ELECTRICAL ANISOTROPY AND BEDROCK FRACTURING: IS THERE A RELATIONSHIP BETWEEN THEM?

Melvyn Best[1,2]; Gordon Guy[1]; George Spence[1];
Stan Dosso[1] & Kevin Telmer[1]

Abstract - Recently EM-31 and ground penetrating radar (GPR) surveys were carried out over the Hartland landfill located just north of Victoria, British Columbia, Canada. The bedrock geology in the area of the landfill consists mainly of gneiss overlain by a thin layer (up to 2 m thick) of till. Outcrop in the area reveals the presence of fracture discontinuities throughout the bedrock. A ground and surface water monitoring program for the landfill has shown that contaminated groundwater escaped from the leachate containment and collection systems.

Vertical-dipole EM-31 data collected every 2 m along east-west oriented lines spaced 10 m apart clearly outline the direction and extent of leachate propagation. Several approximately north-south conductive features (most likely associated with fractures) about 10 to 20 m in width are also visible. The conductivity of these features decreases with distance from the landfill, thus indicating conductive groundwater is flowing down-gradient. Dipping events that line up with the linear EM conductors can be seen on several east-west GPR profiles.

Vertical-dipole azimuthal conductivity data were collected at a number of stations along these lines. Azimuthal conductivity data is obtained by rotating the line joining the transmitter and receiver coils about a vertical axis and taking readings at equal angles (in our case 15 degrees). Signal-to-noise was improved by using reciprocity, i.e using the fact the EM response should be the same when the transmitter and receiver coils are interchanged, and averaging responses separated by 180 degrees. Preliminary results indicate that azimuthal conductivity can vary by as much as 30% between maximum and minimum values. Maximum conductivities line up approximately along north-south,

[1] School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, V8W 3P6 Canada, T(250)721-6120, F(250)721-6200, seosuvic@uvic.ca
[2] Bemex Consulting International, 5288 Cordova Bay Road, Victoria, BC, V8Y 2L4 Canada, T/F(250)658-0791, best@islandnet.com

northeast-southwest and southeast-northwest directions, depending on where they are relative to the linear feature described above. These directions are aligned with the known fracture directions within the area.

Keywords - geophysics; bedrock fractures; leachate

INTRODUCTION

Water in bedrock fractures is one of the main sources of well groundwater in the greater Victoria region. Most wells drilled in the area are still located using geological and remote sensing methods. However, a significant number of these wells have flow rates too low even for domestic use. In addition there are a number of locations where leachate and other contaminants have entered bedrock through fractures. The fractures determine, at least in part, the direction of leachate movement. Consequently information on the location and direction of fractures is essential for understanding where to drill for groundwater as well as the direction of contaminant movement.

This paper discusses the application of geophysical methods to locate and map fractures in bedrock. In particular electromagnetic (EM) and ground penetrating radar (GPR) methods were used to map shallow bedrock fractures in a region where the ground water contains leachate from a municipal landfill. EM and GPR field data were collected and processed and then interpreted in terms of the known leachate distribution and bedrock fracture system.

EM azimuthal conductivity is a relatively new method for mapping bedrock fractures (Slater et al., 1998). Azimuthal resistivity data were collected at stations along a number of the east-west lines and analysed in terms of maximum and minimum directions of conductivity (electrical anisotropy). Fracture orientation measurements on outcrops in the region were consistent with the maximum directions of conductivity (electrical anisotropy).

Geographical overview and history of the Hartland landfill:

The Hartland municipal landfill is located in the bedrock highlands of the Gowland Range, about 14 km northwest of Victoria, British Columbia, Canada (Fig. 1). The landfill has been in continuous operation since the 1950's and is now the principal waste disposal site for the Victoria metropolitan area (population 300,000). The original landfill area (Phase 1) reached its capacity in 1996 and was subsequently capped during the summer of 1997. At that time, a new landfill (Phase 2) located just north of Phase 1 commenced operations. The Phase 2 landfill will be considerably larger than the original landfill and is expected to supply the needs of the Victoria region for the next 40 years or more.

The terrain surrounding the landfill is moderately rugged with relief up to 445 m, with the landfill situated in a north-south trending bedrock saddle. Mount Work lies to the west of the landfill and a bedrock knoll lies to the east. The crest of the landfill forms a drainage divide (Fig. 1) between the northern Heal Creek (flowing towards Durrance Lake) and the

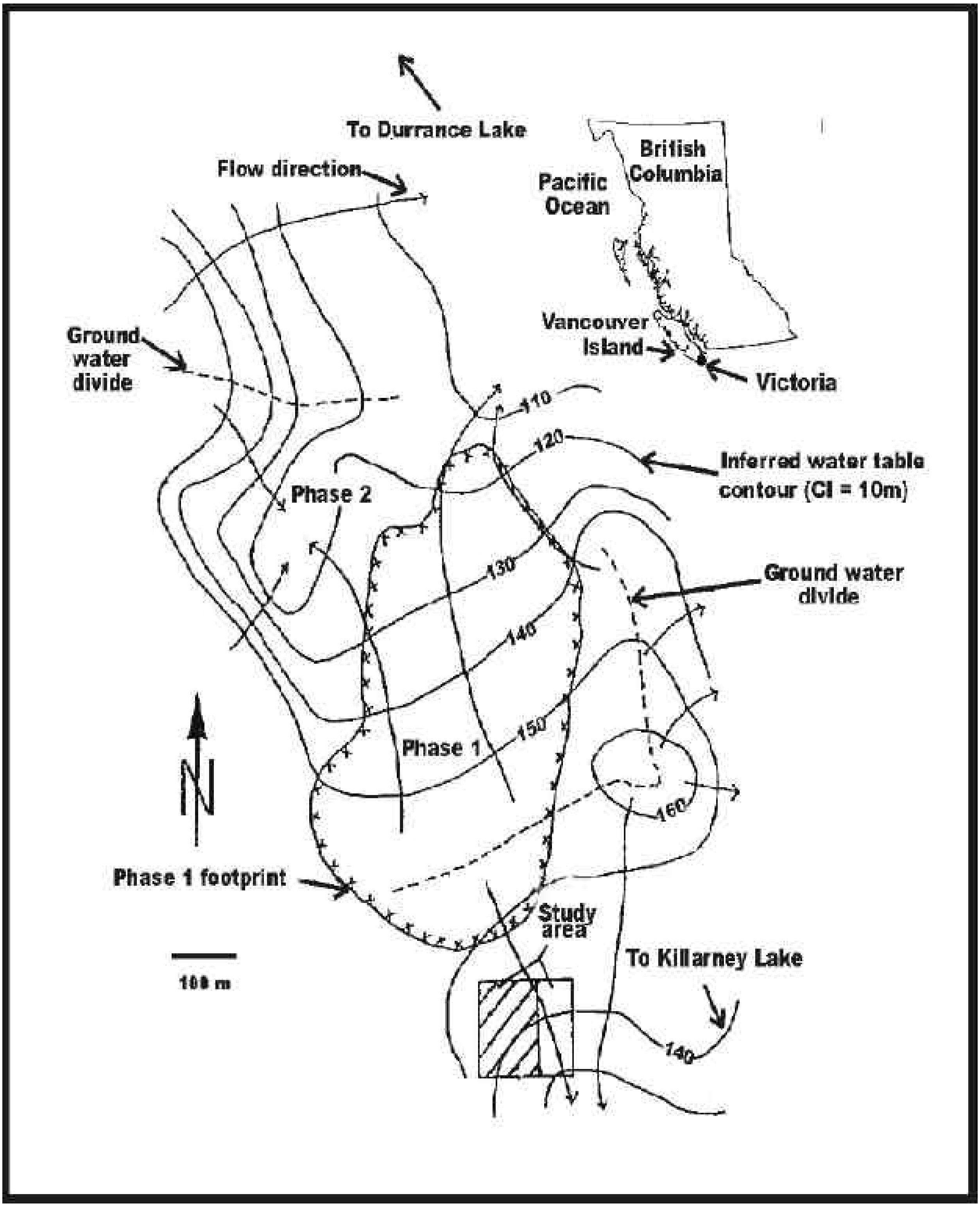

Figure 1.. Location of the Hartland Landfill, 14 km north of Victoria, B.C. The large scale map shows the position of the inferred water table, flow direction and groundwater divides. The boxed area in the south is our study area and the hatched area indicates where the contour map in Fig. 4 is located. The berm discussed in the paper follows the Phase 1 footprint.

southern Killarney Creek drainage basins.

Groundwater flow at the Phase 1 site, being strongly influenced by topographic relief, is predominantly north to northeast (Fig. 1). Most groundwater flows towards a leachate lagoon located on the northern perimeter of the Phase 1 landfill and just west of the Phase 2 landfill. Leachate is collected in the lagoon and delivered to the Victoria sewer system by a connecting pipeline. A groundwater flow divide is located approximately 100 m north of the clay berm which marks the southern boundary of the Phase 1 landfill. This divide causes some southward flow of leachate away from the leachate lagoon into the Killarney Creek drainage basin and into our study area shown in Fig. 1.

Substantial precipitation in the area allows water to percolate through the landfill into the underlying bedrock. This water leaches considerable amounts of ions (dissolved solids) as it passes through the landfill, forming a leachate which enters the bedrock through fractures, joints and shear zones and mixes with the groundwater. This mixture travels in the direction of groundwater flow. After the Phase 1 landfill was capped, the amount of water percolating through Phase 1 decreased, but remains large enough to allow some leachate to form. Leachate was detected in monitoring wells located south of Phase 1 in the southeast corner of the study area. Several domestic groundwater wells down-gradient of these monitoring wells were subsequently shut in and replaced with surface water from the Victoria water system.

GEOLOGY

The bedrock in the area is mainly comprised of Paleozoic Wark Diorite gneiss which was metamorphosed during the Jurassic. The Diorite gneiss is dark green to black in colour. It is generally competent, except in local shear zones, where weathering to clay and chloritization is prominent. Discontinuities, including shear zones, fractures, joints, and altered veins, are ubiquitous in bedrock outcrops. Cogenetic Colquitz gneiss outcrops locally in the northern and eastern margins of the area but is not present in the study area.

Bedrock outcrops are common. In localities where bedrock is not exposed, only a thin veneer of glacial till composed of silty, gravelly sand, with minor cobbles and boulders overlays the bedrock. Minor fluvial deposits consisting of well sorted sands and gravels are also present in localized bedrock depressions and channels.

HYDROGEOLOGY

Groundwater flow in the landfill area is predominantly confined to the bedrock. A few local areas exist with several metres of sand and gravel (unconsolidated sediments) where groundwater can flow down-gradient into creeks within the drainage basins. Vertical flow within these local aquifers also provides a path for surface water to enter the bedrock aquifer. Direction and rate of groundwater flow in the bedrock is controlled by topography as well as by the direction of bedrock fractures(including joints and shear zones) and the fracture density (number of fractures per unit surface area). Consequently, information on the direction and density of dominant fractures is essential in order to understand groundwater flow within the bedrock.

Some fractures do not have openings large enough to allow groundwater flow while others are isolated and not connected to other fractures. Groundwater will not flow through these fracture systems. On the other hand, there are many fractures that will be open and connected to other open fractures. These will form continuous flow paths for groundwater. Water moving through these open, connected fractures can interact with the minerals on the fracture surfaces to produce a zone of interaction several cm or more thick, thus allowing alteration products (clays and other minerals) to form. Often these alteration zones have different physical properties than the surrounding bedrock, permitting geophysical methods to map these zones.

ELECTROMAGNETIC (EM) SURVEY

Electrical resistivity is one parameter that is frequently affected by the alteration discussed above. Indeed, EM methods have been used to map bedrock fractures and shear zones associated with groundwater around the Victoria area for several years. The depth to bedrock is typically shallow, varying between 0 and 15 m. Consequently, shallow, frequency-domain EM surveys such as the Geonics EM-34 and Geonics EM-31 systems (McNeill, 1980) and the Apex MAXMIN system (Best and Boniwell, 1989) with a transmitter-receiver spacing of less than 50 m are often used. These systems measure the in-phase and quadrature components of the normalized secondary magnetic field at one or more frequencies. The EM-31 and EM-34 systems are also designed to measure the conductivity, which is directly related to the quadrature component, as well as the in-phase component.

Figure 2 shows an example of the MAXMIN electromagnetic response over a known shear zone located in similar geology to that at the landfill, but located a few kilometres away. The shear zone response is only above the background for frequencies of 7040 Hz and greater, indicating the conductor associated with the shear zone is relatively poor. The conductivity-thickness (σt) product and depth to top of the conductor estimated from free space Argand diagrams (Best and Boniwell, 1989) are approximately 2 S and 3 m respectively. The σt value is again consistent with a poor conductor at shallow depth. The free space Argand curves assume the conductor is infinitely long, vertically dipping and in free space. These assumptions are reasonable for this conductor as the bedrock resistivity (computed from the EM responses on the left side of Fig. 2 in the area away from the shear zone) is greater than 1000 ohm-m.

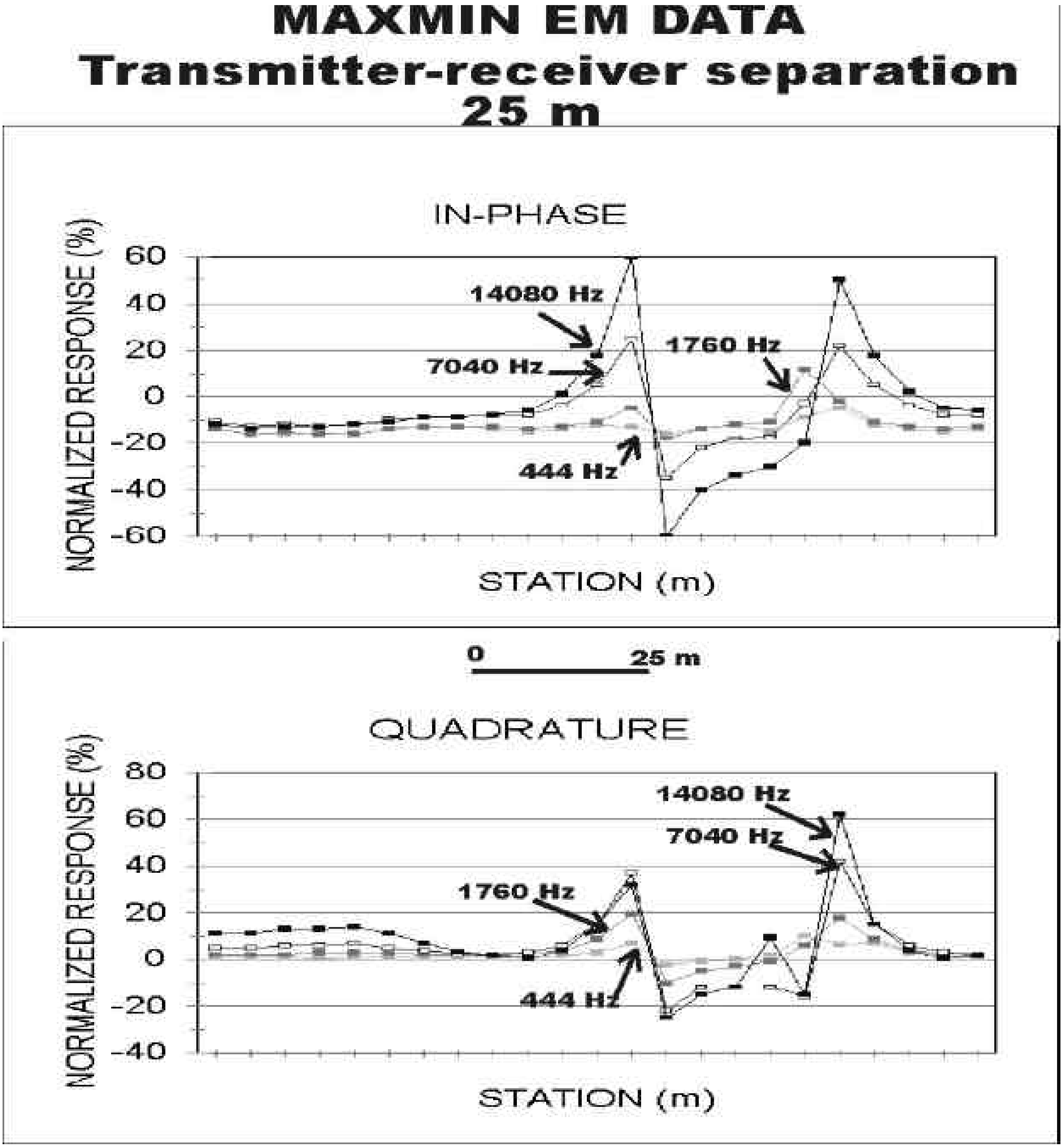

Figure 2. Example of MAXMIN response over a known shear zone. The background response indicates the bedrock around the conductor is resistive. The conductor is shallow and relatively poor since only higher frequencies have a response larger than background. As expected, the distance between the two peaks is 25 m which is equal to the transmitter-

receiver separation.

A well drilled into this conductor flowed groundwater at more than 20 gallons/minute (more than 90 litres/minute). Wells drilled on several other conductors within the Victoria region had similar results. However, the drilling results were not so consistent for those fractures located from air photo interpretation and geology. Apparently water flowing through the fractures produces alteration products such as clays that are conductive. The tight fractures where no water is flowing do not have alteration along the walls and consequently have no EM response. These will not be seen with EM methods but will be mapped from air photos and geology. If only geological interpretation is used fractures with and without flowing water will therefore be drilled.

Alteration products along fracture walls are not always conductive. For example, Slater et al.(1998) found the fractures they were mapping in southern Maine were more resistive than the surrounding bedrock. In some cases there will be no conductivity difference between the fracture and the surrounding bedrock. Fortunately, the bedrock fractures in the Victoria area tend to be conductive.

Based on these observations and the fact the till covering the bedrock is very thin, an EM-31 survey was carried out in the study area outlined in Fig. 1. Monitoring wells located in and adjacent to the study area indicated that leachate was present in the study area. The objective of the EM-31 survey was therefore to map the leachate front and to determine if the leachate was travelling along fracture paths. Vertical-dipole measurements, with the transmitter and receiver coils oriented horizontally, were recorded every 2 m along east-west lines spaced 10 m apart. Horizontal-dipole measurements, with the transmitter and receiver coils held in a vertical plane, were recorded at 2 m intervals along several of these east-west lines as well. In addition, both vertical- and horizontal-dipole measurements were recorded at 2 m intervals along a number of north-south lines. Figure 3 is a map of the line locations in the survey area.

Figure 4 is a contour map of conductivity values for the east-west lines located within the diagonally hatched area in Fig. 1. The eastern portion of the area was covered with dense bush and was only surveyed in patches where line cutting was not required. Environmental considerations limited access to those lines where cutting was not necessary. The berm for the Phase 1 landfill is approximately 50 m north of the northern boundary of the contour map. Several large metal bins about 30 m north of the north boundary caused so much cultural interference that surveying could not be carried out north of line 30N.

There are several features that stand out on the contour map. The conductivity in the northern portion of the map is significantly higher than in the southern portion, indicating the leachate front is propagating from the berm towards the south. The background conductivity values in the northern portion of the map are typically 4 mS/m or greater while the background conductivity in the southern portion is between 0.5 and 1 mS/m. The higher conductivity region continues southward to approximately 60S (-60) before returning to background levels. This is an indication that the leachate front has only traveled this far.

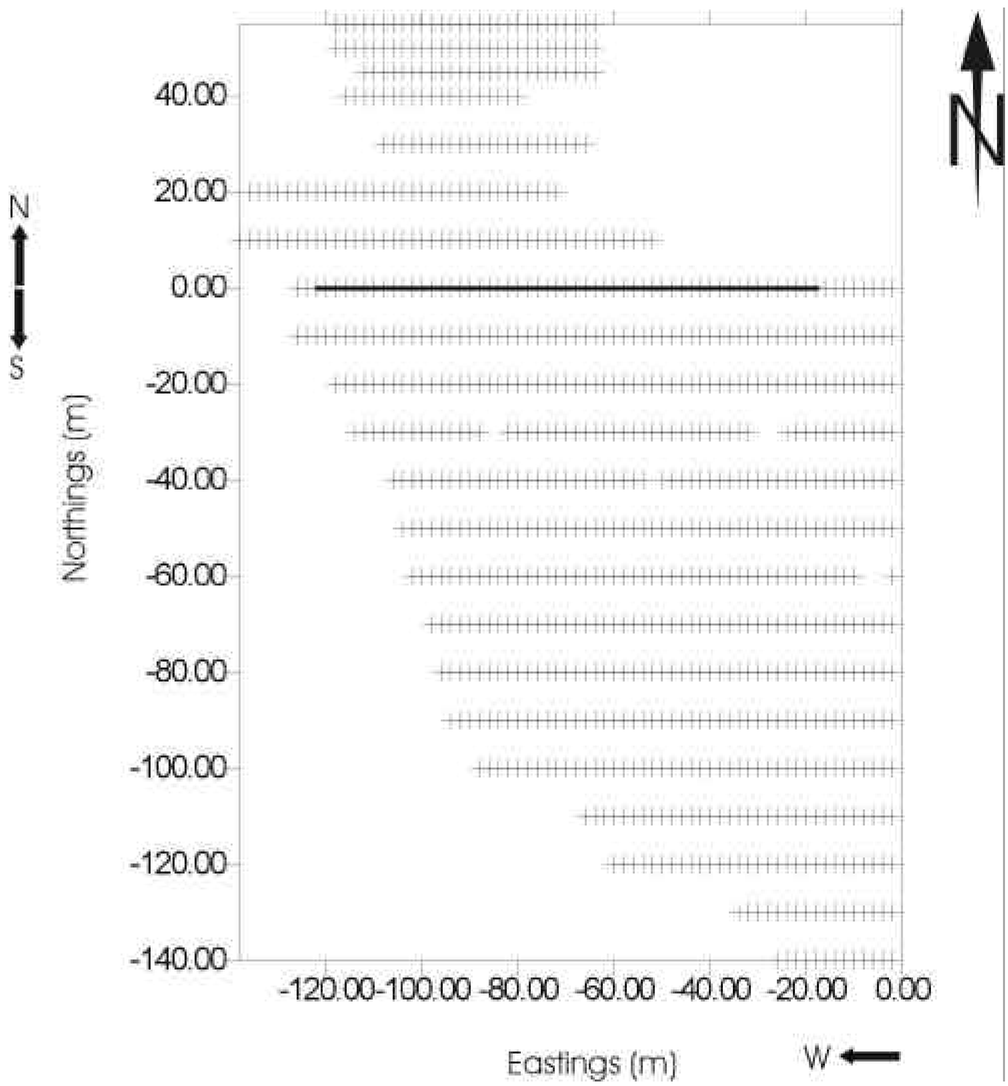

Figure 3. Each tick represents a station where EM measurements were taken. Darkened survey line 0S indicates position of GPR profile as in Fig. 9.

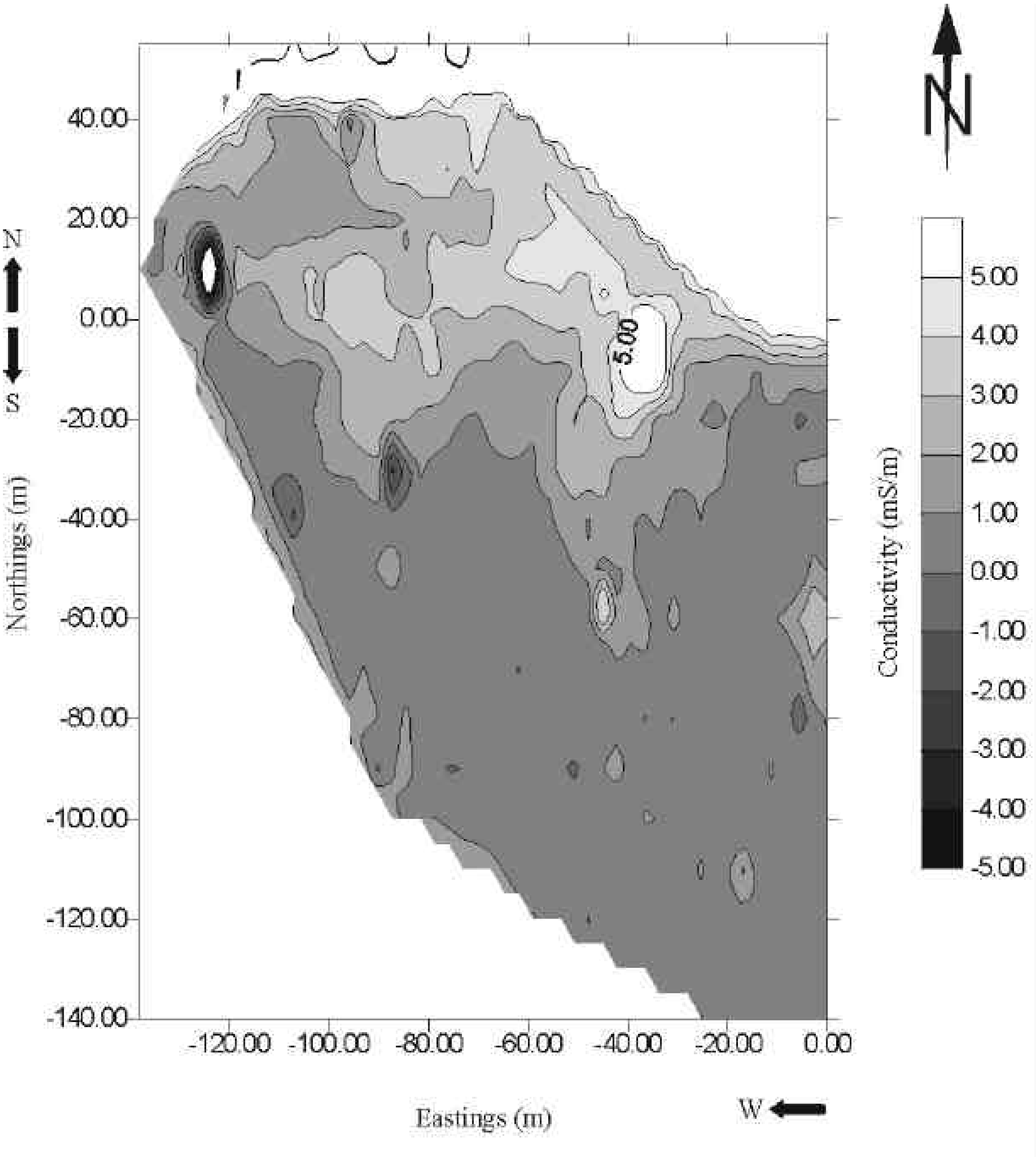

Figure 4. Contour map indicating apparent conductivity measurements in mS/m.

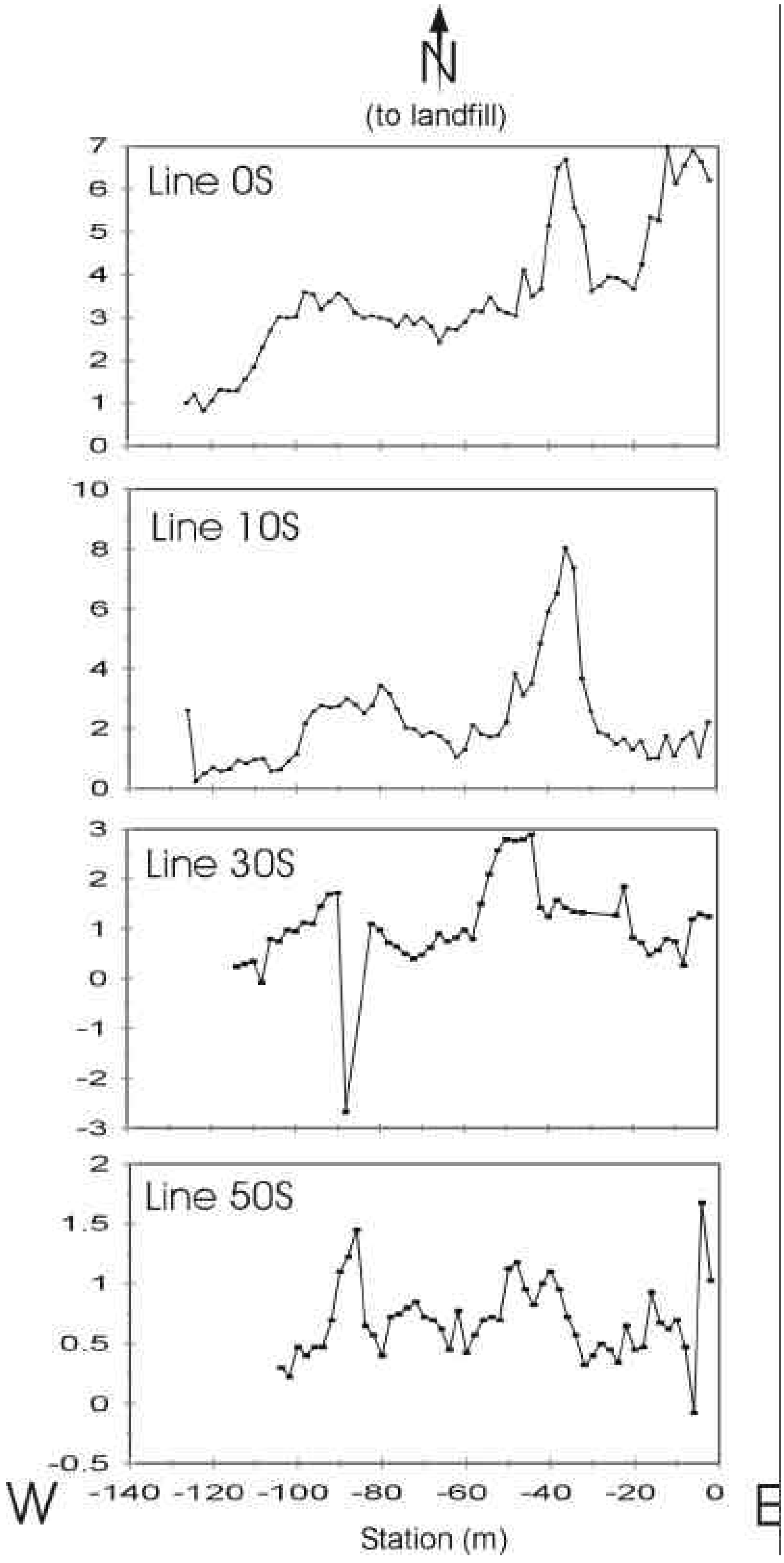

Figure 5. Four east-west profiles along lines 0S, 10S, 30S, and 50S.
The vertical axis is conductivity in mS/m.

In addition, there are two approximately linear north-south conductors, one near station 36W (-36) with a width between 10 and 15 m, and one near station 85W (-85) with a width between 12 and 25 m. These linear zones are thought to be fractures containing leachate. The conductivity of these zones is higher than the surrounding bedrock and approaches values between 1.0 and 1.5 mS/m south of line 60S. These strong, narrow conductive features are easy to recognize on the east-west profiles in Fig. 5. A north-south profile (40W) that closely follows the axis of the easternmost linear conductor clearly shows the increase in conductivity when going from south to north (Fig. 6(a)).

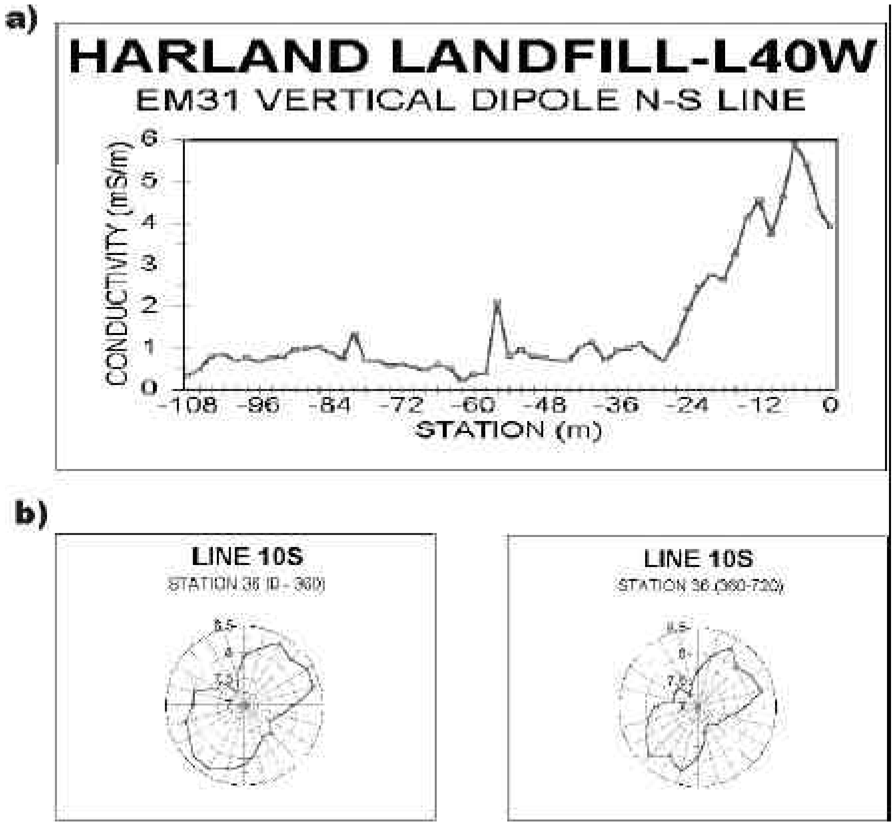

Figure 6. (a) North-south line (40W) going from south (left) to north. Note the large increase in conductivity at the north end of the line. (b) Azimuthal conductivity plot for station 36W on Line 10S. The left plot shows the data for rotations from 0 to 360^{o} and the right plot shows the data for rotations from 360 to 720^{o}. North points upward in the diagram and the numbers represent conductivity in mS/m. Each radial spoke is 15^{o} apart. The data is quite repeatable, although there is some noise in it. The direction of maximum conductivity is approximately 45 to 55^{o}.

In addition to these data, azimuthal conductivity measurements using the vertical-dipole orientation were carried out at 4 m intervals along several of the east-west lines. Data for azimuthal conductivity are collected by rotating the line joining the transmitter and receiver coils about a vertical axis and measuring the conductivity at equal angular intervals (in our case every 15°). At some stations measurements were made through two complete rotations (from 0° to 360° and from 360° to 720°) to investigate noise. Figure 6(b) is an example at station 36W on line 10S showing the data for rotations of 0° to 360° and 360° to 720°. We can see the data are quite repeatable, although there is some noise present.

Azimuthal conductivity measurements are similar to DC azimuthal resistivity measurements, where the objective is to map the maximum (minimum) conductivity and relate these to electrical anisotropy (Taylor and Fleming, 1988). The objective is therefore to determine the directions of maximum (and sometimes minimum) conductivity and correlate these with the direction of fracturing in the bedrock. For example, the maximum conductivity lies approximately along the NE-SW direction for the data in Fig. 6(b).

Noise on the azimuthal data is caused by (1) the coils not being kept in a horizontal plane, (2) the coils not being kept at 15 degree increments, (3) local changes in conductivity and (4) cultural noise. The signal-to- noise can be increased in several ways. One approach is to design a filter based on the azimuthal amplitude spectrum (Slater et al., 1998). A simpler approach is to use the reciprocity theorem that states the EM measurement must be the same when the transmitter and receiver are interchanged. In other words, the measured conductivity at 0° is equal to the measured conductivity at 180°, the measured conductivity at 15° is equal to the measured conductivity at 195°, etc. Therefore, averaging conductivity values measured 180° apart can eliminate some of the noise due to the factors mentioned above. Figure 7 illustrates this averaging procedure for stations 32W and 36W along line 10S. Note how the noise is reduced and the direction of maximum (and minimum) is clearer after averaging. Conductivity variations of 15 to 30 % between maximum and minimum values are not uncommon in this data set. The absolute values of conductivity are also consistent with the values on the east-west lines and, for that matter, on the north-south lines as well.

The dominant fracture directions at the Hartland landfill strike approximately NE-SW, SE-NW, and S (Fig. 8). These are consistent with the conductivity data. The angle of the maximum conductivity tends to change direction at different stations along a line but is fairly consistent along the maximum of the easternmost linear conductor. These changes from station to station could be an artifact related to the short spacing of the EM-31 since this system averages over a small region of the subsurface at any given measurement point.

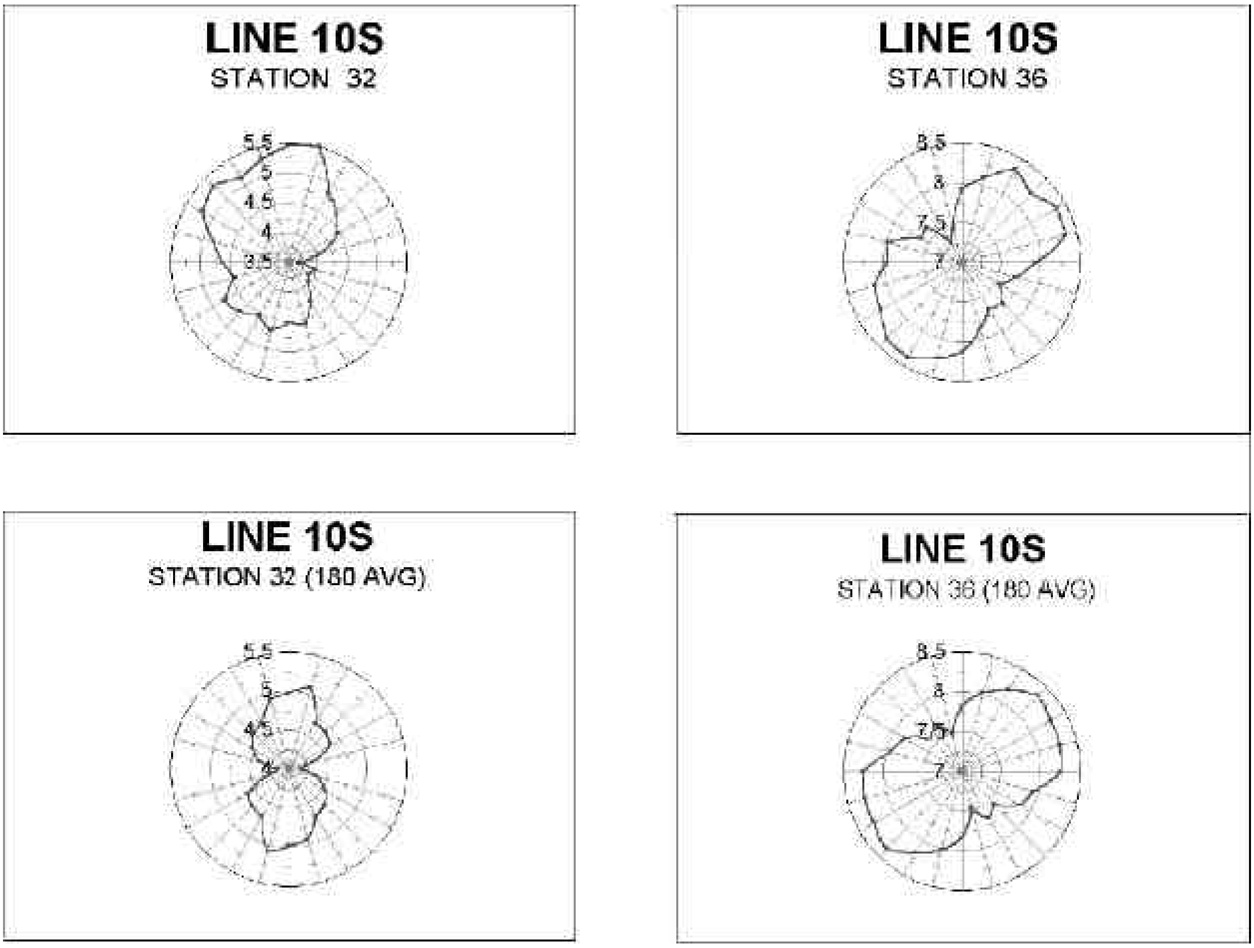

Figure 7. Comparison of stations 32W and 36W on Line 10S before and after averaginbg data 180° apart. Note the decrease in noise and the sharper definition of maximum and minimum conductivity values.

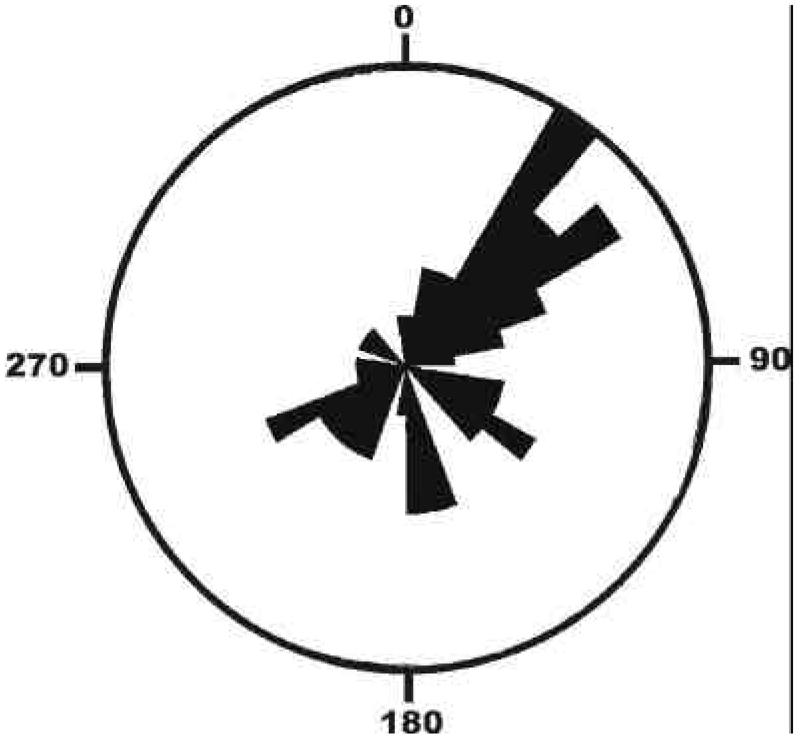

Figure 8. Rosette diagram indicating that the main fracture directions in outcrops strike approximately NE-SW. SE-NW, and S.

GROUND-PENETRATING RADAR (GPR) SURVEY

GPR offers a high resolution sounding capability with detection of features a few centimetres in thickness down to depths of several metres to tens of metres. The radar system uses a short pulse of high frequency (100 MHz in this case) electromagnetic energy which is transmitted into the ground. The propagation of the radar signal depends on the high frequency electrical properties of the ground. The electrical properties of geological materials are primarily controlled by water content. Therefore, radar reflections seen in the bedrock are most likely caused by fluid-filled fractures (Davis and Annan 1989).

A Software and Sensors PulseEKKO 100 (Sensors and Software, 1999) was used to perform the GPR survey. GPR profiles were collected along pre-existing EM survey lines where variations in conductivity were noted. Antennae were separated by 1 m and the step size along the lines was 0.5 m. The measurement point is the mid-point between the transmitter and receiver coils.

As an example, Fig. 9 shows a GPR profile along east-west line 0S. In the near-surface, from about 0 m to 2 m, a band of continuous high-amplitude reflectors is disrupted over the region from approximately 32W to 45W m. The only processing

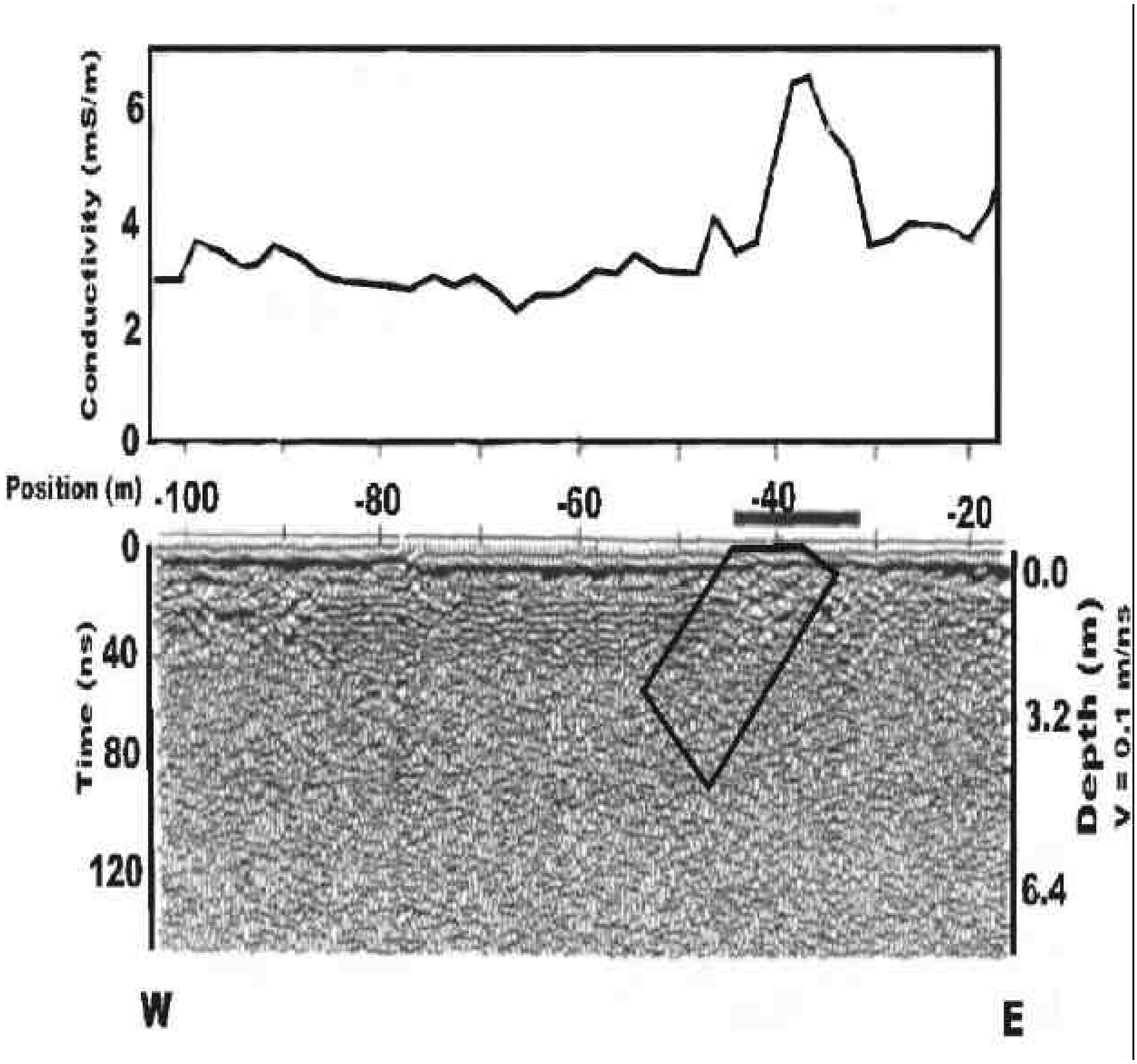

Figure 9. EM (above) and GPR profile (below) of line 0S from –103 (103W) to –17 m. The solid bar from –45 to –35 m shows the region where shallow continuous reflectors (0-2 m depth) are disrupted. This region coincides closely with the conductivity high at –36 m. The boxed region shows the presence of what may be a set of fractures.

applied to this profile was a trace-to-trace averaging plus an automatic gain control with a window width of 10 ns. As previously noted, an EM conductive high is present along 40W from approximately 0S to 70S. The boxed area on Fig. 9 outlines the region where the continuous reflectors are disrupted and indicates the region where fractures are present. The EM-31apparent conductivity for Line 0S is shown above the radar plot and demonstrates that high conductivity responses are present in the same area. It appears that the GPR data and the EM data agree well with one another. The same is true for other GPR profiles south of Line 0S which also show continuous features that may be interpreted as fractures near 40W.

CONCLUSIONS

Landfills and fresh groundwater are both increasing in importance as populations increase and resources diminish. The use of geophysical methods, such as EM and GPR surveying, provide methods to map the presence of subsurface fractures in bedrock. The mapping of such features is very important since it provides scientists and engineers with the ability to (1) identify flow paths for contaminated groundwater and (2) to identify drilling locations for groundwater wells.

This study has shown that it is possible to map bedrock fractures using EM and GPR techniques. Significant increases in bedrock conductivity generally indicate some form of conductive material in them such as leachate or clays. The decrease in conductivities away from the landfill suggests that contaminated groundwater is flowing through the fractures.

Subsurface fracture orientation measurements can me made by performing an azimuthal conductivity EM survey. It was shown that a greater EM response occurs when the EM-31 instrument was positioned parallel to conductive subsurface fractures. Therefore, it seems reasonable to assume that azimuthal conductivity surveys may be used to aid in fracture detection and mapping. As well, it was shown that simple procedures can be performed to filter out a large portion of the noise encountered in this type of surveying.

By repeating the EM survey in a few years, estimates of flow rates can be obtained.

ACKNOWLEDGEMENTS

This study would not have been possible without the generous support of Geonics Ltd. who provided the EM-31 equipment free of charge. As well, we would like to thank

Sensors & Software Inc. for providing reduced rental rates. Finally, we would like to extend thanks to Mr. Nigel Lomas and other employees of the CRD for generously providing important background information, assistance, and access to the site. Presentation of this paper at Fortaleza 2000 was sponsored by the Northeastern Brazil Groundwater Project, an initiative funded by the Canadian International Development Agency (CIDA) in collaboration with Agência Brasileira de Cooperação (ABC), the Geological Survey of Canada (GSC), the Geological Survey of Brazil (CPRM) and their partners, Superintendência do Desenvolvimento do Nordeste (SUDENE), Associação Brasileira de Águas Subterrâneas (ABAS) and Comunidade Solidária.

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