GPR AND EM SURVEYS TO DETECT AND MAP PEAT AND PERMAFROST- A PILOT STUDY

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Abstract

Ground penetrating radar (GPR) and electromagnetic terrain conductivity (EM) surveys were performed to detect frozen ground and peat layers at a proposed landfill site in Fairbanks, Alaska. Geotechnical test pits showed frozen ground and peat layers in places, prompting a concern that differential settlement would disrupt the planned leachate collection system—a network of pipes installed beneath the refuse. A geophysical pilot study was undertaken to determine if GPR and EM could be used to map the extent of peat and frozen ground at the site. These methods were selected because they use readily available instruments, straightforward field procedures, and provide continuous subsurface information in a rapid and economical fashion, with the potential for significant cost savings compared to digging enough test pits to fully characterize the site.

Ground truth from the existing test pits indicated that GPR identified areas containing peat, although the thickness of peat layers could not be determined. Low-conductivity zones could be correlated to areas of frozen ground. Overall, however, terrain conductivity was affected by variations in both soil condition (i.e., frozen vs. unfrozen) and soil type (e.g., silt vs. gravel) to such a degree that EM could not reliably detect frozen ground in every instance. In conclusion, GPR and EM surveys could rapidly delineate gross lithology and indicate potential areas of frozen ground. As such, the surveys could be used for a rapid preliminary assessment of virgin sites and the findings could be used to direct a more efficient test pit program.

Introduction

During the initial stages of a landfill expansion project in Fairbanks, Alaska, design engineers recognized that problem geologic conditions, in the form of peat deposits and ice-rich frozen soils, were likely to exist. Backhoe test pits dug in the proposed 900- by 900-foot landfill expansion area verified the presence of peat and frozen ground. The engineers knew that pressure and heat generated by decaying refuse would cause decomposition and compression of peat deposits and thawing and consolidation of frozen soils.

It was feared that the resulting settlement would disrupt the planned leachate collection system, producing flat or inverse slopes that would cause leachate to pool within the system. Collection pipes might even break. Geotechnical consultants recommended that the settlement-prone materials be removed and replaced with unfrozen sandy gravel. Faced with the prospect of excavating and backfilling a 900- by 900-foot area to a depth of 6 feet (about 180,000 cubic yards), the borough of Fairbanks decided to assess the extent of peat and frozen ground before proceeding any further.

Although the test pits provided excellent subsurface information, they were too widely spaced for mapping purposes. Subsurface layering could be interpreted in some areas where good correlation between adjacent test pits was observed; however, many areas showed such poor correlation that the extent of peat and frozen ground could not be discerned with any confidence. To fill in the data gaps between the test pits and develop a more complete picture of the subsurface, a geophysical pilot study was initiated. It was recognized that the existing “ground truth” from the test pits provided an excellent opportunity to assess the effectiveness and accuracy of the geophysical methods employed. The objective of the pilot study was to identify areas of frozen ground and determine the extent and thickness of peat layer(s).

The pilot study comprised a dual method geophysical investigation using electromagnetic terrain conductivity (EM) and ground penetrating radar (GPR). These methods were chosen because they have an appropriately shallow investigation depth, good vertical and lateral resolution capabilities, and they respond readily to the expected contrast in electrical properties between frozen and unfrozen ground, and peat and sand. Moreover, these methods use readily available instruments, straightforward field

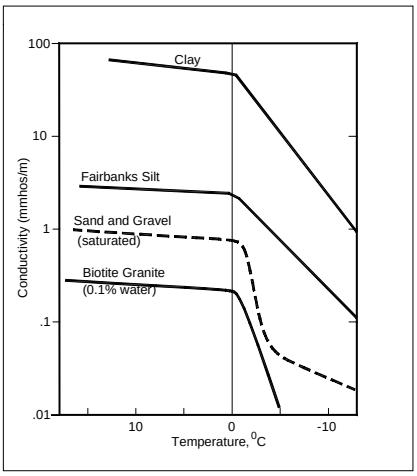
procedures, and provide continuous subsurface information in a rapid and economical fashion, with the potential for significant cost savings compared to digging enough test pits to fully characterize the site.

Concepts

Electromagnetics (EM)

Electromagnetic terrain conductivity (EM) is a surface geophysical technique whereby the electrical conductivity of subsurface materials is measured by means of electromagnetic induction. Briefly, a transmitter coil is energized with an alternating current. The (primary) magnetic field arising from the alternating current causes very small electrical currents to flow in the earth. These currents produce a secondary magnetic field which is sensed by a nearby receiver coil. Under certain constraints, which are incorporated into the EM instrument, the ratio of the secondary to the primary magnetic field is linearly proportional to the terrain conductivity. By measuring this ratio, the EM instrument becomes a direct reading terrain conductivity meter. The common unit of conductivity is the mho (Siemen) per meter or, more conveniently, the millimho per meter (mmho/m). Investigation depth is controlled by the distance between the transmitter and receiver coils; the larger the separation the greater the investigation depth.

Terrain conductivity survey with EM31-D. Transmitter and receiver coils are mounted on each end of the Iona PVC boom.



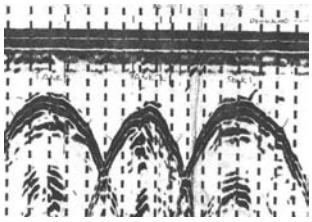
Conductivity vs. Temperature for several soils and one rock type (after Hoekstra & McNeil).

Terrain conductivity is primarily electrolytic and takes place through microscopic moisture filled pathways in the soil and rock. Terrain conductivity is affected by one or more of the following parameters:

1. Moisture profile
2. Clay content
3. Moisture salinity
4. Moisture temperature

The moisture profile refers to the distribution of the moisture pathways within the soil. Clay content will increase conductivity because ions adsorb readily to the negatively charged, sheet-like clay molecules. Salinity will also increase terrain conductivity due to the greater number of ions in solution. Lower temperatures will decrease terrain conductivity because ionic mobility is reduced. In particular, frozen ground will exhibit anomalously low conductivity because the conductivity of ice is extremely low. It should also be noted that EM devices respond strongly to metal objects, which makes them useful as metal detectors; however, metal objects within a survey area may produce noise that will inhibit the detection of geologic targets.

While it is evident that many parameters can affect terrain conductivity, a few will predominate at any given location. For the landfill expansion study at Fairbanks it was expected that frozen ground would be indicated by the lowest conductivity measurements.



GPR image of three underground storage tanks

Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) uses radar technology to obtain a continuous, high-resolution profile of the subsurface. GPR profiles can show soil layering and images of buried objects. GPR transmits a radar signal that is coupled to the ground by a transducing antenna towed or hand-pulled along the ground surface. When the subsurface signal

GPR survey using a 500 MHz antenna. Signal processing unit and printer are mounted in a nearby vehicle.

encounters a boundary between media with different electrical properties a portion of the signal is reflected back to the surface, detected by the antenna, and recorded on a graphical recorder. The GPR profile can be evaluated in the field to facilitate real-time interpretation of subsurface conditions. GPR data can also be digitally recorded for computer processing to reduce noise and enhance images of more subtle subsurface features. Different antennas with different radar frequencies can be used. In general, higher frequency antennas can resolve thinner layers and smaller objects but have shallower penetration depths, while lower frequency antennas can penetrate more deeply but at the expense of target resolution. Typical GPR antenna frequencies range from 80 MHz to 1200 MHz.

The electrical properties of geological materials are primarily controlled by water content. These properties determine the radar signal velocity and the power of the signal reflected at layer boundaries. The velocity of a radar signal is measured in nanoseconds; hence, GPR profiles are typically displayed with the vertical axis in time (nanoseconds), not depth.

Material	Conductivity (mmhos/m)	Dielectric Constant
Air	0	1
Fresh Water	0.5	80
Sea Water	30,000	80
Dry Sand	0.01	3-5
Saturated Sand	0.1-1.0	20-30
Limestone	0.5-2.0	4-8
Shales	1-100	5-15
Silts	1-100	5-30
Clays	2-1000	5-40
Granite	0.01-1	4-6
Ice	0..01	3-4

Typical electrical conductivity and dielectric constants (after Davis and Annan, 1989)

As with the EM method, GPR is affected by the electrical conductivity of subsurface materials. In a simple view, subsurface layers with a conductivity contrast will produce GPR reflection at the layer interface. More properly, conductivity is a component of a more complex electrical property, the dielectric constant, which is a measure of the capacity of a material to store a charge when electric field is applied. The dielectric constant is related to radar signal velocity and can be used to estimate the depth of features observed on GPR profiles.

Peat has an extremely low resistivity (i.e., is highly conductive) due to mobile electrical charges from decaying vegetative matter and its abundant moisture content. Studies have shown that the conductivity of peat is approximately 50 mmhos/m. It was expected that electrical properties of the peat at the Fairbanks site would contrast sufficiently with the surrounding silt and sand to produce high-amplitude reflection patterns that could be readily identified on the GPR profiles.

Subsurface Mapping Using Geophysics

Shallow subsurface mapping usually entails the use of intrusive methods, typically soil borings or test pits. Intrusive methods provide excellent subsurface information. A few test pits are usually all that's needed to characterize a small site if the subsurface consists of laterally continuous layers of uniform thickness. However, characterizing a large site with highly variable subsurface conditions could require a large number of borings or test pits, a costly, disruptive, and time-consuming process compared to a geophysical survey.

By combining intrusive sampling with a surface geophysical investigation the number of test pits required to characterize large, complex sites can be greatly reduced. Geophysical data are continuously recorded along closely spaced survey transects. These data are examined for variations indicative of changes in subsurface conditions. Borings or test pits can then be positioned in selected areas to "ground truth" different types geophysical signatures. Geophysical anomalies can be targeted, while areas showing a homogeneous geophysical response can be bypassed or investigated with a single test pit. Geophysical surveys can extend solid ground truth information a great distance away from the test pit location.

Geophysical data are acquired rapidly, usually at a brisk walking pace, with hand-carried or towed instruments. Data are typically downloaded and processed each evening with results available the next day. Findings can be examined further while the site investigation is still in progress, minimizing the chances of later delays in site development.

Geophysical Investigation at Fairbanks, Alaska

As stated previously, the objective of the Fairbanks geophysical investigation was to delineate areas of frozen ground and determine the extent and thickness of peat layer(s) within a 900- by 900-foot landfill expansion area. Exploratory test pits confirmed the presence of frozen ground and peat. Because the test pits indicated the peat/frozen ground occurred as discontinuous layers/lenses it was suspected that the preliminary subsurface maps produced from the widely spaced test pits were not accurate. It was thought that geophysical methods could be used to in-fill subsurface information between the test pits and provide a more complete and accurate picture of the distribution of peat and frozen ground. An additional objective was to determine if the thickness of the peat layers could be assessed.

The investigation was preformed using a combination of Electromagnetics (EM) and Ground Penetrating Radar (GPR). Briefly, EM was used to delineate areas of anomalously low electrical conductivity indicative of frozen ground, and GPR was used to obtain graphical profiles of the subsurface from which peat layer(s) could be identified. The investigation was designed as a pilot study to assess the effectiveness of EM and GPR for detecting and mapping peat and frozen ground. At a minimum, the geophysical data combined with the existing test pit information provided an opportunity to assess the effectiveness of EM and GPR for detecting and mapping peat and frozen ground at the subject site and future landfill expansion areas.

Site Characteristics

The 900- by 900-foot site is topographically flat and was cleared of vegetation. At the time of the survey the ground surface was covered by 1 to 2 feet of snow. Test pit data showed near-surface soils to consist of peat and slightly plastic to nonplastic silt. Underlying soil becomes sandier with depth, grading from silt to sand and sand and gravel. Peat deposits observed in the test pits ranged from 1 to 5 feet in thickness.

Field Procedures and Instrumentation

Fieldwork was preformed in October 2001. EM and GPR data were acquired along six 800 to 900-foot parallel survey transects positioned in pairs along either side of the test pits (Figure 1). EM and GPR data were obtained along the same transects. EM data were acquired with a Geonics Limited EM31-D terrain conductivity meter that was hand-carried along the survey transects. The EM31-D was connected to a chart recorder to provide real-time analog output of the conductivity curves, and to a digital data logger to facilitate the production of computer contour maps and scaled conductivity profiles. With an intercoil spacing of 3.7 meters, the EM31-D has an investigation depth of approximately 6 meters.

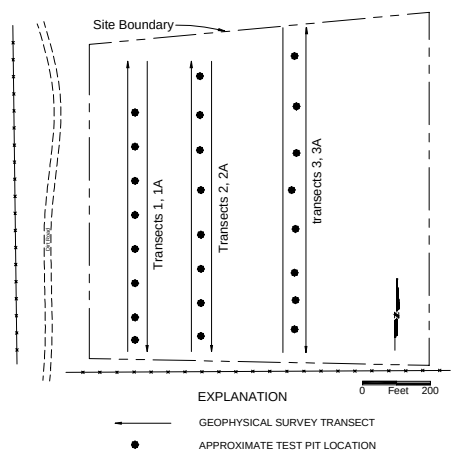


Figure 1 – Site Map

GPR data were acquired with a GSSI Model SIR-10 connected to a 500-megaHertz antenna. GPR profiles were output to a thermal printer. The GPR system was housed in a vehicle that was driven at approximately 2 miles per hour along the survey transects with the GPR antenna mounted on the vehicle bumper. A 60 nanosecond time window was used, which corresponds to an investigation depth of approximately 10 feet assuming a dielectric constant of 5, which is typical for unsaturated sand.

Horizontal control was provided by a 50- by 50-foot pin flag grid. Distance marks were placed on the data profiles at 50-foot intervals as the instrument sensor passed next to a pin flag. After the six pilot study transects were surveyed the data were returned to the office for analysis to determine if a site-wide production survey along more closely spaced transects was warranted.

Data Processing and Interpretation

Geophysicist examines GPR and EM profile data

Digital EM data were downloaded to a laptop computer and conductivity profiles were plotted at the same horizontal scale as the GPR profiles. GPR records output in the field were placed alongside the EM profiles to facilitate direct comparison between the two data sets. Graphic logs of the test pit data were prepared at the same vertical scale as the GPR profiles to facilitate the identification of GPR images corresponding to peat layers observed in the test pits. A site map showing the locations of both the test pits and geophysical survey transects was used to place test pit logs at the appropriate position along the geophysical records.

The interpretation procedure was straightforward. Geophysical data obtained near test pits were examined in an effort to establish characteristic geophysical signatures for peat and frozen ground. Geophysical responses near all test pits showing peat and frozen ground were compared to the to established signatures to assess its reliability for predicting the occurrence of peat and frozen ground. The signatures were then used to identify potential areas of peat and frozen ground in areas without a test pit. In addition, GPR profiles in areas of peat were examined closely for images indicative of both the top and bottom of the peat layer.

Results

GPR and EM profiles are presented on Figures 2 – 8. Figure 2 shows the terrain conductivity profile for transect 3A, along with graphic logs of the soils observed in the adjacent test pits. The occurrence of frozen ground is also indicated on the logs. Figure 3 shows the corresponding GPR profile at the same horizontal scale as the conductivity profile. Figure 3 is positioned directly below Figure 2 to facilitate a comparison between gross GPR reflection character, terrain conductivity, and soil lithology observed in test pits TP-16 through TP-22.

Figures 4 – 7 are expanded views of GPR profile 3A. Note that hand-drawn logs of soil lithology have been superimposed on the GPR data to facilitate identification of GPR reflection patterns associated with peat. The remaining conductivity profiles are shown on Figure 8. GPR data for transects 1 and 2 are omitted for brevity.

Terrain Conductivity

In general, terrain conductivity ranges from less than 10 to greater than 20 mmhos/m, with the northern half of the site exhibiting lower conductivity than the southern half of the site (Figure 8). The frozen ground observed in test pits TP-17 and TP-18 is indicated by a conductivity dip between stations 200 and 350, where the terrain conductivity falls below 13 mmhos/m. It should be noted, however, that the lowest conductivity (10 mmhos/m) is seen between stations 500 and 700, even though no frozen ground was observed. Low conductivity in that area can be attributed to a predominance of sand and gravel, as indicated in the test pits TP-20 and 21. The low conductivity in that area might also be caused by frozen ground, as TP-21 is only 4 feet deep and frozen ground was not observed shallower that 4 feet in any of the other test pits.

While higher terrain conductivity readings appear to be associated with the occurrence of peat, as indicated by TP-16, TP-19, TP-22, silt likely contributes to the elevated conductivity response in those areas.

Ground Penetrating Radar

GPR profiles exhibit a highly varied reflection character indicative of heterogeneous subsurface conditions. Of particular note are the extensive, laterally continuous zones of high-amplitude (dark) reflection patterns that correlate with the occurrence of peat in test pits TP-16, -17, -18, and –19, between stations 100 and 450 (Figures 4, 5). A similar GPR pattern between stations 550 and 650 suggests that a

peat layer may be present between TP-20 and TP-21. The peat may extend beneath TP-21, which is only 4 feet deep (Figure 6).

Conclusions

- Lower conductivity at the Fairbanks site appears to be associated with both frozen ground and sand and gravel deposits.
- Higher conductivity at the Fairbanks site appears to be associated with both peat and silt deposits.
- Conductivity is affected by both soil type (e.g., sand vs. silt) and soil condition (i.e., frozen vs. unfrozen) to such a degree that discrimination between frozen and unfrozen ground may prove difficult. Low conductivity “dips” in otherwise higher conductivity areas may be the most reliable indicator of frozen ground, although using those criteria alone could cause areas of frozen sands and gravels to be overlooked.
- GPR shows some promise for identifying areas containing peat. High-amplitude GPR reflection patterns show fair correlation with the occurrence of peat in the test pits. Additional test pits to investigate other high-amplitude GPR anomalies would help determine the reliability of this correlation.
- GPR as configured was not useful for assessing the thickness of the peat layers. Additional testing with higher-frequency antennas may prove helpful.
- A site-wide production survey was not recommended because of the abundance of existing ground truth and the fact that the established EM and GPR signatures did not predict presence or absence of peat and frozen ground at every test pit location. Nonetheless, EM and GPR surveys could be used for a rapid preliminary assessment of virgin sites. They could readily delineate gross lithology and indicate potential areas of frozen ground. The findings could be used to direct a more efficient test pit program.

References

Davis, J. L., and Annan, A.P, 1989, Ground-Penetrating Radar For High-Resolution Mapping of Soil and Rock Stratigraphy, Geophysical Prospecting **37**, 531-551.

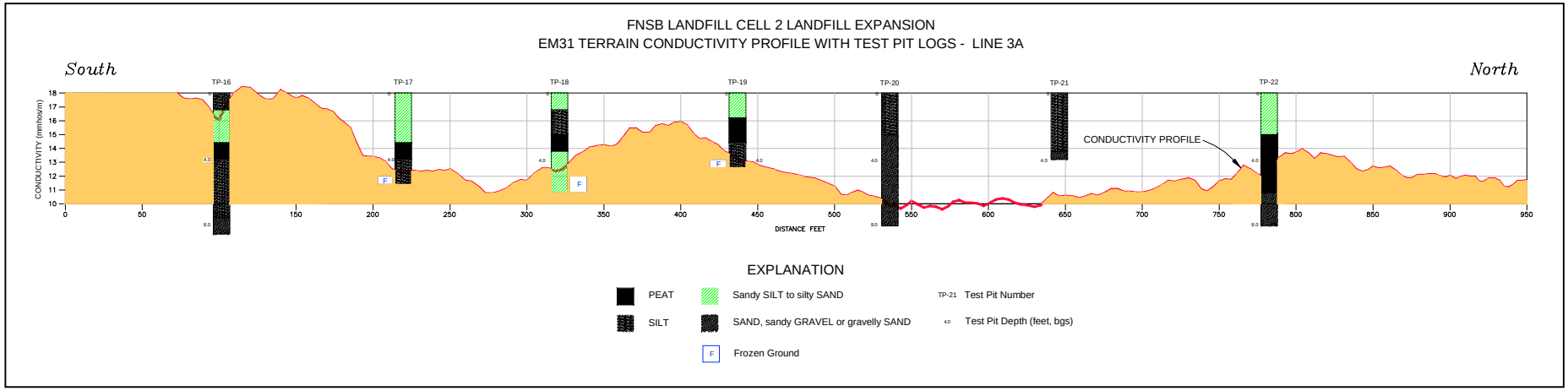


Figure 2 - EM31-D Conductivity Profile 3A with Test Pit Logs

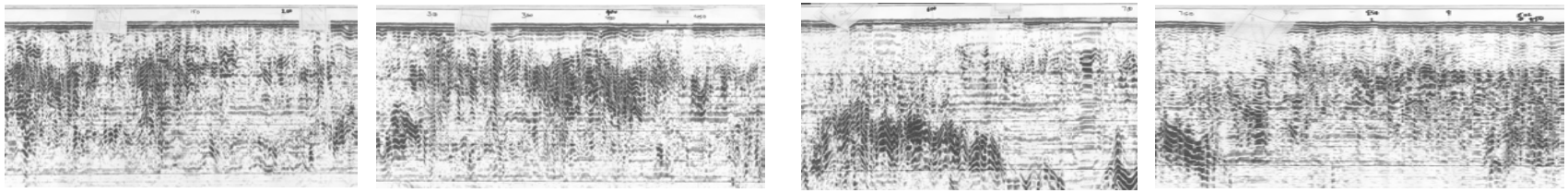


Figure 3 - Ground Penetrating Radar Profile 3A

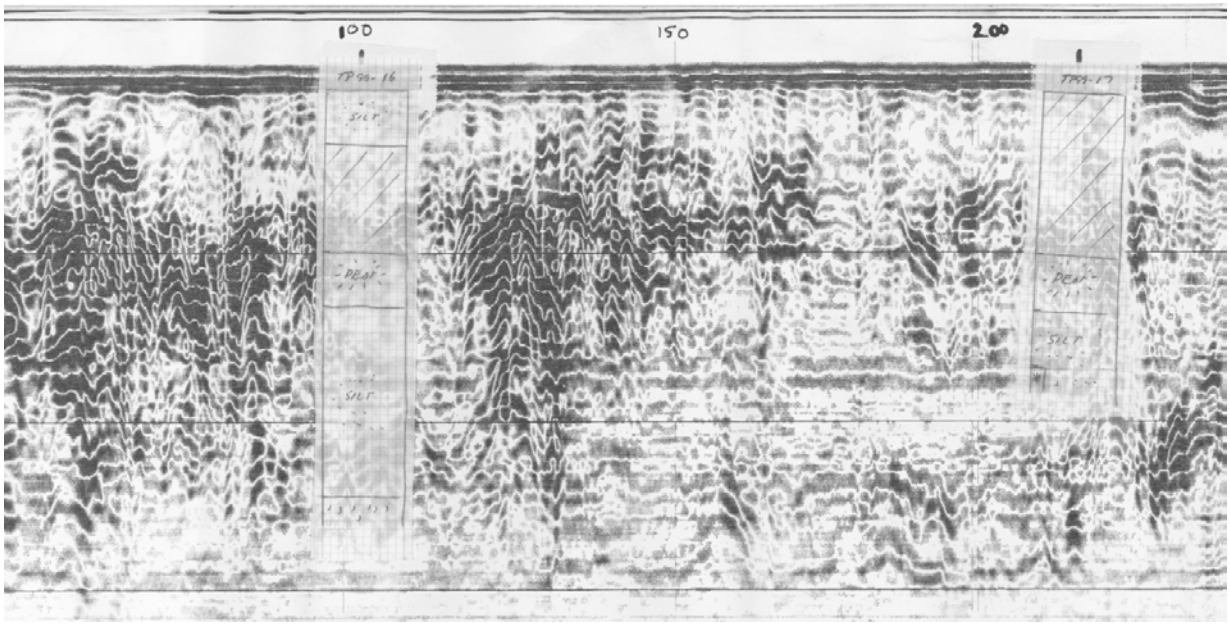


Figure 4 - GPR Profile 3A Detail, Stations 50 to 250

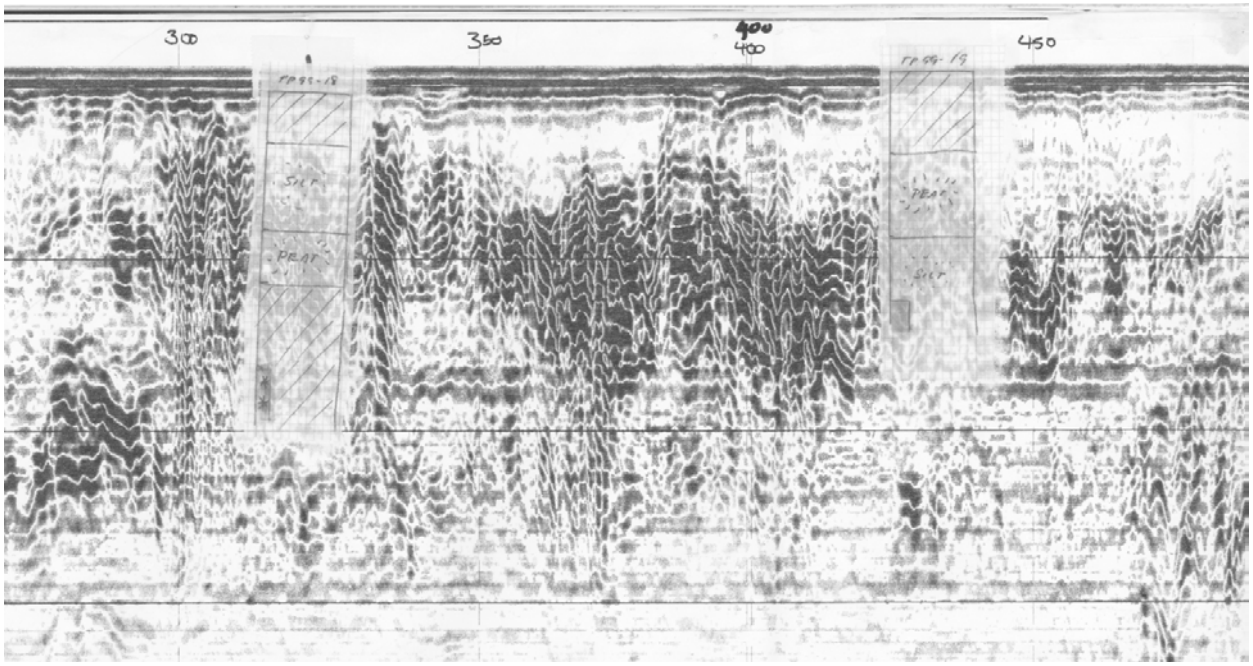


Figure 5 - GPR Profile 3A Detail, Stations 250 to 500

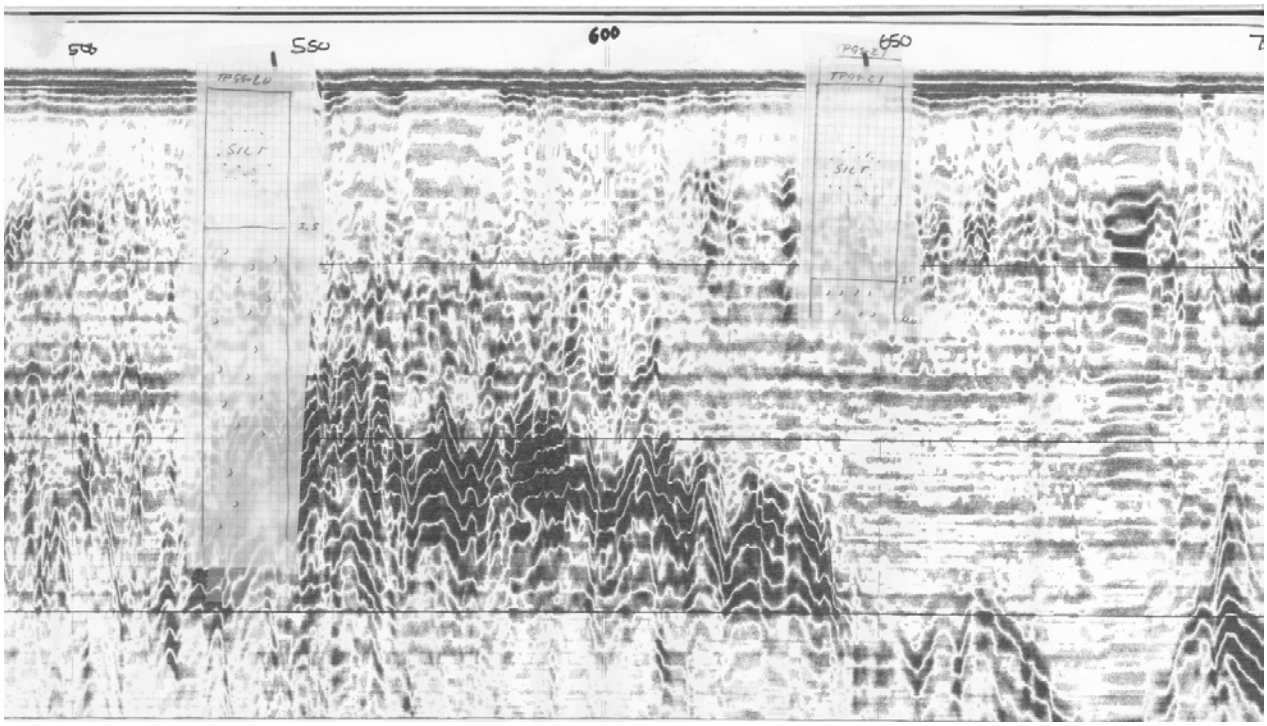


Figure 6 - GPR Profile 3A Detail, Stations 500 to 700