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

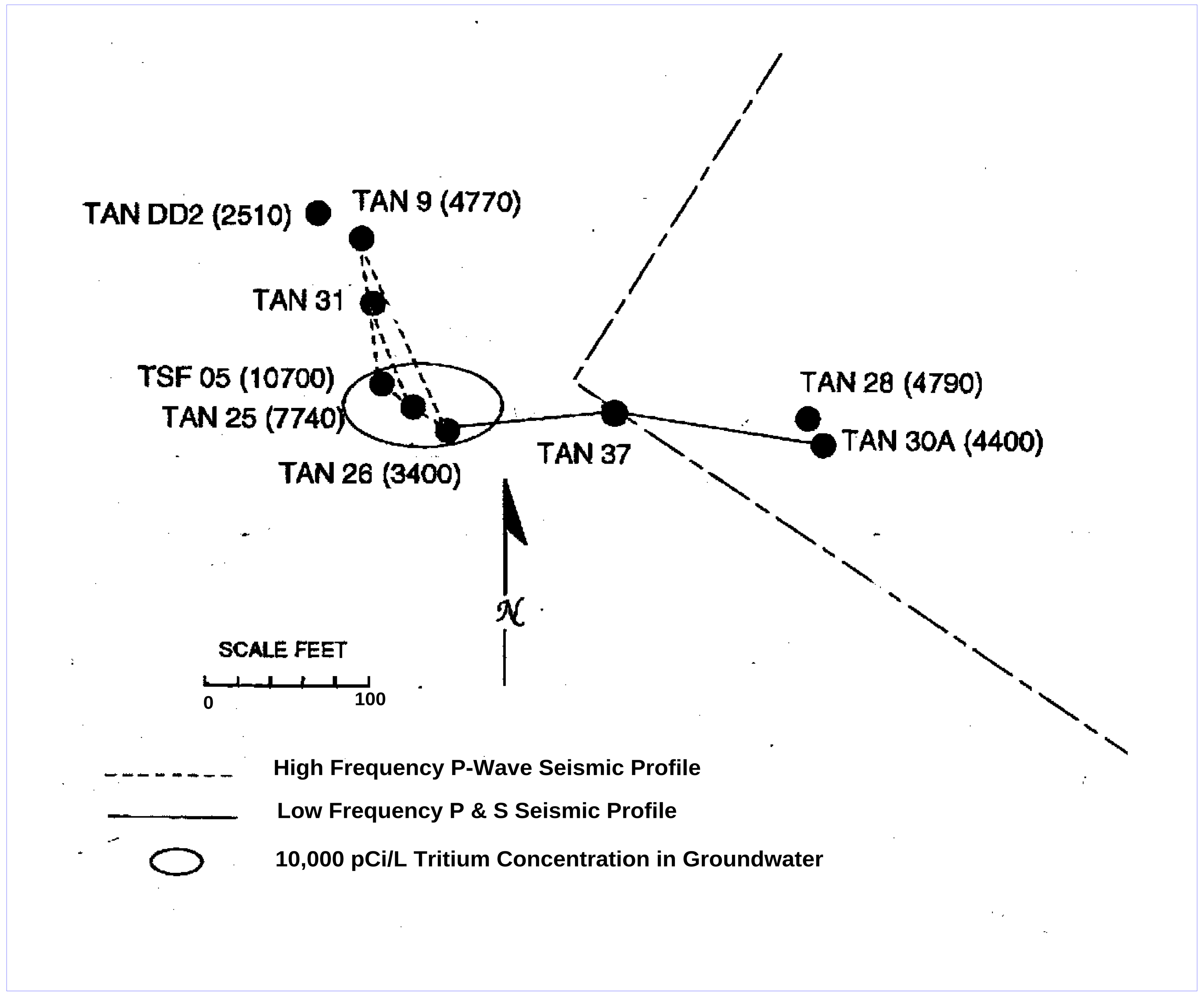
This research is an integrated physical (geophysical and hydrologic) and microbial study using innovative geophysical imaging and microbial characterization methods to identify key scales of physical heterogeneities that affect the biodynamics of natural subsurface environments. Data from controlled 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 will be an improved understanding of the relationship between physical and microbial heterogeneity, thus facilitating the design of bioremediation strategies in similar environments.

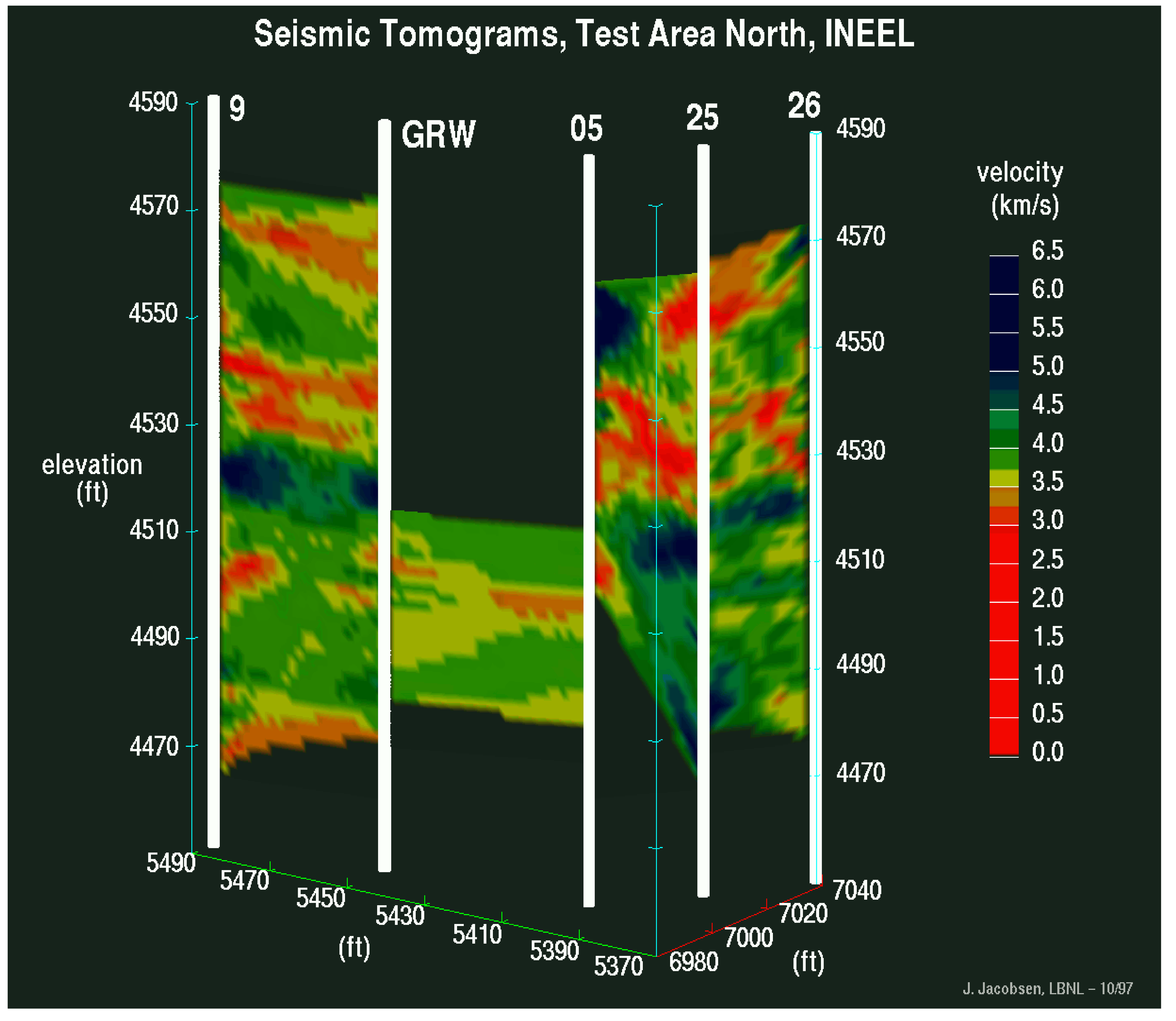
Research Progress and Implications

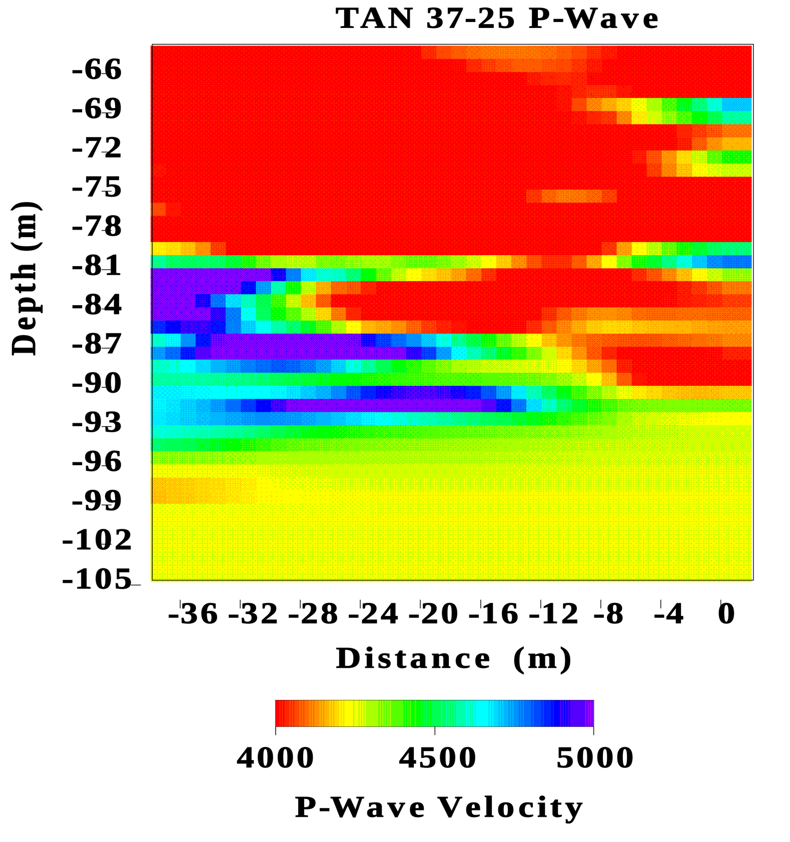
This report summarizes work as of May 1998, the second year of the project. This work is an extension of basic research on natural heterogeneity first initiated within the DOE/OHER Subsurface Science Program (SSP) and is intended to be one of the building blocks of an integrated and collaborative approach with an INEEL/PNNL effort aimed at understanding the effect of physical heterogeneity on transport properties and biodynamics in natural systems. The work is closely integrated with other EMSP projects at INEEL (Rick Colwell et al.) and PNNL (Fred Brockman and Jim Fredrickson).

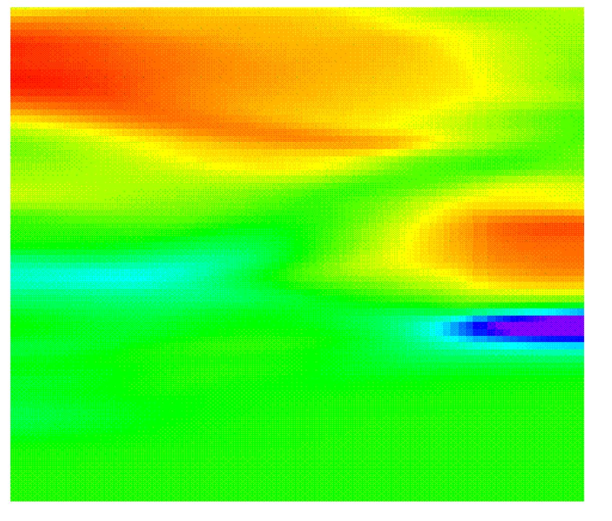
The research is being carried out in both the laboratory and at DOE field sites under natural conditions. This work addresses issues that will aid in the understanding of what scales one must sample in order to design effective remediation strategies. A critical question is the existence of one or more self-averaging quantities for microbial properties. Stated in another fashion: Are the microbial properties a function of the randomness of the media? If so, what is the size of the representative volume at which the significant properties can be characterized? A specific goal of the research is to advance the understanding of how to effectively use the information from geophysical imaging (i.e., volumetric measurements of physical properties) to predict the effect of physical heterogeneity and fluid transport properties on microbial behavior.

A key hypothesis being addressed is that nutrient flux and transport properties are key factors in controlling microbial dynamics. A related hypothesis is that complexity of the subsurface environment is also correlated to the behavior of microorganisms. With seismic information on location of fractures, layer continuity, layer thickness and other structural and lithologic features, improved predictive models on flow and transport can be developed and applied. This is then correlated to the microbial behavior and distribution. Several different seismic processing approaches are being used to obtain improved information on physical properties controlling transport behavior, including: conventional and advanced ray and waveform tomography; guided/channel waves; scattered energy from voids/high contrast anomalies; and crosswell reflection imaging.







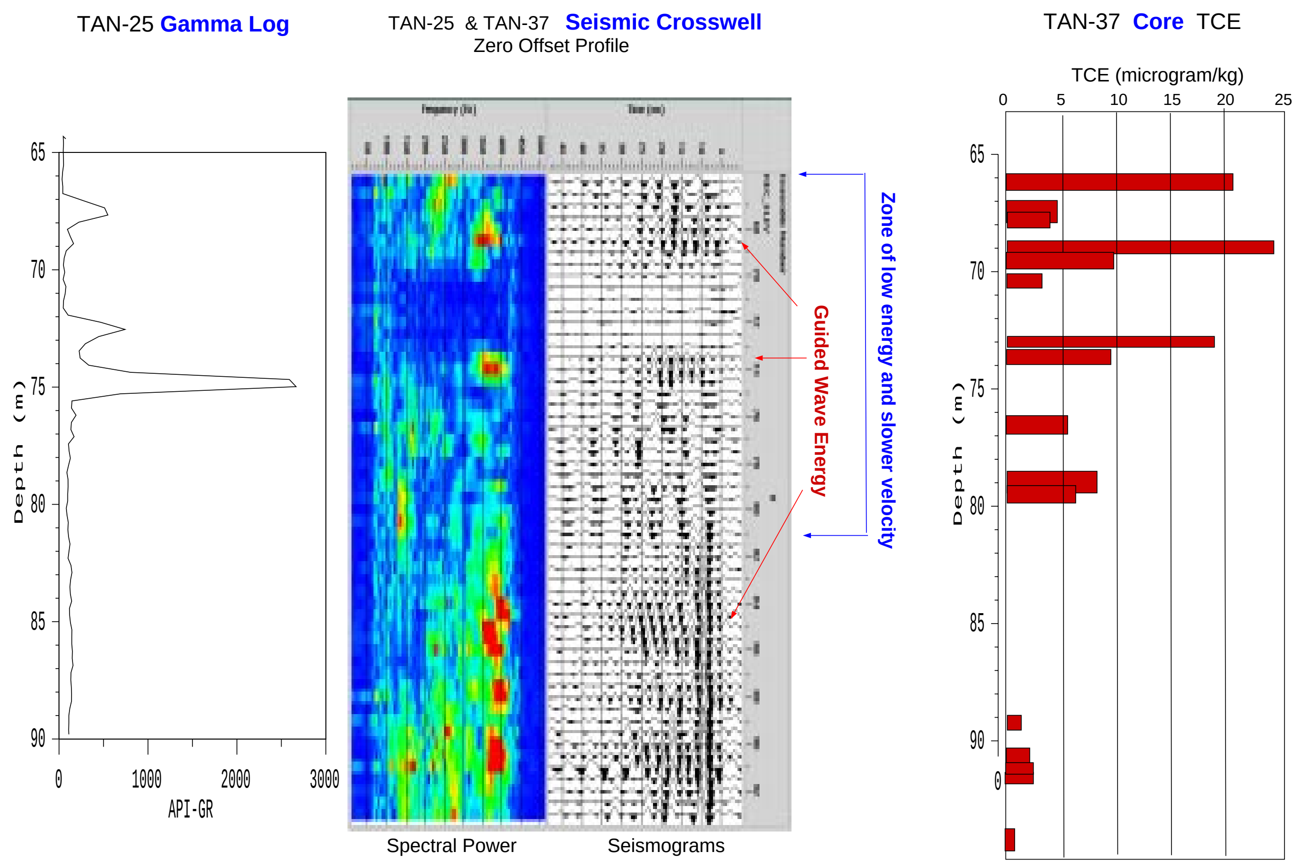


PROGRESS TO DATE OF THE GEOPHYSICAL IMAGING

During 1997 the geophysics concentrated on obtaining crosswell seismic data at the sub-meter resolution scale at several wells in the TAN area. The initial crosswell seismic surveys used LBNL's high frequency piezoelectric source which generates energy from 1 kHz to over 5 kHz. Tomographic imaging was carried out for crosswell pairs, T-GRW to TAN-9, TAN-25 to T-GRW, TAN-25 to TAN-26, and TAN-25 to TSF-05.
Subsurface coverage was good from 64 m (the water table) to over 90 m (depending on well depth). The tomographic imaging allowed identification of velocity heterogeneity in regions as thin as 2 meters and velocity homogeneity over larger regions with sub-meter resolution. From this initial seismic imaging several results were evident. The seismic response of the surveyed area is quite varied, with large changes in seismic velocity and attenuation with depth. From our experience in other fractured environments, this indicates extreme variability in fracture/rock properties and from past experience is an indication of fracture permeability. After completing initial velocity analysis of the piezoelectric data in 1997, we refined the results by including well deviation and anisotropy corrections. A significant result from the initial crosswell surveys was large variations in attenuation. We were not able to propagate the kilohertz frequencies more than about 15 - 20 m between wells, and in some regions the seismic energy was attenuated below measurable levels over distances less than 15 m. Thus, while the piezoelectric source produced high resolution of heterogeneities, the imagable volume was limited by well spacing. We also observed little coherent reflectivity, which focused our study on transmission tomography and guided/channel wave analysis.

In 1998 we wanted to apply crosswell imaging using a well drilled for the EMSP program, TAN-37, which will be used for multi-level sampling and microbial studies. Because the distance from TAN-37 to the nearest wells was over 30m, we felt the piezoelectric source would not be satisfactory.
Instead, we deployed a recently developed borehole seismic source know as an orbital vibrator. The orbital vibrator provides greater seismic energy, although at lower frequencies, and it generates both compressional and shear waves providing the ability for simultaneous P and S-wave imaging. This source, which was originally developed by Conoco Inc., has to date been used only in oil industry research. Two crosswell surveys were obtained using the orbital vibrator, TAN-37 to TAN-25, and TAN-37 to TAN-30a. To date, we have processed the TAN-37 to TAN-25 data set, obtaining both P and S-wave velocity tomograms. The successful use of this source in the INEEL geologic environment (fractured basalts) allows study of larger well spacings and unique use of P and S-wave comparisons. Although the frequency content is lower (70 to 425 Hz), we were still able to resolve heterogeneous regions 2 to 4 m thick with a resolution of about 1 m. We are also looking at anomalous depths which appear to generate guided waves or interface waves which may be indicative of fracture connectivity between wells. In particular, one apparent guided wave at 74 m in the TAN-37 to TAN-25 well pair agrees with logs showing contaminant flow at that depth in nearby wells. In all well pairs the tomography has given good resolution on structure and possible areas of fast paths.

Comparison of Heterogeneity Scales



Comparison of heterogeneity scale from three types of measurements. In TAN-25 the gamma log (left) is used to identify zones of contamination by radionuclides and, by inference, TCE. In TAN-37 core measurements (right) provide a direct measurement of TCE. The seismic data indicates fracturing (and by inference permeability) using spectral power and seismic velocity. Guided wave energy may indicate thin zones of velocity variation (such as fracture zones) which are continuous between wells.The zone of low seismic energy in blue correlates well with the higher gamma log and the higher TCE concentrations observed in cores. The scale of heterogeneity seen with variation of seismic properties is comparable to that observed with well logs and cores, about 0.5 to 1 m.

PROGRESS TO DATE OF MICROBIAL CHARACTERIZATION AND SCALE EFFECTS

The objective of this work is to characterize small-scale variations in subsurface microbiological properties for the following purposes: providing quantitative estimates (using variogram models) of the spatial variability of these properties; and 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. An additional objective is to 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. The final objective is to 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.

TAN-33 Rock samples were obtained from one EMSP-funded borehole in FY97. Although we worked closely with personnel at INEEL , it was not possible (given their funding, schedule, and logistical considerations) to obtain the number, type, and quality of rock samples required for meeting the stated objectives. However, in FY98 we are addressing our first two objectives based on sampling and analysis of groundwater from the borehole described above. In TAN-33, after a delay in obtaining samples from the EMSP-funded borehole, we obtained samples from a Subsurface Science Program-funded borehole to refine DNA extraction protocols in basaltic rock material. The TAN-33 borehole was located in a region containing low levels of contamination (less than 0.5 ppm trichloroethylene, TCE). Community DNA was successfully extracted from several of the rock samples, the 16S rRNA genes were amplified and cloned, and phylogenetic analysis was performed.

Compared to TAN-33, the TAN-37 borehole is closer to the source of contamination and contained 5-10 times more TCE. Microbial activity (determined by other investigators) in the TAN-37 borehole was much higher than in the TAN-33 borehole. DNA was extracted and successfully amplified from all rock samples to date; these samples correspond to the depths where the multi- level groundwater sampling will occur in FY98. DNA extraction is being performed on the remaining 15 rock samples from the TAN-37 borehole. Timecourse degradation (1-12 weeks) of 14C-labeled organic substrates (methane and phenol aerobically; lactate and methanol anaerobically) and 14C-trichloroethylene, in the presence and absence of additional inorganic and organic nutrients, was performed on 8 rock samples, and analysis by gas chromatography-gas proportional counting is underway.