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Non-invasive flow path characterization in a mining-impacted wetland

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ABSTRACT

Time-lapse electrical resistivity (ER) was used to capture the dilution of a seasonal pulse of acid mine drainage (AMD) contamination in the subsurface of a wetland downgradient of the abandoned Pennsylvania mine workings in central Colorado. Data were collected monthly from mid-July to late October of 2013, with an additional dataset collected in June of 2014. Inversion of the ER data shows the development through time of multiple resistive anomalies in the subsurface, which corroborating data suggest are driven by changes in total dissolved solids (TDS) localized in preferential flow pathways. Sensitivity analyses on a synthetic model of the site suggest that the anomalies would need to be at least several meters in diameter to be adequately resolved by the inversions. The existence of preferential flow paths would have a critical impact on the extent of attenuation mechanisms at the site, and their further characterization could be used to parameterize reactive transport models in developing quantitative predictions of remediation strategies.

1. Introduction

Weathering of sulfide deposits creates a serious environmental water quality issue by generating acidic conditions and mobilizing heavy metals (see Da Rosa et al., 1997; Nordstrom, 2011b, for reviews). Although acid rock drainage forms naturally as a byproduct of sulfide oxidation, mining operations can increase the weathering rate by up to three orders of magnitude by increasing the reactive mineral surface area (Alpers et al., 2007). The effects of acid mine drainage (AMD) can persist for decades or even centuries after mining operations have ceased through continued oxidation and dissolution of acid-releasing minerals (Younger, 1997).

Effective remediation of AMD requires detailed knowledge of contaminant transport through the subsurface, where longer retention times may allow for extended contact with attenuating or neutralizing agents (Zhu et al., 2002). Heterogeneity and preferential flow path development in AMD settings has been shown to decrease the efficiency of contaminant attenuation (Malmström et al., 2008), likely because preferential flow paths reduce the residence time of solutes in the subsurface and contact with attenuating agents (Brusseau, 1994). Preferential flow paths would be expected in mining-disturbed settings because deposition of mining waste piles typically results in graded bedding with a wide range of hydraulic conductivities (Morin and Hutt, 1994; Smith, 1995). Unfortunately, the subsurface is rarely mapped to a sufficient extent to identify and characterize flow paths, especially at historical mine sites, where efforts generally contend with a lack of site data and highly disturbed aquifer material (e.g., Oram et al., 2010; Nordstrom, 2011a). Many AMD remediation projects expend considerable effort quantifying flow and transport parameters through tracer injections (Benner et al., 2002), hydrograph separation (Smith, 1995), flow balance calculations (Gélinas et al., 1994), and aquifer permeability tests, or are otherwise forced to make simplifying assumptions regarding subsurface homogeneity.

The high pore fluid conductivity of AMD has been demonstrated to be a useful tracer for mapping mining contamination

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(Gray, 1996), and an excellent target for electrical geophysical methods (Merkel, 1972). Electrical resistivity (ER) is a geophysical technique that measures the bulk electrical conductivity of the subsurface by both establishing a potential gradient between a pair of electrodes and measuring the potential drop across one or more pairs of other electrodes (Binley and Kemna, 2005). The procedure is repeated for many different electrode locations to develop a spatially distributed dataset of subsurface conductivity (See Loke et al., 2013 for a recent review). Where a consistent relationship exists between pore fluid and bulk conductivities, ER can be used to delineate the extent and magnitude of a contaminant plume (e.g., Spindler and Olyphant, 2004).

Time-lapse ER can circumvent the reliance on a consistent relationship between pore fluid and bulk conductivities by monitoring changes in subsurface electrical properties and attributing them to changes in pore fluid conductivity. Many time-lapse ER studies inject a conductive tracer to facilitate flow path imaging (e.g., Kemna et al., 2002; Ward et al., 2010; Pollock and Cirpka, 2012); however, the ‘first-flush’ behavior demonstrated by many mine sites creates an ideal natural electrical signal. The largest contaminant loads emanating from mine sites are typically coincident with large storms following prolonged dry conditions (Miller and Miller, 2007; Nordstrom, 2009). This results in a seasonal pulse of AMD that can be used in place of a traditional tracer study, allowing for the exploration of a greater support volume and the characterization of natural flow fields (Tiedeman and Hsieh, 2004).

The goals of this paper are twofold: (1) to demonstrate the use of time-lapse ER to map AMD flow paths with application to characterizing contaminant transport, and (2) to investigate the sensitivity of ER to different conductivity anomaly sizes and magnitudes. Inverting ER measurements using a standard L2-norm to calculate model resistance values necessarily involves smoothing, which may lead to some smaller features being difficult to resolve (Day-Lewis et al., 2005). An understanding of the capabilities of ER to resolve features of different sizes is crucial for quantitative analysis in AMD settings, where target anomaly sizes may not be easily constrained. ER has been previously used to characterize the extent of AMD contamination, but only using a single snapshot in time with application of rock physics relations (e.g., Oldenburg and Li, 1994; Rucker et al., 2009). Here, time-lapse ER is used to image the dilution of the natural AMD conductivity pulse to characterize subsurface flow.

2. Field site description

This research was conducted in a wetland between the historic Pennsylvania Mine and Peru Creek, a headwater stream to the Colorado River in central Colorado (Fig. 1). The Peru Creek basin is bracketed on the north and east by the Continental Divide, and drains west into the Snake River. Because 80% of precipitation falls as snow, the hydrograph is dominated by a spring snowmelt pulse (Crouch et al., 2013).

The local geology includes part of a heavily mined Oligocene quartz monzonite porphyry of the Montezuma district. The Montezuma stock intruded Precambrian schist and gneiss, causing extensive fracturing and faulting and widely disseminating pyrite (Fey et al., 2001). The mineral assemblage includes abundant sulfides, in particular pyrite (Fes$_2$), sphalerite ([Zn,Fe]S), and galena (PbS) (Lovering, 1935). The Snake River contains ecologically toxic concentrations of zinc, cadmium, and copper as a result of natural and anthropogenically induced pyrite weathering (Wood et al., 2005). A study of the nearby Handcart Gulch, an unmined drainage near the edge of the Montezuma district, found deposits of ferricrete (iron oxide) coating the streambed (Verplanck et al., 2009), indicating that background metal concentrations are high even in unmined drainages in the area, likely due to natural weathering of sulfide minerals. Fracture flow associated with the Colorado Mineral Belt has been suggested to enhance the rate of pyrite weathering in both mining impacted and unimpacted areas, though the precise nature and cause of the fractures is uncertain (Wood et al., 2005; Caine and Tomusiak, 2003).

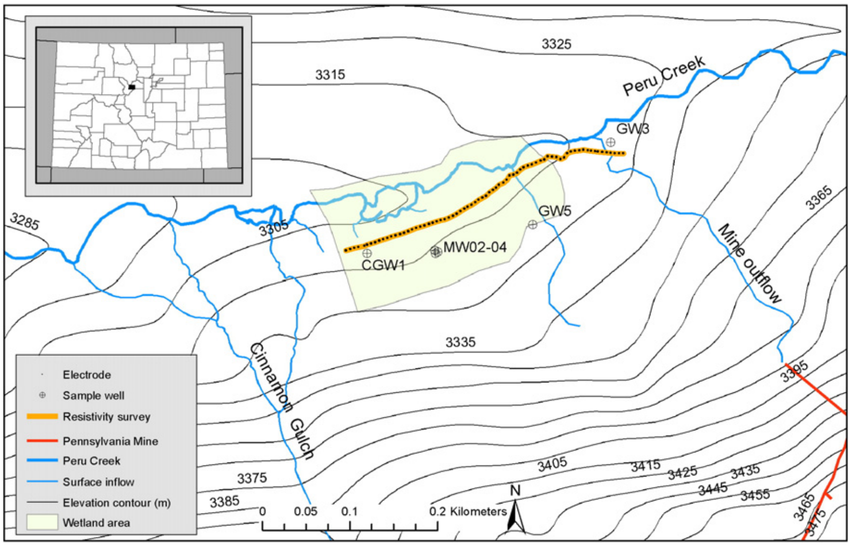

Fig. 1. Map of study region with Peru Creek, ER array, and borehole sample locations.