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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Abstract

This research is an integrated project which uses physical (geophysical and hydrologic) and innovative geophysical imaging and microbial characterization methods to identify key scales of physical heterogeneities that affect bioremediation. In the this effort data from controlled laboratory and in situ experiments at the Idaho National Engineering and Environmental (INEEL) Test Area North (TAN) site were used to determine the dominant physical characteristics (lithologic, structural, and hydrologic) that can be imaged *in situ* and correlated with flow and transport properties. Emphasis was placed on identifying fundamental scales of variation of physical parameters that control transport behavior relative to subsurface microbial dynamics that could be used to develop a predictive model. A key hypothesis of the work was that nutrient flux and transport properties are key factors in controlling microbial dynamics, and that geophysical techniques could be used to identify the critical physical properties and scales controlling transport. This hypothesis was essentially validated. The goal was not only to develop and apply methods to monitor the spatial and temporal distribution of the bioremediation in fractured sites such as TAN, but also to develop methods applicable to a wider range of DOE sites. The outcome has been an improved understanding of the relationship between physical, chemical and microbial processes in heterogeneous environments, thus applicable to the design and monitoring of bioremediation strategies for a variety of environments. In this EMSP work we demonstrated that high resolution geophysical methods have considerable resolving power, especially when linked with modern advanced processing and interpretation. In terms of basic science, in addition to providing innovative methods for monitoring bioremediation, the work also provided a strong motivation for developing and extending high resolution geophysical methods.

Statement of Problem and Needs

Bioremediation of contaminated sites offers great promise for cost savings. Although there has been considerable progress in developing and applying bioremdiation methods, there is a need for methods to monitor and validate the effectiveness of the remediation. Although permeability and microbiological properties can be measured on core samples in the laboratory or in the field by using pumping and water sampling tests, these sample and/or borehole techniques are costly, time-consuming, and invasive, all of which limit the ability to estimate the distribution of the biologic properties needed for detailed site characterization and process monitoring. For example, chemical analysis of ground water samples is extremely useful for monitoring of bioremediation success at the sampling location(s), but provides limited (or no) information for nearby low flow matrix regions and for high flow features distant from the monitoring well(s). Additionally, the "support scale" sampled by some of these techniques may not be compatible with the scale of the effective parameters needed for detailed site characterization and monitoring. Because the number of monitoring wells is very limited due to depth and expense, and geophysical methods image over many tens of meters, geophysical methods potentially provide an important complementary characterization and monitoring capability. Thus, there is a need for non-invasive techniques that can capture spatial variations in physical and chemical parameters at a scale appropriate for site characterization and monitoring, such that they can be related to the microbial parameters. In addition to understanding the significant scales of nutrient flux and transport, several factors are emerging as critical elements in predicting the behavior of microorganisms in natural environments. Bacterial transport, ecology and other factors that govern the success of bioremediation are generally understood at the bench scale, but when one introduces complexities such as natural heterogeneity and larger scales of application, the path to monitoring bioremediation is not as apparent.

Geophysical techniques such as crosshole seismic and radar tomography offer a means of providing two-, and three-dimensional high resolution physical parameter estimates at site characterization scales in a less invasive manner than conventional sampling techniques, as well as possibly providing the only means to relate pore scale processes that can be measured in the lab (point measurements), to properties that can be measured at the field scale (volume measurements). Although geophysical methods have promise there is still much basic work to be done in scaling from the lab to the field when one is in a natural environment. Therefore, we feel that in the initial work we have demonstrated a path to employ geophysical methods for characterizing properties controlling flow and transport at the field scale. A more complete solution to the issue of effective bioremediation requires a cost effective means to monitor the progress and success of bioremediation on a site-wide scale.

Goals and Significance

The broad goal of this research is to contribute to the overall understanding of the interrelationships between spatially varying physical properties, chemical properties, and subsurface microbial processes. More specifically, the field and laboratory studies will advance the understanding of how to effectively use the information from geophysical imaging (i.e., volumetric measurements of physical and hydrologic properties) to make inferences regarding specific biogeochemical (i.e., microbial) processes . In doing so, this work will increase knowledge of what scales one must sample, as well as how to sample, in order to design and monitor effective bioremediation strategies. The significance of the proposed research is several-fold. First, geophysics is ideally suited for extrapolating measurements made in a borehole to the large-scale volume away from the hole. In this application, geophysical measurements made on the surface or between holes can be used to assess the continuity and homogeneity of the intervening material. Geophysics can also serve to map the subsurface in the absence of boreholes and can be used to detect the unexpected, e.g., a fracture zone or channel not revealed in surface geologic mapping. Last and most importantly, geophysical methods are most sensitive in the mode of detecting changes from a baseline or in a time-lapse sense. In all cases, the imaging provides an improved overall understanding of the site. Second, the work will evaluate the ability of images performed in a time series during bioremediation to detect the end-products of microbiological processes that have the potential to alter physical phases (gas, aqueous, DNAPL, solid). If successful, geophysical methods could eventually provide rapid and inexpensive proxy measurements of microbiological processes occurring away from the monitoring well. Third, the volumetric nature of the imaging measurements are extremely useful for understanding field-scale transport and bioremediation processes, for scaling point information to the field, and for developing improved (i.e., directed) sampling strategies.

Background

The solution to the problem of monitoring microbial behavior can be stated quite broadly. First, the processes, properties, and scales that control bioremediation must be understood and quantified. Next, the distribution of the physical, chemical, and microbial properties that are involved in these processes must be determined. These two steps permit the creation of a model that will describe the microbial behavior. In practice this simple scenario is difficult to realize: heterogeneity, anisotropy, and time-dependent processes are factors that combine to complicate one's ability to accurately describe the system model and its performance. Therefore, one must create a system model that obeys the data.

The three inputs to the system model are:

1. The three-dimensional distribution of the physical, chemical, and biological properties.

2. The fundamental physical, chemical, and biological processes that control bioremediation.

3. The distribution and state of the properties and processes at a given time that sets an initial condition for the problem.

The work here has mainly addressed the physical elements of the first input and partially addresses the problems associated with the second and third inputs to the system model. Techniques that determine these properties in a volumetric sense have been emphasized. This is not to reduce the importance of point measurements, (point measurements will in fact be employed in this effort through core scale measurements to establish the relationship on a small scale between geophysical, hydrological and microbial properties) but for purposes of three-dimensional distribution of properties at the field scale, volumetric measurements are desired.

. *Microbiological Processes and Scaling*

Microbiological processes are very heterogeneous in subsurface environments (Brockman and Murray, 1997a, b), with several order of magnitude differences in samples separated by centimeters to meters. In some environments, the majority of the samples lack the potential for a particular process and the process occurs in localized "hotspots", resulting in extremely skewed distributions (e.g., Brockman et al., 1997) and averaging scales that vary by at least 3 orders of magnitude (Brockman et al., 1996). The spatial heterogeneity in subsurface microbiological properties/processes can be handled by geostatistical sampling and analysis approaches (Brockman and Murray, 1997a, b), but requires large numbers of samples with specific spacing. An alternative approach is to determine the appropriate scale of averaging for a microbiological process. This requires an understanding of what general scale is appropriate for the scientific question or applied problem under investigation. For example, the most appropriate scales for studying global biogeochemical fluxes, bioremediation, dynamics of microbial colonization, and microbial alteration of physical properties would likely be the scales of ecosystem, geological strata, laminae/lenses, and pore network, respectively. Thus, for bioremediation, one can characterize material from the contaminated strata with increasing scales of measurement to determine the minimum scale at which variation around the mean stabilizes. The problem with this approach is that classic microbiological methods have an upper size range of tens of grams to a few kilograms. In the early 1990's the in situ respiration test was developed and applied for measuring biodegradation in hydrocarbon-contaminated unsaturated zones by injecting air and measuring use of oxygen over time (Hinchee 1994). This method interrogated porous media volumes on the order of cubic meters, providing effective volume averages for scaling microbial oxygen uptake (and through stochiometric relationships, hydrocarbon biodegradation) if performed in multiple locations at the site to incorporate long-range spatial variability. More recently, an analogous method has been employed in contaminated saturated zones by injecting soluble terminal electron acceptors (microbially reactive "tracers") and recovering groundwater after a reaction period to analyze use of the acceptor (Istok et al., 1997; Haggerty et al., 1998). To our knowledge the later method has not been applied for determining average values for microbiological processes within high-flow fracture networks, but would in theory be very useful if injected material can be recovered (i.e., fracture flow is not too fast and microbial kinetics are rapid enough). Likewise, the method may be useful for characterizing microbial processes in low permeability matrix regions which are known to serve as a contaminant reservoir at a contaminated site, although the ability to inject (advect or diffuse) and extract substrate may be limited to small volumes.

In the fractured rock system at TAN, mobile contaminants will be transported through high flow horizontal zones related to bedding features and partition into slow transport "matrix" regions. In matrix regions, contaminants may be immobilized by physical trapping/diffusional limitations or by chemical or microbial reactions. In the absence of these immobilization reactions in matrix regions, contaminants will re-encounter higher flow features when concentration gradients reverse (due to passage of the plume in fracture, or biodegradation of contaminant in rock adjacent to the fracture) or when contaminants are eventually transported with flow out of the matrix into faster flowing regions. Thus, from a biodegradation standpoint, it is critical to understand microbial processes occurring in fast flow regions, and matrix regions adjacent to fast flow regions if contaminant exists in the matrix. A 3-d understanding of contaminant distribution and the physical and hydrologic system identifies important locations to interrogate and characterize for microbial processes pertinent to bioremediation of a specific contaminant. Thus, geophysical methods of characterizing the physical and hydrologic system, and distribution of certain contaminants (e.g., DNAPL) are extremely valuable for developing informed and guided microbiological sampling and monitoring strategies.

Microbiological characterization at TAN has included characterization of cores, point groundwater samples, and a multilevel groundwater sampler. These approaches provided information that resulted in selection of anaerobic reductive dechlorination as the in situ bioremediation method of choice. During bioremediation, chemical analysis of ground water samples was used almost exclusively to assess bioremediation progress. While extremely useful for immediate monitoring of bioremediation success at the sampling location(s), this approach provides limited (or no) information for nearby low flow matrix regions and for high flow features away from the monitoring well(s). Because the number of monitoring wells is very limited due to depth and expense, and geophysical methods image over many tens of meters, geophysical methods potentially provide an important complementary characterization and monitoring capability. One of the major objectives of this proposal is to follow-up on observations made during our initial EMSP project which suggest that geophysical methods can detect the byproducts of microbial processes. If found to be true, geophysical methods would provide rapid, indirect, and nondestructive proxy measures for interpreting subsurface bioremediation at locations not being interrogated by monitoring wells. Such information would be invaluable for improving the ability to scale microbiological processes from point measurements (monitoring wells) to the field scale.

RESULTS

In addition to the work described here, more detailed information on the previous EMSP project can be found in Daley et al. 1997, 1998, 1999a, 1999b and Wood et al. 1997.

1. TAN Site Description

   Note: More detailed information can be found on the TAN site in Sorenson et. al. 1996, Bukowski and Sorenson 1998, Bukowski et. al. 1998.

   INEEL lies on the Eastern half of the Snake River Plain in southern Idaho. The geohydrologic framework has been described by Wood and Low (1984). A conceptual model of the subsurface geology is shown in Figure 1a. The eastern plain is underlain by Quaternary age basalt of the Snake River Group with some sedimentary interbedding. The basalt can be over 1.5 km thick. The eastern plain has a sequence of thin-layered basalt flows which can yield large volumes of groundwater. The groundwater at the Test Area North (TAN), is contaminated with trichloroethene (TCE), cesium-137 (137Cs) and strontium-90 (90Sr) from past disposal directly into the Snake River Plain Aquifer (SRPA). The SRPA is used regionally for drinking water and has been designated a sole source aquifer. A Record of Decision was signed in August 1995 to remediate groundwater to the maximum extent practicable, as part of the Federal Facility Agreement/Consent Order under the Comprehensive Environmental Response and Compliance Act. Currently bioremediation is the method that the ROD had chosen to remediate the site. Lactate is being injected in a well to provide nutrients for the microbes. The principal source of groundwater contamination at TAN is an injection well, which was used from 1953 to 1972, to dispose of waste into the fractured basalt of the Snake River Plain Aquifer. These wastes included organic sludge, treated sanitary sewage, process wastewater, and low-level radioactive waste streams. Historical records provide little definitive information on the types and volumes of organic wastes disposed via the injection well. These wastes were generated from a variety of programs such as efforts to develop a nuclear-powered aircraft and tests to simulate accidents involving the loss-of-coolant from nuclear reactors.

   The contaminated portion of the aquifer ranges from 200 to 400 feet below land surface and is approximately 1.7 miles long and 0.5 miles wide. Well logs indicate that the basalt is heterogeneous and varies from dense to highly vesicular and from massive to extensively fractured. A sedimentary interbed, which underlies the contaminated aquifer, acts as a barrier to downward migration of contaminants. The presence of dense non-aqueous phase liquids (DNAPLs) in the immediate vicinity of the injection well is suspected, (see plume location in Figure 1b) as suggested by the disposal history and the high concentrations (greater than 10% of the solubility limit for TCE). On the basis of available data, a conceptual model has been derived that includes a typical DNAPL behavior. The waste was injected under pressure into horizontal fractures until the well eventually became plugged. The DNAPL does not appear to have migrated very far from the injection well either vertically down or horizontally, or pooled on the top of the underlying low permeability interbed. We hypothesize that the DNAPL exists entrained in the sludge trapped around the injection well and that it is acting as a constant source of dissolved VOCs. There is also a possibility that radionuclide transport is being facilitated by colloids.

   A groundwater treatment facility consisting of carbon adsorption, air stripping, and ion exchange was constructed at TAN. Due to the tremendous volumes of secondary waste that were expected to be generated, alternative treatment technologies were considered several years ago (bioremediation was chosen) in order to minimize waste streams and greatly reduce the overall project costs (estimated at $30 million present value). In addition, the G-250 resin beads being used for ion exchange are not efficient at removing Sr90 and Csl37, particularly in the presence of calcium and magnesium. Five post-ROD treatability studies will be conducted over the next three years to determine whether there is a feasible alternative to conventional pump and treat. These treatability studies entail in situ bioremediation, reductive iron dechlorination, in situ chemical oxidation, natural attenuation, and monolithic confinement. At the same time, the project will keep abreast of new and emerging technologies to determine if a more cost-effective approach is feasible, and the project approach should be modified.

In summary, remediation of the groundwater below TAN presents an enormous technical challenge due to the great depths involved, the highly heterogeneous and fractured rock environment, and the presence of sludge and probable DNAPLs. While the primary objective is to remove the organic contaminants, treatability solutions should also address radionuclide removal in order to make the remediation effort truly effective.

2. Seismic Imaging Results

The main motivation for the original 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. Although surface seismic reflection imaging has been widely developed and used, the resolution is limited compared to the requirements of most remediation applications. Therefore, 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 (see above).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).

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. 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. 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. 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. Velocity and attenuation tomograms for the piezoelectric source data image apparent fracture flow zones with about 1 - 2 m resolution. 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. Guided waves are observed in zones inferred to have fracture flow.

Data Acquisition Methods

In November 1996, LBNL acquired seismic cross-well at the TAN site using a high frequency (1000 - 8000 Hz) piezoelectric source and borehole hydrophone sensors. The source and sensor spacing was 0.5 m from the water table (approximately 65 m) to 100 m (or to the well bottom). While piezoelectric data was obtained from 5 well pairs (Figure 1c) limited propagation distance of the high frequency waves (about 25 m maximum) restricted the area extent of our imaging. Other well pairs were attempted, but we did not obtain usable data. In addition to strict distance limitations (caused by spatially constant attenuation), localized high attenuation appeared to limit propagation between some well pairs. The piezoelectric source could only propagate usable energy about 20 m between wells, with some zones having poor data at well spacing of 10 -15 m.

In 1997 a new well was drilled with support for scientific studies including multi-level fluid sampling. Our desire to image around this new well, named TAN-37, led us to consider the orbital vibrator which has higher energy output and lower frequency than our piezoelectric source. While the lower frequency content (50 to 400 Hz) lowers the spatial resolution available, it also increases the propagation distance in material of a given attenuation. Orbital vibrator data was successfully acquired in two well pairs using TAN-37 as a source borehole (Figure 1c). We show here the results from the TAN-37 / TAN-25 well pair. The well spacing was 38 m. We also acquired test data between TAN-37 and TAN-31 showing usable energy at a distance of 57 m. The orbital vibrator did successfully extend the range of crosswell seismic surveys.

Piezoelectric Source Data

A typical crosswell fan (one sensor for all sources) from the piezoelectric source is shown in Figure 2a, along with a typical orbital vibrator fan from the same depth zone, Figure 2b. The first arrival times for each seismic trace (each source-receiver pair) are used for a tomographic inversion. The 2-D cross-section between wells is divided into 0.5 m square pixels and the seismic velocity is estimated in each pixel. The resolution of each pixel is dependent on the seismic ray density (Peterson, 1985). We do not think sedimentary interbeds are present because no coherent reflections are observed. We expect the sediment / basalt contact to be a laterally coherent reflector which would be observed in crosswell data. The TAN-31 / TAN-9 data set has also been inverted for attenuation. In this analysis the amplitude of the first arrival is computed for each seismic trace with sufficient signal-to-noise ratio. The 2-D cross section between wells is then divided into pixels and each pixel is inverted for amplitude attenuation in dB/m. Seismic amplitudes are affected by many factors including the velocity structure , but they can provide useful information in a fractured aquifer (Vasco, et. al., 1996). Figure 3a shows the attenuation and velocity tomograms for the TAN-31(GRW)/ TAN-9 well pair. Both tomograms show horizontal features with low velocity associated with high attenuation, as predicted by most models of seismic wave propagation in fractures. The resolution of features in both tomograms is on the order of 1 to 2 m. m We had hoped that the tomograms (all within - 40 m) would have similar features related to basalt flows, fracture zones or sedimentary interbeds. However, the tomographic images are not consistent. For example TAN-31 / TAN-9 (Figure 3a) shows a horizontal feature at 74 m depth, but TAN-25 / TAN-26 does not show the same feature. We believe the variation in tomograms represents heterogeneity in the subsurface, most likely in the fracture properties.

Orbital Vibrator Source Data

Our desire to extend the TAN site imaging to the scientific well TAN-37 (interwell imaging distance of nearly 40 m) led to use the orbital vibrator source. The orbital vibrator was developed by Conoco, Inc. as part of oil exploration research in borehole seismic sources and the orbital vibrator technology was later transferred to LBNL. The orbital vibrator propagated P-waves up to 60 m distance in the fractured basalt aquifer, significantly farther than a piezoelectric source used at the same site (albeit with a lower frequency band than the piezoelectric source). The frequency range of the orbital vibrator is 70 to 400 Hz. The DC powered version of the orbital vibrator runs on a standard 7-conductor armored cable.

This test of the orbital vibrator in the fractured basalt aquifer of the TAN site proved successful in acquiring P- and S-wave tomography data using fluid coupled hydrophone sensors. Figure 2b shows sample seismograms. Because the source is also fluid coupled, (with no clamping required) data acquisition within aquifers is efficient. The high amplitude of S-waves generated can overcome the reduced sensitivity of hydrophones to S-waves. The use of multi-level hydrophone sensors means that the orbital vibrator source can acquire simultaneous P- and S-wave data quickly and at reduced cost compared to borehole clamping sources and sensors.

The operating principle of the orbital vibrator is rotation of an eccentric mass, in the horizontal plane, at increasing speeds, generating a swept frequency signal. The source is swept clockwise and counter-clockwise at each source location. The processing of orbital vibrator data is unique because the source generates circularly polarized seismic waves. The waves are linearized via superposition of clockwise and counter-clockwise polarizations (Daley and Cox, 1999). The linearized data is then decomposed into in-line and cross-line data sets by eigen vector analysis of the 2-component P-wave arrival. The in-line data set is primarily P-wave and the cross-line data set is primarily S-wave. Figure 2b shows an example of the resulting seismograms.

Orbital vibrator crosswell data was acquired for two well pairs, a set of P and S-wave tomograms was then generated for wells TAN-37 / TAN-25. These tomograms (shown in Figure 4) were computed using an LSQR algorithm. We find good general agreement between P- and S-wave tomograms, with a low velocity region above 78 m.

A significant result of the orbital vibrator survey was demonstration of S-wave crosswell propagation with fluid coupled sources and sensors. With the acquisition of an S-wave crosswell survey, in addition to the standard P-wave survey, significant additional information about subsurface materials can be inferred. The ability to use fluid coupled sensors (such as multi-level strings of hydrophones) means that crosswell imaging is more economic for environmental and engineering applications. The orbital vibrator is a lower frequency source (50 - 400 Hz, vs 800 - 8000 Hz for our piezoelectric source) so the spatial resolution is reduced, but the propagation distance is increased. In our work we have shown that the orbital vibrator can be used to obtain P- and S-wave arrivals in fractured basalt, a media with generally poor seismic propagation, and we compare the results to a high frequency piezoelectric seismic source. Crosswell Results and Interpretation

Results and Interpretations

High quality P- and S-wave arrivals were obtained at the TAN site over much of the 65 to 100 m survey depths. 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. 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 4 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 Figure 3a 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 orb ital vibrator data include apparent guided wave energy at 73.5 to 74.5 m depths (Figure 5).

One of the results that led us to the conclusion that we may be detecting by-products of microbial products is shown in Figure 3b. 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.
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. 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.

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. High amplitude guided waves were observed and were coincident with an interpreted contaminant flow zone. We believe the guided waves are caused by low velocity zones and define the thickness of the zone within 1- 2 m. This observation provides much better resolution than velocity tomograms for the orbital vibrator source. The combination of piezoelectric data for closer well spacing and orbital vibrator for larger well spacings has provided optimal imaging capability.

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. 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 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 N_2 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.

3. Microbiology Results

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). Dr. Majer worked in very close collaboration with Dr. Colwell's project throughout the 3 years. Thus, both co-PI's contributed directly to the total scientific effort at TAN, but the contributions of Dr. Majer and Dr. Brockman were not directly linked as originally proposed.

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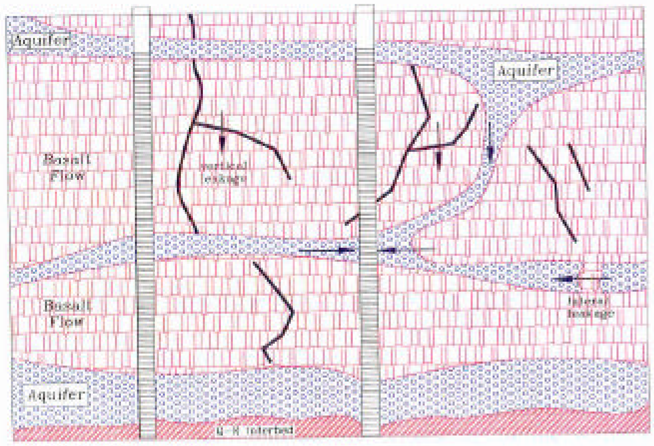

Figure 1a. Conceptual model of multi-layered aquifer underlying TAN (not drawn to scale). From Bukowski et.al., 1998.

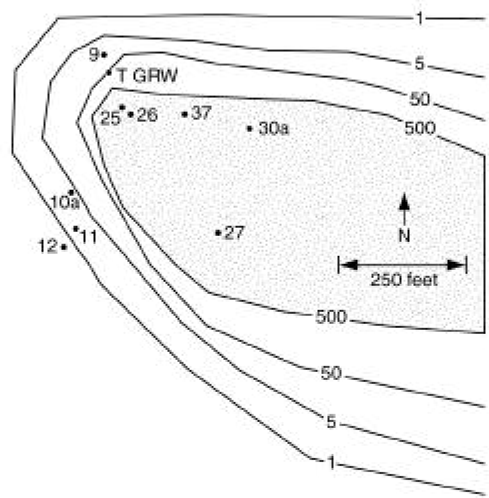

Figure 1b. Wells used for cross-well imaging at the TAN site relative to the DNAPL plume, units of contour are µg/L.

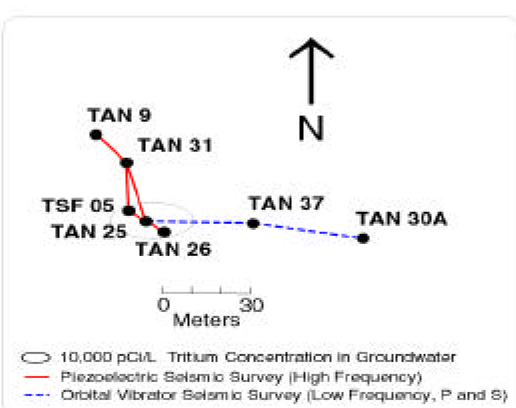

Figure 1 Well locations at the INEEL TAN site. Contaminant concentration contour is approximate. Other attempted crosswell surveys are not shown.

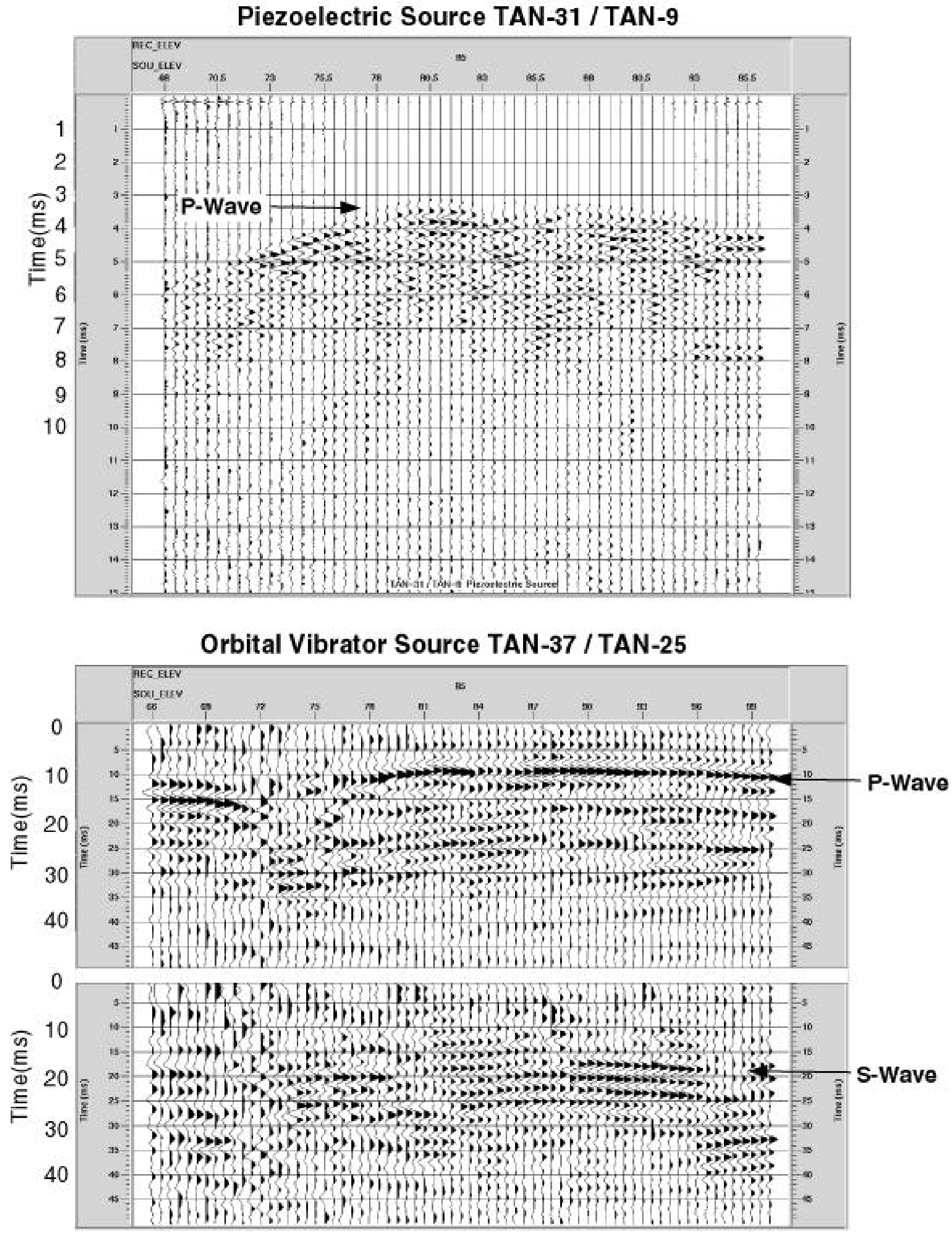

Figure 2a (top) and 2b (bottom) Receiver gathers for the two seismic sources. The receiver depth is 85 m, the source depths are 66 to 100 m. The orbital vibrator data (bottom) contains in-line (P-wave) and cross-line (S-wave) components.

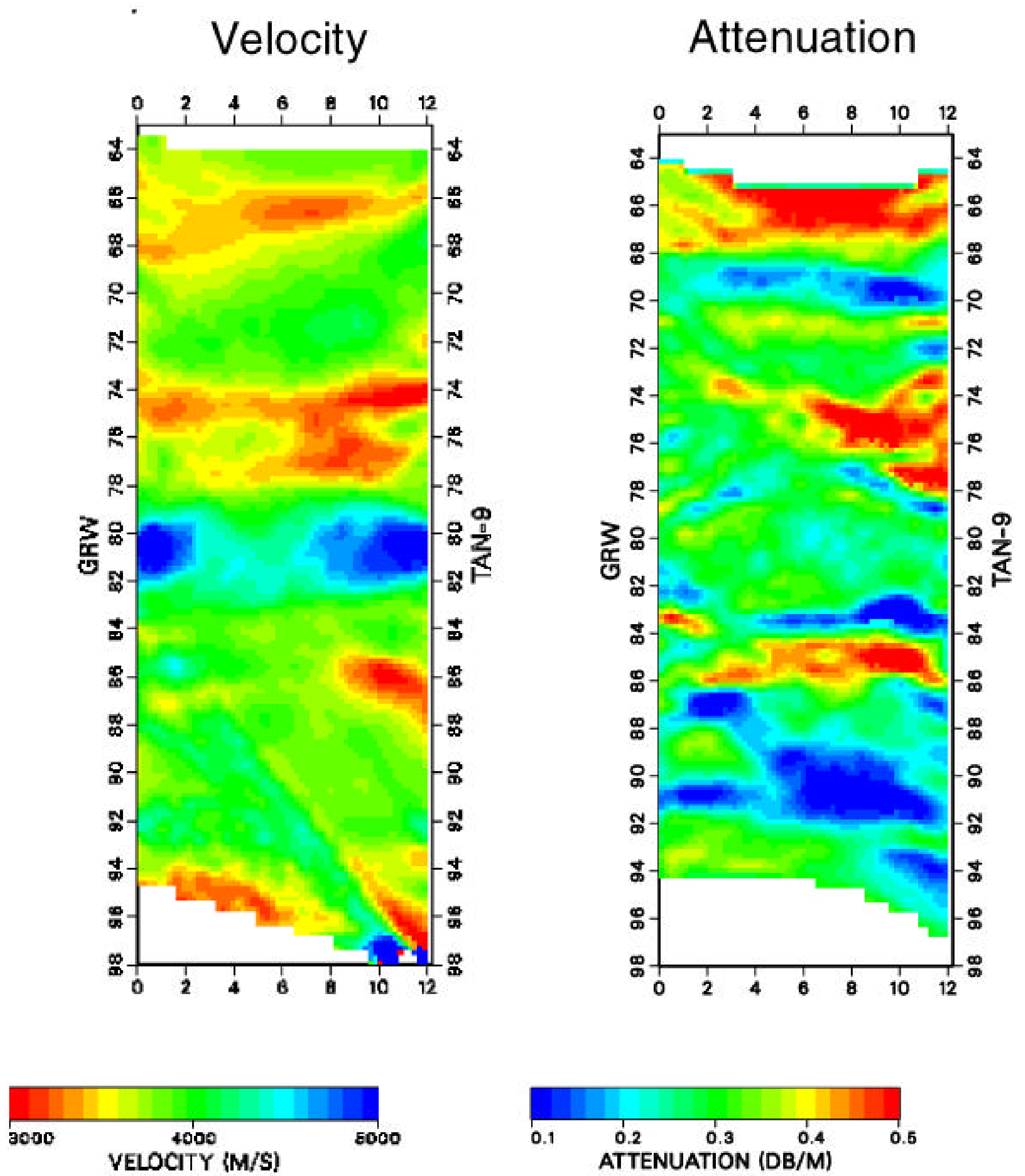

Figure 3 Seismic tomographic inversion results for well pair TAN-31 / TAN-9. This data used the high frequency piezoelectric source giving 1- 2 m resolution. Zones of low velocity and high attenuation (such as 73 - 76 m, and 65 - 67 m) are interpreted as fracture zones which provide fluid flow zones for contaminant transport.

TAN Site Piezoelectric Source Tomograms
P-Wave Velocity Interpreted for Flow and Barrier Zones

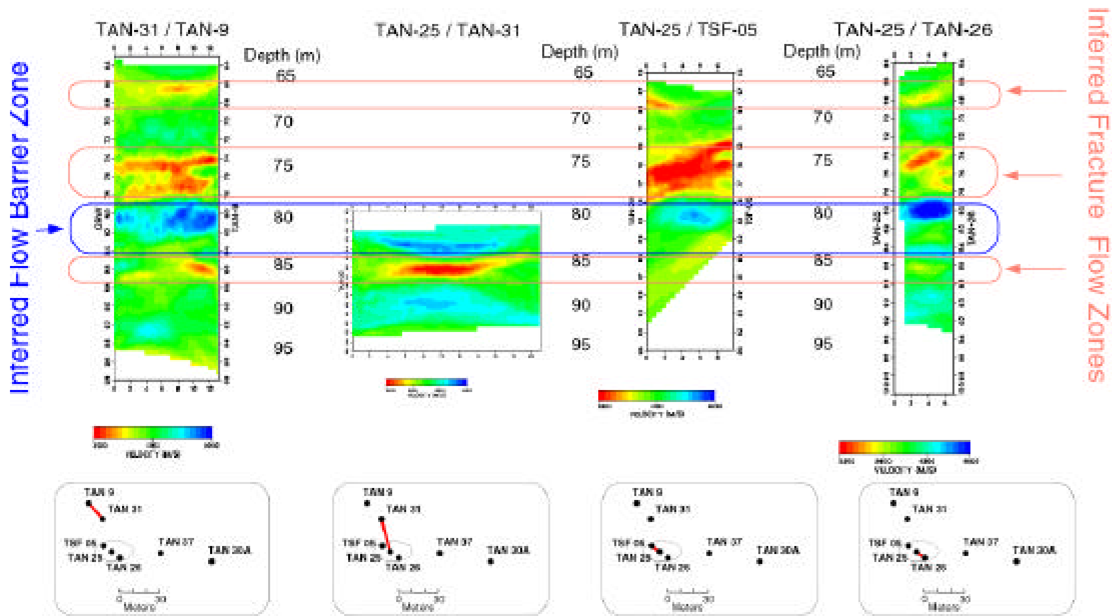

Figure 3b Seismic Velocity tomograms interpreted for hydrologic flow and barrier zones. High velocity (blue) corresponds to dense, unfractured basalt. Low velocity (red) corresponds to fractured basalt or interflow rubble zones. The upper portion of the TAN-25 / TAN-31 tomogram is missing because of anomalously high attenuation.

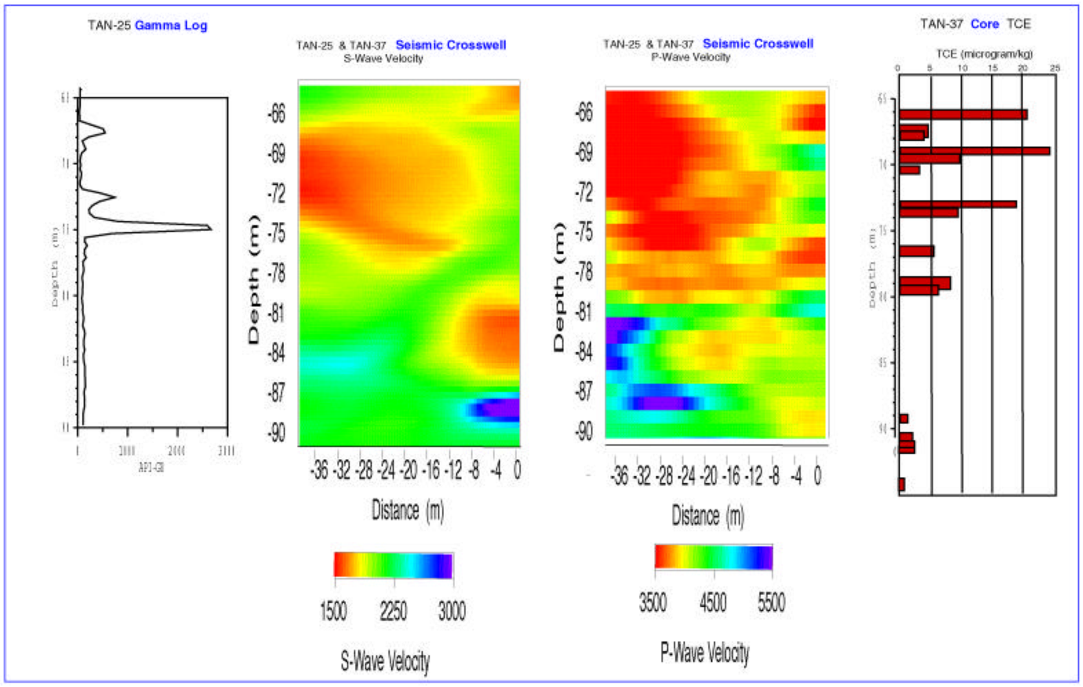

Figure 4 Comparison of contaminant sampling in boreholes and croswell velocity tomogram. TAN-25 Gamma Log (left) indicates presence of radionuclide contamination. TAN-37 TCE contamination from core measurement (right) indicates TCE concentration. Seismic S-Wave and P-Wave velocity (center) indicates 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.

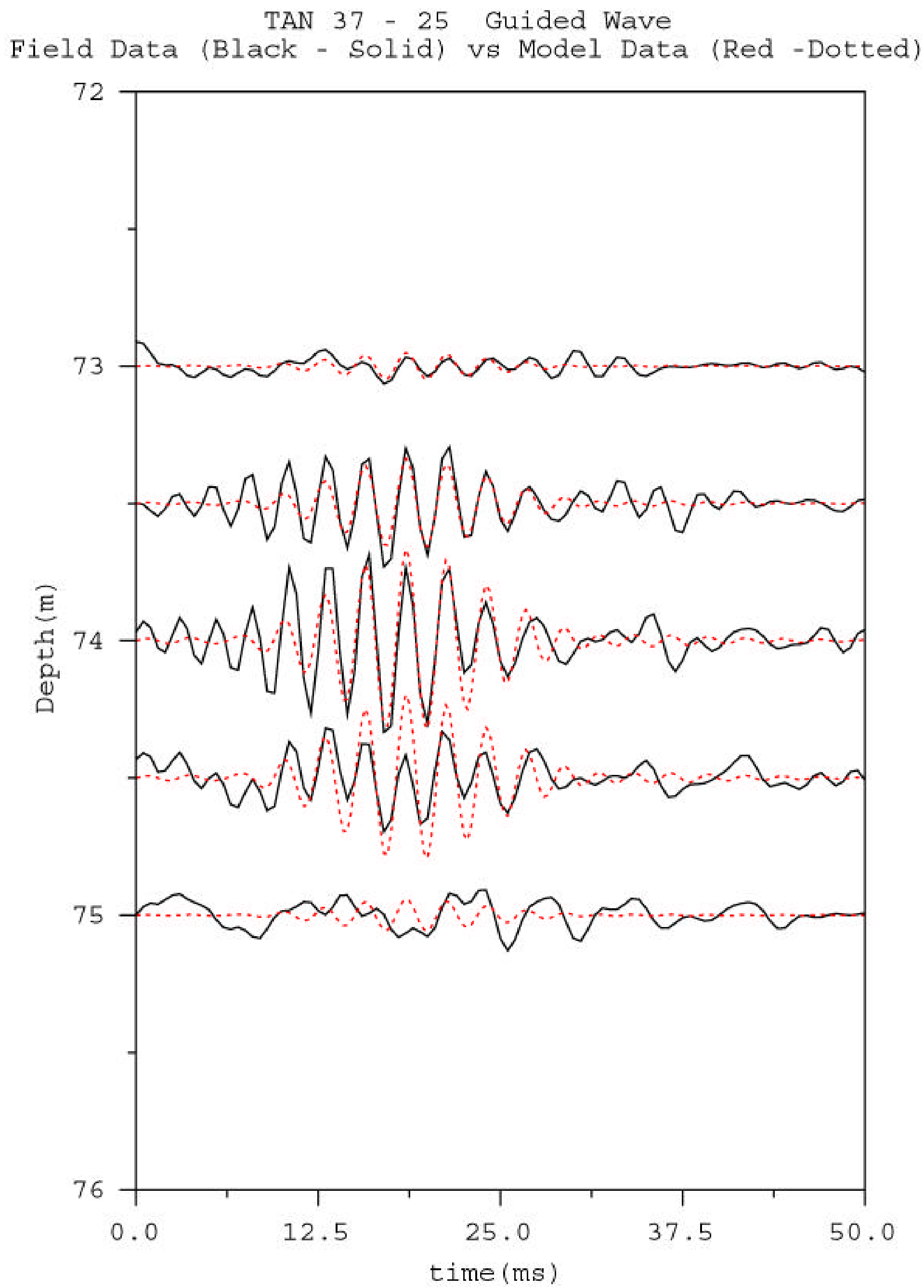

Figure 5 Recorded seismograms (solid line) interpreted as guided wave energy in crosswell seismic data between wells TAN-37 and TAN-25. The data was modeled using a finite-difference acoustic wave equation solution (dotted line). The model was a 1 m thick low velocity zone, centered at 74 m, continuous between wells. The modeling supports the interpretation of a hydrologically important interbed flow zone acting as a seismic wave guide.