U. S. DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

SUMMARY OF GEOPHYSICAL INVESTIGATIONS FOR DNAPL REMEDIATION AT SAVANNAH RIVER SITE, SOUTH CAROLINA

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INTRODUCTION

At Savannah River Site, South Carolina, the Westhinghouse Savannah River Company is remediating dense non-aqueous phase liquids (DNAPLs) that have contaminated the ground water at the Site. To make the remediation faster and less expensive, information about the location of DNAPL is needed; to assess the success of the remediation, information about removal of DNAPL as a free phase is needed. It is believed that some of the needed information for both applications can be obtained with geophysical methods. Because the Westhinghouse Savannah River Company needs advice about such geophysical methods, they developed a cooperative program with the former Branch of Geophysics, U. S. Geological Survey. This cooperative program was implemented formally via Modification No. A007 to Interagency Agreeement No. DE-AI09-91SR18222, which is between the U. S. Department of Energy and the U. S. Geological Survey.

The project was divided into three phases:

> Phase 1, Initial Feasibility Studies: Several field and laboratory studies were conducted to determine which geophysical method, if any, would be suitable for monitoring DNAPL remediation. If a method were found, then the project would immediately shift to Phase 3, Remediation Monitoring. Otherwise, the project would shift to Phase 2.
>
> Phase 2, Contingency Feasibility Studies: Additional field and laboratory studies that were different from those in Phase 1 would be conducted to find a suitable geophysical method. If a method were found, then the project would immediately shift to Phase 3.
>
> Phase 3, Field Monitoring During Remediation: The most suitable geophysical method would be used to monitor a field test of DNAPL remediation.

Some geophysical methods investigated during Phase 1 were successful, and so contingency feasibility studies (Phase 2) were not performed. One of the successful methods could have been used during remediation (Phase 3), but Westinghouse Savannah River Company did not perform a remediation test during the project. Consequently, the geophysicists conducted additional studies pertinent to DNAPL remediation at the Site.

This report summarizes the findings of Phase 1 and the additional studies pertinent to DNAPL remediation. Recommendations for future geophysical investigations are also given.

PHASE 1, INITIAL FEASIBILITY TESTING

Task (a) Interpretation of Existing Geophysical Log Data

Electrical resistivity logs display a decrease in resistivity within the saturated zone in certain sectors of the A/M area (Nelson and Kibler, 1996). Examination of groundwater chemistry and electrical conductivity reveals an association between nitrate ion and conductivity, and between nitrate ion and chlorinated hydrocarbons (Nelson and Kibler, 1995).

Groundwater in the A/M area is inherently quite fresh: its electrical conductivity is on the order of 20 μS/cm. This means that the conductivity of the groundwater is quite sensitive to the introduction of small amounts of solute. Water samples collected from screened wells at SRS show that conductivity varies from 20 to 3000 μS/cm; the high values result from two types of contamination: leaching of grout and introduction of nitrate ion. Water samples that contacted grout have conductivity values exceeding 300 μS/cm, occur in only a few wells, and are not of further interest here. Samples with conductivity ranging from 20 to 300 μS/cm have nitrate concentrations ranging from near zero to 25 mg/L. Nitrate ion concentration appears to be the dominant control on conductivity over this range. The nitrate ion is attributed to salt solutions codisposed with chlorinated hydrocarbon in the M-Area Settling Basin.

Within the saturated zone and within some sectors of the A/M area, the electrical resistivity from well logs and cone penetrometer runs exhibit a decrease in resistivity: the resistivity at the water table is on the order of 1000 Ω-m and over a depth range of 25 to 60 ft decreases roughly an order of magnitude. The resistivity decrease occurs in two wells immediately west of building 321-M (see maps in Figs. 11 and 12 of OFR 96-75). This decrease exists at least 4000 ft southwest of the Settling Basin, 1400 ft to the west, and 1000 ft to the east, and its extent in these directions is unknown due to lack of well control. It also extends about 800 ft to the northeast of the Settling Basin, where its boundary is well defined within the MHT-series of wells. It is unambiguously absent in the MSB-wells, farther northeast of the Settling Basin.

This observed gradient could be caused by an increase with depth either in the occurrence of smectite or in the nitrate concentration in groundwater. If smectite can be eliminated as a factor in controlling rock resistivity, then electrical resistivity can be used to track a nitrate plume in the A/M area.

Thus, examination of groundwater chemistry and electrical logs has resulted in four findings and one assumption.

> Finding 1: There is an association between nitrate ion and the concentration of chlorinated solvents.
>
> Finding 2: Nitrate ion controls the conductivity of groundwater in samples from the A/M area.

Finding 3: Electrical logs from cone penetrometer runs and from well logs show a resistivity decrease (conductivity increase) with depth below water table in certain sectors of the A/M area.

Finding 4: The resistivity decrease observed in the resistivity logs is compatible with the change in resistivity from low nitrate to high nitrate concentration (Nelson and Kibler, 1996, p. 5–8).

Assumption: The conductivity increase observed on the logs is due to groundwater conductivity and not to smectite. (The clay mineral smectite has high cation exchange properties and could cause the conductivity increase).

If these four findings and one assumption hold, then electrical resistivity logs can be used to map migration pathways (if the nitrate ion has segregated from the chlorinated solvents) or even the distribution of chlorinated solvents (if segregation has not occurred).

Task (b) Laboratory Studies of Electromagnetic Properties of M-Area Core

Laboratory measurements were never made because the equipment was unavailable. As a substitute for laboratory measurements, during 1997 we propose to conduct in situ measurements; these measurements will be made with a dielectric logging system and a high power, low frequency radar system. The objective of these measurements was to obtain detailed information about the variation in sediment properties near wells and in between them. Such information should help monitor DNAPL remediation. Additional information about the dielectric logging system is in the section "Monitoring DNAPL remediation with Dielectric Logging."

Task (c) Borehole Radar Monitoring During Remobilization Pump Test

For this feasibility test, water and DNAPL were supposed to be pumped from the wells on the north side of the M-Area Basin. Before, during, and after the pumping, borehole (cross-well) radar data were to be collected to confirm that changes associated with DNAPL movement could be detected. The pumping was not done because toxic chemicals (polychlorinated biphenyls) were found in the water extracted from some of these wells. Nonetheless, cross-well radar data were collected between the five wells on the north side of the M-Area Settling Basin, and the data were interpreted to determine whether this method has even the potential for monitoring remediation.

In the unsaturated zone, three statistical relations were developed by comparing the radar data, which were collected between wells MSB-3A and MSB-3B, to the average percentage of clay-size particles, which were measured in core extracted from well MSB-3B: (1) Where radar waves are present in the scans, the median percentage is 10. (2) Where radar waves are absent from the scans, the median percentage is 38. (3) The slowness of the radar waves is positively correlated to the logarithm of the percentage; the correlation coefficient (r) is 0.77. Using these three relations, the percentages of clay-size particles were predicted across the entire well cluster. These predictions show that the sediments are horizontally-layered and that the composition of the layers sometimes changes in the horizontal direction.

In the saturated zone, two statistical relations were developed by comparing the radar data, which were collected between wells MSB-3C and MSB-3B, to the average percentage of clay-size particles, which were measured in core extracted from well MSB-3B: (1) Where radar waves are present in the scans, the median percentage is 9. (2) Where radar waves are absent from the scans, the median percentage is 23. These two relations in conjuction with forward modeling were used to interpret the radar scans between 144 and 158 ft (depth), an interval contaminated with dense non-aqueous phase liquids. The results indicate that the sediments within this interval are horizontally-layered.

The findings of this feasibility test clearly show that crosswell radar data can be collected near the M-Area Settling Basin and that the attributes of the radar waves are strongly related to the geology. The detailed results of the feasibility test are in Ellefsen (1996b), and the wave theory, which was used to analyze the data from the feasibility test, is in Ellefsen (1996a). It is still not known, however, whether this method can be used to monitor remediation; this can be determined only with a field test.

Task (d) Laboratory Studies of Complex Resistivity (CR) and Clay-Organic Reactions

The goal of the laboratory tests was to determine if complex resistivity (CR) measurements could be used to detect differences in the electrical properties of non-contaminated and DNAPL-contaminated clays. To meet this goal, laboratory studies were conducted on samples collected from pre-drilled A/M area cores to determine the composition and electrical properties of the sediments present in the A/M area. The laboratory methods included X-ray diffraction (XRD) measurements, clay-organic reaction experiments and complex resistivity (CR) measurements. The laboratory studies were to be conducted in four stages including:

1. Determine the type and distribution of clay minerals present in the A/M area.

2. Determine if those clay minerals and the DNAPLs present at the A/M area formed clay-organic complexes.

3. Identify the CR spectral signature of clay-bearing A/M area sediments.

4. Determine if the CR spectra were modified by DNAPL exposure to provide a means of differentiating contaminated from non-contaminated A/M sediments.

Twenty two core samples were collected and analyzed to determine the composition and electrical properties of clay bearing sediments. The core samples were obtained from 4 drillholes (MSB-3B, MHT-17C, MHT-20C and MSB-79C) in the A/M area. The core samples were analyzed using X-ray diffraction (XRD) techniques to determine the type of clay minerals present. Clay minerals identified in the core samples include kaolinite, illite, smectite, and possibly vermiculite. Halloysite, although reported at SRS, was not observed.

Kaolinite and illite were the most commonly observed clays in the A/M area samples. Kaolinite was observed in all 22 core samples and was generally the most abundant clay in a given sample. Illite was observed in 21 of the samples; however, it is thought to occur in relatively small amounts. Swelling clays were observed in 9 samples. The swelling clays include smectite and possibly vermiculite. Horton (section 1, 1996) gives the results of the XRD analysis.

Clay-organic experiments were conducted to determine if the clay minerals present at A/M area reacted with the solvents present at A/M area (PCE and TCE) to form interlayer clay-organic complexes. Reference clay standards and 6 A/M area cores samples containing swelling clays were exposed to PCE and TCE then analyzed using XRD techniques. The samples were exposed to both liquid-phase and vapor-phase solvents. In addition, a halloysite-isopropyl alcohol experiment was conducted to determine if the alcohol would dehydrate the clay and collapse its crystal structure.

The kaolinite and illite clays did not appear to form clay-organic complexes. However, the two smectite reference clays (Na- and Ca-montmorillonites) and 4 A/M area samples did form interlayer clay-organic complexes as indicated by an increase in d-spacing. Four A/M samples reacted with TCE; one of the four reacted with PCE. The clays that did react with the solvents, did so with both liquid- and vapor-phase exposures. The results of the halloysite-isopropyl alcohol experiment determined that alcohol exposure does not collapse the 10Å halloysite structure. Horton (section 2, 1996) gives the results of the clay-organic reaction experiments.

Complex resistivity (CR) measurements were also made on the A/M area samples. The purpose of the CR measurements was to characterize the electrical properties of the A/M area sediments, and determine if CR measurements could be used to differentiate contaminated from non-contaminated sediments. All samples were measured in their "as received" condition. In addition, the resistivity of some samples was measured as a function of water weight percent.

The resistivities of the samples, in their "as received" condition, range from 30 to 18,500 Ω-m. The resistivities vary due to the amount of water present in the samples and due to different sediment composition. In general, dry samples had the highest resistivities. The CR data indicate that the type of clay has a greater effect on the sample's resistivity than the amount of clay. Samples containing swelling clay minerals generally have lower resistivities than samples not containing swelling clay minerals.

The final stage of the laboratory studies, to determine if the electrical properties of the A/M sediments were modified by DNAPL exposure, was not conducted. Phase 1 projects, the initial feasibility studies of the SRS geophysical project, were reviewed and a decision was made to discontinue the CR laboratory studies. Therefore, CR measurements of A/M area sediments exposed to PCE and TCE were not made. Horton (section 3, 1996) gives the results of the CR measurements of A/M area sediments in their "as received" condition. The "as received" measurements provide baseline CR data for comparison with water saturated and DNAPL exposed measurements, should they be made in the future.

Because the laboratory studies were not completed, we have not determined if CR measurements can be used to differentiate contaminated from non-contaminated A/M area sediments, or if CR measurements can be used to monitor remediation progress. However, the laboratory studies have determined that some A/M area clay-bearing sediments do react with the solvents present, forming interlayer complexes. Interlayer complexes result from both liquid-and vapor-phase exposures. These findings could have implications regarding DNAPL remediation: In the vadose zone, DNAPL vapors may be demobilized when they come in contact with reactive clays. DNAPL molecules bound within the interlayer spaces of a clay may require additional energy to be remobilized for site remediation. When evaluating potential remediation techniques, the clay's ability to form interlayer complexes with the DNAPL should be considered.

Task (e) Borehole Seismic Feasibility Test

The goal of the feasibility test was to determine whether stratigraphy could be mapped between wells in both hydrologic zones. In the unsaturated zone, two different configurations were used: sources on the surface and receivers in a fluid-filled monitoring well (surface-to-well geometry), and sources and receivers in two fluid-filled monitoring wells (cross-well geometry). In the saturated zone, only the cross-well geometry was used. The findings are summarized in Table 1.

Hydrologic Zone	Configuration	Findings			Feasibility for mapping stratigraphy
		Smallest heterogeneity that was resolved (ft)	Correlation between clay-size fraction and *P*-wave velocities	Other	
unsaturated	surface-to-well	10	poor		unsuitable
unsaturated	cross-well	3	excellent	severe attenuation and dispersion	suitable if wells are close together
saturated	cross-well	3	moderate	only moderate attenuation and dispersion	suitable

Table 1. The findings of the borehole seismic (seismic tomography) feasibility test.

In the unsaturated zone with the surface-to-well geometry, seismic tomography cannot be used for mapping stratigraphy because the resolution, 10 ft, is much greater than the thickness of the major sedimentary layers. The poor resolution is the cause of the poor correlation between the clay-size fraction and the velocities. In the unsaturated zone with the cross-well geometry, seismic tomography can be used for detailed mapping of stratigraphy because the resolution is high and the correlation is excellent. The wells, however, must be close together (that is, within approximately 20 ft) because of the severe attenuation. In the saturated zone with the cross-well geometry, seismic tomography can be used for detailed mapping of stratigraphy because the resolution is high and the correlation is moderate. The distance between the wells can probably be greater than that used in the test (approximately 30 ft) because the attenuation of the wave is only moderate. The detailed results of the feasibility test are in Ellefsen (1995).

ADDITIONAL STUDIES RELEVANT TO DNAPL REMEDIATION

Application of Geophysical Logs in the Unsaturated Zone

Logs from the MHT-series of holes, collected during the Integrated Demonstration Program and comprising the most complete set of logs, were evaluated in detail. Borehole corrections and smoothing filters were applied to the neutron, density, gamma-ray, and electrical logs. Partially saturated sands can be recognized from combinations of the neutron and density logs or from resistivity and density logs. Porosity and saturation were calculated from the density and resistivity log (despite the unusually high water resistivity values), and a clay flag (that is, an indicator of clay-rich sediments) from the neutron and resistivity logs.

The calculated logs suggest a three-way partition of vadose zone lithologies into clay-rich, high-silt/low-clay, and partially saturated sand zones. Clay-rich zones are delineated by low resistivity or high neutron porosity or both. High-silt/low-clay zones occur where resistivity values are moderate and where the rock is saturated or nearly so. Partially saturated sand occurs where saturation is less than 1 — where moisture content is less than vadose-zone porosity. This three-way division of the vadose zone is believed to be important in terms of contaminant, water, and gas transport.

A complete set of well logs, fully analyzed in conjunction with cuttings data, is of great help in delineating the transport properties of sediments in the unsaturated zone.

Monitoring DNAPL Remediation with the Cross-well (Borehole) Seismic Method

The goal of this investigation was to detemine whether the cross-well seismic method could be used to directly image the thin layers containing DNAPL, which are found near the M-Area Basin. To this end, the seismic frequencies that would be needed to resolve a thin layer were calculated. To resolve a layer 0.10 m thick in the unsaturated zone when the spacing between the wells is 10 m, the minimum required frequency is 6 kHz when using diffraction tomography and is 8 kHz when using travel time tomography. (This frequency for travel time tomography pertains to the region near the well; the frequency needed to resolve a 0.10 m layer halfway between the wells is much higher.) The required frequency increases significantly as the thickness of the layer decreases. The results for the saturated zone show the same trends except that the required frequencies are much higher.

The necessity for high frequencies presents two significant problems. First, the frequencies generated by most modern seismic sources are too low (generally less than 6 kHz) to resolve the thin layers containing DNAPL. Second, the attenuation at the frequencies needed to resolve the thin layers is very, very high — in the field, the high frequency components in a seismic wave would not propagate more than a few meters. Because of these problems, the cross-well seismic method at its current state of technological development appears to be unsuitable for imaging the thin layers containing DNAPL. Addition details of this investigation are in Appendix A.

Effect of DNAPL Remediation on the Travel Time of Radar Waves

The goal of this investigation was to determine how DNAPL remediation would affect the travel time of radar waves. To this end, the effects of the remediation were estimated using a volumetric mixing law for the dielectric permittivity. The effects, if any, that the remediation process might have on the mineralogy of the clays, are not known and so were not included in the calculations. For the unsaturated zone, it was assumed that during remediation free water and DNAPL will be removed from the sediments. It was assumed that after remediation all free water will eventually return and that some additional free water will be in those pores formerly occupied by DNAPL. Consequently, the travel time of the radar wave will increase approximately 4 to 8%. The increase will be greatest in the clayey sediments because the concentration of DNAPL is greatest there. For the saturated zone, it was assumed that after remediation free water will have replaced the DNAPL. Consequently the travel time of the radar wave will increase approximately 0 to 20%; the percentage increase is proportional to the amount of DNAPL that was originally present.

Even though the estimated, relative changes in the travel times are large, these changes pertain only to a representative volume of sediment, which, for example, might be a very thin layer. The changes that would be measured from field data depend upon the concentration of DNAPL and the volume it occupies. Because this information is unknown at this time, the effect on the field data is also unknown: Only a field test will indicate whether cross-well radar is suitable for monitoring DNAPL remediation. Additional details regarding this investigation are in Appendix B.

Monitoring DNAPL Remediation with Dielectric Logging

Because polychlorinated biphenyls are in the wells on the north side of the M-Area Basin, dielectric logging was not permitted during the alcohol injection/recovery experiments. As a substitute, we propose to log uncontaminated wells during Fiscal Year 1997. These logging measurements will indicate how the electromagnetic properties of the sediments, pore fluids, and grout change with depth. If the changes for the grout are small, then we hope to find a empirical correlation between an attribute of the electromagnetic wave and previously measured properties like the fraction of clay-size particles. Such information will help map the stratigraphy in between wells and help monitor DNAPL remediation near wells.

RECOMMENDATIONS

Water Chemistry

In existing wells that are cased with polyvinyl chloride plastic and that a resistivity decrease, we recommend that an induction log be used in a monitoring mode: A sequence of induction logs acquired twice per year, or perhaps when water from the screened intervals is sampled, can be used to monitor the migration of the nitrate plume. With cessation of nitrate input and continued infiltration of rain water from the unsaturated zone, changes in the resistivity profiles in these wells should be observed if nitrate concentration controls the resistivity.

We recommend further investigation into the issue of smectite occurrence and distribution within the saturated zone. Mineralogical investigation should include measurement of cation exchange capacity as well as quantititative x-ray diffraction work. Sampling should be carried out using the map of wells containing the negative resistivity gradient.

Beyond the wells, the resistivity decrease might be mapped inexpensively using surface measurements of electrical conductivity. These measurements might be made with the time-domain electromagnetic method.

Geology

In newly drilled holes, we recommend that the standard logging suite be upgraded to include a guard or focused resistivity log, a neutron log, and a density log. The guard log has superior resolution and requires less correction than does a 16-inch normal log. The neutron log helps sort out clay zones and partially saturated sands. The density log is important for determining porosity.

Within well clusters for which information about lateral changes in stratigraphy is needed, we recommend cross-well radar for mapping the clay-size fraction. This method may be particularly helpful at depths that cannot be reached with the cone penetrometer.

We recommend that the dielectric logging tool be tested in uncontaminated wells to determine whether it can provide useful information about sediment properties and pore fluids.

Monitoring DNAPL Remediation

During field tests of DNAPL remediation, we recommend that cross-well radar data and dielectric logging data be collected to determine whether these methods could be used to monitor the remediation. Separate tests must be conducted for the unsaturated and the saturated zones because in the two zones the emplacement of DNAPL and the techniques for remediation are different.

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APPENDIX A
SUITABILITY OF THE CROSS-WELL SEISMIC METHOD FOR MONITORING DNAPL REMEDIATION

In this appendix, the suitablity of using the cross-well seismic method (seismic tomography) for monitoring DNAPL remediation will be investigated.

The velocity of a *P*-wave in sediments saturated with DNAPL may be as much as 39% lower than that in sediments saturated with water (Geller, 1993, written commun.). Thus, tomography seems to be an appropriate method for mapping the velocity anomaly associated with the DNAPL. To test the suitablity of tomography, the most straightforward method is numerical modeling — different velocity models representing sediments with different amounts of DNAPL would be constructed; seismograms for each velocity model would be calculated; seismic tomograms for each model would be computed; and finally the tomograms would be analyzed to determine how well the sediments saturated with DNAPL can be resolved. Because of all these steps, numerical modeling would require much time.

Recent investigations on the resolution of tomography make numerical modeling unnecessary. For travel time tomography using data without noise, the resolution is approximately equal to the diameter of the Fresnel zone (Williamson and Worthington, 1993). The diameter will be calculated for a homogenous medium, an idealization which is adequate for establishing the upper bounds on resolution. The resolution is best at the wells (where the diameter of the Fresnel zone is the smallest) and is

$$r \approx \lambda \tag{A-1}$$

where λ is the wave length. The resolution is poorest halfway between the wells (where the diameter is the largest) and is

$$r \approx \sqrt{\lambda d} \tag{A-2}$$

where d is the distance between the wells. At other points between the wells, the resolution is between these two extremes. The wave length is related to the frequency f via:

$$\lambda f = v \tag{A-3}$$

where v is the velocity. To calculate the frequency that is required for a desired resolution, equation A-3 is substituted into equations A-1 and A-2. At the wells the required frequency is

$$f \approx \frac{v}{r}, \tag{A-4}$$

and halfway between the wells the required frequency is

$$f \approx \frac{vd}{r^2} \; . \tag{A-5}$$

For diffraction tomography using data without noise, the smallest spatial frequency of heterogeneity that can be resolved is

$$s = \frac{4\pi}{\lambda} \; . \tag{A-6}$$

(Wu and Toksöz, 1987). The spatial frequency is related to the resolution via:

$$r = \frac{2\pi}{s} \; . \tag{A-7}$$

Equations A-3, A-6, and A-7 are combined and solved for the frequency that is required for a desired resolution:

$$f = \frac{v}{2r} \; . \tag{A-8}$$

The frequencies that would be required to map a layer of sediments saturated with DNAPL were calculated for the conditions near the M-Area Basin. The desired resolution was chosen to range from 0.01 m (3.3×10^{-2} ft) to 0.1 m (3.3×10^{-1} ft); the distance between wells was chosen to be 10 m (3.3×10^{1} ft); the velocities were chosen to be 1690 m/s (5550 ft/s) for the saturated zone and 760 m/s (2500 ft/s) for the unsaturated zone, which are both the average values obtained with tomgraphy (Ellefsen, 1995). Although the required frequencies for these Site conditions display many interesting trends (Figure A-1), the most important is that the required frequencies for both methods and for both hydrologic zones are very, very high.

The necessity for high frequencies presents two significant problems. First, the highest frequencies that are generated by modern sources are only about 6 kHz. Even though this is adequate for one special situation — a thick layer (about 0.1 m) in the unsaturated zone imaged with diffraction tomography (Figure A-1) — it is not enough for most of the conditions expected at the Site. Second, the attenuation at these high frequencies is so great that the energy at these frequencies will not propagate between the wells. To estimate this effect, assume that the quality factors are 100 for the saturated zone and 30 for the unsaturated zone. Using 20 kHz for the saturated zone and 10 kHz for the unsaturated zone, frequencies which are high enough to image a thick layer with diffraction tomography, the attenuation coefficients (Aki and Richards, 1980, p. 169) are 0.36 and 1.4 Np/m, respectively. These coefficients are so high, that 97% of the wave energy in the saturated zone and 99.9999% of the wave energy in the unsaturated zone will be dissipated when the wave propagates the 10 m to the well with the receiver.

Because of these two significant problems, the cross-well seismic method (seismic tomography) at its current state of development appears to be unsuitable for monitoring DNAPL remediation.

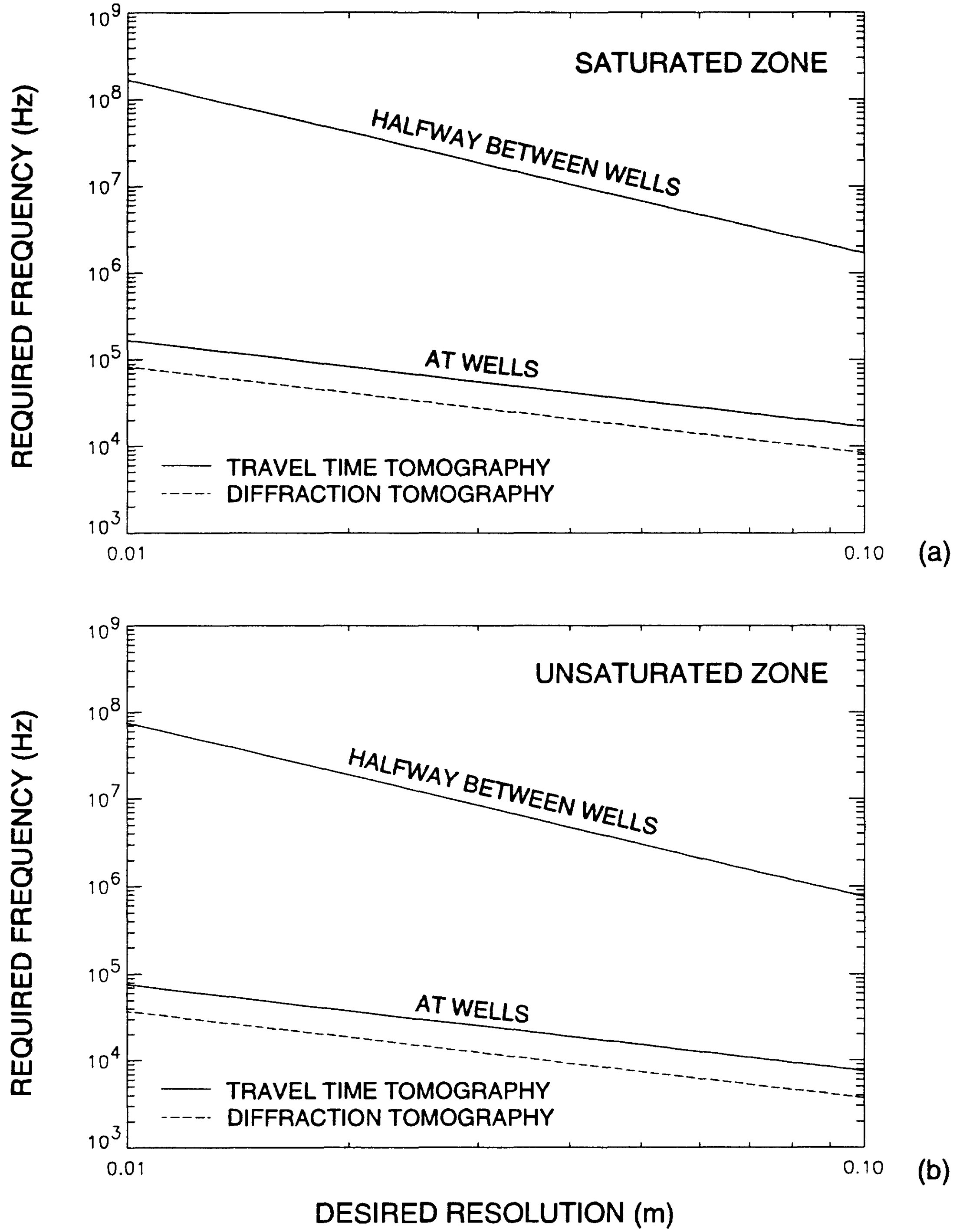

Figure A-1. Frequencies required to image, using the cross-well seismic method, a thin layer in (a) the saturated zone and (b) the unsaturated zone. The values used for the calculations are listed in the text.

APPENDIX B
EFFECT OF DNAPL REMEDIATION ON THE TRAVEL TIME OF RADAR WAVES

In this appendix, effect of DNAPL remediation on the travel time of the radar waves will be estimated for a representative volume of sediment.

The travel time is determined only by the velocity of wave propagation. As a first approximation, the velocity in a slightly conductive medium is

$$v = \frac{1}{\sqrt{\mu\varepsilon}} \tag{B-1}$$

where μ is the magnetic permeability and ε is the dielectric permittivity (Stratton, 1941, p. 274–277). Assuming that the magnetic permeability is unaffected by the remediation, the relative change in the travel times between an initial state i and a later state l is

$$\frac{t_l - t_i}{t_i} = \sqrt{\frac{\varepsilon_l}{\varepsilon_i}} - 1 \tag{B-2}$$

This relative change will be calculated for both the unsaturated and the saturated zones. The dielectric permitivity will be calculated with a volumetric mixing formula, which Heimovaara and others (1994) found to be suitable for soils. As a first approximation, the effects of the electrical conductivity and of the imaginary part of the dielectric permitivity will be ignored.

Unsaturated Zone

Before remediation, the dielectric permitivity of a representative volume of unsaturated sediment is the weighted sum of the dielectric permitivities for each constitutent in that volume:

$$\varepsilon^u_{bc} = \upsilon_a\varepsilon_a + \upsilon_s\varepsilon_s + \upsilon_{fw}\varepsilon_{fw} + \upsilon_{bw}\varepsilon_{bw} + \upsilon_d\varepsilon_d \; . \tag{B-3}$$

The constituents are air (in the pores), solid (that is, minerals), free water (in the pores), bound water, and DNAPL, to which the subscripts *a*, *s*, *fw*, *bw*, and *d*, respectively, refer. Each weight υ is the ratio of the volume occupied by the constituent to the entire representative volume. Superscript *u* refers to "the unsaturated zone," and subscript *bc* refers to "before cleanup." Although the individual terms in this equation are not known, the range for ε^u_{bc} is known from measurements of travel times (Ellefsen, 1997):

$$8.3\varepsilon_0 \le \varepsilon^u_{bc} \le 19\varepsilon_0 \tag{B-4}$$

where ε_0 is dielectric permittivity of free space. The low end of this range is associated with sandy sediments for which the partial saturation is low to moderate; the high end of this range is associated with clayey sediments for which the partial saturation is high.

If the DNAPL is removed with ohmic heating, it is assumed that air will replace the free water and the DNAPL but probably not the bound water. For this case, the dielectric permitivity is

$$\varepsilon^{u}_{dc} = \upsilon_a\varepsilon_a + \upsilon_s\varepsilon_s + \upsilon_{fw}\varepsilon_a + \upsilon_{bw}\varepsilon_{bw} + \upsilon_d\varepsilon_a \; . \qquad \text{(B-5)}$$

Subscript *dc* refers to "during cleanup." If the DNAPL is removed with steam heating, it is assumed that steam will replace the free water and the DNAPL but probably not the bound water. Because the dielectric permittivity of steam is practically identical to that of air (Weast and Astle, 1981, p. E-56), the formula for the dielectric permittivity is identical to that of B-4. Again, the individual terms in this equation are not known, and so they will be estimated. Since υ_d is at most 0.04 (J. Rossabi, 1996, oral commun.), the last term is small compared to the first four taken together. Therefore, ε^{u}_{dc} is the dielectric permittivity of partially saturated sediment, which was chosen to be $8\varepsilon_0$, plus a small perturbation to account for the volume formerly occupied by the DNAPL. This perturbation is at most $0.04\varepsilon_0$, and will decrease as the amount of clay decreases because the DNAPL tends to be in the small pores (Westinghouse Savannah River Company, 1992, p. 28). As a first approximation, the perturbation can be neglected.

After substituting equation B-5 and B-3 into equation B-2 and making these approximations, the relative change in travel time during remediation is

$$\frac{t^{s}_{dc} - t^{s}_{bc}}{t^{s}_{bc}} \approx \sqrt{\frac{8}{\dfrac{\varepsilon^{u}_{bc}}{\varepsilon_o}}} - 1 \; . \qquad \text{(B-6)}$$

This relative change has been plotted (as a percentage) in Figure B-1a for the range in dielectric permittivity specified in equation B-4. The change is always negative because either air or steam, both of which have low permittivities, is replacing water, which has a high permittivity. The magnitude of the change increases as the amount of clay increases (that is, the relative dielectric permitivity increases) because the clays tend to be highly saturated (Nelson and Kibler, 1995). These changes are large, and so they should be easily detectable with cross-well radar.

After remediation, water will have replaced the DNAPL. For this case, the dielectric permitivity is

$$\varepsilon^{u}_{ac} = \upsilon_a\varepsilon_a + \upsilon_s\varepsilon_s + \upsilon_{fw}\varepsilon_{fw} + \upsilon_{bw}\varepsilon_{bw} + \upsilon_d\varepsilon_{fw} \qquad \text{(B-7)}$$

Subscript *ac* refers to "after cleanup." After substituting equation B-7 and B-3 into equation B-2, the relative change in travel time after remediation is

$$\frac{t_{ac} - t_{bc}}{t_{bc}} = \sqrt{1 + \frac{\upsilon_d\left(\varepsilon_{fw} - \varepsilon_d\right)}{\varepsilon^{u}_{bc}}} - 1 \; . \qquad \text{(B-8)}$$

The dielectric permittivities for the free water and the DNAPL are $81\varepsilon_0$ and $4\varepsilon_0$, respectively. The volume fraction occupied by DNAPL is about 0.04 in the clayey sediments and probably decreases as the amount of clay decreases. Therefore a simple linear relation was chosen for υ_d:

$$\upsilon_d = 2.80 \times 10^{-3} \frac{\varepsilon^u_{bc}}{\varepsilon_o} - 1.327 \times 10^{-2} \,. \tag{B-9}$$

With this formula υ_d is 0.04 when the sediments are clayey and is 0.01 when the sediments are sandy. After substituting these values into equation B-9 and simplifying the square root with a binomial expansion, the relative change in the travel time is

$$\frac{t^u_{ac} - t^u_{bc}}{t^u_{bc}} \approx 0.10 - \frac{0.47}{\dfrac{\varepsilon^u_{bc}}{\varepsilon_o}} \,. \tag{B-10}$$

This relative change has been plotted (as a percentage) in Figure B-1a for the range in dielectric permittivity specified in equation B-4. The change is always positive because water, which has a high permittivity, is replacing DNAPL, which has a low permittivity. The magnitude of the change increases as the amount of clay increases because DNAPL tends to be in sediments with small pores (that is, in clays).

Saturated Zone

Before remediation, the constituents in a representative volume of saturated sediment are solid, free water, bound water, and DNAPL. Therefore, the dielectric permitivity is:

$$\varepsilon^s_{bc} = \upsilon_s \varepsilon_s + \upsilon_{fw} \varepsilon_{fw} + \upsilon_{bw} \varepsilon_{bw} + \upsilon_d \varepsilon_d \,. \tag{B-11}$$

Superscript *s* refers to "the saturated zone." After remediation, it is assumed that the DNAPL will be completely replace by water, and so the equation for the dielectric permitivity is

$$\varepsilon^s_{ac} = \upsilon_s \varepsilon_s + \upsilon_{fw} \varepsilon_{fw} + \upsilon_{bw} \varepsilon_{bw} + \upsilon_d \varepsilon_{fw} \,. \tag{B-12}$$

After substituting equations B-11 and B-12 into equation B-2, the relative change in travel time after remediation is

$$\frac{t^s_{ac} - t^s_{bc}}{t^s_{bc}} = \sqrt{\frac{\varepsilon^s_{ac}}{\varepsilon^s_{ac} - \upsilon_d(\varepsilon_{fw} - \varepsilon_d)}} - 1 \,. \tag{B-13}$$

Suitable values for ε^s_{bc}, ε_{fw}, and ε_d are $20\varepsilon_0$, $81\varepsilon_0$ and $4\varepsilon_0$, respectively. After substituting these values and simplifying the square root with a binomial expansion, the relative change in travel time is

$$\frac{t_{ac}^{s} - t_{bc}^{s}}{t_{bc}^{s}} \approx 1.9\upsilon_d \,. \qquad \text{(B-14)}$$

This relative change has been plotted (as a percentage) in Figure B-1b for υ_d between 0 and 0.10, which is a suitable range for the saturated zone (J. Rossabi, 1996, oral commun.). The relative change is always positive because water, which has a high permittivity, is replacing DNAPL, which has a low permittivity. The relative change increases as the volume fraction of DNAPL increases because the change in the permittivity of the representative volume increases.

Conclusion

Even though the relative changes in the travel times that in Figure B-1 are large, these changes pertain only to a representative volume of sediment. The changes that would be measured from field data depend upon the concentration of DNAPL and the volume it occupies. Because this information is unknown at this time, the effect on the field data is also unknown: Only a field test will indicate whether cross-well radar is suitable for monitoring DNAPL remediation.

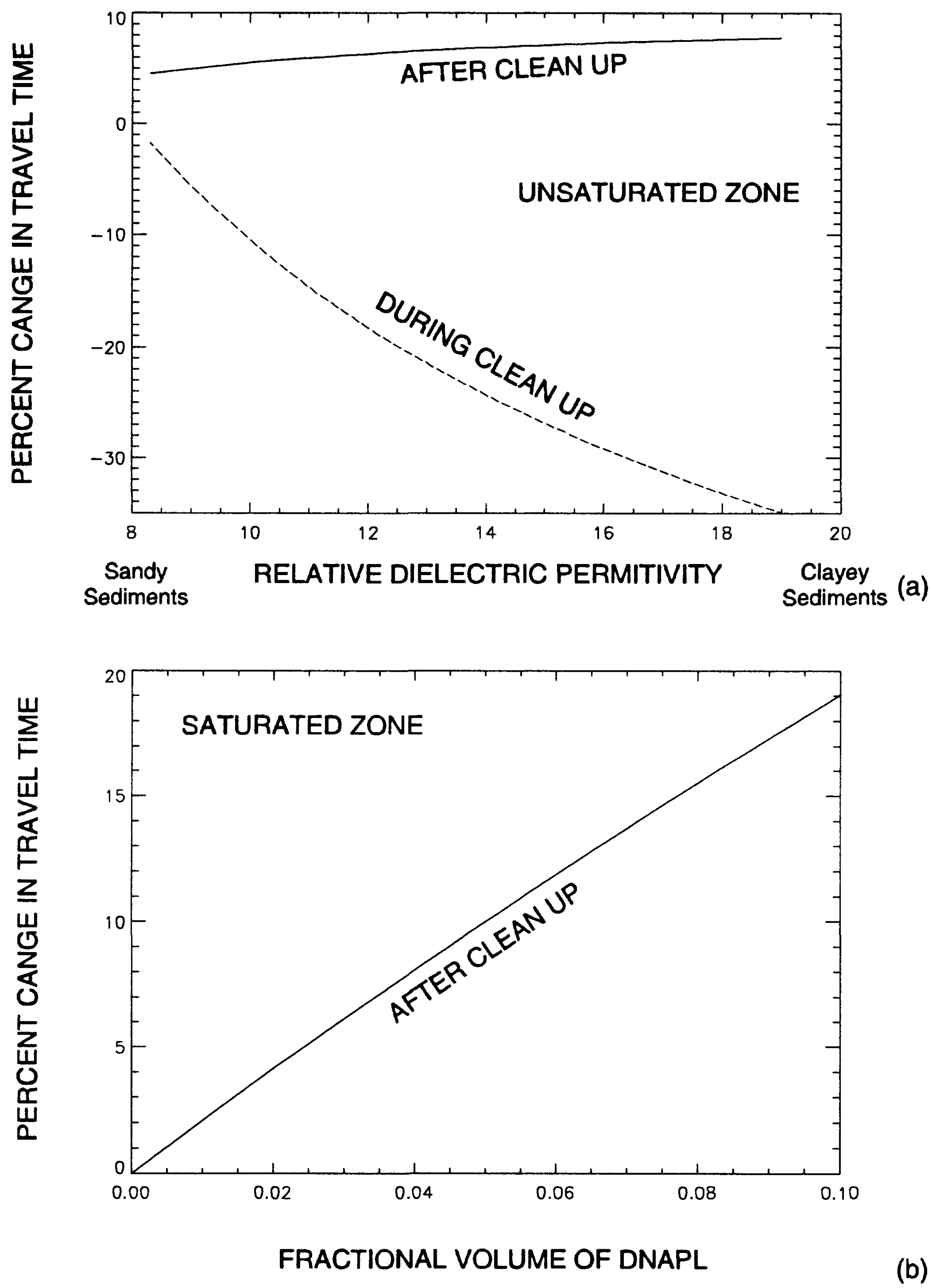

Figure B-1. Percent changes in the travel time of a radar wave propagating in (a) the unsaturated zone and (b) the saturated zone. These changes would be caused by the removal of DNAPL. The values used for the calculations are listed in the text.