Non-invasive Imaging of Hydrocarbon Contamination in Permafrost Soils at Marble Point, Mcmurdo Sound Region, Antarctica

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Abstract

Hydrocarbon spills can cause extensive environmental damage and can last a long time in dry permafrost environments like that in Antarctica. Intrusive sampling and attempts at remediation can cause more harm to a site already damaged, particularly in the harsh yet fragile Antarctic environment. Additionally, even carefully planned intrusive sampling programmes can miss the target, in this case the location and extent of contamination. With negligible physical disturbance, non-invasive, non-destructive geophysical methods determined the extent of hydrocarbon contamination in the permafrost soil at Marble Point, in the McMurdo Sound region. Limited sampling was done for calibration, with minimal and highly restricted disturbance. The contamination is 35 to 40 years old; however the electromagnetic response was electrically resistive, the same as relatively young contamination in temperate soils, whereas older temperate spills tend to be electrically conductive. Radar profiles were acquired across the eastern half of the site, crossing two contaminated locations. The radar reflections were enhanced, again as observed for young contamination in temperate soils. Correlation between the radar and electromagnetic responses was excellent. The cold polar climate slows chemical and physical changes to contaminants, so that they respond as if young and relatively fresh. Geophysical imaging provided a viable non-invasive means to map the extent of hydrocarbon contamination in Antarctic permafrost soils with little or no site disturbance.

Introduction-Context and Motivation

Hydrocarbon spills can cause significant damage to permafrost environments, particularly the dry permafrost soil environments of Antarctica. The soil processes occur slowly (Campbell & Claridge 1987; Campbell et al. 1998), and the effects of contamination can thus be amplified by the lack of biological, chemical and physical factors that may otherwise serve to disperse and diminish the effects of contamination over time (Campbell et al. 1994, 1998). In temperate settings, contamination is often mapped simply by drilling a series of intrusive sampling wells, and remediation is done by excavating the contaminated material or by pumping contaminant from wells. In Antarctica, however, the very act of intrusive sampling and remediation can cause further damage to a site that is already harmed by contamination; the permafrost layer when disturbed begins to melt at its top.

An alternative approach to intrusive sampling is to carry out non-invasive, non-destructive mapping. Even a carefully planned intrusive sampling programme can miss the contamination that would otherwise be detected and delineated by geophysical imaging (e. g., Barinaga 1989). Thus at the very least a programme of geophysical imaging is advisable to delineate the location and extent of the target feature, regardless of the nature of the target and its setting. In a sensitive environment, however, sampling may not be possible, as for indigenous burial sites (Nobes 1999), or may be restricted, as in Antarctica. Geophysical imaging thus becomes essential both to delineate the extent of, in this case, contamination, and to guide whatever restricted sampling may be allowed. The need for such sampling is not eliminated by the use of geophysical imaging, but only such samples as are needed for calibration are acquired. For example, the intrusive sampling can be restricted to the location with the maximum anomalous response and to a location that is representative of the background response.

Hydrocarbon spills have been successfully mapped and monitored using geophysical imaging in temperate climates (Greenhouse et al. 1993: Sauck et al. 1998), but the results differ depending on the age of the spills. Fresh or young spills appear to be electrically resistive and enhance the strength of ground penetrating radar (GPR) signals from subsurface boundaries (Greenhouse et al. 1993), whereas old contaminant spills (of the order of decades in age) may be electrically conductive and attenuate the propagation of radar energy (Sauck et al. 1998). Because of the sensitive nature of the dry permafrost environment in Antarctica, specifically in the McMurdo Sound region, we wanted to investigate the utility of near-surface geophysical methods for delineating the extent of hydrocarbon contamination in soils. Part of the study required us to first characterise the nature of the anomalous geophysical response, if indeed any was present. Because of the proximity of the saline waters of Ross Sea, which should cause increased soil conductivities during at least the southern summer, we had hoped that the contaminated soils would be electrically resistive and would enhance the radar response, as is observed for young contaminant spills (Greenhouse et al. 1993). A strong seasonal response has already been identified at Scott Base (Pettersson and Nobes 2003). However, while the contaminant response appeared to confirm our hypothesis, the degree of signal interference from the buildings and buried services made it difficult to isolate the anomalous geophysical response due to hydrocarbon contamination. Thus, we carried out geophysical surveys at Marble Point, on the shore of McMurdo Sound (Fig. 1), in order to (1) unequivocally determine the nature of the geophysical response of hydrocarbon contaminants in Antarctic permafrost soils and (2) show that non-invasive geophysical methods could be used to map the extent of contamination, with limited and restricted sampling for limited calibration of the geophysical response.

Site Description

Marble Point currently has a small helicopter refuelling base, but at one point it was to be the main base for the US Antarctic Program (USAP) (Anonymous 1958). The site is located on a thin strip of ice-free ground between Gneiss and Marble Points along the western coast of McMurdo Sound. Because of the possible development of a permanent base, construction crews and equipment were located here, and hydrocarbon spills inevitably occurred. Eventually, the site was deemed inappropriate for a permanent USAP base, because the weather was frequently unsuitable for take-offs and landings, and was abandoned. The contamination, however, remains, both from spills and from construction materials.

The soil at Marble Point is a remnant of the retreating Wilson Piedmont Glacier (Fig. 1), and is derived from the underlying parent material consisting of marble, schist and granodiorite covered by a layer of till (Campbell et al. 1994). The soil is 0.4 to 15 m deep, and is underlain by angular boulders. The surface consists of a weakly developed, boulder-strewn desert pavement. The depth to the ice-cemented layer is typically 40-60 cm during the peak of the January thaw (Campbell et al. 1994). The site is snow-free during the summer melt period, December and January.

Because the spill site investigated was used for refuelling, maintenance and fuel storage, surface staining is visible in large patches (Fig. 2). Most of the visible staining is from lubrication oils; the lighter diesel fuels have little or no surface expression (Aislabie et al. 1997). The spills occurred during the main period of occupation, when the site was studied for runway feasibility, and were thus 35 to 40 years old at the time of the geophysical surveys. The Marble Point spills had been investigated previously for the physical effects on the soil and for the potential for biological degradation (Campbell et al. 1994; Aislabie et al. 1997; Balks et al. 2002).

Survey Methodology

A 24 m by 60 m survey grid was used, with 2 m line and station spacings, to include as many of the contaminated soil patches as were visible at the surface. The corners of the grid were surveyed using a handheld global positioning satellite (GPS) unit. The surveys were completed using a Geonics EM31™ horizontal loop electromagnetic (HLEM) ground conductivity meter, and a Sensors & Software Noggin™ 30 ground penetrating radar (GPR) system. HLEM uses the principle of current induction to yield values of the ground electrical conductivity (e. g., McNeill 1990). EM31 readings were taken every 2 m along lines spaced 2 m apart. The values of apparent conductivity are averages over some volume of the subsurface, and are expressed in millisiemens per metre (mS/m). GPR, on the other hand, uses the reflection of high-frequency radar signals from subsurface boundaries to obtain information about the subsurface structure and stratigraphy (e. g., Davis and Annan 1989). The GPR surveys were acquired along a subset of the EM survey, lines 10 to 22, but with readings taken about every 0.2 m at a slow walking pace. The GPR time window, the interval over which subsurface radar echoes are measured, was 150 nanoseconds (ns).

Our working hypothesis was that the contaminated soils would be electrically resistive (low electrical conductivity) compared to the relatively conductive background conductivity and would enhance the depth of penetration of the GPR signal. The hypothesis is consistent with work by Sheppard et al. (1999, 2000) showing that diesel fuels percolate through the soil, coating the salt grains in the soil. The salt is thus isolated and cannot be dissolved by the water present in the soil; as more salt is dissolved in water, so the electrical conductivity increases. As the salt water concentration increases, the radar propagation is degraded, because the radar signal is attenuated (Davis and Annan 1989). Therefore, contaminated soils are expected to be more electrically resistive and enhance radar propagation, if, as we expect, older contaminated soils in Antarctica behave like freshly contaminated soils in temperate climates.

The results cannot be fully interpreted and understood without some degree of calibration. The question then becomes: How much? In a sensitive area, such as Antarctica, we wish to keep any disturbance to a minimum. The minimum sampling would thus be a sample from a location that appears to be uncontaminated, both in the geophysical response and from visual inspection if possible, and a sample from a location that has an anomalous geophysical response and which may or may not also appear contaminated from a visual inspection. While more sampling improves the calibration and gives greater confidence to the interpretation, the result is greater disruption and disturbance to the soil and the permafrost. Such additional disturbance can cause greater harm than the original contamination, because the permafrost must adjust to the changes in the conditions and thus is no longer stable and in equilibrium. Our philosophy for sensitive areas like Antarctica, therefore, is to minimise the sampling, and thus the additional site disturbance, at the expense of greater confidence in the interpretation. Instead we use the additional evidence provided by visual inspection and the use of multi-parameter geophysical imaging to improve our confidence in the interpretation.

Results and Discussion

The raw EM31 data (Fig. 3a) are strongly influenced by background trends due to changes in lithology (i. e. silt and clay content), the depth of the ice-free layer, and the salinity. In this case, the proximity to the shore may have introduced a gradient in the response due to changes in the background soil salt content. This background trend can be removed by subtracting the median value for each survey line, a process similar to the one proposed by Nobes (1999). If (x) is the measured apparent conductivity at location x, and m is the median value for that survey line, then r(x) is the residual conductivity as:

$$r(x) = (x) - m$$

The plot of residual conductivity (Fig. 3b) shows some areas with clearly anomalously low conductivities (dark, corresponding to resistive soils). It was not necessary in this situation, but sometimes we wish to normalise the residual values for comparison with other data sets. The residual values are normalised by dividing the residual by the median absolute deviation, the median equivalent of the standard deviation, a method that has been previously shown to be effective for isolating the anomalous geophysical responses of graves in burial sites (Nobes 1999; Field et al. 2001).

Figure 1.

Marble Point is located on the western shore of McMurdo Sound, near the Dry Valleys region of Antarctica (inset). The locations of the US and New Zealand permanent bases in the McMurdo Sound region, McMurdo Station and Scott Base, respectively, are also shown. (The Radarsat image is modified from the USGS Atlas of Antarctic Research,. The inset map is modified from http://usarc.usgs.gov/antarctic_atlas, the small Antarctic map at http://www.lib.utexas.edu/maps/cia03/antarctica_sm03.gif in the Perry-Castañeda Map Collection, University of Texas at Austin.)

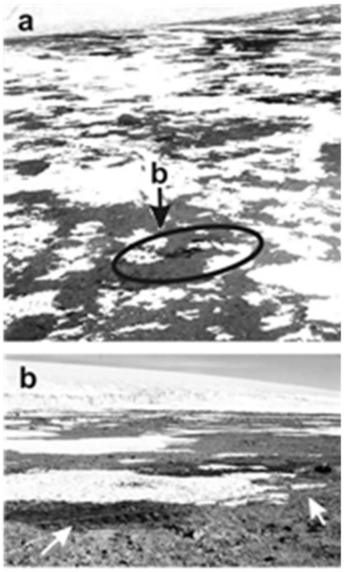

Figure 2.

a. Photograph taken from a helicopter above the Marble Point site. The approximate location of the survey area is indicated by the oval. The arrow shows the vantage point for the ground photograph shown in **b**. The dark patches in the soil are often indicative of hydrocarbon contamination (dark arrow in b). The white arrow indicates a tape measure laid out for accurate survey positioning

Those areas that were identified as contaminated did have anomalous EM responses. Thus the EM31 survey was able to delineate contaminated areas beyond what was visually apparent on the surface. The areas with obvious surface discolouration were mapped after the geophysical imaging was completed using the same geophysical survey grid (Fig. 4a). However, most of the anomalous areas were not identified as contaminated from a preliminary visual inspection because of the snow cover, which initially obscured much of the survey site (Fig. 4b). In some cases, the outlines of the discoloured soil could be followed but the coverage extended beneath patches of snow (Fig. 4c), much of which sublimated (vapourised) during the period of the imaging, so that by the end the contamination visible at the surface was more readily observed. The inferred extents are shown as connected where the outermost boundaries could be clearly traced.

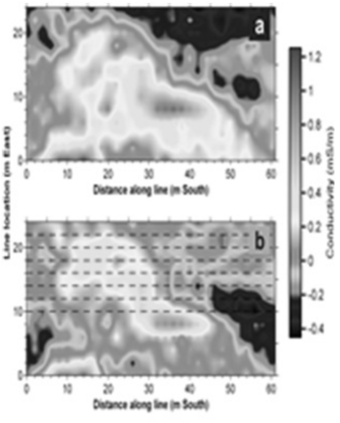

Figure 3.

a. The raw EM31 apparent conductivity data show a distinct trend across the site from west (bottom) to east (top). Such trends often occur because of changes in silt or clay content, or changes in the depth to the permafrost layer. **b**. The trend is readily removed by subtracting the median value for each survey line. The residual value, expressed in standard deviation (dimensionless) units, clearly shows some isolated anomalously resistive (blue) areas. The locations of the GPR imaging are shown (dashed lines).

Table 1. Total Petroleum Hydrocarbon (TPH) content in mg/l for samples from the Marble Point site. Sample 1 was from a contaminated soil, Sample 2 was from an uncontaminated soil. C7-C9 are light hydrocarbons; C10-C14 are medium-weight hydrocarbons typical of modified diesel fuels, and C15-C36 are heavy hydrocarbons, such as crankcase and other lubrication oils. See Fig. 4 for sample locations.

Hydrocarbon Types	Sample 1 (0-15 cm)	Sample 1 (15-30 cm)	Sample 2
C7 – C9	24	9	< 4
C10 – C14	311	386	< 8
C15 – C36	21300	17700	70
Total	21700	18100	70

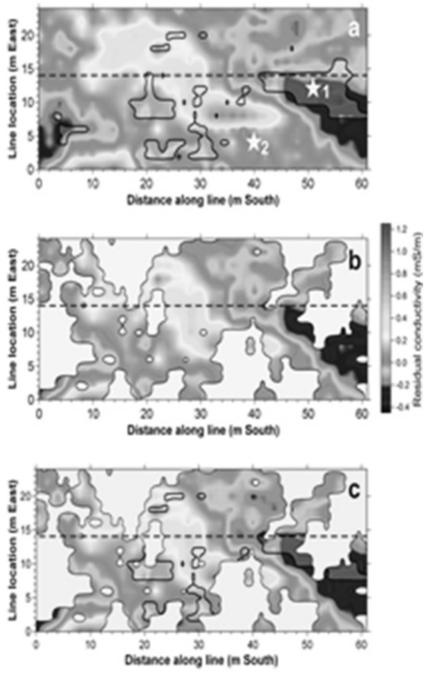

Figure 4.

a. The areas that appeared to be contaminated based on the visual inspection for soil discolouration are shown superimposed on the residual EM response. The locations of the soil samples measured for TPH (Table 1) are indicated by the star labels. b. Extensive snow initially obscured much of the site. c. The initial extent of the snow (as shown in b) is superimposed on the extent of the contamination based on visual inspection (as shown in a). In some cases, discolouration was at least initially partly obscured by snow, and contamination was inferred to continue beneath the snow if the discolouration edges were clearly visible. The location of the comparison GPR line shown in Fig. 5 is indicated on a, b and c.

To aid and calibrate the interpretation, the total petroleum hydrocarbon (TPH) concentrations were measured at two locations within the survey area, and are indicated in Fig. 4a: one sample was obtained at a location that appeared to be contaminated and had an anomalous EM response; and a second sample was acquired that did not appear to be contaminated and did not have an anomalous response. These TPH samples represent the end members for the calibration of the results, and are presented in Table 1.

GPR survey lines were acquired across the upper (eastern) portion of the site, focussing on two anomalous areas in the SE quadrant (upper portion, as indicated in Fig. 3b). The results were consistent across the site, and are exemplified by the results from Line 14 (Fig. 5). The standardized residual conductivity is shown superimposed on the radar profile in Fig. 5, and the correlation is excellent, both qualitatively and quantitatively (Fig. 6). Where the soil was more resistive, and thus indicative of hydrocarbon contamination, the radar penetration was greater, as had been observed for young spills in temperate soils (e. g. Greenhouse et al. 1993). Where the soil was more conductive, and thus less contaminated, the radar propagation was less.

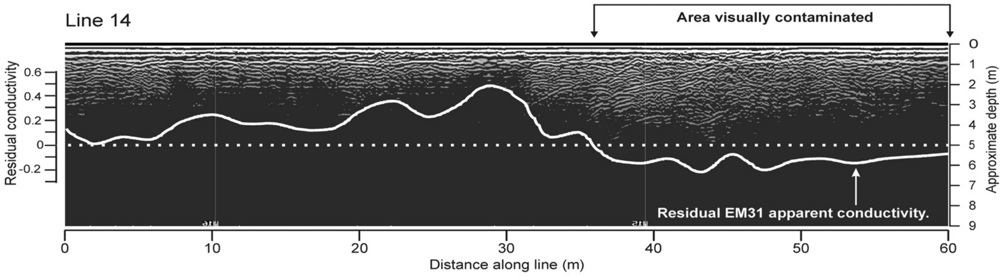

Fig. 5. A sample GPR profile shows the variable depth of penetration of the radar signal in the soil at Marble Point, which correlates well with the residual EM31 apparent conductivity from the same line. Where the penetration is much greater than average (on the right), we see a corresponding decrease (lesser conductivity, greater resistivity) in the EM response. The area of surface visual contamination is indicated.

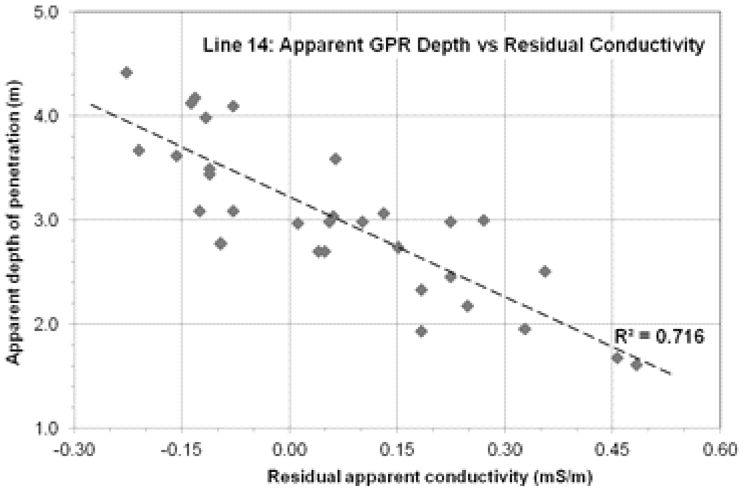

Fig. 6. A direct comparison of the GPR depth of penetration versus the residual conductivity supports the qualitative analysis of Fig. 5.

Conclusions

The geophysical response of hydrocarbon-contaminated permafrost soil at Marble Point, Antarctica, was similar to that for much younger contaminants in temperate soils. Our results support the hypothesis that contaminant alteration, including degradation, is much slower in polar climates. Such contamination can affect the soil processes and degrade the permafrost soils of environmentally sensitive sites such as the Dry Valleys of the McMurdo Sound region of Antarctica. Geophysical imaging provides a viable alternative approach to invasive sampling of contaminated soils, particularly in the permafrost Antarctic soils, and thus avoids disturbing sites already affected by activities that are environmentally damaging.

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