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Geophysical Assessment of Salt and Hydrocarbon Contaminated Soils

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Abstract

Environmental impacts associated with high salt concentration related to industrial activities can be assessed and monitored using geophysical methods. Repeated three-dimensional electrical resistivity imaging (ERI) was used over a three-year period to map the distribution and level of the salt concentration as well as evaluate the efficiency of a system of tile drains installed as a part of the remediation efforts, at a salt contaminated site in central Alberta. Maps of electrical conductivity distribution of the subsurface, collected at different times, were calibrated for environmental changes (temperature) between the survey times before they were interpreted for the distribution of high salt concentration. The corrected results exhibit the importance of the environmental factors in observed changes in the electrical conductivity of the subsurface which can completely obscure the subtle changes caused by natural or induced remediation of salt in the subsurface. The corrected difference maps of conductivities show clear reduction of EC along the tile-drain system in the region of high salt concentration.

The corrected maps were further converted into the saturated-paste EC values using relationship developed in saturated-past laboratory experiments. The results were categorized into the map of regulatory values, using Alberta Environment Salt Contamination Assessment & Remediation Guidelines, to identify regions of subsurface which require further remediation.

It has been hypothesized that chargeability changes due to free phase hydrocarbon contamination may be detected with induced polarization (IP) surveys. An IP line over a known hydrocarbon plume produced a zone of elevated chargeability coincident with the know location of the plume. Although not definitive, the results indicate that further research is warranted.

Introduction

Accurate assessment of the distribution and volume of the contaminated soils is essential in designing an efficient remediation program as well as monitoring the effectiveness and speed of the remediation progress. Contaminated soils with high salt concentration usually exhibit high electrical conductivity (EC) that provide ideal targets for electrical resistivity imaging methods, in which conductivity of subsurface are calculated using mapping of the electrical potential distribution due to an electrical current injection. The results are expressed in terms of apparent resistivities that are further processed to produce map of electrical conductivity distribution of the subsurface. Traditionally, these maps are interpreted as diagnostic of level of salt concentration in the subsurface. However, the estimated EC is a function of several environmental factors which need to be accounted for before a quantitative interpretation of the EC map can be conducted. Among these factors, temperature has been shown to be a significant parameter and the estimated EC maps need to be compensated for temperature variations over the region mapped by the survey. This correction is even more essential when comparing surveys conducted along the same survey line but in different times. In remediation sites, time-lapse ERI surveys are usually conducted to detect evolution of contaminations in terms of their electrical conductivity signature, however strong EC variations due to changes in subsurface temperature could completely mask the subtle EC variations due to contaminant movement or removal.

Non-uniqueness of geophysical results suggests that the interpretation needs to be conducted along with auxiliary hard data. Push tool vertical EC profiling at a few locations over the survey area provides depth information as well as reference point and ground truthing. In addition, core sampling is required to develop laboratory pertophysical relationships between EC values and temperature and salt concentration. These relationships are used for temperature correction as well as transforming ERI EC values into salt concentration that are need for a qualitative interpretation.

Certain geological settings, such as clay-rich beddings, can introduce additional non-uniqueness into the interpretation of geophysical results. Clay minerals are known as high EC materials and uneven subsurface distribution of the clay over the survey area is superimposed ont the high EC signature associated with salt concentration and introduces additional ambiguity in interpretation of salt distribution. Geophysical Induced Polarization (IP) method, in which residual voltage decay is measured after switching off of a DC current source, can be used to differentiate between EC variations caused by geological variations and groundwater quality variations. The chargeability effect measured in IP surveys can also be an indicator of hydrocarbons or LNAPL plumes in subsurface (Slater and Lesmes, 2002).

In this study, we describe protocols for assessing the distribution and evolution of salt in soils and groundwater, using repeated 3-D ERI surveys. Since the distribution of contaminants in subsurface are predominately heterogeneous, 2D ERI surveys are usually inadequate (Bentley and Gharibi, 2004). The following demonstrates the use of 3-D electrical resistivity imaging along with other measurements for site remediation in heterogeneous geological areas with high salt concentrations to produce an integrated time-lapse framework to image the evolution of the salt distribution within the subsurface. We also present an application of IP method in hydrocarbon and LNAPL plume detection.

Site and surveys

The research site is located in central Alberta and is characterized by high concentration of salt due to historical releases of produced water. A previously collected electromagnetic survey data was used to locate two areas of interest to conduct quasi three-dimensional ERI surveys (Figure 1). Both survey zones are located over a three-plot phytoremediation research area. The area is also underlain by a tile drain system at a depth of about 2 m. The installation is designed to remove saline waters and thereby reduce the mass of salt in the soils.

The first ERI survey zone consists of 10 parallel lines with 2 m electrode spacing and 4 m line spacing. The EM survey indicated a highly conductive subsurface associated with high concentration of salt in this area. The second ERI survey zone, with 5 parallel lines and the same survey configuration as that of the first survey zone, is located at the far end of a phytoremediation area where salt concentrations are lower.

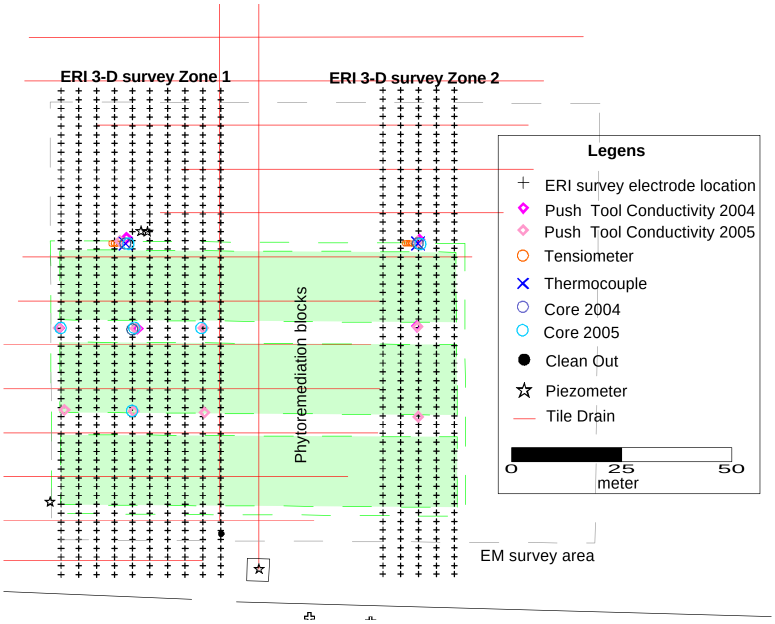

Figure 1. Location map. Zone 1 consists of 10 parallel lines with 56 electrodes along each line. Zone 2 consists of 5 parallel lines with 56 electrodes along each line. Electrode spacing and line spacing are 2 m and 4 m, respectively, and dipole-dipole configuration was used in both zones. Crosses show electrode positions.

During three years of study six repeated time-lapse ERI surveys have been completed in the spring and fall. The surveys were conducted with a single-channel Advanced Geoscience Inc. unit using 56 smart electrode stations in an automatic preprogrammed sequence of measurements. In each survey time, the data from zone 1 were combined and inverted using a 3-D finite-element inversion code as were the data from zone 2.

As an example, a set of selected horizontal slices of the 3-D inversion results at different depths in zone 1 from surveys conducted in October 2005 and May 2006 as well as their difference map are shown in Figure 2A. Electrical conductivity anomalies as high as more than 300 mS/m, seen in red, image areas of high concentration of salt starting from the surface and extend to a depth of several meters. The image clearly outlines the geometry of the salt distribution. The thickness and the distribution of the high concentration areas are quite irregular and demonstrate the ability of the ERI design to delineate heterogeneity that may otherwise go uncharacterized (Gharibi and Bentley, 2005). In the difference map, blue areas indicate a reduction of EC, red areas represent areas of increased EC and green areas represent areas of no or minor change. Figure 2A) exhibits an overall significant reduction in EC from the surface to about 4 m, however, an interpretation of salt distribution changes requires that the EC values are adjusted for their temperature differences.

To account for influence of temperature variation, data from two sets of multilevel thermocouple installations are used (Figure 3). The data are used to compensate for differences between surveys with the objective that the EC differences would only be due to changes in chemistry and salt concentration.

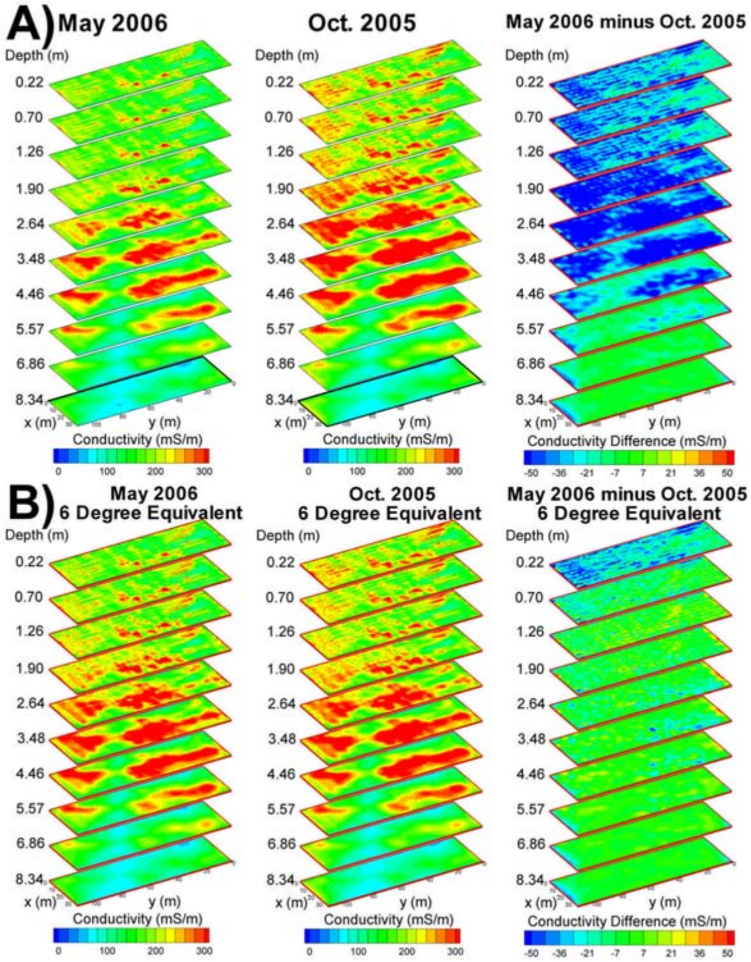

Figure 2. Selected horizontal slices of electrical conductivity at different depths from the 3-D inversion results in zone 1; A) October 2005, May 2006, and their difference in in-situ temperature. B) Results shown in A) corrected to 6°C.

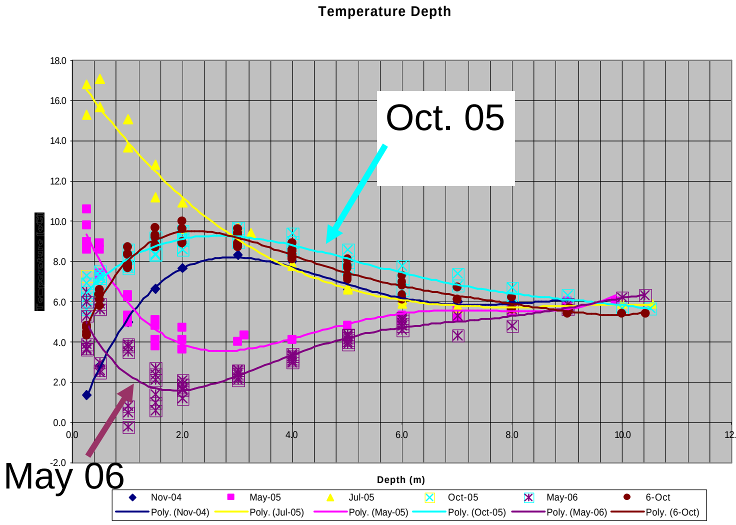

Figure 3. In situ temperature vs. depth profiles.

Core lab tests were conducted to develop EC vs. Soil Paste EC as well as EC vs. T curves (Hayley, K. et.al., 2007) and the relationship is shown in figure 4. The EC vs. T curve along with the temperature profile from thermocouple installations were used to correct ERI results to a standard temperature (6°C). Figure 2B) shows the temperature corrected results and difference maps between October 2005 and May 2006 surveys. This correction demonstrated that most of the observed change in the shallow EC was due to difference in temperature of the two survey times and not necessarily salt migration.

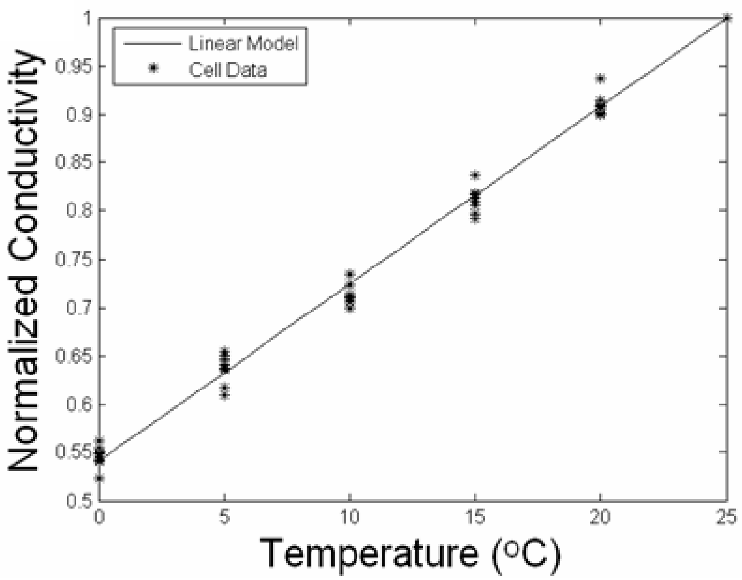

Figure 4. Core EC vs. T curve.

Using the procedure described above we constructed a temperature corrected difference map between surveys conducted in October 2006 and July 2004 as a measure of the total reduction of EC in the subsurface as well as to evaluate performance of the tile-drain installation over three years of the study period (Figure 5). The results clearly indicate two effects in subsurface EC variations. The first one is that the greatest reduction in subsurface EC correlates with a shallow (15 cm) closed depression. Apparently, the leaching distribution is uneven and focused beneath depressions. The second effect is that the traces of tile drains clearly correlate with linear reductions in EC. We hypothesize that soil disturbance during the installation of drains enhances the permeability in these zones.

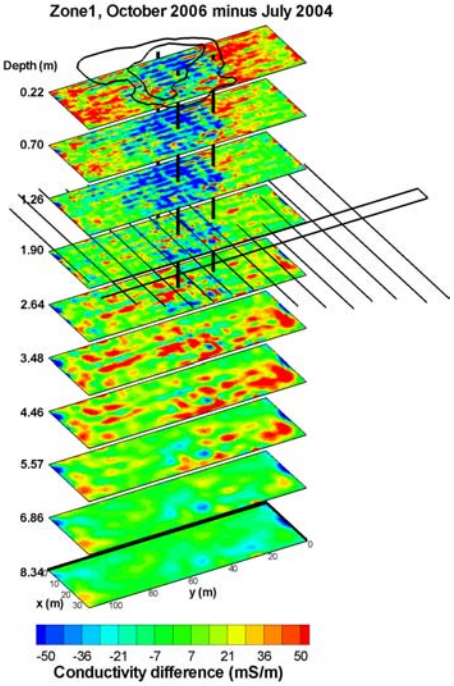

Figure 5. Temperature correct difference EC map between surveys conducted in October 2006 and July 2004. Surface shallow (15 cm) closed depression counters and tile-drain system are shown.

In order to perform a regulatory interpretation of the data, the ERI EC results were converted to saturated paste EC values using the lab core EC vs. Soil Paste experimental curves. The results were converted to a map of Good, Fair, and Unsuitable regions according to the Alberta Environment Salt Contamination Assessment & Remediation Guidelines (Figure 6).

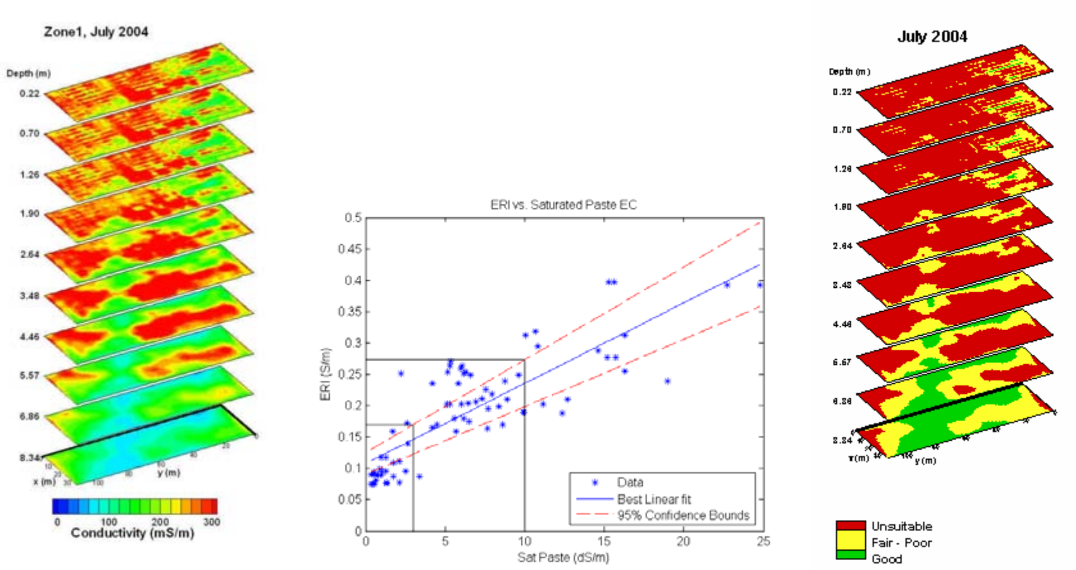

Figure 6. Map of ERI EC (left), ERI EC versus saturated past EC curve (middle), and map of regulatory measures (right).

IP surveys

Delineating free phase hydrocarbon contamination is a challenging problem. It has been hypothesized that chargeability effect associated with hydrocarbon plumes can be detected and measured with IP methods. In addition, IP data also may be useful in separating effects of geological variation from the variations of salt concentration in groundwater (Slater and Lesmes, 2002). Figure 7 shows the location of IP survey Line 2 as well as the extent of an LNAPL plume at a legacy refinery site in Calgary.

The results of Line 2 ERI resistivity, IP chargeability and normalized chargeability (chargeability divided by resistivity) are shown in Figure 8. The red arrow in chargeability cross sections (Figures 8B and 8C) indicates the extent of high IP values that may be indicative of free phase hydrocarbon. The location coincides well with the boundary associated with minimum extent of the LNAPL plume in Figure 7. Although the survey was able to detect IP anomaly coincident with the location of separate phase hydrocarbons, its geometrical relationship is still unclear.

Summary

Electrical resistivity imaging method has proven to be a powerful tool for detecting the distribution of the salt concentration and in monitoring its redistribution with time. Time-lapse 3-D ERI survey design assures accuracy of the resulting EC distribution map at heterogeneous contaminated sites. Auxiliary data and corrections for spatial and time varying environmental conditions are absolutely essential for both qualitative and quantitative interpretations of the time-lapse results. The time-lapse ERI design and corrections applied to the survey data collected over the research site in this study revealed that the zone of highest impact by remediation program is associated with a shallow closed depression. It indicates that leaching distribution is uneven and focused beneath surface depressions. It suggests that an adaptive focused remediation program may be designed by an occasional recontour of the remediation area.

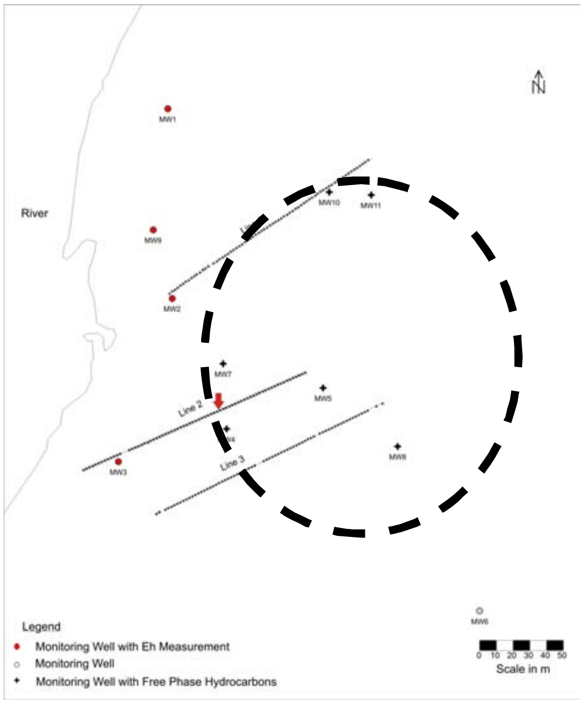

Figure 7. IP survey Line 2 over a hydrocarbons contaminated area. Black crosses indicate piezometers with free phase hydrocarbon and red dots indicate piezometers with no free phase hydrocarbon. Dash circle depicts the minimum extent of the LNAPL plume.

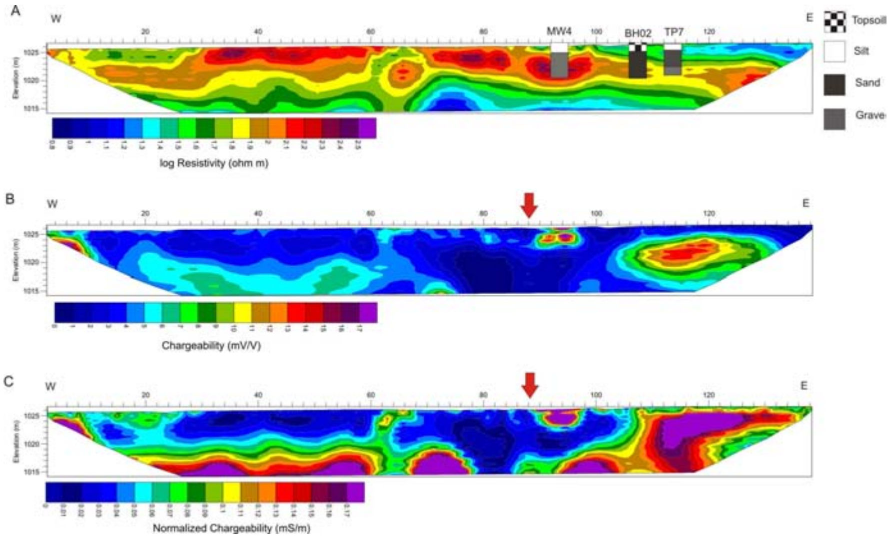

Figure 8. A) ERI Resistivity, B) IP chargeability and, C) IP normalized chargeability cross-sections along line 2. Red arrow indicates the possible boundary between free phase hydrocarbons and uncontaminated groundwater

In addition, a quantitative interpretation of the ERI results can be made by converting the ERI EC into saturated paste EC values. The results can further be categorized into the map of regulatory values, using Alberta Environment Salt Contamination Assessment & Remediation Guidelines, which can help industry and regulatory bodies in conducting conclusive risk-based closure assessments.

IP results showed that IP surveys may have the potential to detect free phase hydrocarbon. However, more work is needed before the association of observed IP effect with distribution and phase of LNAPL plume is conclusive. A 3-D IP survey will reduce degree of ambiguity in understanding this association.

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