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Improving the delineation of hydrocarbon-impacted soils and water through induced polarization (IP) tomographies: A field study at an industrial waste land

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ABSTRACT

Without a good estimation of samples representativeness, the delineation of the contaminated plume extent and the evaluation of volumes of hydrocarbon-impacted soils may remain difficult. To contribute to this question, a time domain induced polarization (IP) field experiment was conducted on an industrial waste land. Boreholes were drilled to specify the local geological context. Cross-hole seismic tomographies were performed to extend borehole logs and to draw an interpreted geological cross-section. Soil samples taken during drillings were analysed in laboratory. A preliminary survey was conducted to locate the IP profile. The polarization signatures linked to the presence of clayey sediments were filtered out from the data set. Chargeability and resistivity depth soundings were computed and compared to mean concentrations of total organic products to overcome the data support issue between the geophysical models and the spot samples of soils. A logarithmic relation between chargeabilities and smoothed hydrocarbon concentrations in soils was found. Taking into account contaminant's concentration thresholds defined in local codes and regulations allows defining chargeability classes to delineate hotspots on this site. This showed that IP tomography can be an accurate screening methodology. A statistical methodology is proposed to assess the efficiency of the investigation strategy.

1. Introduction

Characterization of hydrocarbon-impacted soils and groundwater remains one of the most challenging problems when dealing with the restoration of contaminated sites, especially on industrial waste lands. The task of delineating and quantifying the amount of NAPL (non aqueous phase liquids) present in soils and groundwater has presented significant challenges to engineers and scientists involved in soil and groundwater remediation. To overcome the NAPL plume characterization problem, soil and groundwater samples collected in boreholes and piezometers are usually analysed. Currently, sample analyses allow identification of the nature of contaminants and assessment of sample concentrations. However, extending this information to delineate the plume extent or to estimate the volume of polluted soils is difficult. Due to technical and/or economic reasons, the number of boreholes is often limited as well as the number of samples analysed. Because of the complex non-linear nature of NAPL transport, distributions of NAPL tend to be highly heterogeneous. The soil samples representativeness with respect to the surrounding soils is therefore often poor. This is partly explained by a data support issue. Due to the poor soil sample representativeness, a significant uncertainty may remain in plume delineation or estimated volumes of impacted soils. As a result, designing appropriate remediation plans remains difficult. This often leads to costly or failed attempts to minimize risks associated with the contamination.

Supplementary methods are thus necessary to reduce this uncertainty and improve site characterization. Since at least 30 years, geophysical methods have been tested on hydrocarbon-

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impacted sites to assess their efficiency in detecting and delineating contaminated areas. These methods are sensitive to variations in soil and groundwater properties which are affected by the presence of NAPL. These methods are minimally intrusive and may be cost effective.

They are integrative and less sensitive to small and localized "hot spots" in contrast to soil sampling techniques. Imaging techniques in two (2D) or three dimensions (3D) or even temporal monitoring (4D) of changes in subsurface properties are nowadays available. Although identifying contaminants and evaluating their concentrations unattainable targets, geophysical investigations allow imaging highly impacted area. They may therefore help to estimate sample representativeness and improve the mapping of hydrocarbon concentrations in soil.

Among the methods tested, Electrical Resistivity Tomographies (ERT) and Ground Penetrating Radar (GPR) techniques showed great potential in detecting hydrocarbon-impacted areas. Bulk electrical resistivities of the subsurface are affected by the presence of NAPL (Atekwana and Atekwana, 2010; Sauck, 2000). However, authors reported different signatures at hydrocarbon polluted sites depending especially on site geological context, nature of contaminants and contaminants degradation. Daily and Ramirez (1996), Deceuster and Kaufmann (2004), Kaufmann and Deceuster (2007), Newmark et al. (1996, 1998), Olhoeft (1992), Osella et al. (2002), Pettersson and Nobes (2003) reported higher resistivities in areas where NAPL were found through ERT measurements. These investigations were mainly conducted on freshly polluted soils. Conversely, conductive signatures were detected over NAPL contaminated areas for investigations performed on sites where contaminants are present for several years (*e.g.* Atekwana et al., 2000, 2002, 2004a; Frohlich et al., 2008; Godio and Naldi, 2003; Sauck et al., 1998; Shevnin et al., 2003; Werkema et al., 2003). As shown by laboratory and field experiments (*e.g.* Atekwana et al., 2000, 2002, 2004b, 2004c, 2006; Burton et al., 2003), the biodegradation of NAPL contaminants modifies the bulk electrical conductivities (inverse of resistivities) of impacted soils. Che-Alota et al. (2009) proposed a conceptual model to explain the expected temporal variations of geophysical signatures undergoing contaminant-mass remediation. Bulk electrical conductivities are also affected by lateral variations in clay content, porosity and water saturation as well as by variations in ion concentrations in groundwater. As variations in bulk electrical conductivities have various origins, pointing out the conductivity signature of hydrocarbon-impacted areas is difficult without adding independent relevant data to improve the knowledge of the underground context. Due to this non-uniqueness of the origins of the conductivity signatures at hydrocarbon-impacted sites, the detection of contaminated soils based on ERT investigations alone remains a work for experts in biogeophysics.

As dielectric properties of soils are affected by conductivity variations, GPR investigations also face this non-uniqueness in expected signatures of contaminated areas. Daniels et al. (1995), DeRyck et al. (1993), Olhoeft (1992) and Sneddon et al. (2000) reported high reflexion anomalies in GPR radargrams due to a decrease in attenuation of the signal over fresh hydrocarbon-impacted soils. Conversely, shadow zones (zones with higher attenuation) were found over aged hydrocarbon spills (*e.g.* Atekwana et al., 2000, 2002; Bradford, 2003; Kim et al., 2000; Liu and Oristaglio, 1998; Porsani et al., 2004; Redman et al., 1994; Sauck et al., 1998). Lopes de Castro and Branco (2003) and Cassidy (2007) reported both signatures on sites where biodegradation occurred locally on portions of the contaminant-mass.

The self potential (SP) method may be useful for detecting hydrocarbon-impacted soils undergoing natural attenuation of the contaminant-mass (*e.g.* Béhaegel et al., 2004; Naudet and Revil, 2005; Naudet et al., 2003, 2004; Nyquist and Corry, 2002; Perry et al., 1996; Vichabian et al., 1999). However, further work is needed to improve the imaging abilities of this method in order to delineate hydrocarbon-impacted volumes. Moreover, the SP signal is highly affected by buried man-made structures which are commonly encountered on industrial sites.

Since the works of Olhoeft (1985, 1986) and Olhoeft and King (1991) who first pointed out a link between IP (induced polarization) signatures and the presence of contaminants adsorbed to soils, laboratory measurements (*e.g.* Abdel Aal et al., 2004; Börner et al., 1993; Cassiani et al., 2009; Chambers et al., 2003; Davis et al., 2006; Losito and Angelini, 2002; Martinho et al., 2006; Schmutz et al., 2010; Schwartz et al., 2012; Vanhala, 1997b; Vanhala et al., 1992) and field experiments (*e.g.* Abdel Aal et al., 2006; Briggs et al., 2004; Deceuster et al., 2005; Ramirez et al., 1996; Sogade et al., 2006; Vanhala, 1997b) have been conducted to assess the potential of the induced polarization method for detecting hydrocarbon-impacted areas. In most cases, high chargeability (measure of the polarization mechanisms) anomalies were reported over contaminated areas during field experiments. However, as for resistivity measurements, laboratory experiments show that IP signatures changed with time (Börner et al., 1993; Vanhala, 1997b). Atekwana et al. (2006) and Abdel Aal et al. (2004, 2006) showed that these variations in IP signatures were also linked to the biodegradation of the contaminant. The IP signature of soils samples contaminated with LNAPL (light NAPL) and containing microorganisms and nutrients increases with time while the contaminant mass decreases. Evidence of a direct link between the intensity of the IP signature and the contaminant concentrations has not yet been clearly established. IP signatures also vary with clay content (Slater and Lesmes, 2002b), water saturation (*e.g.* Binley et al., 2005; Ghorbani, 2007; Jougnot et al., 2010; Titov et al., 2004; Ulrich and Slater, 2004) and structure and arrangement of pores (Binley et al., 2005; Börner and Schön, 1991; Slater and Lesmes, 2002a; Tong et al., 2006). In contrast to ERT measurements, the origins of IP signatures may be identified through the use of empirical or conceptual models which describe the polarization mechanisms. Therefore, the IP method should be a useful tool to supplement ERT and to improve the delineation of hydrocarbon-impacted soils and groundwater on contaminated sites.

Most of these prior works have focused on development of theory based on controlled laboratory experiments. Published works applying IP for NAPL characterization in the field identify IP anomalies in contaminated areas without directly linking these IP signatures to the contaminant concentrations. A practical investigation methodology is proposed here to improve the identification of NAPL hotspots on industrial sites. This methodology includes IP imaging