Use of Borehole Radar Methods and Borehole Geophysical Logs to Monitor a Field-Scale Vegetable Oil Biostimulation Pilot Project at Fridley, Minnesota

John W. Lane, Jr. (U.S. Geological Survey, Office of Ground Water, Branch of Geophysics, Storrs, CT)
Clifton C. Casey (U.S. Navy, Naval Facilities Engineering Command, Southern Division, Charleston, SC)
Frederick D. Day-Lewis (U.S. Geological Survey, Office of Ground Water, Branch of Geophysics, Storrs, CT; and Bucknell University, Lewisburg, PA)
Alan Witten (University of Oklahoma, Norman, OK)
Roelof J. Versteeg (Idaho National Environmental and Engineering Laboratory, Idaho Falls, ID)

ABSTRACT: Cross-hole and surface-to-borehole radar and conventional borehole geophysical logs were used to monitor subsurface injections of vegetable oil emulsion conducted as part of a field-scale biostimulation pilot project at the Anoka County Riverfront Park (ACP), located downgradient of the Naval Industrial Reserve Ordnance Plant (NIROP), in Fridley, Minnesota. The pilot project was undertaken to evaluate biostimulation using emulsified vegetable oil for treatment of ground water contaminated with chlorinated hydrocarbons. The objectives of the geophysical investigations were to delineate the distribution of vegetable oil injected at NIROP, and evaluate the utility of adding geophysical tracers to the vegetable oil emulsions.

Geophysical data were acquired by the U.S Geological Survey in five site visits over 1.5 years. This paper presents (1) level-run radar traveltime and amplitude data; (2) radar cross-hole traveltime tomograms; (3) vertical-radar profile diffraction tomograms; and (4) borehole electromagnetic induction logs. Based on comparison of pre- and post-injection data sets, a conceptual model was developed to define the distribution of emulsified vegetable oil and the extent of ground water having altered chemistry resulting from injections and, possibly, enhanced microbial degradation of chlorinated hydrocarbons. Radar slowness (reciprocal velocity) anomalies indicate that the emplaced oil emulsion remained close to the injection wells, whereas attenuation anomalies indicate changes in ground-water chemistry downgradient of all three injections.

INTRODUCTION

Biostimulation involves subsurface injection of a material, such as vegetable oil, to serve as substrate to the native microbial population and promote biodegradation of chlorinated hydrocarbons (Frederickson and others, 1993). The effectiveness of this remediation strategy relies on emplacement of the substrate in proximity to the contaminant at a concentration sufficient to support microbial breakdown of chlorinated hydrocarbons into carbon dioxide, water, and chloride. Lane and others (2003) first demonstrated the use of cross-hole radar tomography to monitor emplacement of vegetable oil emulsion for biostimulation at a site near the Naval Industrial Reserve Ordnance Plant (NIROP), Fridley, Minnesota. Through petrophysical models relating geophysical anomalies to oil saturation, synthetic examples, and field experiments, they showed that radar methods can provide valuable information about the spatial and temporal distribution of injected vegetable-oil emulsion in the subsurface; furthermore,

Citation: Lane, J.W., Jr., Casey, C.C., Day-Lewis, F.D., Witten, A., and Versteeg, R.J., 2004, Use of borehole radar methods and borehole geophysical logs to monitor a field-scale vegetable oil biostimulation pilot project at Fridley, Minnesota, in Proceedings of the Fourth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 24-27, 2004, Monterrey California. Proceedings: Battelle Memorial Institute, CD-ROM, 9 pages.

Lane and others (2004) inferred changes in ground-water chemistry occurring downgradient of injections. Emulsified vegetable oil in the subsurface was detected in multiple cross-hole planes as well-defined radar slowness anomalies; and changes in ground-water chemistry manifested as increased radar attenuation.

The goal of the U.S. Naval Facilities Engineering Command, Southern Division pilot study is to evaluate biostimulation using vegetable oil emulsions for remediation of chlorinated hydrocarbons including trichloroethene (TCE) and dichloroethene (DCE) present in ground water at the site (CH2M Hill Constructors, Inc., 2002). The aquifer materials include glacial-fluvial deposits consisting of unconsolidated coarse- to fine-grained sand and silts. In support of the biostimulation effort, borehole geophysical logs, cross-hole radar level-run, cross-hole radar tomography data, and vertical radar profile (VRP) data were acquired by the U.S Geological Survey (USGS) at the Anoka County Riverfront Park (ACP) downgradient of NIROP (Figure 1). This paper extends previous work (Lane and others, 2004) by incorporating borehole logs and VRP data into a conceptual model of the subsurface distributions of emulsified vegetable-oil and ground water with altered chemistry as a result of the vegetable oil injections.

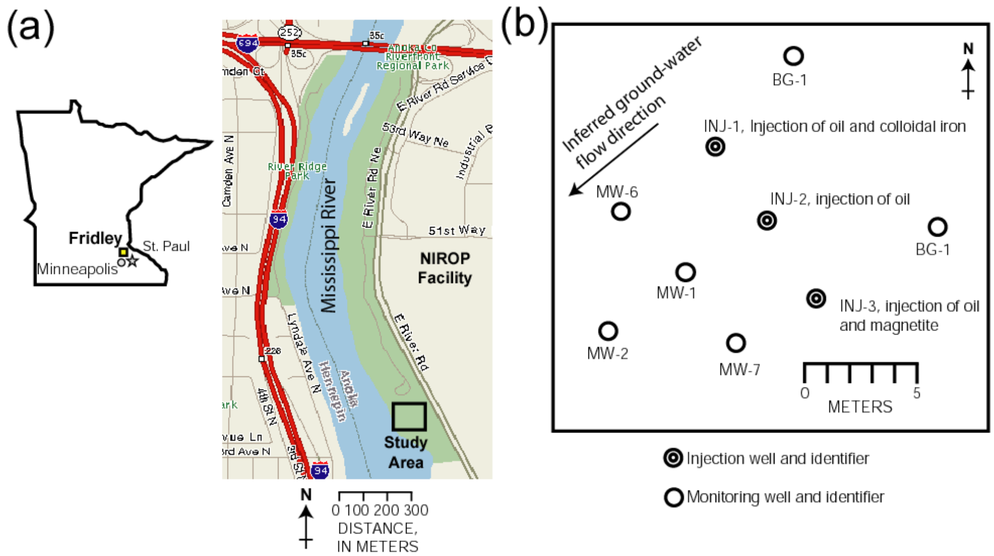

FIGURE 1. (a) Location of the study area, Anoka County Riverfront Park, Fridley, Minnesota; (b) Map of the study area (after Lane and others, 2004.)

BOREHOLE RADAR METHODS

The USGS used three radar acquisition geometries at the NIROP site: (1) cross-hole level-run radar, (2) cross-hole radar tomography, and (3) vertical radar profiling (VRP). In all three geometries, electromagnetic (EM) waves propagate from a transmitter antenna, and waveform traces are recorded at a receiver antenna. Measurements of arrival time are used to estimate EM-wave velocity, and measurements of amplitude are used to estimate EM-wave attenuation. Radar velocity is a strong function of porosity, saturation, and the dielectric permittivities of the pore fluid and soil. Attenuation depends on electrical conductivity and thus total dissolved solids (TDS). The contrast between the relative dielectric permittivity of vegetable oil and that of water is expected to increase radar velocity in the saturated zone. The lower electrical conductivity of oil relative to that of ground water is expected to decrease radar attenuation; however, the addition of magnetite and colloidal iron tracers renders the electrical conductivity of the resulting mixtures greater than that of native ground water. Also, the electrical conductivity of ground water in contact with, or downgradient of, the vegetable oil emulsion may increase as a result of oxidation-reduction reactions and microbial activity that increase TDS. In sediments, reduction of minerals to aqueous species (for example, reduction of ferric to ferrous iron) is expected as a result of the injections; in addition, microbial activity ultimately breaks down chlorinated hydrocarbons into chloride.

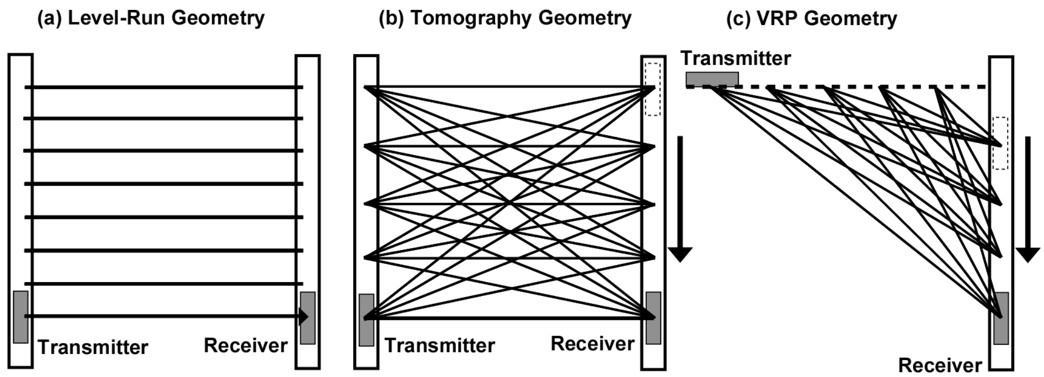

FIGURE 2. Radar survey geometries for (a) cross-hole level-run, (b) cross-hole tomography, and (c) vertical radar profiling (VRP).

Level-Run: The level-run geometry consists of measurements taken between transmitter and receiver antennas located at identical depths in different boreholes (Figure 2a). Level-run data provide horizontally averaged measurements of slowness (reciprocal velocity) and amplitude at different depths. Although the level-run geometry provides less information about spatial variability than cross-hole or VRP surveys, the acquisition of level-run data is fast, and the processing and interpretation of level-run data are straightforward.

Cross-Hole Radar Tomography: In cross-hole radar tomography, the transmitter antenna is located at multiple depths in one borehole, and for each transmitter location, measurements are made at multiple receiver locations in a second borehole (Figure 2b). Tomograms of radar slowness or attenuation are generated from measurements of arrival time or amplitude, respectively. Tomograms provide qualitative information about vertical and lateral variations in radar properties between wells; however, resolution depends on data error, the survey geometry, and prior information used for inversion. Quantitative estimation of oil saturation from tomograms is therefore difficult. Lane and others (2003) used a novel object-based inversion approach to estimate oil-emulsion saturation at NIROP.

VRP Tomography: In VRP, a transmitter antenna is located at multiple positions on the ground extending radially outward from a borehole, in which a receiver antenna is placed (Figure 2c). EM waves are propagated from the transmitter to the receiver at different vertical positions downhole. Tomograms of radar slowness or attenuation are generated using a variety of inverse methods, including diffraction tomography (Witten and Lane, 2003). The principal advantages of VRP over cross-hole methods are (1) it requires only one borehole, and (2) it provides superior resolution at shallow depths; however, due to the limited raypath coverage of the single-hole geometry, the method does not resolve deeper contrasts farther from the borehole.

BOREHOLE GEOPHYSICAL LOGGING METHODS

At the ACP, the USGS collected borehole geophysical logs, including natural gamma, neutron, EM induction, and magnetic susceptibility. In this paper, we focus on EM induction data. EM logs measure the electrical conductivity of the bulk medium, averaged over a volume extending radially from the borehole into the surrounding formation. A Geonics EM39[1] logger was used. The EM log is capable of seeing through PVC, but not metal casing. In this study, the EM log is used to monitor emplacement of the oil emulsion, which manifests as a low conductivity anomaly, and to monitor changes in ground-water chemistry.

FIELD EXPERIMENT

The field data presented here were acquired from 3-inch-diameter PVC wells at the ACP (Figure 1b). The well constructions, which include long, blank sections of casing, were designed to facilitate geophysical monitoring. The site is underlain by sediments consisting of glacial drift and gracio-fluvial deposits (CH2M Hill Constructors, Inc., 2002). Injections of emulsified vegetable oil were performed between December 11-12, 2001. Three fluid mixtures were injected: (1) 13,700 liters of 65% native water and 35% soybean oil and a lecithin emulsifier in INJ-2; (2) 13,700 liters of 65% native water and 35% soybean oil and a lecithin emulsifier and 3.5 kg of dissolved magnetite in INJ-3; and (3) 13,700 liters of 65% native water and 35% soybean oil and a lecithin emulsifier and 50 kg of colloidal iron in INJ-1. The first mixture was more electrically resistive than native ground water; hence it is expected to decrease radar attenuation and EM-log conductivity relative to background. The second and third mixtures were more conductive than ground water, and thus expected to increase radar attenuation and EM-log conductivity. All mixtures are expected to increase radar velocity due to the higher dielectric permittivity of oil relative to water. The water table was about 8 m below ground surface at the time of injection.

Borehole Radar Experiments. Radar data were acquired with a Malå GeoScience RAMAC borehole-radar system. Broad-band electric-dipole antennas with a center frequency in air of about 100 MHz were used. Level-run data were collected in 0.2-m depth increments. For tomography surveys, the transmitter antenna was positioned at different locations in one well, and the receiver antenna was moved down a second well, taking measurements at 0.2-m depth increments. VRP data sets were collected in planes extending from five wells at the site (Witten and Lane, 2003). For each transmitter position on the ground, measurements were collected at the receiver in 0.2-m vertical intervals along the well. The horizontal interval between transmitter locations was 0.5 m, with maximum offsets from the well ranging between 4 and 8.5 m.

Well-defined anomalies are evident in the level-run radar data. The datasets for well pair INJ-2 to MW-1 are shown in Figures 3a and 3b. Changes in traveltime are observed in all planes connected to injection wells, but no significant changes in

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[1] Use of brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

traveltime are observed for well pairs that do not include an injection well. Petrophysical modeling (Lane and others, 2003) indicates that the presence of oil emulsion should produce a decrease in radar slowness (increase in velocity); thus, the field data indicate that the emulsified oil has not migrated far from the injection wells. Decreases in amplitude, diagnostic of increased TDS, are observed for well pairs downgradient of the injection wells. Small increases in amplitude, indicative of the presence of iron-free oil, are observed only in planes connecting to INJ-2, where the tracer-free emulsified oil mixture was injected; however, over time the amplitude in these planes decrease, a possible result of biodegradation and increased TDS.

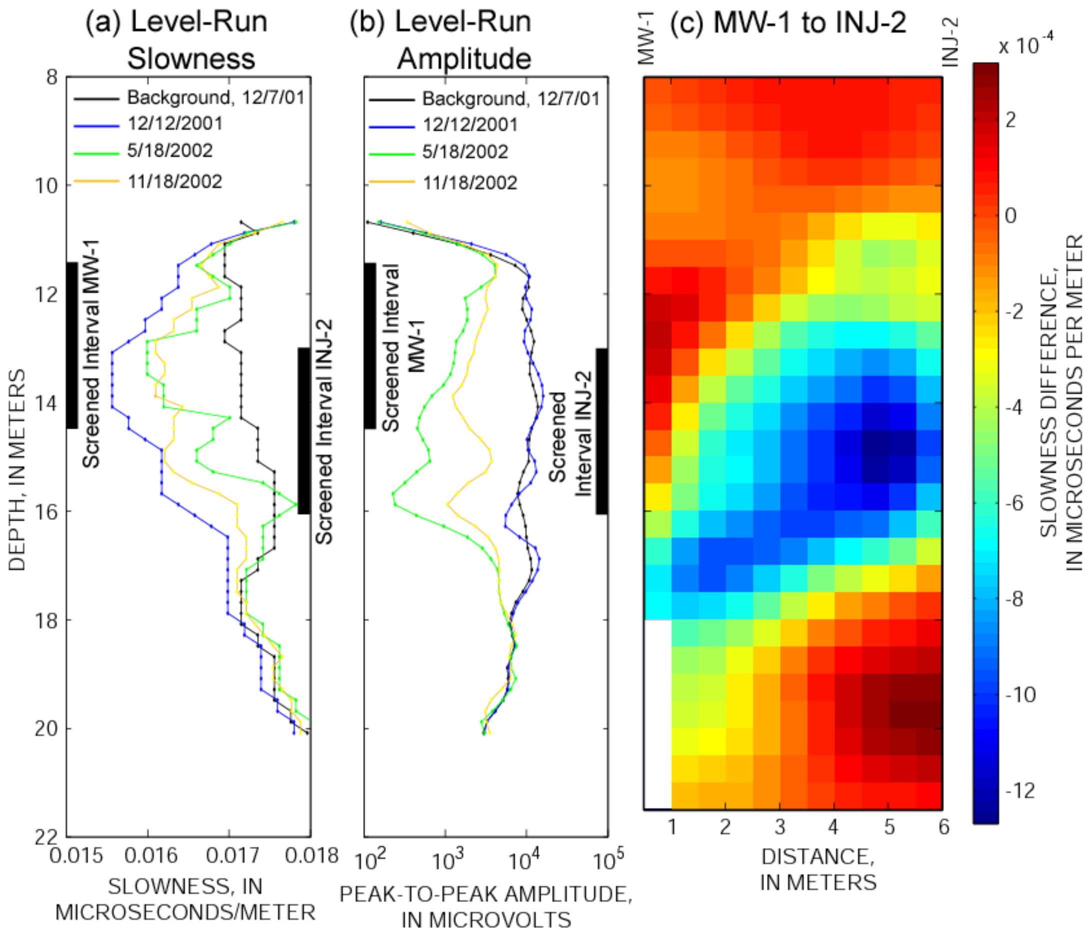

FIGURE 3. (a) Level-run radar slowness, (b) level-run radar amplitude, and (c) cross-hole radar slowness difference tomogram for the well pair MW-1 to INJ-2 for December 12, 2001.

Cross-hole radar tomography at the site corroborates our interpretation of the level-run data. The difference-slowness tomogram for the MW-1 to INJ-2 plane (Figure 3c) indicates a decrease in radar slowness (increase in velocity) between 14 and 16 m depth, indicating the presence of emulsified vegetable oil in the cross section. The anomaly extends away from the injection well, INJ-2, but appears to pinch out at about 18 m depth, near MW-1. Results for the MW-7 to INJ-3 plane are similar, with the anomaly localized to well INJ-3.

Results of VRP tomography at the ACP were previously reported by Witten and Lane (2003); we summarize their findings here. VRP tomography was conducted for planes extending radially outward from five wells at the site. Based on the suite of tomograms, a 3-D rendering of radar velocity was generated (Figure 4). The volume shown in red in Figure 4 is bounded by an isosurface of radar velocity corresponding to 0.12 m/ns (or 8.3 ns/m slowness). The estimated velocity is absolute, not differenced against the background dataset; thus the high velocity region in the saturated zone may indicate either the presence of oil or sedimentary heterogeneity. The branching of the anomaly extending from INJ-1 may be an artifact of the interpolation procedure. Due to the limitations of the surface-to-hole VRP geometry compared to the cross-hole geometry, the imaged volume extends only to a depth of about 12 m; thus the VRP surveys image only the topmost part of the region affected by oil injections.

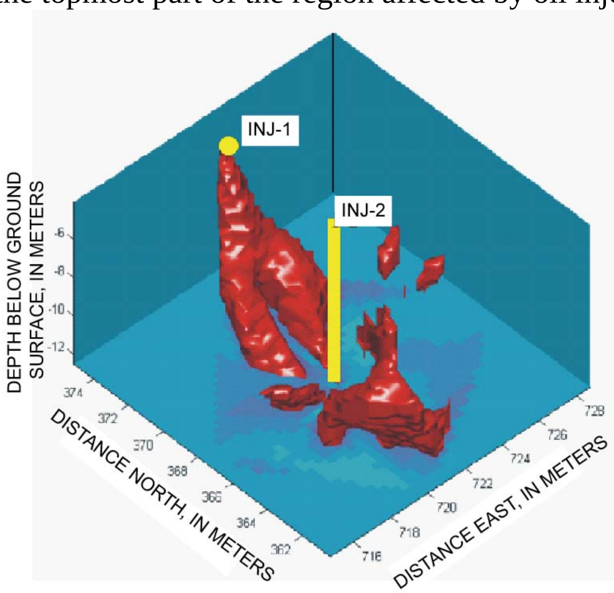

FIGURE 4. Three-dimensional visualization of the radar velocity anomaly, interpolated from VRP tomograms (after Witten and Lane, 2003). The red isosurface corresponds to high velocity (low slowness) regions.

Borehole Geophysical Logging. EM logs collected at the ACP indicate changes in electrical conductivity at the injection wells and wells downgradient of the injections. Data for wells INJ-2 and MW-1 are shown in Figure 5. These logs were calibrated using the background dataset as reference; thus the numerical conductivity values should be considered as qualitative, not quantitative, measures relative to the background. In general, there is good correlation between the EM-log data and the radar results. The only significant decreases in the EM logs were observed at INJ-2, where the electrically resistive, tracer-free mixture was injected. Over time, the magnitude of this anomaly diminished; by May 2002, the electrical conductivity in the vicinity of INJ-2 had increased to higher than the background level. Well-defined increases in conductivity were observed in many of the downgradient wells, at depth ranges similar to the locations of radar-attenuation anomalies.

Comparison of borehole logs and level-run radar data is useful to interpret the proximity of target anomalies to wells. Whereas level-run data give horizontal averages between wells, the logs give measurements local to a single well. For example, a level-run radar attenuation anomaly observed between two wells in which no EM anomalies were seen, might indicate that high TDS ground water was migrating between, but not to, the two wells.

Magnetic susceptibility logs collected at the site show no changes, except at wells INJ-1 and INJ-3 where the colloidal iron and magnetite tracers were used. This finding supports a conceptual model in which the oil mixtures remain close to the injection wells during the 1.5 years of data collection.

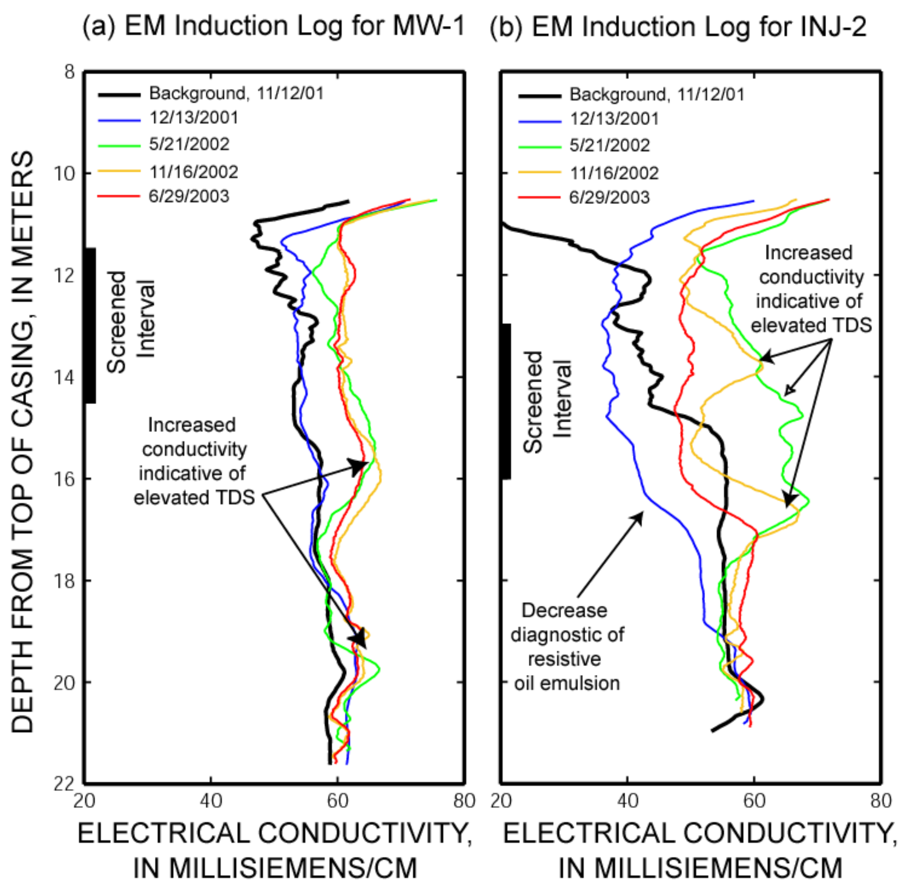

FIGURE 5. (a) EM-log conductivity at MW-1, (b) EM-log conductivity at INJ-2. Increases in conductivity are indicative of higher total dissolved solids (TDS).

DISCUSSION

Based on the results of cross-hole and VRP radar data and borehole geophysical logs, the injected oil emulsion mixtures appear to remain close to the injection wells at the ACP. Radar slowness anomalies are observed only in the vicinity of the injection wells; however, radar attenuation anomalies, indicative of changes in ground-water chemistry, are observed at multiple wells downgradient of the injection wells. EM and magnetic susceptibility logs support this conceptual model. Decreases in EM-log conductivity are observed at INJ-2, whereas increases are observed at wells downgradient of the injections. Magnetic susceptibility changes are likewise observed only at wells INJ-1 and INJ-3, where the iron-tracer mixtures were injected.

The geophysical data provide valuable, qualitative site-specific insights regarding changes in ground-water chemistry; however, direct comparison to water-chemistry data is not straightforward. As shown in Figure 3, geophysical anomalies are not confined to the screened intervals; thus, the geophysical data may detect changes in ground-water chemistry not observed in direct fluid sampling. For example, in the MW-1 to INJ-2 level-run radar amplitude and INJ-2 EM-log data, there appear to be two layers in which altered ground water is (1) moving more quickly and/or (2) occupying a larger volume of the soil, presumably due to higher porosity. These intervals are perhaps 1 m thick and centered around depths of 14 and 16 m in the radar level-run data or about 14 and 16.5 m in the INJ-2 EM log.

CONCLUSIONS

Cross-hole radar level-run, tomography and VRP data, and borehole EM induction logs were collected in support of a vegetable-oil emulsion biostimulation project at the ACP, downgradient of NIROP, Fridley Minnesota. The geophysical data indicate that the vegetable oil does not migrate far from the injection wells; however, changes in EM-log conductivity and radar attenuation are observed at wells downgradient of the injections, a possible result of higher TDS, which could be explained by oxidation-reduction reactions, resulting from the injections and (or) from enhanced biodegradation of chlorinated hydrocarbons. The attenuation and EM data cannot be explained by the migration of iron tracers, because changes are observed across the site, even at and downgradient of the well where the tracer-free injection was performed.

This work has shown that geophysical monitoring can provide valuable insights into the spatial and temporal distribution of vegetable oil emulsion injections for biostimulation, and the extent of resulting ground-water chemistry changes; however, additional work is needed to relate the geophysical results presented here to water-chemistry data from the site.

ACKNOWLEDGMENTS

This project was supported by the U.S. Naval Facilities Engineering Command, Southern Division, under MIPRs N6246701MP01929 and N6246703MP03935, and by the U.S. Geological Survey Toxic Substances Hydrology Program. The authors acknowledge the assistance of Peter Joesten, Eric White, Chris Kochiss, Perry Jones, Stephanie Johnson, and Mike Menheer USGS); and B. Venky Venkatesh and Samuel Tate, Jr. (CH2M Hill). We are also grateful to Richard Willey, Carole Johnson, Pierre Lacombe, and Alison Waxman for reviewing this paper.

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