Mapping biogeochemically active zones at the catchment-scale with induced polarization

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Summary

We demonstrate the application of the induced polarization (IP) imaging method to map biogeochemical hot-spots at the catchment scale. Measurements were collected at the Hydrological Open Air Laboratory (HOAL), a 66 ha. research field. Data collected across the entire site reveal relative modest electrical conductivity values (between 60 and 80 mS/m) and low polarization values (quadrature conductivity < 0.5 mS/m) corresponding to the soils with high fractions of fine grains (silt and clay content over 70%).
Our results focus on a selected location, where measurements revealed a polarization anomaly (quadrature conductivity > 1 mS/m and conductivity phase above 20 mrads). Mapping IP lines permitted to delineate the geometry of the IP anomaly and select the location for the drilling of boreholes. Analysis of the sediments revealed high carbon and iron concentrations, as expected for a biogeochemically active area; however, negligible concentration of sulfides or magnetite which are the common IP targets. Although the polarization mechanism is open to debate, our results demonstrate the applicability of the IP method as a diagnosis tool to delineate in-situ biogeochemical activity in metal-free media.

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Introduction

Biogeochemical hot-spots refer to relatively small areas (patches) related to disproportionally high reactions rates in comparison with their surroundings; thus playing a critical role in the cycling of Carbon and other nutrients (e.g., McClain et al., 2003; Cole et al., 2007; Frei, 2012 and references therein). Hence, there is a growing interest in the understanding of such hot-spots and their temporal dynamics (e.g., Duncan et al., 2013). To date, the analysis of samples in the laboratory offers the only possibility to quantify chemical and biological parameters in soil and water, as required to investigate biogeochemical activity in the subsurface. However, the collection of samples bears the risk to modify the reaction rates, and most commonly lacks the spatial resolution to delineate the geometry of spatially constrained areas such as hot-spots. Non-invasive geophysical methods permits to improve the spatial resolution of subsurface investigations without the necessity of drilling (e.g., Binley et al., 2015). In particular, the induced polarization (IP) method has demonstrated to be sensitive to both textural and geochemical properties of the subsurface (e.g., Revil and Florsch, 2010; Lesmes and Frye, 2001); thus, emerging as a suitable method to investigate biogeochemical activity (e.g., Atekwana and Slater, 2009). At the field scale, IP has demonstrated its sensitivity to monitor the biostimulation of iron-reducing bacteria towards the immobilization of uranium (e.g., Williams et al., 2009), with further experiments suggesting the ability to discriminate between iron- and sulfate-reducing conditions (e.g., Flores Orozco et al., 2011), as well as changes in the polarization length scale due to the accumulation of iron sulfides (Flores Orozco et al., 2013). Built on such findings, Wainwright et al. (2016), demonstrated the possibility to delineate the geometry of naturally-reduced sediments in a floodplain (ca. 6 ha) by means of IP imaging. This study represents the first application of land IP surveys at a relative large scale targeting small anomalies associated to the biogeochemical hot-spots. Recently, IP applications have permitted to delineate biogeochemical active zones in peatlands (McAnallen et al., 2018; Katona et al., 2021) and in municipal solid waste (Flores Orozco et al., 2020). However, to date no study has demonstrated the possibility to map biogeochemical hot-spots in natural soils.

In this study, we present IP imaging results for data collected in the Hydrological Open Air Laboratory (HOAL), a 66 ha research catchment, where multiple investigations have been conducted to understand surface-groundwater interactions (e.g., Blöschl et al., 2016). Geophysical investigations aimed at delineating the hydrogeological units and aid in the understanding of groundwater flow. During a mapping campaign, IP surveys identified a region associated with anomalous high polarization response. Analysis of sediments around the anomaly revealed minimal variations in the textural parameters of the soils. Hence, we hypothesize here that anomalies in the electrical images correspond to biogeochemically active zone. Similar to Wainwright et al. (2016), we assume that the activity of indigenous iron-reducing bacteria results in the accumulation of iron sulfides responsible for the IP anomaly. We present the chemical data obtained by the analysis of materials recovered after drilling to sustain the interpretation of the IP images. The objective of our study is to demonstrate applicability of the IP method to map the geometry of hot-spots and discuss that the accumulation of iron sulfides may not be the main parameter controlling the polarization response.

Methods

Time-domain IP (TDIP) measurements were conducted for a general characterization along two cross-sectional profiles, roughly with an orientation N-S (about 700 m length each). These measurements were collected with 1 m electrode separation aiming at 15 m depth of investigation using a roll-along with independent segments of 72 electrodes with 36 electrodes overlap. Mapping data sets were collected at two locations corresponding to an area where high phase values were observed (i.e., IP anomaly suggesting a hot-spot) and a control area (as illustrated in Figure 1). Around the IP anomaly, 10 lines were collected with 1 m electrode separation (five oriented N-S and the other five oriented NE-SW), and 18 lines (NE-SW) with 0.5 m separation between lines and electrodes for high resolution. At the control area, three lines (roughly NW-SE) were collected with 1 m electrode spacing and 5 m separation between them, and nine parallel lines with a spacing of 0.5 m between lines and electrodes for high resolution. All TDIP measurements were collected with a Syscal SwitchPro 72 unit (from IRIS instruments), with a 500 ms pulse length 50% duty cycle and a skip-0 dipole-dipole configuration (i.e., a dipole length given by the electrode spacing) and a maximum separation of 30 electrodes between current and potential dipoles.

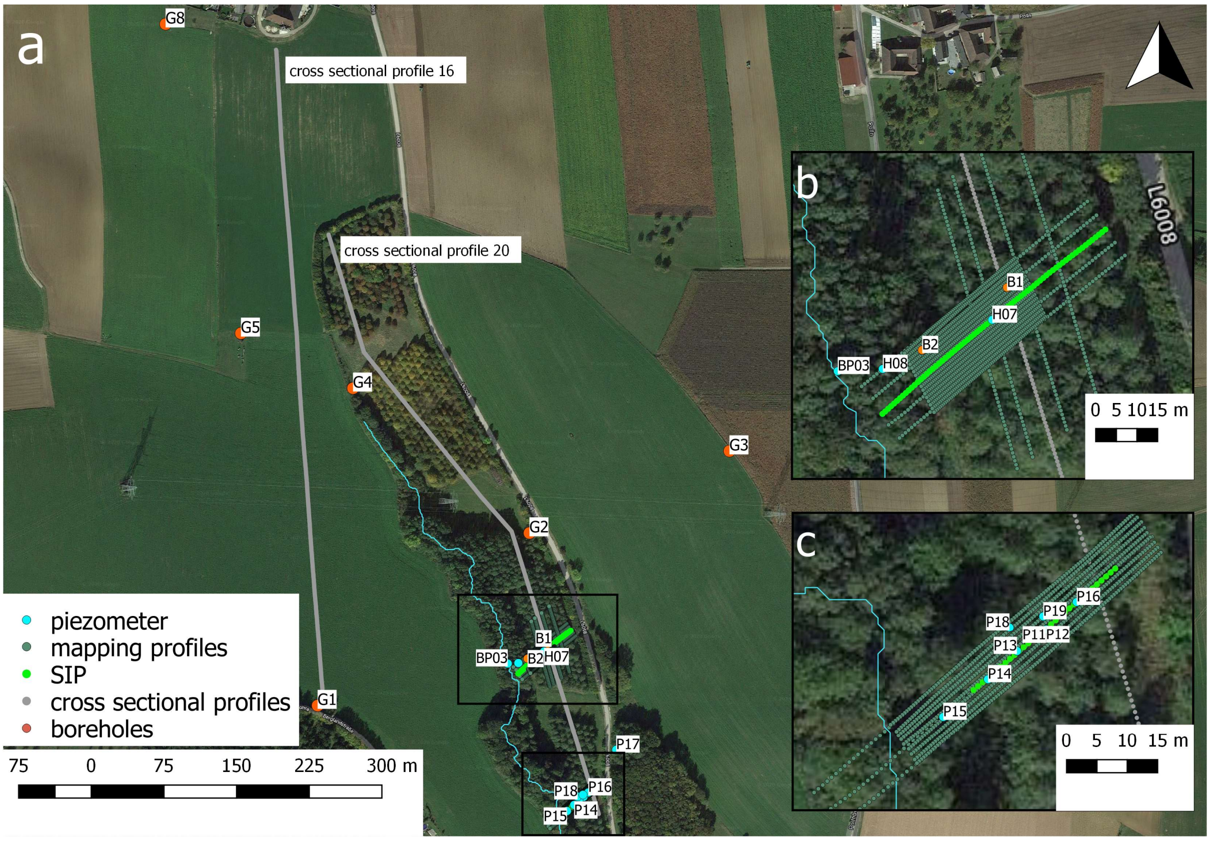

Figure 1: *IP imaging lines collected at the HOAL site: (a) long cross-sectional profiles, and high resolution mapping lines at (b) the IP anomaly region, and (c) in the control area (c).*

Selected profiles were defined for the collection of frequency-domain IP (FDIP) data with a DAS-1 instrument (from MPT) in the frequency range between 0.1 and 225 Hz. For these measurements, we used an electrode spacing of 1 m and a dipole-dipole skip-0 configuration, with a maximum separation of 16 electrodes between current and potential dipoles. To reduce the contamination of the data due to electromagnetic coupling, we used coaxial cables as described by Flores Orozco et al. (2021). Based on the analysis of the FDIP data, the positions of two boreholes (B1 and B2) were selected to recover sediments for chemical analysis. Directly after the drilling, we packed the sediments in plastic bags and kept them in freezing conditions to reduce chemical alterations. Chemical analyses in the sediments were similar to those presented in Katona et al. (2021), such as measurements of the total iron (Fe_{tot}), total organic carbon (TOC), cations exchange capacity (*CEC*), X-ray powder diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR), among others. We also conducted grain size analysis of soil samples to investigate the correlation between the IP signatures and textural parameters. In general, the soils are characterized by high content of fine grains (ca 70% silts and clays) within the first 6.5 m depth. A lignite layer has been found roughly at the same height in all borehole excavated at the HOAL and constitutes a lower boundary to groundwater flow. Slug tests were planned at the mapping areas for the estimation of hydraulic conductivity; however, the extremely slow flow rendered such investigations unfeasible.

Results: Delineation of a biogeochemical active zone by means of IP imaging

Figure 2 presents the IP imaging results for data collected along the FDIP line in the anomalous region, expressed in terms of the complex conductivity. These plots reveal that the polarizable anomaly ($\sigma'' >$

1 mS/m and ϕ> 20 mrads) cannot be resolved in the conductivity images ($\sigma' \sim 40$ mS/m) and cannot be attributed to variations in the textural properties of the sediments.

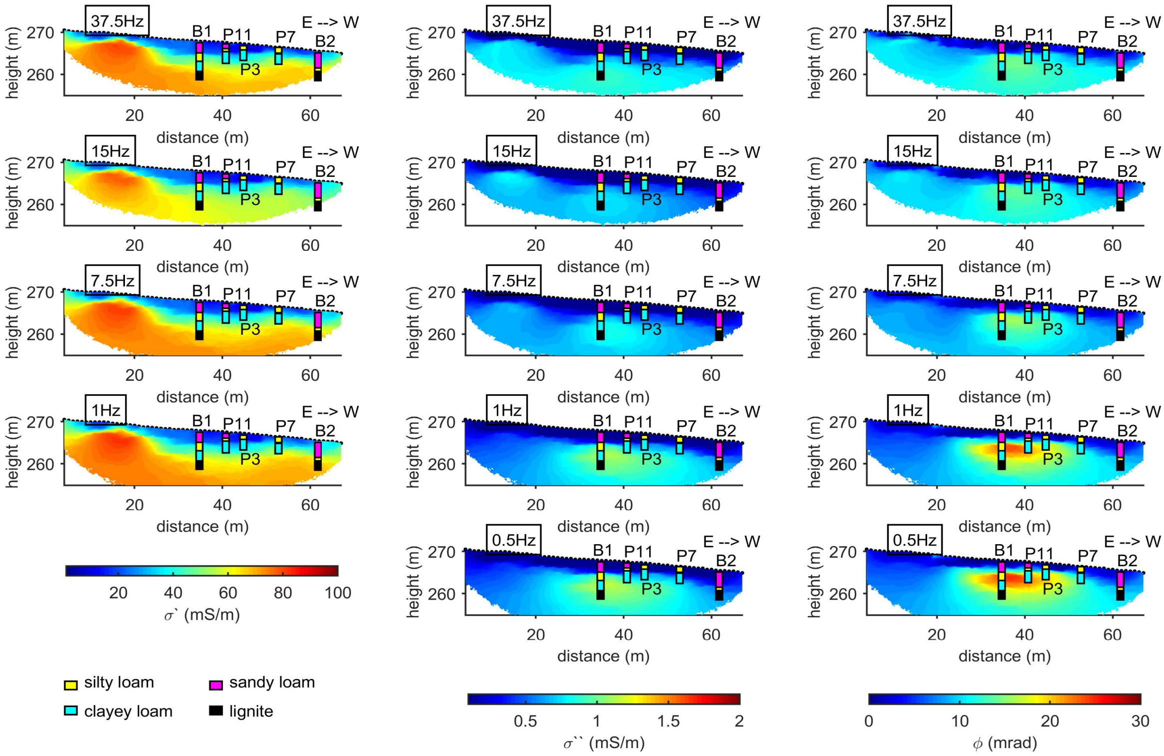

Figure 2 *Imaging results for multi-frequency TDIP data collected along a profile in the anomalous region. IP results are expressed in terms of the real (σ') and imaginary (σ'') components as well as the phase (ϕ) of the complex conductivity. The geological information from the analysis of sediments is imposed on the electrical images as well as the position of the electrodes (black dots at the surface).*

Chemical parameters measured in the sediments recovered in B1 and B2 are presented in Figure 3 and are compared with the vertical variations in phase values (as a proxy for polarization). These plots reveal higher Fe_{tot} and carbon concentration in the sediments recovered in B1 (in the polarizable anomaly) than those observed in B2 (at the non-polarizable area). Such results may point to an IP response due to the accumulation of iron sulfides (e.g., Williams et al., 2009; Flores Orozco et al., 2011; 2013; Wainwright et al., 2016). However, analysis shows negligible concentration of reactive iron (i.e., sulfides), with the Fe_{tot} controlled by the presence of iron oxides; which cannot explain the high polarization (e.g., Flores Orozco et al. 2019). Especially as magnetite was not detected. Ongoing research aims at understanding the mechanism underlying the polarization response. Nonetheless, it is clear that the IP anomaly corresponds to a biogeochemically active zone (i.e., hot-spot).

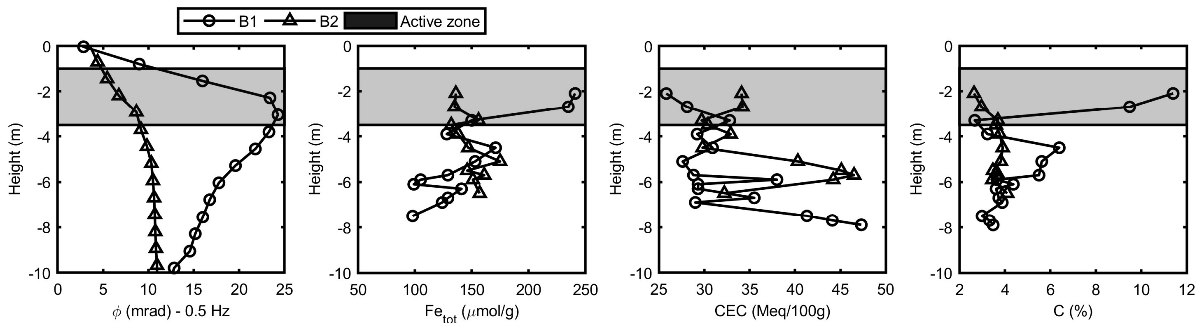

Figure 3 *Comparison of the polarization response (given in terms of the conductivity phase, ϕ) and geochemical parameters measured in sediments recovered during the drilling of boreholes B1 and B2 The polygon marks the potential geochemical active zone.*

Conclusions

Our results demonstrate the possibility to delineate biogeochemical hotspots at the catchment scale by means of IP imaging. In comparison to previous studies, our investigations reveal that polarizable anomalies (ϕ> 20 mrads) in biogeochemical hot-spots can be observed at low frequencies (< 1 Hz) even in the absence of iron sulfides. Analysis of the sediments demonstrates abundant iron oxides, which cannot explain the IP response, especially as magnetite was not detected. Although the polarization mechanism is open to debate, our results demonstrate the applicability of the IP method as a diagnosis tool to delineate in-situ biogeochemical activity in metal-free media.

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