Induced polarization imaging at the floodplain scale for the delineation of naturally reduced zones

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Measurements of time-domain Induced Polarization (TDIP) were performed in order to spatially delineate Natural Reduced Zones (NRZ's) at the floodplain scale, within an aquifer underlying a former uranium mill tailings at the U.S. Department of Energy's (DOE) Integrated Field Research Challenge site (IFRC) in Rifle, Colorado (USA). Previous experiments at the site have repeatedly demonstrated the ability of microorganisms to reductively immobilize uranium (U) in U tailings-contaminated groundwater accompanying organic carbon amendment. At the same time, geophysical monitoring during such amendment experiments has proven that Induced Polarization (IP) datasets can provide valuable information regarding geochemical changes induced by stimulated microbial activity, such as precipitation of metallic minerals (e.g. FeS) and accumulation of reactive, electroactive ions (Fe^{2+}).

Based on these findings, we present a novel application of the IP imaging method. Specifically, we utilized time-domain IP measurements to delineate areas where fluvially deposited organic material within aquifer sediments naturally stimulates the activity of subsurface microorganism. Natural reduction of aquifer sediments leads to both the natural immobilization of uranium and accumulation of reduced end-products (minerals and pore fluids), and thus, capable of generating IP anomalies. These so-called 'naturally reduced zones' (NRZ's) are characterized by elevated rates of microbial activity relative to sediments having a lower concentration of organic matter. These zones are a critical component of the natural attenuation process enabling the slow but sustained removal of uranium from groundwater. The delineation of such NRZ's is an important aspect of assessing the potential for natural attenuation. Nonetheless, prospection of NRZ's at the floodplain by means of direct methods (drilling followed by further analysis of soil and water samples) is impossible; whereas geophysical methods permit the collection of almost continuous data on the subsurface with higher spatial resolution and in reduced exploration times.

As noted, and based on our previous experiments at the site, the accumulation of metallic minerals represents suitable targets for the exploration with IP tomographic methods. Here, we explore the application of the IP imaging method for the characterization of NRZ's at the scale of the floodplain. We present imaging results obtained through the inversion of 77 independent lines distributed along the floodplain (~600 m^2). TDIP measurements were collected using an electrode separation of 1.8 m and a square-wave current injection with 50 % duty cycle and a pulse length of 2 s. Measurements were collected as normal and reciprocal pairs for estimation of the data error, where reciprocal measurements consist of those readings where current and potential dipoles are interchanged compared to the normal measurements. Inversion results presented here were obtained, as a first approach, with a 2D inversion algorithm, which permits to account for an improved error model in phase readings for the inversion of TDIP measurements.

Resistivity images (as presented in Fig. 1) show a strong correlation with the lithological units of the site, as noted in previous studies, permitting to delineate changes in the geometry (e.g., thickness) of the aquifer.

Moreover, as presented in Fig. 2, phase images revealed clear anomalies to the South of the floodplain, characterized by relatively high polarization values (absolute values above 5 mrads), suggesting the presence of NBZ's. A consistent response is also observed in those areas where previous biostimulation experiments resulted in the accumulation of metallic minerals and electroactive ions (Fe^{2+}), sustaining our hypothesis.

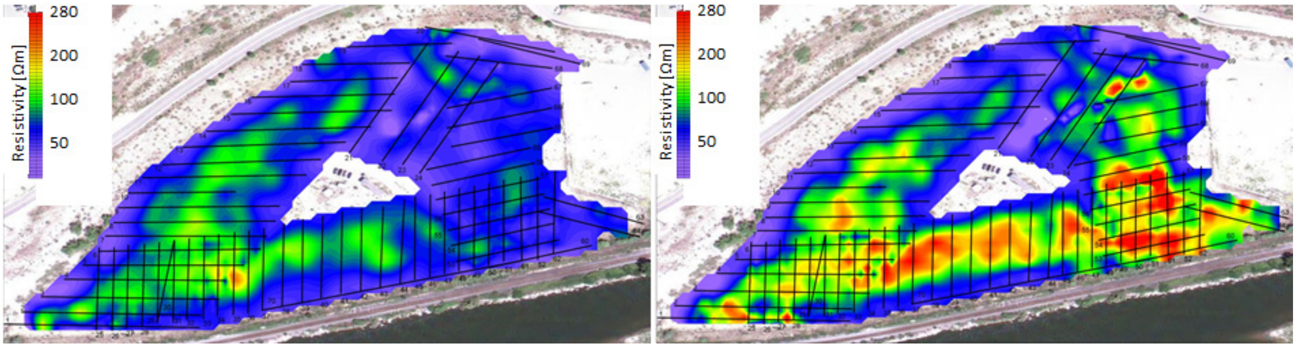

Fig. 1: Map of the electrical resistivity values computed for a depth of 3.5 m (left side) and 7 m (righ side), accounting for the upper and lower levels of the aquifer.

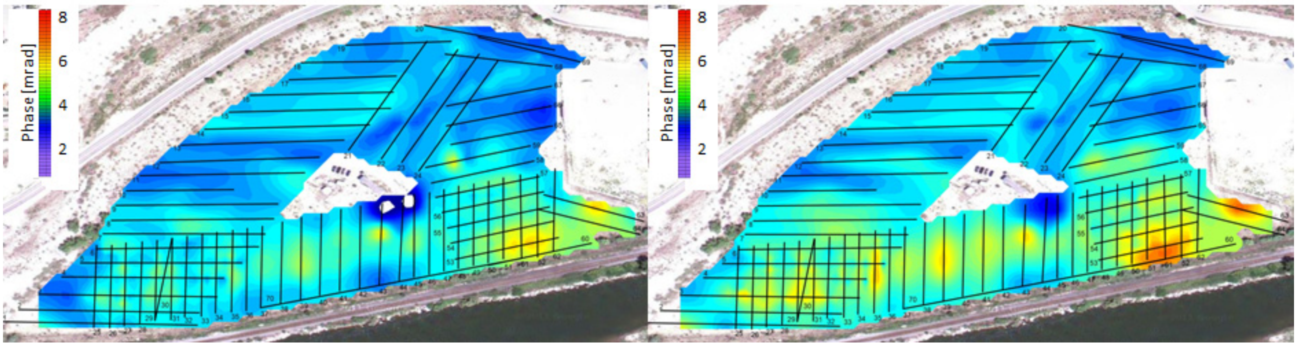

Fig. 2:. Map of the phase values computed for a depth of 3.5 m (left side) and 7 m (righ side), accounting for the upper and lower levels of the aquifer.

Imaging results are validated through comparisons with lithological data obtained from wells drilled at the site and laboratory analysis of sediment and groundwater samples. Our results show the applicability of the IP method for characterizing regions of the subsurface having a greater propensity for elevated rates of microbial activity, with such regions (themselves often highly localized within a larger sedimentary matrix) exerting an outsized control on contaminant (e.g. U) fate and transport.