Environmental and Agricultural Applications of GPR

Susan Hubbard , Jinsong Chen, Ken Williams, and John Peterson
Earth Science Division
Lawrence Berkeley National Laboratory,
Berkeley, CA 94720 USA
SSHubbard@lbl.gov, JSChen@lbl.gov, KHWilliams@lbl.gov, JEPeterson@lbl.gov

Yoram Rubin
Civil and Environmental Engineering
UC Berkeley, CA 94720
rubin@ce.berkeley.edu

Abstract— **It is widely recognized that natural heterogeneity and the large spatial variability of hydraulic parameters control the spread of contaminants and water in the subsurface. Similarly, hydrological and biogeochemical processes are variable over a wide range of spatial scales. The inadequacy of conventional (wellbore) approaches for characterizing or monitoring the parameters and processes at over large enough areas yet with high enough resolution hinders our ability to optimally manage our natural water resources. GPR methods hold promise for improved and minimally invasive characterization and monitoring of the subsurface. This paper will review several case studies where we have successfully used GPR for a variety of environmental and precision agricultural investigations.**

***Index Terms*—biostimulation, characterization, environmental remediation, heterogeneity, hydraulic conductivity, monitoring, precision agriculture, water content.**

1. Background

It is well recognized that the inadequacy of conventional (wellbore) approaches for characterizing the key parameters and monitoring the key processes at over large enough areas yet with high enough resolution hinders our ability to optimally manage our natural water resources [1]. High resolution geophysical methods, such as GPR, hold promise for improved and minimally invasive characterization and monitoring of the subsurface. Here, we review several case studies where we have successfully used GPR for a variety of environmental and precision agricultural investigations. Section 2 focuses on the use of GPR for estimating parameters that are important for environmental and agricultural applications, such as hydraulic conductivity, sediment geochemistry, lithofacies zonation, and water content. Section 3 focuses on the use of time-lapse geophysical methods for assisting with remediation investigations, such as for to detecting biogeochemical-hydrological processes that occur during remediation and the distribution of remediation amendments. This collection of case studies illustrates the utility of GPR for environmental and agricultural applications.

2. Hydrogeological Parameter Estimation using GPR

Geophysical data are being increasingly used in hydrogeological site-characterization to obtain a better understanding of heterogeneity and its control on flow and transport. Such data can bridge the gap between the typically sparse conventional field characterization data and the need to realistically parameterize numerical transport models. In this section, we focus on the use of GPR to estimate hydrogeologic parameters that are important for agricultural and environmental studies, such as: water content, lithofacies zonation, hydraulic conductivity, and sediment geochemistry. Many of these studies also involved the development and use of stochastic estimation methodologies, which have enabled us to systematically fuse GPR and other sparse but direct measurements.

Water Content. Soil water content is a key control on plant growth and health. Recent studies have shown that careful irrigation management can have beneficial effects on many crops, including almonds, citrus, prunes, pistachios and wine grapes. In particular, moderate water stress on grapevines early in the growing season can have a positive impact on grape quality. Thus, understanding when and how much irrigation to apply is critical for optimized wine grape production. Natural geologic processes, however, can cause soil variations and associated water-holding capacity to vary significantly, even over distances of a few meters. Given that the "industry standard" to vineyard soil characterization is to collect soil or water content measurements on a 75 m grid, grape growers typically do not have enough information about water content variations to guide precision irrigation.

We have used GPR methods to estimate soil water content within agricultural sites in a non-invasive and manner and with high spatial resolution. Using 900 MHz GPR groundwave travel time data, we have estimated soil water content distribution in the top 15cm of the soil layers at high spatial resolutions and as a function of time at the Robert Mondavi Vineyard in California. Comparison with conventional 'point' soil moisture measurements, obtained using time domain reflectometry (TDR) and gravimetric techniques revealed that the estimates of GPR-obtained volumetric water content estimates *were accurate to within 1% by volume* [2,3]. The density of the obtained water content estimates was perhaps the *highest density* shallow moisture measurements obtained to date; the study produced 20,000 measurements of soil water content over the 3 acre study site. Water content distribution in deeper layers can also be obtained using GPR reflection arrivals if sufficient contrasts in dielectric properties exist [4, 5]. For example, Figure 1 illustrates the average volumetric water content estimated using data from 100 MHz GPR reflections associated with a subsurface channel, located 1.0-1.5 m below ground surface at a 2 acre Dehlinger Vineyard Chardonnay block in Sonoma County [5]. Figure 1 shows how the channel has influenced subsurface water distribution, and suggests a correlation between water distribution and canopy density (as indicated by the 'low vigor' outline). At this site as well as the Mondavi site, it was clear that water content distribution was linked to soil textural and canopy vigor variations. Huisman et al. [6] provide more information about the use of GPR for water content estimation.

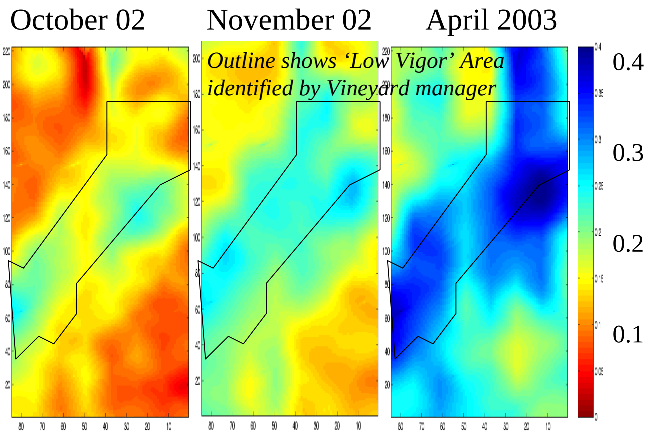

Figure 1 Average volumetric water content in the top 1.0-1.5m estimated over time using 100 MHz GPR reflection travel time data over 3-acre study block at the Dehlinger Vineyards (modified from [5]).

Hydraulic Conductivity We have used cross-hole geophysical data to provide multi-dimensional estimates of hydraulic conductivity at a DOE bacterial transport site located near Oyster, VA [7, 8]. We developed a Bayesian framework that permitted quantitative integration of borehole flowmeter data and crosshole geophysical information for estimating the hydraulic conductivity distribution at each pixel along the tomographic cross sections. Figure 2 illustrates the estimates of hydraulic conductivity along two vertical cross sections at the Oyster site, obtained using the Bayesian estimation framework and radar velocity tomograms. Hydraulic conductivity data from an electromagnetic borehole flowmeter log are superimposed on top of the estimates obtained using radar tomographic data within the Bayesian framework. Tomographic data provided estimates of hydraulic conductivity (and their uncertainties) at a very high spatial resolution (0.25 m × 0.25 m).

Comparison of the estimated (geophysically-obtained) hydraulic conductivity field and tracer breakthrough data suggested that the tomographic estimates were

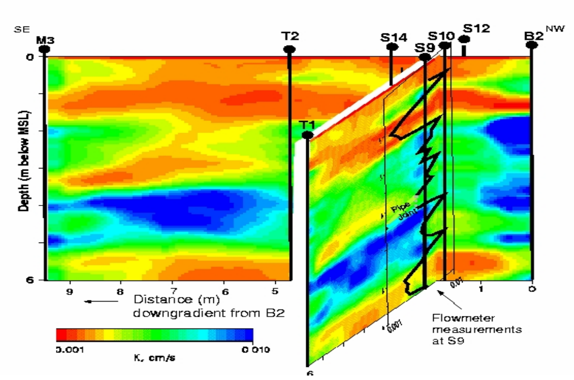

Figure 2. Estimates of hydraulic conductivity from radar tomographic data (from [7]).

extremely useful for helping to reduce the ambiguity associated with interpreting bacterial and chemical transport data collected during tracer tests [9]. Even though this site was fairly homogeneous (the range of hydraulic conductivity is approximately one order of magnitude, i.e., a 'sand box') and it had extensive borehole control (i.e., wellbores every few meters), it was difficult to capture the variability of hydraulic conductivity using borehole data alone sufficiently to ensure reliable transport predictions. By comparing numerical model predictions with tracer test measurements at the Oyster Site, Scheibe and Chien [10] found that conditioning the models to the geophysical estimates of hydraulic conductivity significantly improved the accuracy and precision of the model predictions relative to those obtained using borehole data alone. This study suggested that the geophysical-based methods provided information at a reasonable scale and resolution for understanding field-scale processes. This is an important point, as it is often difficult to scale the information gained at the laboratory scale or even from discrete wellbore samples for use at the remediation field scale.

Estimation of Sediment Geochemistry. In addition to the importance of hydrogeological heterogeneity in controlling contaminant and bacterial transport, geochemical heterogeneity plays a large role in reactive flow and transport. In the same general area as the study discussed above, we used crosshole ground-penetrating radar amplitude data to estimate lithology and sediment Fe(II) and Fe(III). In this study, we developed a sampling-based Bayesian approach (Markov Chain Monte Carlo Approach) to fuse the diverse geochemical, lithological, and geophysical datasets into an integrated interpretation [11]. The geophysical data do not sense the geochemical parameters directly, but the geophysical attribute is sensitive to lithology, which is in turn sensitive to sediment geochemistry. Our developed estimation approach exploited this mutual dependence to estimate lithology and sediment geochemical parameters using geophysical data. Figure 3a illustrates the 2-D geophysical attribute field obtained from inversion of GPR amplitude data. Figures 3b-3d illustrate the mean values of the estimated Fe(II) and Fe(III) distributions; variances associated with these estimates are available but are not shown in the figure. Cross-validation exercises revealed that the estimates obtained using the geophysical data were

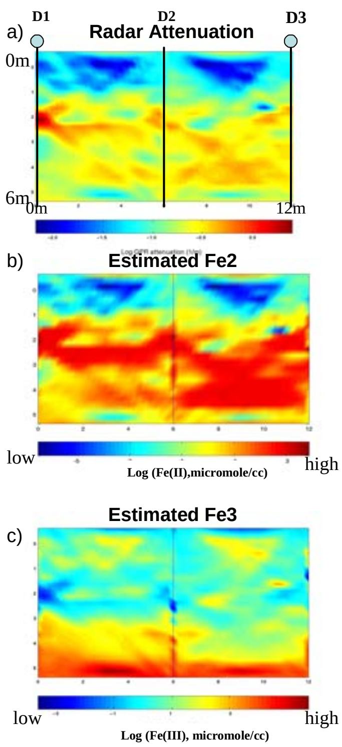

Figure 3. Two-dimensional images of the estimated (a) GPR attenuation, (b), Fe(II) and (c) Fe(III), from Chen et al. [11]

accurate and greatly improved the 2-D identification of the geological and geochemical properties. This study represents perhaps the highest resolution field-scale characterization of geochemical properties performed to date [11].

Hydrogeological Zonation. Although geophysical methods have been used to estimate hydrological parameter probability density functions with very high resolution (i.e., 0.25m by 0.25m), this level of detail may not always be necessary to adequately describe the controls on transport. Many studies suggest that spatial variations of lithological changes tend to be closely correlated with hydrological parameters and with geochemical parameters. As such, if an understanding of the relationships between lithofacies, hydrological and geochemical parameters is available, field-scale mapping of lithofacies may provide sufficient information about the controls on transport over large spatial scales. Figure 4 illustrates how geophysical methods have been used with sparse hydrological data and with stochastic estimation techniques to estimate the probability of being within hydraulically important units. The top image illustrates the probability of being within a transmissive fracture zone at the NABIR Field Research Center at the Oak Ridge National Laboratory in Tennessee obtained using seismic velocity tomographic and flowmeter data within a Monte Carlo markov Chain approach. This fracture zone is the ongoing focus of a Uranium biostimulation experiment at this site (Criddle et al., pers. Comm.). The middle image shows the probably of being within a sandy lense at the Hanford 100H site in WA, and was

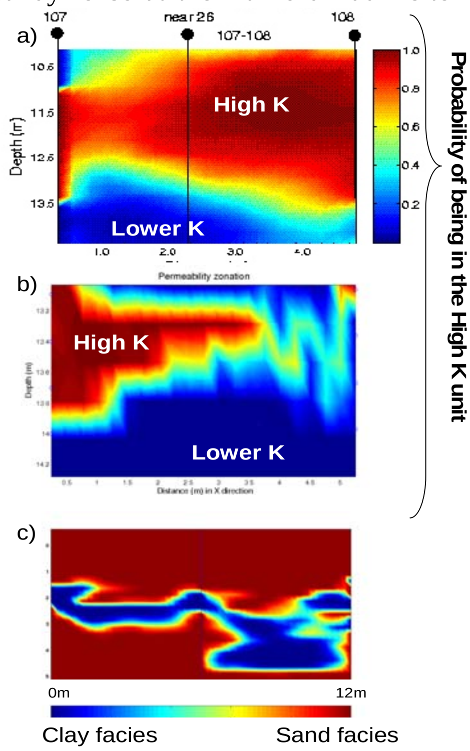

Figure 4 Estimates of hydrogeological zonation

obtained using seismic and radar tomographic data and a discriminant analysis technique. Finally, the lower figure illustrates the probability of being within a sandy (versus a clayey) lithofacies at the DOE Bacterial Transport Site in Oyster, VA (discussed above and shown in Figure 3), which was estimated using radar velocity data within a Bayesian estimation approach [8].

3. Monitoring of Remediation Amendments and Processes

In this section, we review two different studies that focus on the use of GPR to understand environmental remediation processes.

Remote detection of system transformations. Remediation approaches, such as *in situ* chemical manipulation and biostimulation, often induce dynamic spatiotemporal transformations in subsurface systems, such as the dissolution and precipitation of minerals, gas evolution, redox variations, biofilm generation, and changes in permeability and porosity. The limited understanding of biogeochemical-hydrological processes and the inadequacy of conventional approaches for characterizing or monitoring these processes hinders our ability to guide contamination remediation. We have investigated the capability of time-lapse geophysical datasets (including GPR, seismic, and complex electrical methods) for remotely detecting changes in hydrological-biogeochemical properties during biostimulation at both the laboratory and the field scale. Using column-scale experiments, we have tested the sensitivity of different geophysical methods to reaction products that occur during biostimulation, such as gasses, precipitates and biofilms during nitrate and sulfate reduction.

As a consequence of the greater energy available from nitrate reduction, a majority of nitrate in a groundwater system is reduced prior to reduction of the less energetic manganese, iron, and sulfate. Thus, the onset of denitrification is an important indicator for determining the redox state of the aquifer that is being perturbed, and advanced techniques to detect this onset and monitor associated processes in a remote and accurate manner are needed. We conducted laboratory-based experiments to investigate the sensitivity of radar (and other) attributes for detecting N_2 gas generated during denitrification as the gas replaces the original pore water. The key steps in the experimental design included packing and inoculating sand columns with *Acidovorax sp. (*strain OY-107), providing nutrients to the microbes to stimulate denitrification, and measuring the hydraulic and geophysical responses during the biostimulation experiment. TDR measurements were made along the length of the column and over time to estimate the spatiotemporal variations in dielectric constant during the stimulation experiment. We used a volumetric averaging/mixing model to represent the effective dielectric measurement as a function the individual components that contribute to the measurement, including the dielectric constants of N_2 , of water, and of the sand grains. Figure 5 illustrates the estimated percent of the pore space that was filled by N_2 gas as a function of time after the biostimulation experiment began for three different TDR measurement locations. This figure illustrates how the pore water started to be significantly replaced by gas after about thirteen days. Gas was first detected by probe #1, or the top probe in the column. The apparent 'jumps' in the estimated evolved N_2 gas (e.g., at 15, 20 and 23 days for probe 1) are associated with the pressure release procedure. With time, all of the probes sensed the presence of a significant volume of gas. At the end of the experiment, we estimated that approximately 22% of the pore spaces were filled with N_2 gas for the bottom third of the column, about 21% of the pore spaces were filled with gas for the middle third of the column, and that 31% of the pore spaces were filled with N_2 gas at the top third of the column, yielding an average estimated gas saturation over the entire column of 24.6% [12]. The experiment suggested that the radar velocity may be a good indicator of the onset and extent of denitrification that occurs during biostimulation.

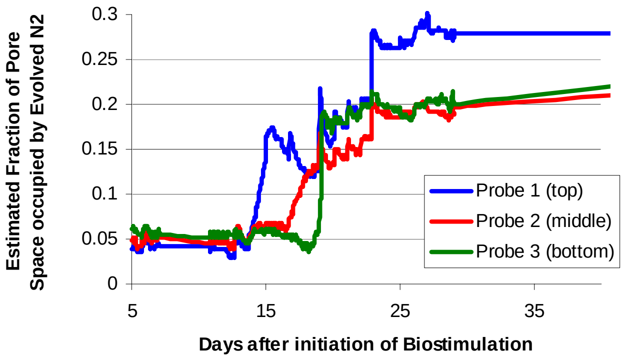

Figure 5 Estimates of gas volume that evolved during denitrification detected using radar velocity.

Amendment Detection using Geophysical Methods. Our laboratory and field-scale experiments have also indicated that the geophysical methods hold good potential for detecting some amendments as they are introduced into an aquifer and as they distribute over time. We have conducted geophysical imaging in support of a Cr(VI) bioremediation effort that is being performed at the 100H Site at the Hanford Reservation in Hanford [13]. Here, HRC, which is a slow-release polylactate (Regenisis, ™) was injected into a sandy portion of a saturated aquifer to reduce and immobilize Cr. Field tomographic data were collected before and after HRC injection. Figure 6 illustrates some of the field-estimates obtained using radar and seismic

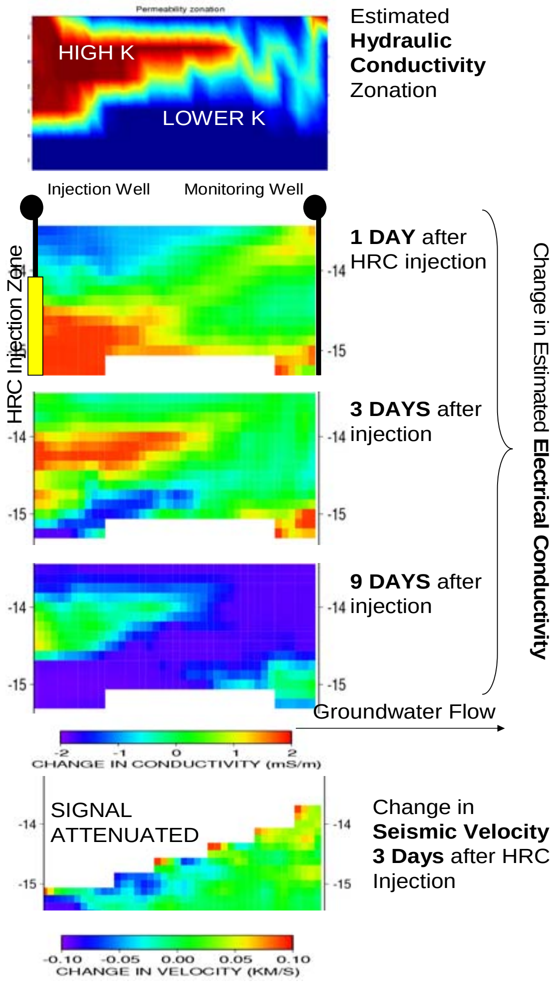

Figure 6 Field scale tomographic imaging associated with a biostimulation experiment. Top: Estimated hydraulic conductivity zonation, Bottom: changes in geophysical responses associated with amendment distribution.

tomographic data at the site. The top image in Figure 6 illustrates the hydraulic conductivity zonation in the stimulation zone, obtained using a statistical approach with radar and seismic tomographic data together with borehole flowmeter data. Although the entire section is characterized as being 'sandy' using conventional data, there are areas within the section that are more permeable (shown by the red zone). The subsequent images in Figure 6 show the changes in electrical conductivity as a function of time after HRC was injected into the aquifer, obtained using radar amplitude and velocity information following Peterson [14]. We find that the HRC, which is electrically conductivity upon injection due to the release of lactic acid when mixed with the groundwater, originally distributes near the injection area. However, very soon after injection (3 days), the lactic acid redistributes itself into the higher hydraulic conductivity section, and migrates downgradient. After 9 days, the change in the electrical response due to the lactate injection is minimal compared to the change in the conductivity associated with the metals precipitation around the HRC reaction front (blue zone on bottom figure). The bottom image in Figure 6 shows that the seismic energy is completely attenuated in the vicinity of the HRC. These images illustrate the utility of high-resolution geophysical methods for imaging the amendment location and redistribution as a function of heterogeneity. The geophysical responses to HRC that we observed at the field scale were similar to the responses observed in the laboratory.

4. Summary

Increasing population and pollution, decreasing natural resources, and changing climatic conditions all contribute to the urgency associated with improving our understanding of hydrogeological parameters and processes, especially in the shallow subsurface. Although there are many obstacles associated with the quantitative use of GPR data for characterization and monitoring, a substantial body of evidence suggests that these methods can be extremely useful for environmental and agricultural investigations.

5. References

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