First Field Test of NAPL Detection with High Resolution Borehole Seismic Imaging

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Abstract

The purpose of this field test is to evaluate the detectability of NAPLs by high resolution tomographic borehole seismic imaging. The site is a former Department of Energy (DOE) manufacturing facility in Pinellas County, Florida. Cross–hole seismic and radar measurements were made in a shallow aquifer contaminated with non–aqueous phase liquids (NAPLs). Cone penetration test (CPT) and induction logging were performed for lithology and conductivity, respectively. The main challenge is to distinguish fluid phase heterogeneities from anomalies arising from geologic structure. Our approach is to compare measurements between locations of known contamination with a nearby uncontaminated location of similar lithology where differences in signal transmission may be attributed to fluid phase changes. The CPT data show similar lithologic structure at the locations both within and outside the NAPL–contaminated area.. Zones of low seismic amplitude at about 7 m depth appear more extensive in the NAPL–contaminated area. These zones may be the result of fluid phase heterogeneities (NAPL or gas), or they may be due to the lithology, i.e. attenuating nature of the layer itself, or the transition between two distinct layers. The presence of lithologic contrasts, specifically from higher pemeability sands to lower permeability silts and clays, also indicate potential locations of NAPL, as they could be flow barriers to downward NAPL migration.

1. INTRODUCTION

Over the last 15 years LBNL's Earth Sciences Division has developed a high resolution tomographic borehole seismic system to image small–scale structural features which are not detected by exploration seismic methods. The travel time and amplitude attributes are a function of the physical properties of the medium through which the wave travels. Relationships between the attributes and properties of interest can be applied for the desired characterization. This paper presents a new application currently under development – to detect and characterize non–aqueous phase liquid (NAPL) contamination in sedimentary aquifers. Successful high–resolution characterization would define the irregular distribution of NAPL source zone, thus significantly reducing the final cost of remediation by accurately targeting source areas for treatment. The method could also be applied to monitoring remediation and determining efficacy of treatment.

Laboratory tests have demonstrated the sensitivity of P–wave transmission to the presence of NAPL contaminants in sand at the centimeter and half–meter scale.[1, 2] In unconsolidated media, the contrast in the acoustic velocity between water and NAPLs results in slower velocities and smaller amplitudes as NAPL saturation increases.

We are currently testing this technique at the field–scale. The main challenge is to distinguish fluid phase heterogeneities from anomalies arising from geologic structure. Our approach is to compare measurements between locations of known contamination with a nearby uncontaminated location. Other characterization data, such as crosswell radar, borehole conductivity and cone penetration testing (CPT) support interpretation. NAPLs typically have low dielectric permittivity and electrical conductivity relative to water, and consequently radar velocities and amplitudes are expected to increase as NAPL saturation increases. Radar signals also respond to lithology changes. Velocities decrease with increasing porosity of water–saturated media. Radar attenuation increases with increasing electrical conductivity, caused by clays and/or high ionic strength water.

2. WORK DESCRIPTION

Measurements were made at the Northeast Site of the Pinellas Science, Technology, and Research (STAR) Center, in Largo, Pinellas County, Florida. From 1956 to 1994, the STAR Center, currently owned by Pinellas County, was a Department of Energy (DOE) facility for manufacturing neutron generators and other electronic and mechanical components for nuclear weapons. The Northeast Site was used for storage of waste solvent and resin drums, and construction debris.

The surficial aquifer at the site is a heterogeneous distribution of beach–type deposits, including fine sands with variable shell content, and silty and clayey sands. The water table depth is about 2 m below ground surface and the aquifer is approximately 9 m deep. The Hawthorn Group, an 18 to 21 m thick confining layer, underlies the surficial aquifer. Below the Hawthorn Group is the Floridian Aquifer, a limestone formation, which is an important regional groundwater resource.

The map in Figure 1 shows one part of the site identified to have NAPL contamination, as determined by soil sampling and analyses performed by DOE and their contractors.[3,4] NAPL has also been directly observed in the wells shown in blue and sampled in the red wells. The NAPL contaminants include trichloroethylene (TCE), toluene, methylene chloride ($MeCl_2$) and oil. TCE has been detected near the top of the Hawthorn Group; no contamination has reached the Floridian Aquifer.

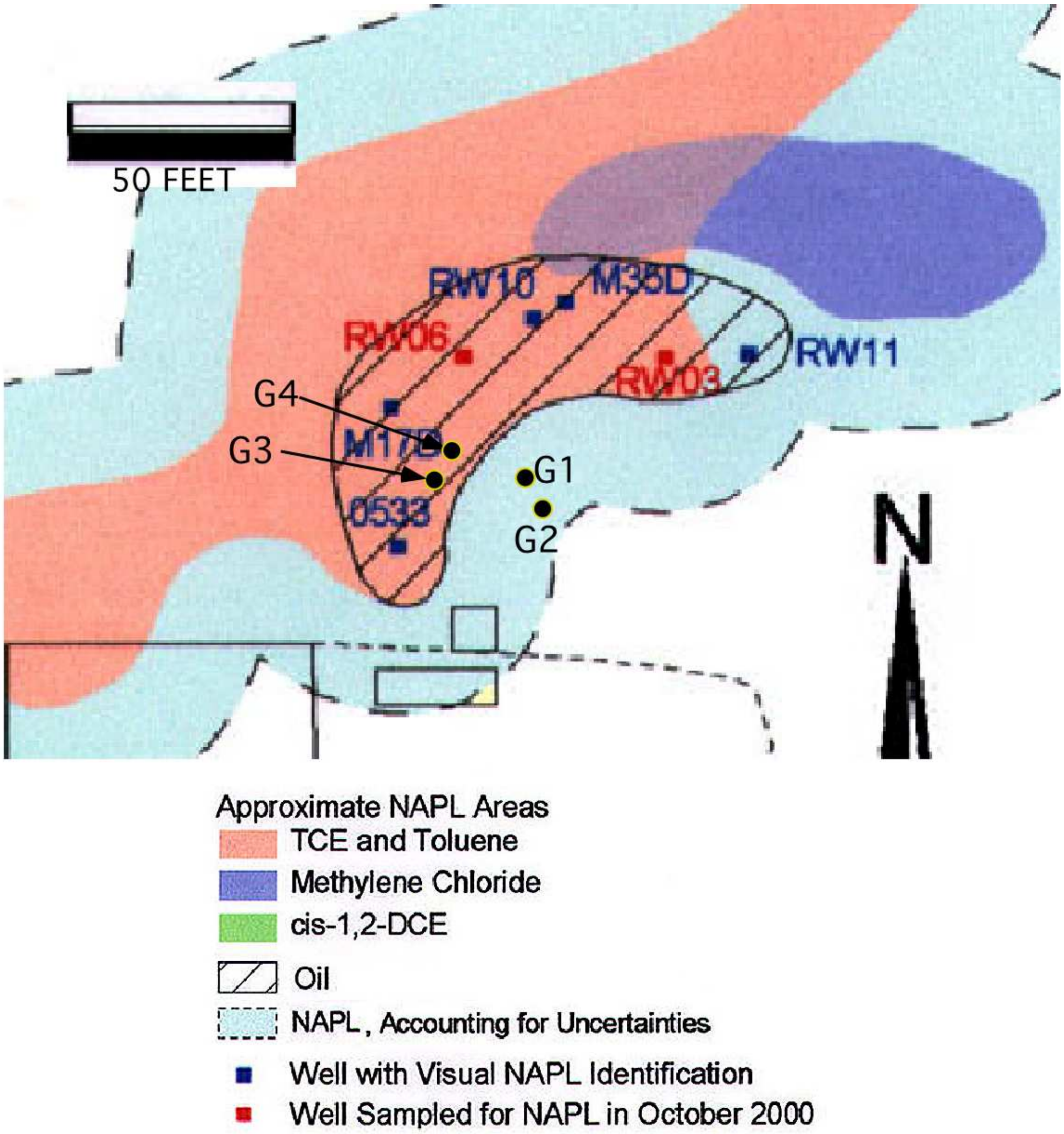


Figure 1. South NAPL area at Northeast site, Pinellas STAR Center.

Figure 1 also shows the locations of survey boreholes within the NAPL area (G3–G4) and at a nearby location in a zone identified as "uncertain" (G1–G2). The boreholes are 2" ID, PVC–cased, 10 m deep and were installed with a CPT rig.

Seismic surveys were performed with a 1.5" piezoelectric source transducer and a 24–element hydrophone string receiver. The radar surveys were performed with a PulseEKKO100 borehole ground penetrating radar system (Sensors and Software, Inc.), with both 100 MHz and 200 MHz borehole antennas. Conductivity logs were taken with a Geonics, Corp. EM–39 electrical conductivity logger. CPT logs of sleeve and tip friction, and water pressure, were obtained in G2 and G4, before the casing was installed, and used to derive lithology. Measurements in boreholes in other locations of the site are described elsewhere.[5]

3. RESULTS

P−wave velocities for various fluids and solids are shown in Table I. NAPLs and air have significant velocity contrasts with water. The reflection coefficient of different NAPL−water pairs varies; lab measurements to−date suggest that scattering of transmitted waves will be more significant for the NAPL−water pairs that have higher reflection coefficients.

Table I. Contrast in P−wave transmission through water and NAPL contaminants

	acoustic velocity (km/s)	density (kg/m3)	acoustic impedance (kg/m^2−s)	bulk modulus (MPa)	reflection coefficient [1]
Fluids					from water to NAPL
Air	0.344[2	1.293	4.447E+02	0.153	9.99E−01
water	1.47[2]	997	1.493E+06	2234	−−
toluene	1.321[3]	870	1.149E+06	1518	1.30E−01
methylene chloride (CH_2Cl_2)	1.080[3]	1335	1.442E+06	1557	1.74E−02
TCE	1.05[3]	1480	1.554E+06	1632	−2.02E−02

(1) a negative number indicates the polarization of the wave changes
(2) ref: http://www.ultrasonic.com/tables
(3) measured in our lab by pulse−transmission with 0.5 MHz contact transducers in a custom−built triaxial test cell
References for other data are available upon request.

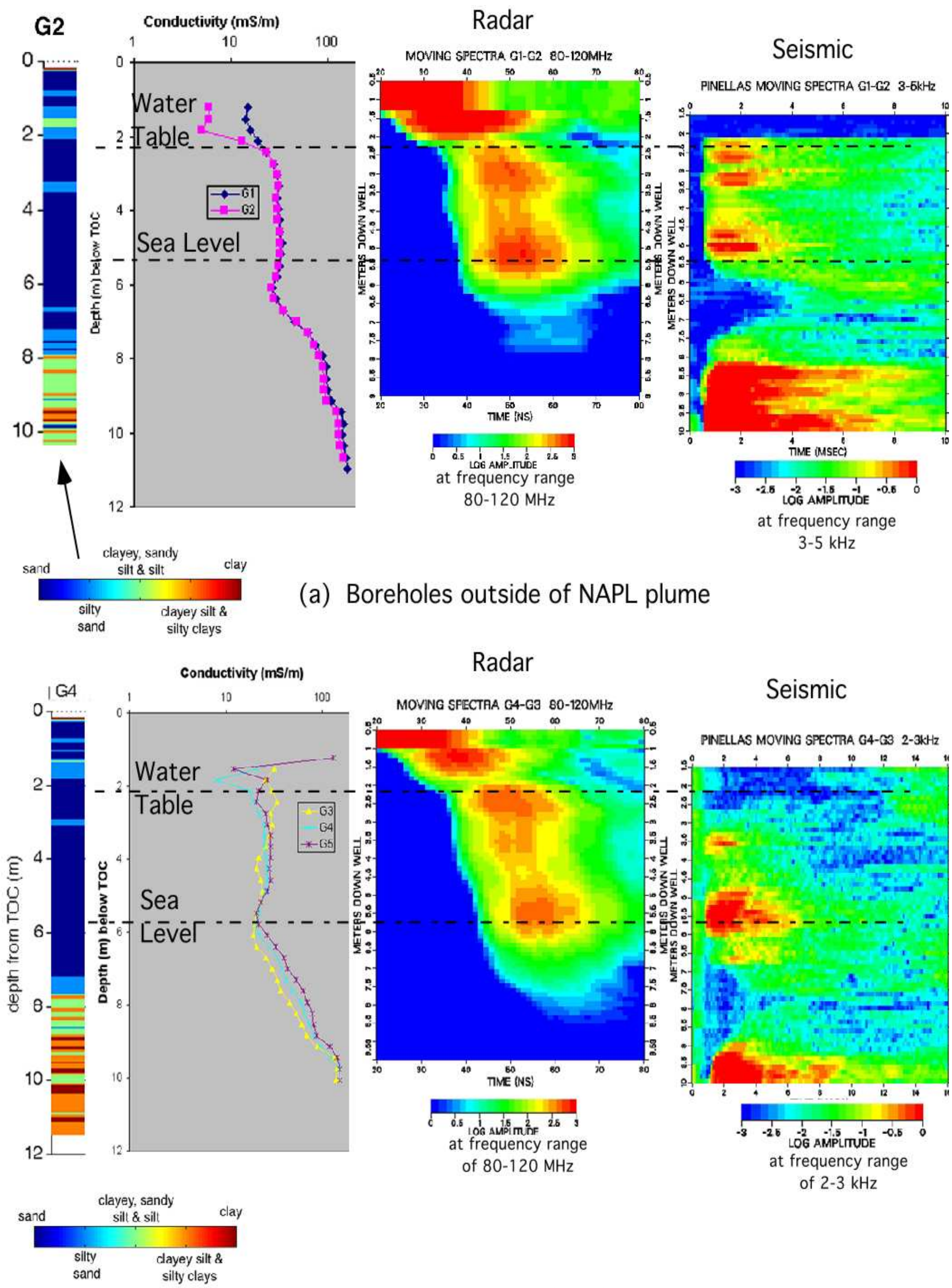
The field data is summarized in Figure 2. The lithology of G2 is similar to G4, with the upper 7 m consisting of sands with some silty−sand layers, which appear at almost the same depths at each location. This zone is referred to as the upper surficial aquifer. The lower surficial aquifer begins at around 6 m depth. Borehole electrical conductivity logs show an increasing trend in conductivity at this depth (near sea level). The G1 and G2 conductivity logs are almost identical, while values vary between G3 and G4.

The crosshole seismic and radar data are displayed as vertical distribution of amplitudes along the time axis of the received wave, called moving spectra. These amplitudes are bounded within a given frequency range and are computed from the zero−offset waveforms (i.e. transmitter and receiver at the same depth.) There is no discretization in the horizontal direction.

The radar plot shows the water table at about 2.25 m, where arrival times sharply increase. Amplitudes are high through the sands, and decrease from the point where borehole electrical conductivity values increase, and finally disappear. Arrival times through the sands in the G3−G4 pair increase with depth due to the deviation of the borehole from vertical, attributed to the bowing of the CPT rod during installation. Radar velocities ranged from 0.057 to 0.070 m/ns.

In the seismic moving spectra for G1−G2, the upper half of the plot shows four discreet high amplitude layers. Just below the middle of the plot (at 6.5 m), there is a layer of almost no energy transmission, and very low velocity (much greater arrival times). This low energy layer occurs just above the silty−sands noted in the lithology and coincides with the beginning of increasing electrical conductivities and the top of the lower surficial aquifer. Below this is a high amplitude layer that corresponds to clayey, sandy silts. Seismic velocities at the site range from 1600 to 1800 m/s, which is typical for clays and sands. For 3 kHz frequency, this gives wavelengths on the order of 60 cm.

The seismic moving spectra plot for G3−G4 shows alternating high and low amplitude zones as in G1−G2, but the zone of low amplitude extends over a greater depth in G3−G4. Another zone of reduced energy transmission occurs at 4 m depth from TOC, which corresponds to a local minimum in conductivity in G3.



(a) Boreholes outside of NAPL plume

(b) Boreholes within NAPL plume

Figure 2. Borehole conductivity, lithology, and zero-offset radar and seismic crosshole data (a) G1-G2 (outside NAPL plume), (b) G3-G4 (within NAPL plume)

4. DISCUSSION AND CONCLUSIONS

The first field test provided important information regarding the seismic and radar transmission properties of the Northeast site and general geological structure. Tomographic imaging with this dataset was not derived due to low signal levels and uncertainty in hole deviation. Current work addresses these issues and data has been obtained to derive tomographic images (in progress.) The borehole and zero−offset data do indicate potential NAPL locations. The CPT data show similar lithologic structure at the locations both within and outside the area of detected NAPL contamination. The low amplitude seismic zones may be due fluid phase heterogeneities, to the attenuating nature of the layer itself, or the transition between two distinct layers. The lithology changes in the low amplitude zones, however the onset of increasing electrical conductivities with depth occurs above lithological transitions detected by the CPT. The presence of lithologic contrasts, specifically from higher pemeability sands to lower permeability silts and clays, also indicate potential locations of NAPL, as they could be flow barriers to downward NAPL migration.

Current efforts to discriminate between the possible causes of the low seismic amplitude zones.include interpretation of the new tomographic data sets, laboratory testing of core from the site and diagnostic modeling.

5. ACKNOWLEDGMENTS

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