High-Resolution Definition of Subsurface Heterogeneity for Understanding the Biodynamics of Natural Field Systems: Advancing the Ability for Scaling to Field Conditions

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Research Objective

This research is an integrated physical (geophysical and hydrologic) and microbial study using innovative geophysical imaging and microbial characterization methods to identify key scales of physical heterogeneities that affect the biodynamics of natural subsurface environments. Data from controlled laboratory and in situ experiments at the INEEL Test Area North (TAN) site are being used to determine the dominant physical characteristics (lithologic, structural, and hydrologic) that can be imaged in situ and correlated with microbial properties. Emphasis is being placed on identifying fundamental scales of variation of physical parameters that control transport behavior relative to predicting subsurface microbial dynamics. The overall goal of this research is to contribute to the understanding of the interrelationships between transport properties and spatially varying physical, chemical, and microbiological heterogeneity. The outcome has been an improved understanding of the relationship between physical and microbial heterogeneity, thus facilitating the design of bioremediation strategies in similar environments.

Background

The main motivation for the EMSP work was detailed characterization for designing appropriate remediation strategies (such as bioremediation or pump-and-treat). This required an understanding of aquifer properties and the subsurface structure which controls those properties. The need for higher resolution imaging has led to borehole seismic techniques which place sources and sensors in wells. One important method for borehole seismology is crosswell tomography. Crosswell seismic surveys have been used for many years to tomographically image P-wave velocity between wells (e.g. Mason, 1981 and Peterson, et al., 1985). More recently, crosswell S-waves have also been used to map S-wave velocity (Harris, et al., 1995) and both P- and S- wave crosswell reflectivity have been analyzed for structural delineation (Rector, et al, 1995). Until our work in fractured rock nearly all crosswell seismic tomography has been performed in sedimentary formations important to oil and gas exploitation (Rector, 1995). The application of crosswell seismic methods to crystalline rock is often a more difficult problem than the application in sedimentary rock. In crystalline rock, the features important to fluid flow are usually fractures or other features which can act as fast paths in fluid transport. Fractures in rocks can cause large velocity and amplitude changes compared to the intact matrix. Various approaches have been taken to develop theory to relate these changes to fracture properties.Without attempting to directly invert for fracture properties, the seismic attributes (velocity and attenuation) can be related to subsurface features determined from borehole methods such as core analysis and well logs. The advantage of seismic imaging is the ability to detect or image features away from the borehole. Crosswell seismic imaging in fractured crystalline rock has been used to define the spatial distribution of velocity and attenuation which are related to fracture zones determined from other borehole techniques (eg. Vasco, et al., 1996, Cao and Greenhaigh, 1997).

Field Experiments

At INEEL, we applied the crosswell seismic technique in a fractured basalt aquifer (part of the Snake River Plain Aquifer) which has been locally contaminated by historic injection into a well used for waste disposal at the Test Area North (TAN) site (Figures 1 and 2). Multiple crosswell surveys were acquired in two field sessions. The initial surveys used a piezoelectric source which provided high frequency, high resolution P-wave data (Figure 4). The second field session used an orbital vibrator source which generates lower frequency, higher amplitude P- waves, thereby providing more spatial coverage (larger well spacings) albeit with lower resolution than the piezoelectric source data. The orbital vibrator is also notable for generating S-waves as well as P-waves providing a separate measure of rock properties (Figure 6a and 6b). Our current analysis of the crosswell data includes results for imaging of fracture flow. Zones of apparent fracture flow of contaminants are inferred from well logs and core sampling (Figures 3 and 6a). Velocity and attenuation tomograms for the piezoelectric source data image apparent fracture flow zones with about 1 - 2 m resolution (Figures 4 and 5). P- and S-wave velocity tomograms for the orbital vibrator source both show low velocity in a l0-15m zone with high apparent contaminant flow (Figure 6a). Guided waves are observed in zones inferred to have fracture flow (Figures 7 - 9).

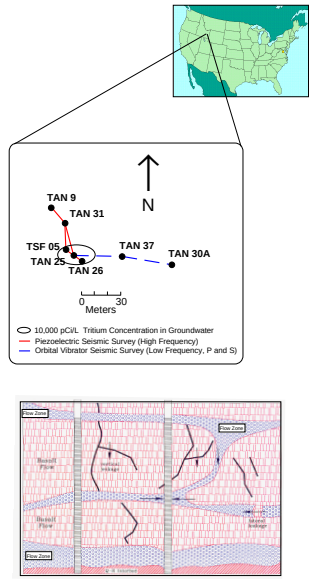

Figure 2 Conceptual model of hydrologic flow within the aquifer at the INEEL TAN site. A sequence of thin basalt flows contain mainly horizontal flow zones with vertical leakage between zones. These zones are believed to be interbed basalt rubble zones. Sedimentary interbeds (e.g. Q-N) can act as a barrier to vertical flow. Figure taken from Rakowski, et al., 1998.

Location map (top) of Tan Site showing wells near the site of historical mixed waste disposal in well TSF-05. Well Tan-37 is the newest well drilled for the EMSP program. Schematic model (bottom) of the aquifer flow zones within the layered basalt flows.

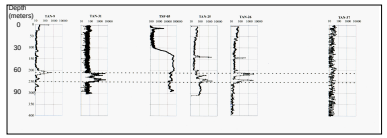

Figure 3 Gamma logs from tomography wells at the INEEL TAN site. Gamma count is dominated by radionuclide contamination in the groundwater. High gamma counts correlated between wells (inside dashed lines) show zones of contaminant flow within the aquifer. These zones are imaged by seismic tomography as low velocity zones.

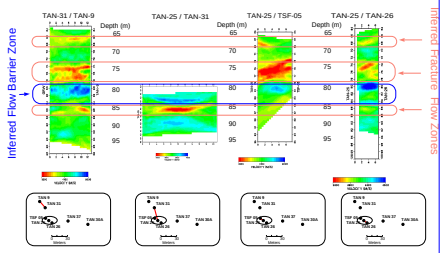

Figure 4 Seismic velocity tomograms (top) from the INEEL TAN site with location map (bottom) showing well pair. Zones of low velocity (yellow - red) are interpreted as fractured basalt (possibly rubblized contacts between basalt flows) which allow high flow within the aquifer. High velocity zones (blue) are interpreted as dense, unfractured basalt which acts as a barrier to contaminant flow within the aquifer. The upper two inferred flow zones have been confirmed as contaminant transport zones by well logs.

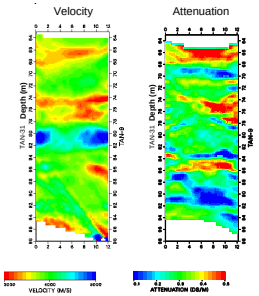

Figure 5 Seismic tomographic inversion results for well pair TAN-31 / TAN-9. This data used the high frequency piezoelectric source giving 1- 2 m resolution. Zones of low velocity and high attenuation (such as 73 - 76 m, and 65 - 67 m) are interpreted as fracture zones which provide fluid flow zones for contaminant transport.

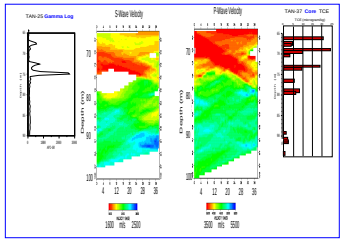

Figure 6a Comparison of contaminant sampling in boreholes and crosswell velocity tomogram. TAN-25 Gamma Log (left) indicates presence of radionuclide contamination. TAN-37 TCE contamination from core measurement (right) indicates TCE concentration. Seismic S-Wave and P-Wave velocity (center) indicates more fractured rock as low velocity (red to green) and less fractured rock as high velocity (green to blue). The 65 to 80 m depth zone has low velocity and increased contaminants, showing the relation between fracture flow and fracture induced seismic velocity variation.

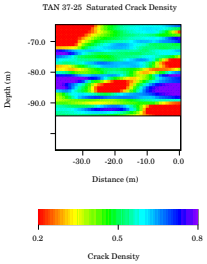

Figure 6b Crack density (dimensionless) calculated from P- and S-wave tomographic velocities. All other material properties are assumed constant over the volume and cracks are assumed to be fully saturated.

Results and Interpretation

The fractured basalt lithology of INEEL's TAN site (with or without sedimentary interbeds) provides a difficult media for seismic profiling. However, we have acquired multiple high frequency P- wave data sets in close well spacings (less than 25 m) and we used an orbital vibrator to acquire P- and S-wave data sets in larger well spacings (nearly 40 m) ,with P-waves recorded at nearly 60 m well spacing. The use of the orbital vibrator with a hydrophone array successfully demonstrated the applicability of a this new type of seismic source for environmental applications needing P- and S-wave measurements. Travel time tomography was accomplished for both P- and S-wave data sets (Figure 6a). From these tomograms, Vp/Vs ratio and Poisson's ratio can be calculated. The direct subsurface measurement of these ratios is very useful for understanding material properties. From Vp/Vs material properties such as crack density can be estimated (Figure 6b). The data recorded at the TAN site showed correlation between slow velocity zones and contaminant flow zones. We believe the horizontal fracture zones between basalt flows are paths for the fluid flow and are causing the drop in seismic velocity. The combination of piezoelectric data for closer well spacing and orbital vibrator for larger well spacings has provided optimal imaging capability.

High quality P- and S-wave arrivals were obtained at the TAN site over much of the 65 to 100 m survey depths. However, attenuation limited data quality in some depth zones. Fluid flow (and associated contaminant flow) within the aquifer is thought to occur in basalt fracture zones or in sedimentary interbeds. We did not observe coherent reflections which would indicate sedimentary interbeds in the depth range of our survey. The best measure of contaminant flow in the TAN site wells is currently provided by gamma logs which show the response of radionuclide contamination (Figure 3). It is assumed that the organic contaminant flow is in the same zones as the radionuclide flow. Additionally, well TAN-37 has had core samples analyzed for contaminants. Figure 6a shows the gamma logs for well TAN-25 along with core samples of TCE concentrations from well TAN-37 and the crosswell tomograms. We interpret fracture flow of contaminants, most likely within a contact region between two basalt flows, at 73 to 75 m. While the orbital vibrator data does not provide the 1 - 2 m resolution necessary to image this zone, the piezoelectric data in Figures 4 and 5 do show a thin zone of low velocity and high attenuation at this depth. The interpretation is supported by observation of guided wave type energy within this zone. Guided waves can be generated by low velocity zones which act as wave-guides. The orbital vibrator data include apparent guided wave energy at 73.5 to 74.5 m depths (Figure 8 and 9). Figure 8 shows the zero-offset (equal depth source-receiver pair) seismograms and their spectra. The guided wave zone is circled in Figure 8. Finite difference modeling using a thin low velocity zone (Figures 9 and 10) matches the seismograms (Figure 9), thereby corroborating the interpretation of a thin fracture zone. With the interpretation of guided waves, we imaged a hydrologically important flow zone about 1 - 2 m thick.

Geophysical Detection of Microbieal Processes ?

In general, at the fractured basalt TAN site, regions of slow seismic velocity are found to correspond with zones of contaminant transport (and by inference higher permeability and increased fracturing). Regions of low amplitude (high attenuation) also appear to correspond with zones of permeability. Evidence also exists to suggest that pore filling may also be contributing to the attenuation of the seismic data.

One of the results that led us to the conclusion that we may be detecting by-products of microbial products is shown in Figure 4. Shown in this figure are all of the P-wave tomograms from the high frequency piezoelectric source (kilohertz data). The data between well pair 25 and 31 crosses a hot spot of contamination within the TAN area. Although we obtained high quality data over most of the well the 65 to 80 meter zone yielded no data which could be used for analysis. This area was a known zone of high concentration of contaminants (sludge). Although we were able to image other fracture zone we suspect that the high attenuation was possibly due to either high concentrations of a material in the fractures which attenuates the seismic energy (DNAPL), or trace amounts of gas from biodegrading products. In any case we could not explain the high attenuation alone from the known physical properties.

Because the experiments were not designed to be time lapse surveys, we could not say for sure if the data supported physical and chemical changes in the subsurface. We do, however, now have a data set (from the initial EMSP) to compare to in a time lapse sense. Augmented bioremediation was started after our last survey by the injection of lactate (density of up to 1.4 water for a 60 percent solution) in the well in which the contaminates were injected .

If we were detecting physical and chemical changes in the last work when only natural bioremediation was occurring, then we have an excellent opportunity now to detect similar results after the beginning of nutrient injection. These injections are planned for at least three and maybe more years, depending on the results of the bioremediation. The results of the first phase of bioremediation at the site (1999) show that lactate addition resulted in rapid lowering of the redox through nitrate-respiring, iron-reducing, and sulfate-reducing conditions to methanogenic conditions within 2-3 months at locations near the injection (personal communication, Ken Sorenson, principal engineer for bioremediation). With high lactate loading, these redox conditions can potentially result in (respectively) microbial generation of N2 gas (from sludge injected at TAN); production of biogenic iron, carbonate, and sulfide minerals; and biogenic methane gas. Thus, there is potential for significant phase changes that geophysical methods may be sensitive to detecting.

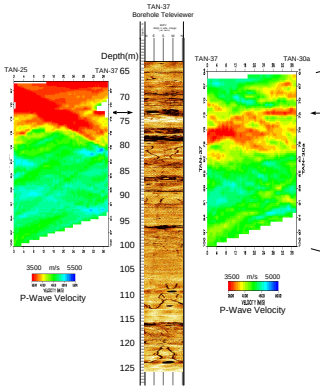

Figure 7 TAN site P-wave seismic tomography (wells 25 and 37 left; wells 37 and 30a right) along with borehole televiewer (center). Regions of low velocity (red to yellow) above 80 m depth define the regions of fracture flow and contaminant transport. Arrow at 74 m indicates depth of observed fracture zone seismic guided wave which indicates fracture connectivity between wells.

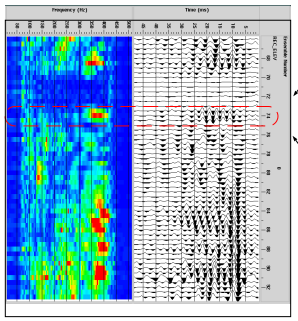

Figure 8 Zero offset profile (source and receiver at the same depth) for the TAN-37 / TAN-25 well pair. Depth in meters is labeled at top as REC_ELEV. Seismograms (top) and spectra (bottom) show large variability. The zone in the dashed lines is interpreted as a guided wave with large amplitude at 74 m depth and peak spectra (yellow to red colors) between 350 and 400 Hz.

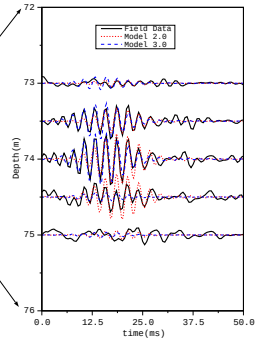

Figure 9 Comparison of modeled and field data for guided wave at TAN site. Model 2.0 is a 1.5 m thick low velocity zone, while model 3.0 is a 1.0 m thick low velocity zone. The low velocity material is 1800 m/s surrounded by 4000 m/s material.

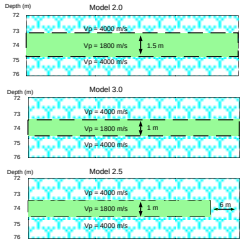

Figure 10 Velocity models used for finite difference seismic modeling of guided wave observed in TAN-37 / TAN-25 well pair. 4000 m/s material represents unfractured, low permeability bsalt, 1800 m/s represents fractured, rubble zone basalt.

Objectives and Progress of Microbiology Work

Objectives

1. Characterize small-scale variations in subsurface microbiological properties for the purpose of a) providing quantitative estimates (using variogram models) of the spatial variability of these properties and b) understanding the relationships between microbiological, physical, and chemical properties (using cross-correlation models). These activities will help identify to what extent geophysical and geochemical properties control the spatial variability of microbiological properties.

2. Determine how the use of different sample supports affects the measurement of microbiological properties. The definition of an appropriate averaging scale is critical in providing more accurate input into predictive models of contaminant transport and will improve the precision of the simulations.

3. Quantify changes in the spatial structure and magnitude of microbiological properties following the impingement of a contaminant plume. An associated objective is to determine how the contamination event affects the measurement of microbiological properties at different sample supports.

Analysis of rock samples from TAN-37

Groundwater samples from the TAN-37 borehole, which addressed objectives 1 and 2, arrived in July 1998. Compared to TAN-33 (work performed in FY1997), the TAN-37 borehole is closer to the source of contamination, contains 5-10 times more TCE, and microbial activity (determined by other investigators) is much higher. DNA was extracted and successfully amplified (i.e., produced a visible band) from 9 of 10 rock samples; these samples correspond to the depths where the multi-level groundwater sampling will occur in FY98.
Amplified rDNA was cloned from 6 of the samples. These samples yielded between 5 and 26 microbial types by ARDRA (amplified ribosomal DNA restriction analysis), with many types represented by multiple clones.
In contrast, samples from TAN-33 (performed in FY1997) did not result in a visible band after PCR amplification, and cloning of the invisible bands yielded 2 to 5 microbial types, but only a single clone of each. The TAN-33 borehole was located in a region containing low levels of contamination (less than 0.5 ppm trichloroethylene, TCE) and low microbial activity.

Aerobic mineralization of methane and phenol, anaerobic mineralization of methanol and lactate, and mineralization of TCE in the presence of each of the 4 substrates was measured on 7 rock samples (plus a combusted rock control sample) from TAN-37 by gas chromatography-gas proportional counting (GC-GPC). Results summarized below are for the 3 month timepoint (1 week and 1 month timepoints were also analyzed). Lactate was the only substrate that showed mineralization after 1 week (4 of 7 samples).
- Surprisingly, phenol was not mineralized in any of the samples.
- Methane was mineralized in 2 samples (8% maximum).
- Methanol and lactate were mineralized in 6 samples (7% maximum) and 5 samples (21% maximum), respectively.
- Low levels of TCE (1%) were mineralized in one sample in the presence of methanol and in one sample in the presence of lactate.

These data indicate that methane-oxidizing microorganisms are present in some samples, and that both methanol and lactate can be effectively used to anaerobically stimulate the microbial community and promote TCE degradation.

Summary

In our original proposal, we outlined a plan for aggressively addressing issues related to scaling microbiological properties in rock and in pumped groundwater based upon (a) obtaining a large number of transect samples in order to apply geostatistical methods and (b) sampling over volumetric scales that varied by orders of magnitude. Although we worked diligently to obtain these microbiological samples, for a variety of reasons it was not possible to obtain the number or type of either rock or ground water samples from the TAN site. When it became evident our microbiological sample needs could not be met, this project contributed its microbiological resources toward collaboration with another EMSP project at TAN led by Dr. Rick Colwell. In particular, molecular biological methods were used to characterize microbial communities in core samples from several boreholes (varying in distance from the contaminant injection well) and lithologies, ground water samples from a multilevel sampler in one borehole, and ground water samples obtained during the in situ bioremediation treatment (lactate injection to support anaerobic reductive dehalogenation of TCE).

Acknowledgments

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