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GEOPHYSICAL SURVEYS ACROSS THE BOISE HYDROGEOPHYSICAL RESEARCH SITE TO DETERMINE GEOPHYSICAL PARAMETERS OF A SHALLOW, ALLUVIAL AQUIFER

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ABSTRACT

At the Boise Hydrogeophysical Research Site (BHRS), we are characterizing the hydrogeophysical parameters of a cobble-and-sand, unconfined aquifer using a wide variety of geophysical methods. Our goal is to develop methods for mapping variations in permeability by combining non-invasive geophysical data with hydrologic measurements. We are using seismic, ground penetrating radar, and electrical methods in a variety of configurations to provide images of and parameter distributions at the BHRS. Issues such as resolution, depth of penetration, and the ability to image the desired parameters will help determine the most effective methods. Supporting data sets from the BHRS include core analyses and geophysical logs from 18 wells at the site. We will use these data to verify our geophysical interpretations. The various geophysical methods and acquisition geometries, combined with the well control, will provide an outstanding data set to characterize the heterogeneity of the subsurface beneath this alluvial aquifer, and find ways to map permeability with geophysical information.

INTRODUCTION

The Boise Hydrogeophysical Research Site, or BHRS (Fig. 1), is being developed to support the goal of using non-invasive geophysical methods to supplement hydrologic data to map the distribution of permeability in 3-D heterogeneous shallow alluvial aquifers. In particular, the BHRS is a research wellfield in a shallow, unconfined, coarse (cobble-and-sand), braided-stream, alluvial aquifer (Fig. 2a) that is broadly similar to many other alluvial aquifers comprised of correlated random fields of facies and hydraulic parameters. Eighteen wells were cored and installed at the BHRS in 1997 and 1998, including 13 wells in the central portion of the wellfield (Fig. 1). These wells provide: (a) a dense network with direct "hard" information such as core (Fig. 2b) and permeability measurements at the individual well scale; (b) access for a wide variety of geophysical and hydrologic testing in individual wells (1-D), between wells (2-D), and in multi-well subsurface and surface-subsurface configurations (3-D); and (c) a configuration designed to support geostatistical analysis of geophysical or hydrologic parameters (Barrash and Knoll, in press; Barrash et al., 1999).

The intention is to thoroughly characterize the wellfield as a control volume with "known" 3-D distributions of sedimentary facies, geophysical parameters, and hydrologic parameters. Then responses from geophysical methods, alone and together, can be correlated against known parameter distributions to develop techniques for mapping the 3-D distribution of permeability with non-invasive geophysical methods. Initial efforts will concentrate on three generally accessible geophysical methods: seismic, ground penetrating radar (GPR), and time-domain or transient electromagnetics (TEM). Also, a variety of borehole geophysical logs are being run in all wells.

The general approach at the BHRS is to establish "control" with dense, high-resolution measurements at wells (1-D), use these as calibration or reference points for level runs and tomography measurements between wells (2-D), and use these as calibration or reference sections for surface profiles (2-D) and multiwell experiments (3-D). We acknowledge that differences will exist: (a) because of measurement scales and data acquisition methods, (b) because of differences in actual parameters measured with similar geophysical methods, and (c) because of differences between information contained in structural images and parameter fields. The task of analyzing any given data set will be assisted by the availability of data sets from other methods, including many coincident data sets. Indeed, part of the overall research effort includes investigation of scaling, petrophysical relationships, and multivariate relationships.

GEOPHYSICAL METHODS

Seismic, GPR, TEM, and borehole geophysical methods are generally accessible, have been used successfully in the shallow, cobble-and-sand aquifer nearby in downtown Boise, Idaho (Barrash et al., 1997a) and are being used at the BHRS. Each of these methods is discussed briefly below. Much of the effort to date at the BHRS has concentrated on optimizing data acquisition. Initial results are presented in companion papers at this symposium (Barrash et al., 1999; Clement et al., 1999; Knoll and Clement, 1999; Liberty et al., 1999; Peretti et al., 1999; Peterson et al., 1999).

Seismic Methods

Previous efforts with seismic methods in the cobble-and-sand aquifer in Boise indicate that reflections within the cobble-and-sand aquifer, other than the water table, are difficult to obtain. However, reflections can be recognized in VSPs, and considerable detail can be discerned from first-arrival, velocity dispersion, and attenuation data. Initial experiments at the BHRS have confirmed and extended findings from previous work and investigated data acquisition issues.

Several types of VSP tests have been run at the BHRS: SH-wave VSPs, P-wave VSPs, and reverse VSPs using core-driving as the energy source. The SH-wave analysis has found anomalous behavior across the water table and high attenuation in the upper part of the aquifer (Michaels and Barrash, 1997; Michaels, 1998). Analysis of dispersion and attenuation using a Kelvin-Voigt model has resulted in estimates of stiffness and damping coefficients from SH-wave data which likely are related to storativity and permeability, respectively (Michaels and Barrash, 1997; Michaels, 1998). The P-wave VSPs contain reflections from four distinct boundaries (Liberty et al., 1999). The VSPs provide detailed, 1-D subsurface models that link travel time information to depth.

A seismic crosshole tomography experiment acquired data using both core-driving and a sparker source (Clement et al., 1999). Results show an increase in velocity with depth from 580 m/s at the surface to 2800 m/s at around 20 m depth (top of clay layer). A 3500 m/s high velocity zone occurs at around 12 m depth. Work with Lawrence Berkeley National Laboratory and their high-frequency source provides detailed images between closely spaced wells and indicates that the upper 10 m of the saturated zone is highly attenuative (Peterson et al., 1999). A sparker source, although lower frequency, propagated P-waves ~20 m between wells across the central area of the BHRS (Liberty et al., 1999). The tomograms show lateral velocity changes below the water table on the scale of 2 to 4 m. Using the seismic tomography results, we can map small scale variations within the cobble-and-sand aquifer.

Ground Penetrating Radar Methods

Previous work in Boise indicates the shallow aquifer at the BHRS has characteristics favorable for relatively high resolution and deep penetration with GPR (Barrash et al., 1997b). Much of the initial effort at the BHRS has involved evaluation of equipment and optimization of data acquisition for single-well, crosshole, and surface profile testing. We have recorded tomographic and VRP data with downhole antennas and surface data as common midpoint (CMP) and reflection profiles. The range of frequencies provides adequate energy penetration to image the base of the aquifer and higher resolution images of the near surface to better delineate the hydrologic units (Peretti et al., 1999).

The surface GPR reflection surveys at the BHRS provide the highest resolution images of the aquifer from surface geophysical methods. We used 25 and 50 MHz antennas to record long, reconnaissance lines at the BHRS (Fig. 3); these low frequency profiles successfully image the basal clay layer of the aquifer and delineate large scale stratigraphic changes across the site. To better understand the lateral changes at the site, we conducted a densely sampled, 3-D GPR reflection survey with 25, 50, 100, and 200 MHz frequency antennas (Peretti et al., 1999). Having closely spaced lines with these frequency ranges will enable us to trace bounding surfaces and facies characteristics as has been accomplished in other unconsolidated Quaternary cobble-and-sand deposits (Huggenberger, 1993). The 3-D data will provide more detailed and accurate information about the lateral changes in sedimentary architecture beneath the BHRS than is possible from the widely spaced core data.

Vertical radar profiles, or VRPs, are used to develop layered velocity models at each well (Knoll and Clement, 1999). From linear regression of first arrivals, we find a 0.141 m/ns velocity layer over a 0.08 m/ns layer. The first layer corresponds to the vadose zone and the lower layer is the saturated zone. Other velocity measures (e.g., interval velocities) provide more detailed velocity models within the saturated zone. Reflections in the VRP data are used to confirm interpretations of the surface GPR data. The VRP data provide 1-D velocity models and determinations of depths to reflecting interfaces.

Crosshole experiments show the potential for high resolution imaging and determination of parameter distributions (Peterson et al., 1999). We acquired crosshole transmission data using 100, 200, and 250 MHz downhole antennas to obtain travel time and waveform information at 0.05 m intervals. These data will constrain the 2-D field and will help extrapolate well information throughout the BHRS. Already, preliminary results from level runs and tomography experiments correlate well with independent information from well logs (Fig. 4a and b) and VRPs (Knoll and Clement, 1999). An advantage of crosshole experiments is the greater penetration distance compared to surface reflection measurements. Because surface experiments record reflected energy, they provide information to only about one-half the depth or distance of crosshole experiments. We take advantage of the increased propagation of higher frequencies to determine highly detailed sedimentary and parameter models of the BHRS (e.g., Peterson et al., 1999).

To provide an initial model of the velocity distribution at the central portion of the BHRS, we conducted 11 crosshole GPR tomography experiments. We acquired these data with 250 MHz antennas to map small scale velocity changes. Figure 4b shows traces from a level run in which the transmitter and receiver are recorded at the same depths in the well. Level run data provide a quick estimate of the velocity changes with depth between the two wells. Ultimately, we intend to correlate changes in electromagnetic wave velocity determined from the tomograms with dielectric constant and porosity changes based on petrophysical relationships.

Transient Electromagnetic Methods

Previous efforts with electrical methods in the cobble-and-sand aquifer in Boise included a resistivity survey with a Schlumberger array and 1-D soundings with TEM. The Schlumberger array, with the assumption of a laterally continuous layered-model, provided poor results because of pronounced lateral heterogeneity in these deposits. However, 1-D soundings using the TEM method yielded reasonable multilayered models including 3-4 layers within the saturated portion of the cobble-and-sand aquifer (Barrash et al., 1997a). Similarly, initial tests at the BHRS using a central loop method had promising results; a 25 m x 30 m grid of TEM soundings has been collected at 5 m intervals over the central area of the wellfield. Also, soundings were collected at the locations of all 18 wells both before and after coring and well installation. Initial inversions provide good fits to discrete-layer models with 4-6 layers (Fig. 4c). Current efforts include forward modeling to match TEM responses based on lithologic interpretations from core and borehole geophysical logs, including induction resistivity logs and porosity logs derived from neutron logs.

Borehole Geophysical Logging

Previous logging in 5-cm PVC wells in the cobble-and-sand aquifer in Boise demonstrated the value of neutron, natural gamma, and induction resistivity log data both individually and in multivariate analysis for recognizing variations in the cobble-dominated units (Barrash and Morin, 1997). These deposits have favorable characteristics including low clay content, lack of diagenesis or compaction, strong natural gamma source strength, and nearly uniform source lithology (Barrash et al., 1997a), so log responses are primarily related to facies variations and are not obscured with effects due to lithologic variation or diagenesis.

In the 10-cm PVC wells at the BHRS, neutron, natural gamma, gamma-gamma density, induction resistivity, fluid temperature, fluid resistivity, and deviation logs were run in the 18 wells in 1998 (Fig. 5). Initial analysis includes petrophysical transform of neutron data to porosity and geostatistical analysis of those data (Barrash et al., 1999). The reduction of other data sets is in progress. Following the promising results with multivariate analysis of log data from this aquifer nearby in Boise (Barrash and Morin, 1997), we will apply principal components analysis to log data from the BRS and we will be able to calibrate our results against core and image data that were not previously available in this aquifer.

FUTURE WORK

We are in the early stages of acquiring and analyzing data from the BHRS. In addition to continued work in the directions noted above, future seismic testing will include 3-D seismic reflection experiments to (a) detect reflections using a source in a well and an array of receivers at the surface, and (b) map the topography on the sediment-clay interface below the BHRS. Future GPR testing will include (a) monitoring of pumping tests, (b) monitoring tracer tests using conservative salts, and (c) full wave-form inversion of the VRP and crosshole data. Future analysis directions with the TEM data include (a) using the 18 coincident induction resistivity well logs, pre-well TEM soundings, and other supporting data to determine a functional relationship between apparent resistivity profiles from TEM soundings and induction resistivity well logs, (b) using the gridded data to test the ability of 3-D modeling to predict the TEM response at the wells, and (c) investigating the petrophysical link between electromagnetic properties and permeability. In 1999, we anticipate running detailed permeability profiles with the electromagnetic borehole flowmeter, spectral gamma logs to trace sedimentary units, and multifunction water chemistry profiles to investigate vertical variations in a number of significant parameters. Additionally, we hope to log vertical dielectric constant changes in the wells. The many, complementary geophysical methods and acquisition geometries will enable us to thoroughly characterize the heterogeneous distributions of sedimentary features and geophysical parameters in the shallow aquifer at the BHRS, and to develop methods for mapping the distribution of permeability using non-invasive geophysical techniques.

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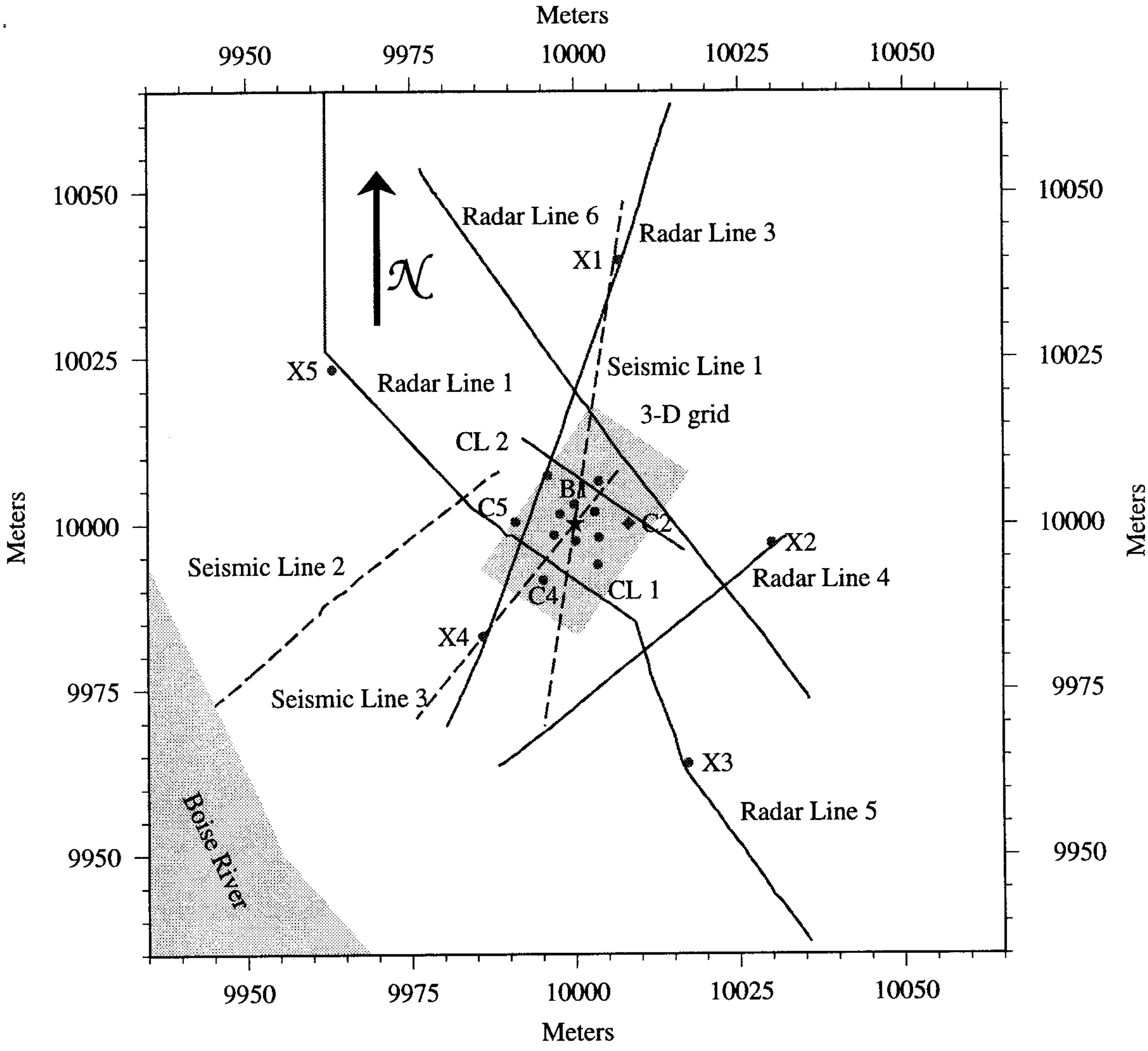

Figure 1. Site map of the BHRS showing the locations of some of the different geophysical experiments discussed in the text, and the locations of wells. The shaded region labeled 3-D grid is the location of the 3-D GPR survey (see Peretti et al., 1999). TEM surveys were conducted at every well and at 5 m grid spacings in the 3-D grid area.

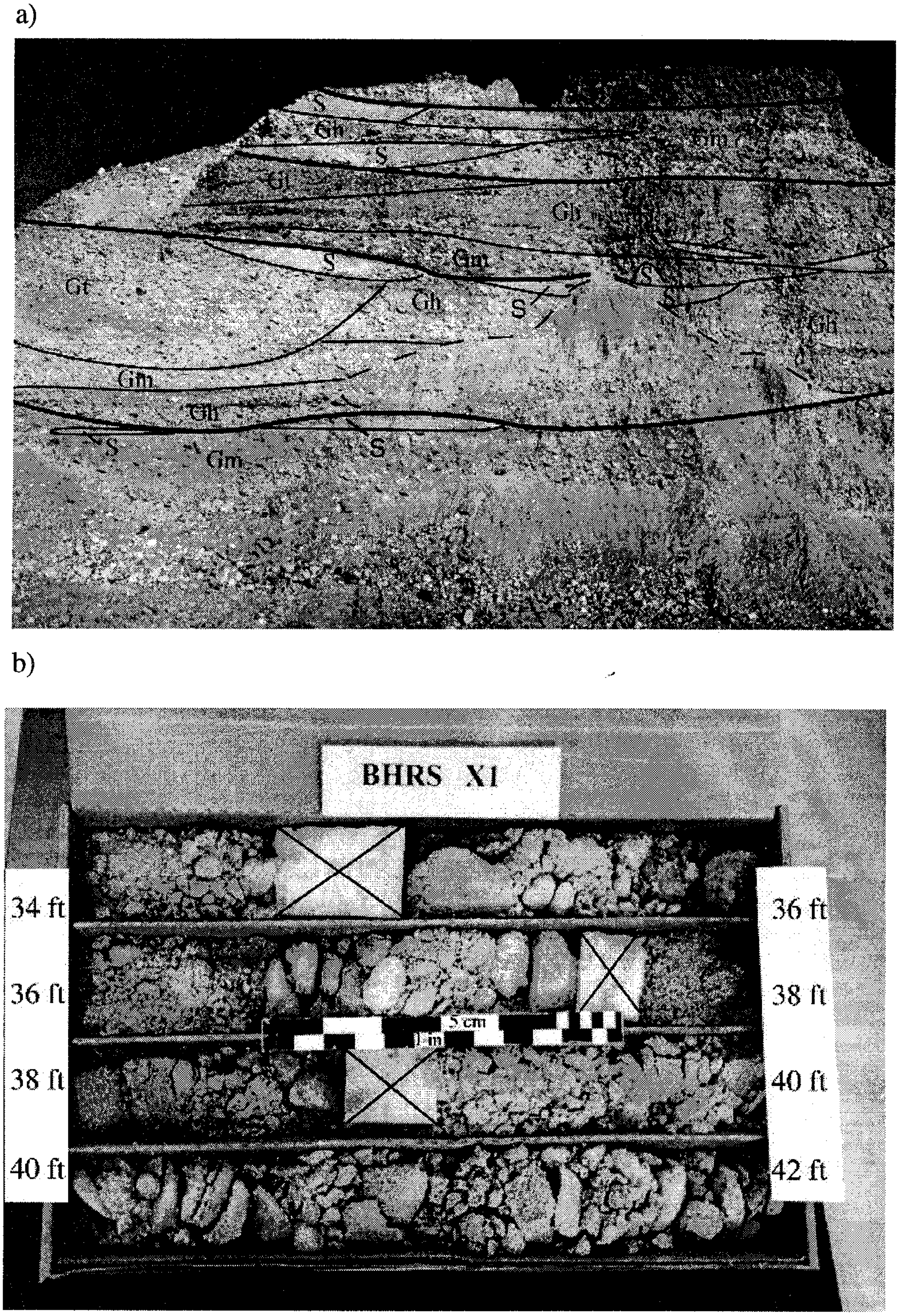

Figure 2. (a) Typical exposure of cobble-and-sand deposits at a nearby quarry showing heterogeneous distribution of facies. S - sand; Gm - massive cobbles; Gt - trough-bedded cobbles; Gh - horizontally bedded cobbles. (b) An eight foot section of core from well X1 (after Barrash and Knoll, in press).

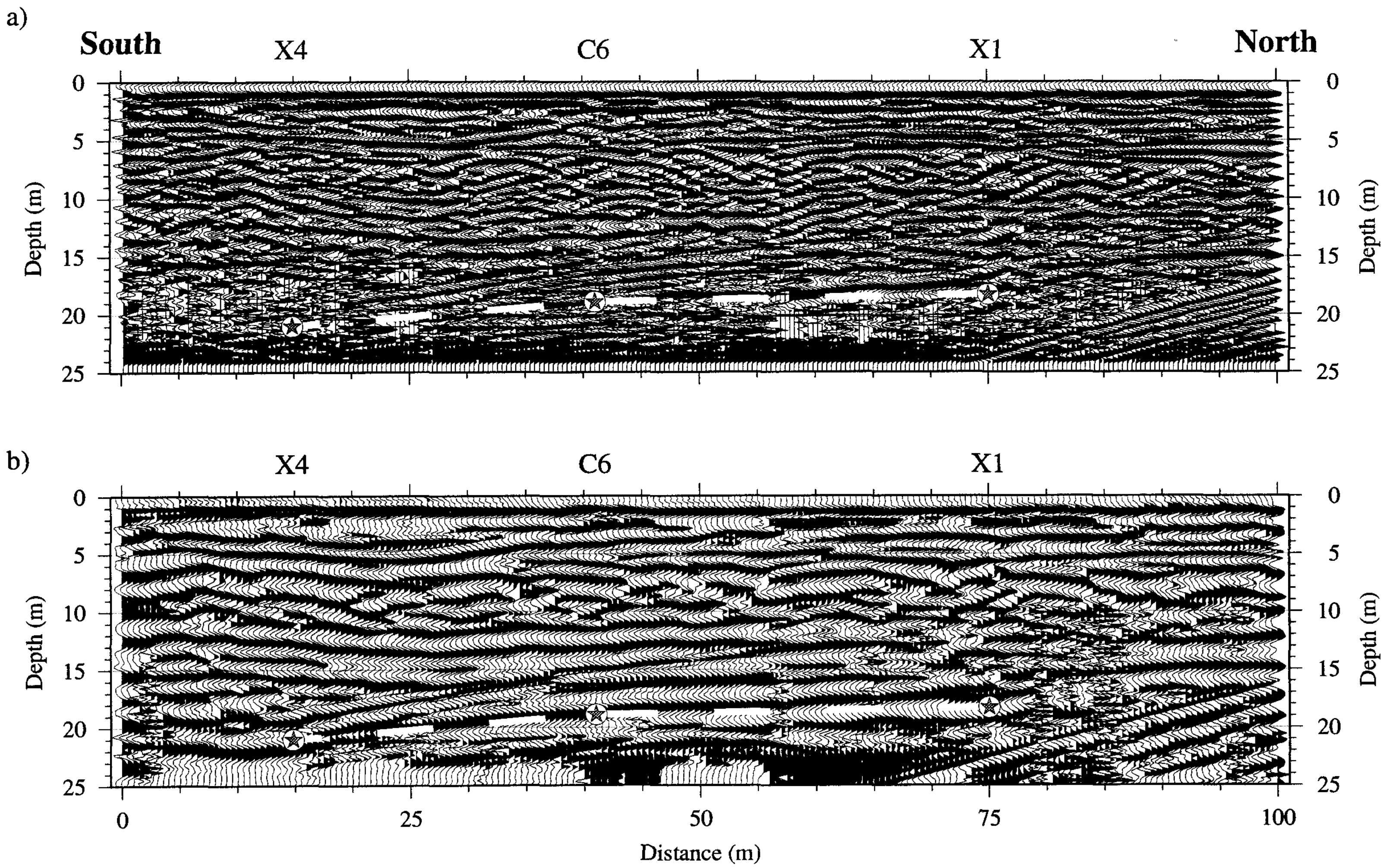

Figure 3. GRP Radar Line 3 (Fig. 1) using (a) 50 and (b) 25 MHz antennas. The dashed white line is the approximate depth of the basal clay layer. The stars are depth measurements to the clay from cores at wells X1, C6, and X4.

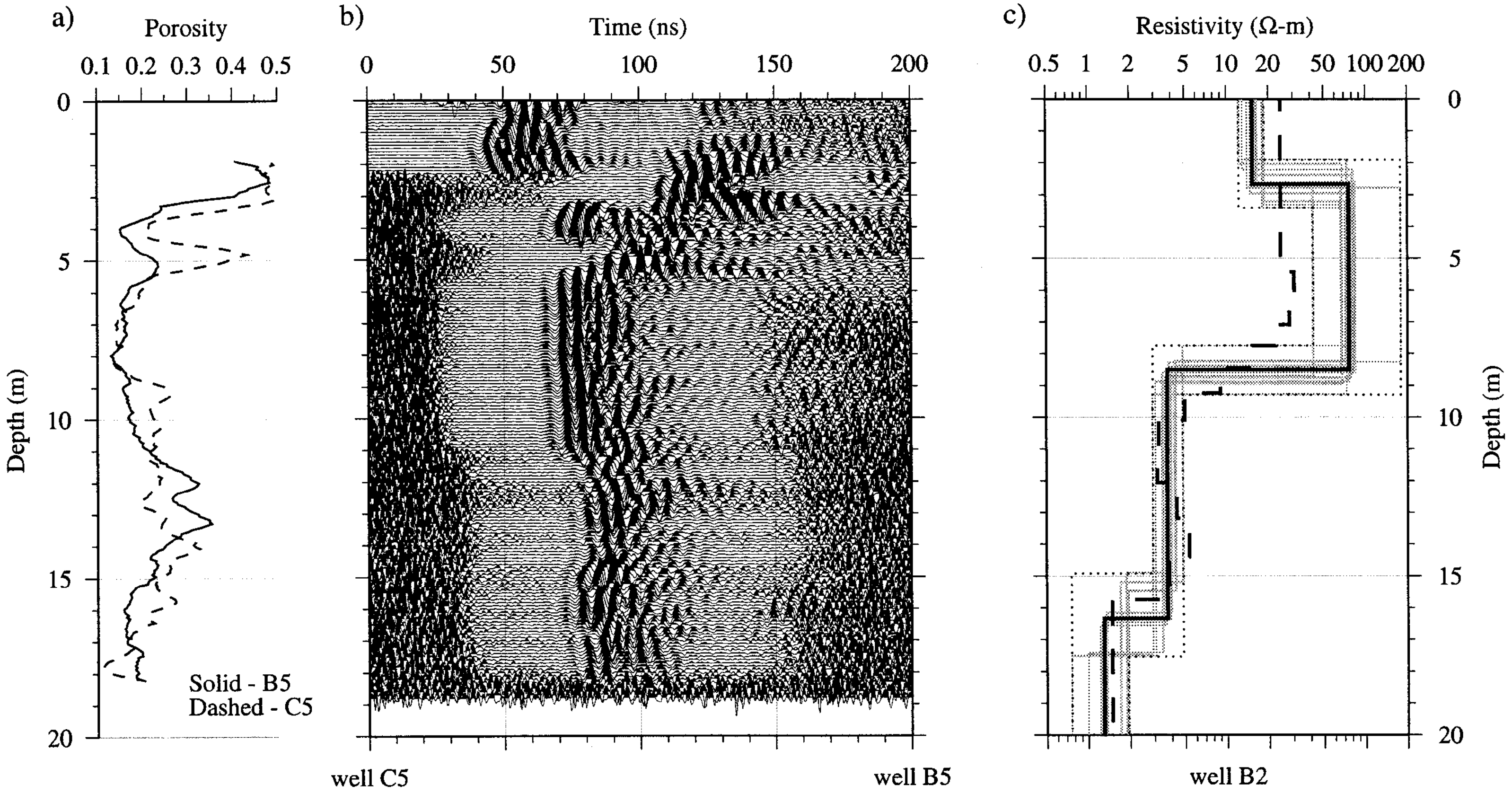

Figure 4. Comparison of (a) porosity in wells C5 and B5 to (b) GRP level run with the transmitting antenna in well C5 and the receiveing antenna in well B5. A strong correspondence is evident between the location and magnitude of increased porosity and the location and magnitude of decreased radar velocity, especially at 2-3 m, 4-5 m, and 11.5-14.5 m. c) TEM model from inverting the data from well B2. The heavy solid line is the best-fitting layered model. The light gray lines are equivalent models. These models have similar error to the best-fitting model. The heavy dashed line is a 15 layer "smoothed" model. The dotted lines are the minimum and maximum bounds on the equivalent models.

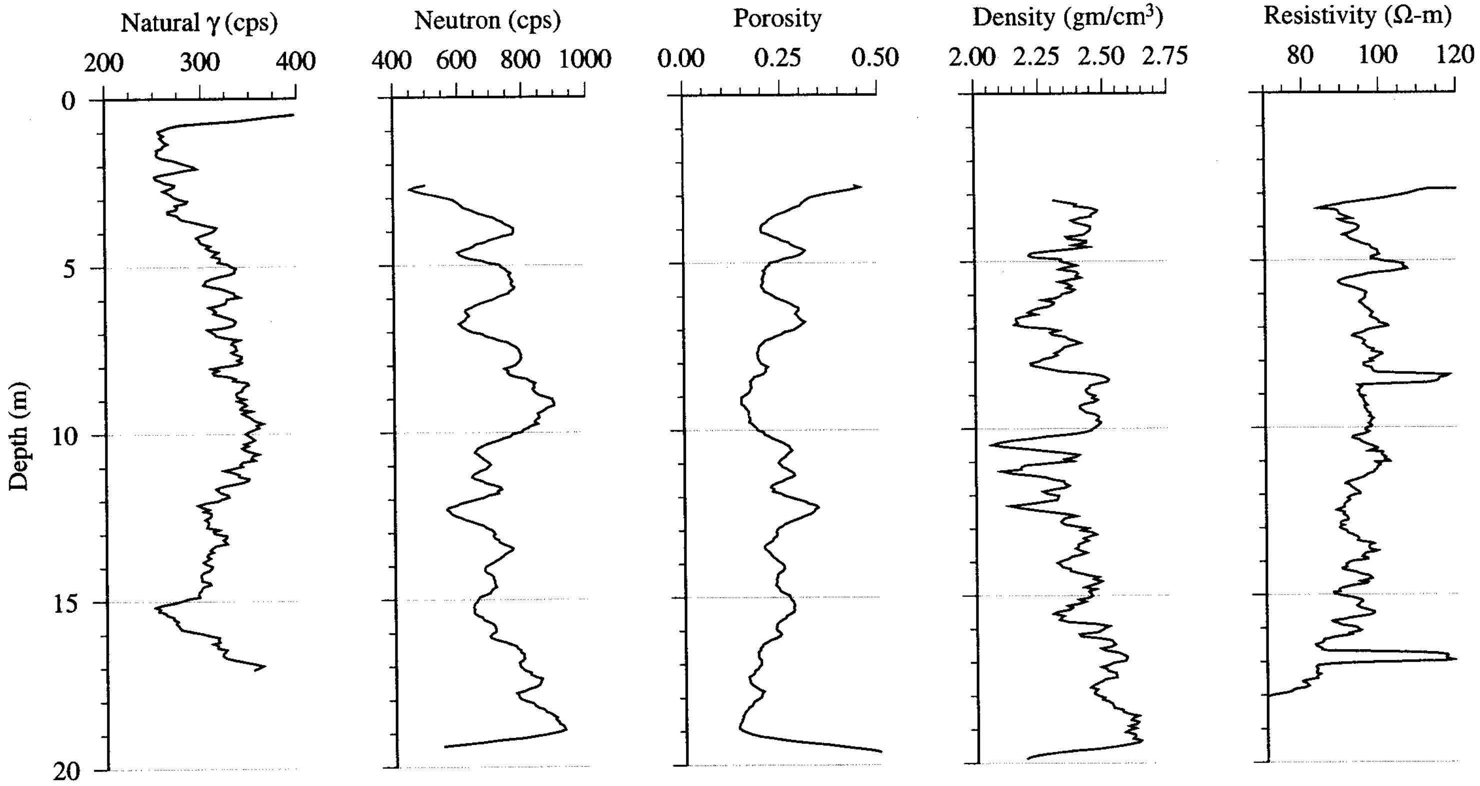

Figure 5. Gephysical logs from well A1. The logs have been smoothed with a 5-point or 10-point running average.