous and chaotic that they obscure reflections from desired features.

The presence of polygonal ground patterns were inferred from reflectors on radar profiles. However, these patterns are clearly visible and obvious on the ground surface and aerial photographs. The use of GPR for the mapping the distribution of these features is therefore considered impracticable. If possible, mapping and characterizing the subsurface or internal features of pattern ground may be a more proper application of GPR

Recommendations:

1. Based on the results of this study, some ambiguity remains in the interpretation of the GPR data. Further studies are needed to improve interpretation and processing techniques. Additional studies are recommended to advance the lessons learned in this study and to more fully assess the appropriateness of GPR in areas of Gelisols.

2. Because of the large number of discontinuous subsurface reflectors, short transects (less than 100 m) are recommended over long transects (greater than 100 m). Short transects with a large number of closely spaced observation points are considered more efficient and informative than long transects with a large number of widely spaced observation points. Based on the results of this study, improved research designs, antenna selection, and control setting adjustments need to be incorporated into succeeding GPR studies.

3. In areas of Gelisols, a large number of soil pits or cores are required to confirm interpretations. In some instances, even with a large number of ground-truth observations, the identity of some subsurface interfaces will remain ambiguous. In these instances the use of GPR is discouraged. This study confirms the value of sufficient ground-truth observations to

verify radar interpretations. Future studies should endeavor to spend less time conducting radar surveys (fewer shorter-length traverses) and more time collecting core data.

4. An objective of this study was to use GPR to chart the thickness of peat in areas of continuous permafrost. The use of GPR for volumetric determination of peat reserves in areas of continuous and discontinuous permafrost should be explored.

With kind regards,

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Relative Topography within the BEO Site

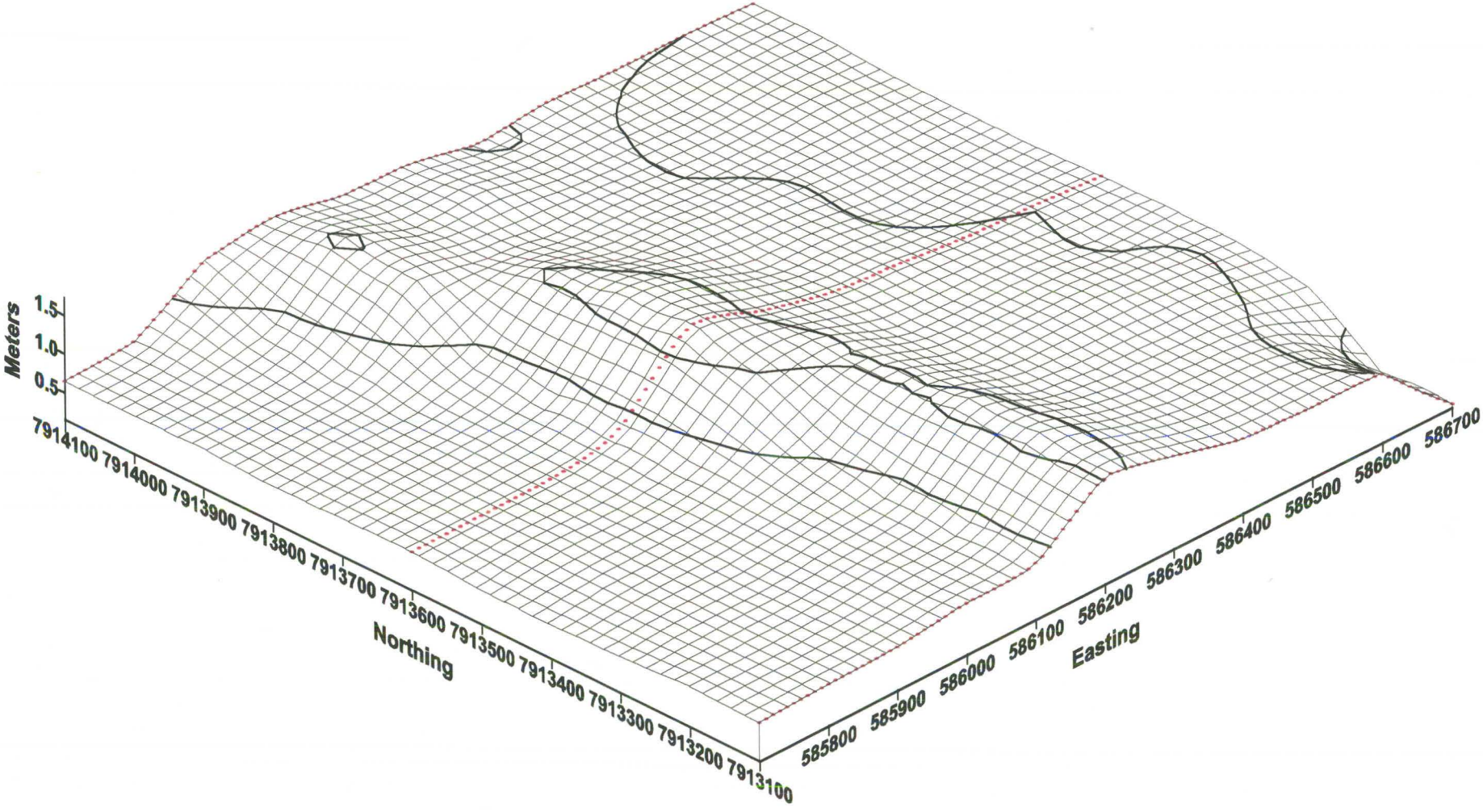
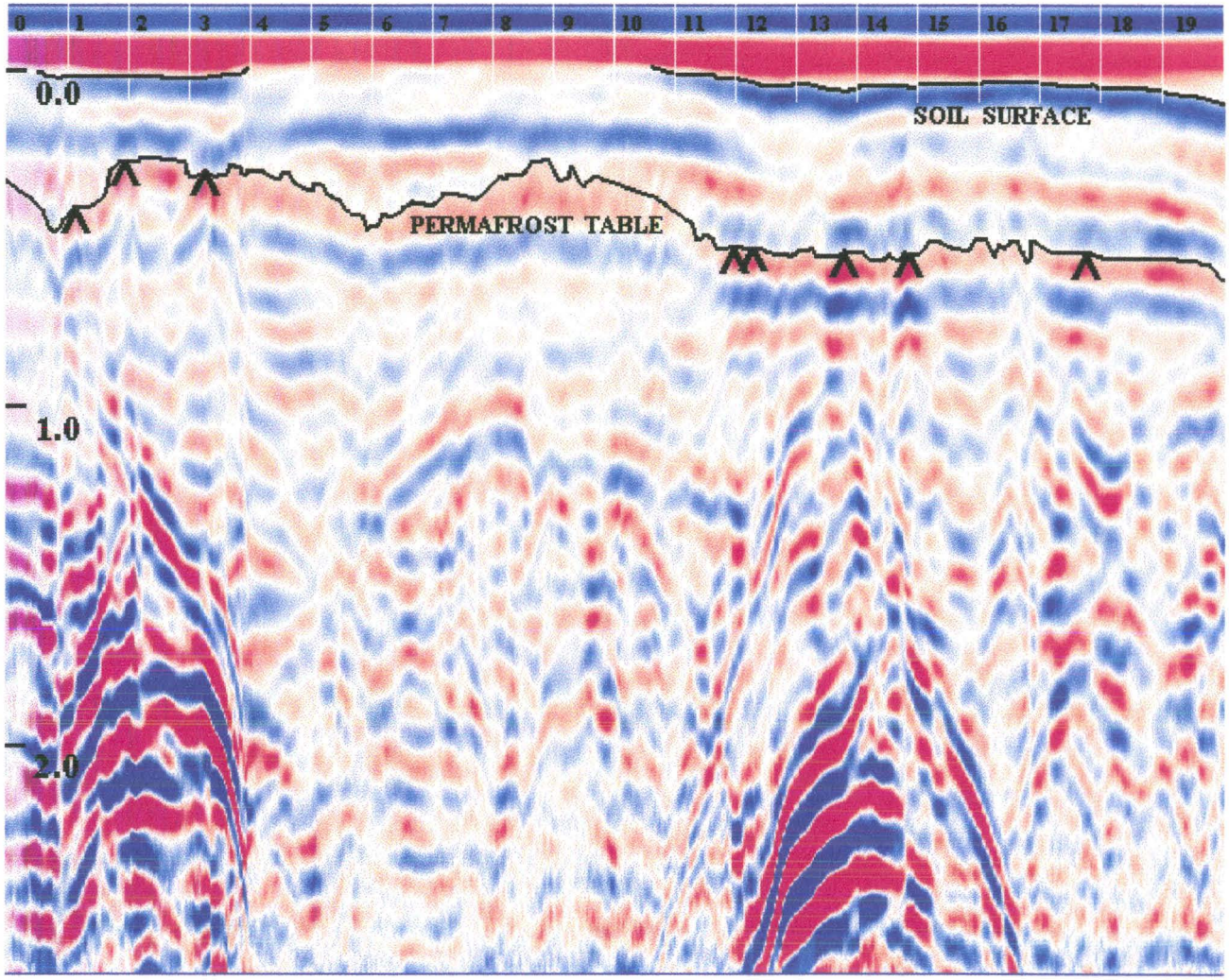


Figure 1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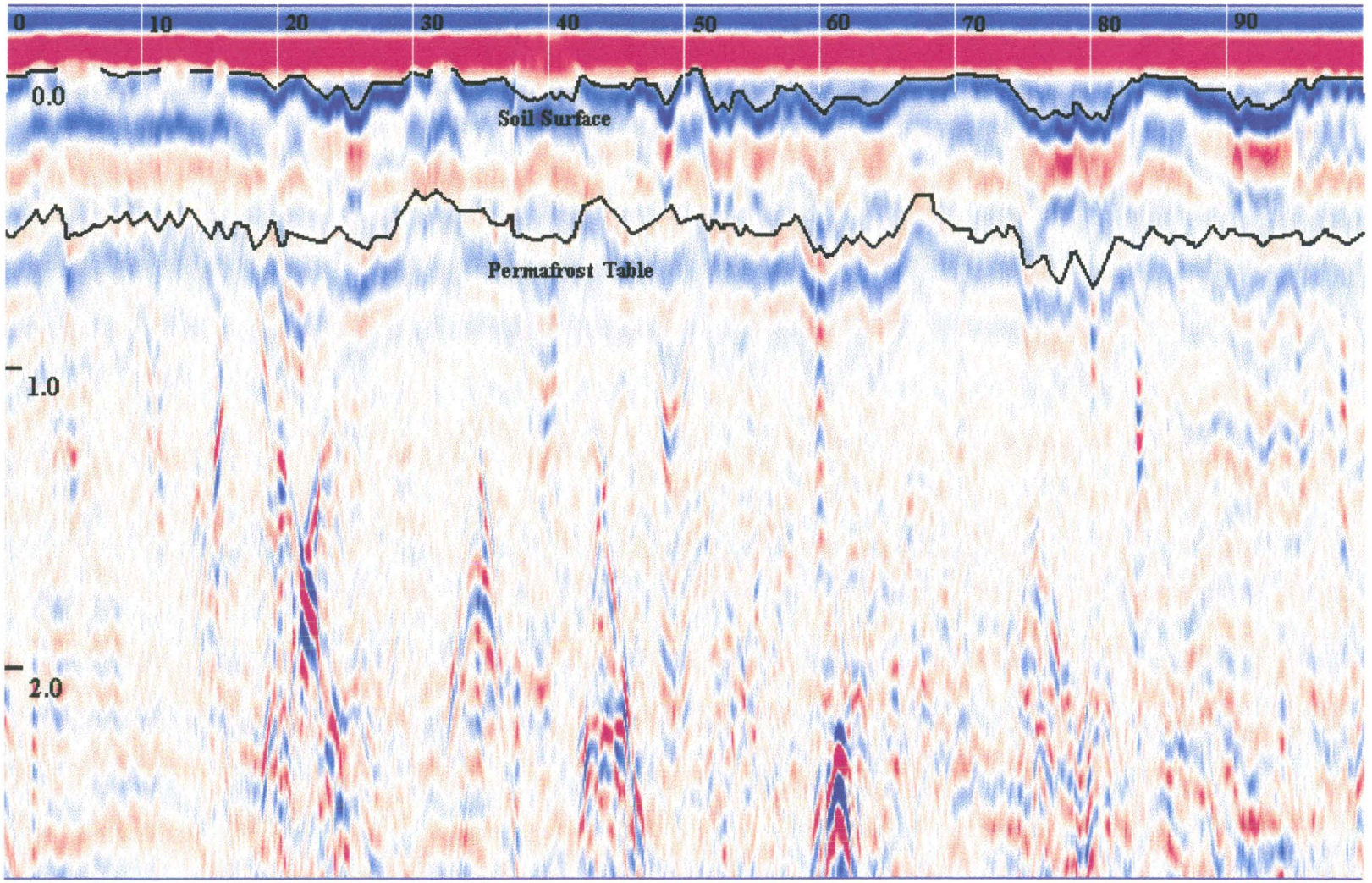
SOIL SURFACE
PERMAFROST TABLE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Soil Surface
Permafrost Table
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