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3-D GPR IMAGING OF COMPLEX FLUVIAL STRATIGRAPHY AT THE BOISE HYDROGEOPHYSICAL RESEARCH SITE

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ABSTRACT

A series of three-dimensional (3-D) ground-penetrating radar (GPR) data sets were acquired over the central wellfield area at the Boise Hydrogeophysical Research Site (BHRS). The survey region is 30 m x 18 m and encompasses 13 wells. The goal of the surveys is to image the complex fluvial (cobble-and-sand) stratigraphy around the wellfield. These images will be used to construct 3-D models of the sedimentary architecture and to help constrain fine-scale models of hydrologic and geophysical parameters at the site. The data sets were acquired using 25 MHz, 50 MHz, 100 MHz and 200 MHz antennas. Depth of penetration ranges from ~9.6 m for the 200 MHz data to ~22 m for the 25 MHz data. Processing significantly improves the reliability and interpretability of the images. The images suggest that the deposit can be subdivided laterally and vertically into several distinct units or radar architectural elements; these elements are typically separated by erosional bounding surfaces. Horizontal bedding, cross-bedding and channel structures are clearly evident in the 100 MHz and 200 MHz data, and a clay layer that underlies the cobble-and-sand aquifer at ~20 m depth is successfully imaged in the 25 MHz and 50 MHz data. The water table, at a depth of 1-2 m, is imaged in the 100 MHz and 200 MHz data. Time slices and vertical cuts through the data volumes are used to identify the shape and orientation of the different architectural elements, and to accurately locate important hydrostratigraphic boundaries. These data are being used to construct a 3-D model of the hydrogeologic zonation of the aquifer. Hydrologic and geophysical parameter values associated with each zone will be determined from additional field measurements (e.g., hydraulic tests in wells, crosshole radar and seismic tomography, transient electromagnetics, and well logs). The 3-D GPR surveys provide valuable information about the location, scale and geometry of different stratigraphic units at the BHRS.

INTRODUCTION

Ground penetrating radar (GPR) is being used at the Boise Hydrogeophysical Research Site (BHRS), along with other geophysical and hydrologic techniques, to develop methods for mapping variations in permeability in shallow, heterogeneous, sedimentary aquifers (Clement et al., 1999). The BHRS is a research wellfield developed in coarse (cobble-and-sand) braided-stream deposits that host a shallow, unconfined aquifer (Barrash et al., 1999). Heterogeneities associated with fluvial deposits can be successfully imaged using three-dimensional (3-D) GPR reflection data (Thompson et al., 1995). In particular, in very coarse fluvial deposits similar to those at the BHRS, GPR has the potential to resolve sedimentary structures (Jol et al., 1996) and architectural elements (Huggenberger, 1993), and GPR reflection data may be analyzed geostatistically (Rea and Knight, 1998) to quantitatively characterize the spatial correlation of properties.

The shallow aquifer at the BHRS has characteristics that are favorable for GPR use: aquifer water has very low specific conductance, and aquifer sediments have high porosity and very low clay content (Barrash et al., 1997). Analysis and interpretation of our 3-D GPR reflection profile data discussed in this paper are being assisted by supplementary data sets collected at the BHRS such as: vertical radar profiles (VRPs) for calibrating travel times against known velocities and depths to specific reflectors in wells; radar tomography images for interpreting lateral changes in facies or contacts (bounding surfaces); and geophysical log and core data for independent information on unit lithology and grain size distribution. The 3-D GPR data will be central to developing a deterministic model of the type, position, geometry, and variation in fluvial facies or architectural elements at interwell scales at the BHRS. We report the initial results of 3-D imaging of the subsurface at the BHRS based on GPR reflection profiles run in a tightly spaced grid.

DATA ACQUISITION

We used a PulseEKKO 100 GPR system from Sensors and Software, Inc., for all data acquisition. The antennas had center frequencies of 200 MHz, 100 MHz, 50 MHz, and 25 MHz. All of the data were acquired using the common-offset reflection profiling method. We completed a series of single line tests using all of the antennas to optimize acquisition parameters, and used these results to design the 3-D surveys. The transmitter-receiver separation for the 200 MHz, 100 MHz, 50 MHz and 25 MHz data is 0.5 m, 1 m, 2 m and 4 m, respectively. The 3-D survey encompasses the 13 innermost wells at the BHRS (Figure 1). The survey area measures 30 m x 18 m with the Boise River located 40 m to the southwest. The spacing between profile lines is 0.2 m for the 100 MHz and 200 MHz data, and 0.5 m for the 50 MHz and 25 MHz data. Station spacing along each line is 0.1 m for the 100 MHz and 200 MHz data, and 0.2 m for the 25 MHz and 50 MHz data.

PROCESSING

We processed the data to improve image quality using EKKO_TOOLS software from Sensors and Software, Inc. and PROMAX software from Landmark Graphics. The first step in processing was to input geometry information and edit headers. Next, a short (3-sample) temporal median trim filter was applied to each trace to attenuate noise spikes that contaminated some of the data. A background dc level was present in all of the data sets. The dc level was removed by calculating the average amplitude before the first breaks and removing this value from each sample of each trace. A residual median filter was then applied to attenuate the wow. Tests show that this filter successfully attenuates both the low and high-frequency components of the wow, without adding precursors or other artifacts to the wavelet. (Gerlitz et al., 1993). Time zero determination and datuming was also performed.

The next step in the processing sequence was amplitude compensation. For each line, we determined the rectified-amplitude versus time fall-off of the data. The inverse of this curve was scaled by a multiplier (0.3) to form the gain function. The multiplier is used to reduce the gain function somewhat so that anomalously high amplitude values are not clipped after amplitude compensation. The direct air and ground waves were attenuated by subtracting the average trace for each line from each trace. The net effect is that the air wave is almost completely removed. Elevation static corrections were then applied using the formula: $\Delta t=2\Delta E/Vunsat$, where Δt is the static shift, ΔE is the elevation difference from the datum (highest elevation in the grid) and

Boise Hydrogeophysical Research Site

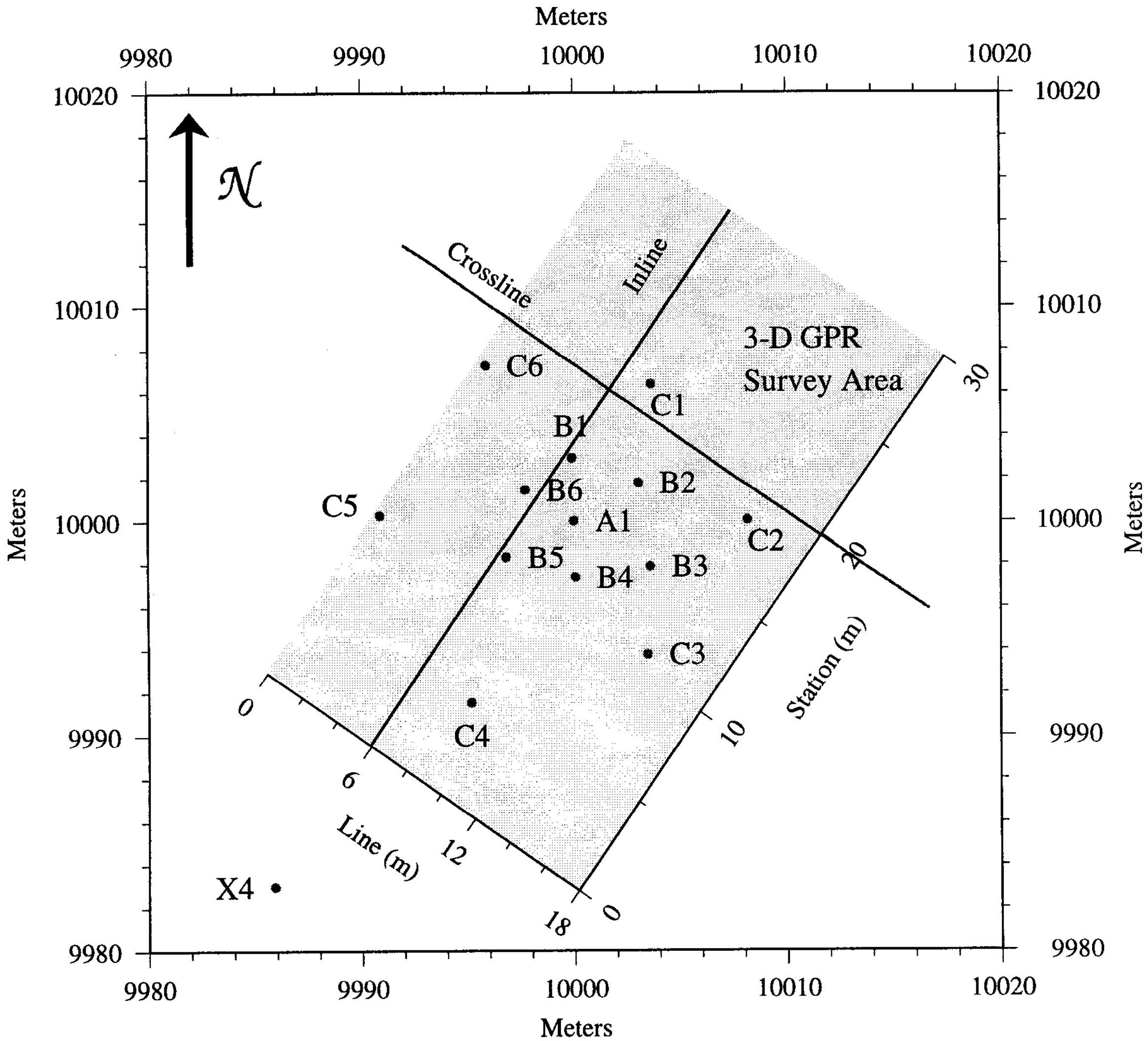

Figure 1. 3-D GPR survey area, local coordinates and well locations at the BHRS. The 3-D GPR survey area is 30m by 18m and encompasses 13 wells (A1, B1-B6, C1-C6). The local coordinate system is defined such that well A1 is located at (10000, 10000). The inline direction for the 1998 3-D GPR surveys is SW to NE, and the crossline direction is SE to NW. The GPR data shown in the next two figures were acquired along Line 6.0 and Crossline 20.0, respectively. The Boise river is located SW of well X4 and flows to the NW.

Vunsat is the radar velocity in the unsaturated zone. A velocity of 0.141 m/ns, determined from vertical radar profiles in wells completed at the BHRS site, was used for Vunsat. After the static corrections, the water table can be seen as a horizontal surface in the uppermost part of every line. An extensive series of 2-D migration tests were performed but the results were judged inferior to the unmigrated data for the purposes of identifying zones of scattering and mapping major bounding surfaces. Finally we applied a bandpass filter (20-300 MHz) and an AGC function for display.

INTERPRETATION

In this section we analyze GPR reflection images to: (1) evaluate GPR penetration and resolution in data collected at four frequencies; (2) compare reflection character at two line orientations; (3) interpret GPR reflections and image patterns as bounding surfaces and architectural elements in profile; and (4) interpret 3-D GPR images in block and chair diagrams (at 200 MHz only). The vertical axis in the GPR reflection images (Figs. 2-5) is two-way travel time which may be converted to depth using velocities derived from common midpoint soundings and vertical radar profiling (Knoll and Clement, 1999).

Two reflection profiles, an inline profile and a crossline profile, are shown in Figures 2 and 3, with data collected using 200, 100, 50, and 25 MHz antennas. Only a dewow filter and an AGC function have been applied to these data to show the quality of the field data. It is readily apparent that: (a) penetration increases with decreasing antenna frequency; (b) resolution decreases with decreasing antenna frequency; and (c) the inline profile shows more lateral variability in reflectors than the crossline profile. The cross line profile runs parallel to the river and shows mostly parallel and subparallel reflectors. In particular, penetration with the 200 MHz and 100 MHz antennas reaches ~200 ns (9.6 m), and at 50 and 25 MHz penetration is >440 ns (>20 m). Although total penetration with the 50 MHz and 25 MHz antennas is >20 m, only major reflectors are evident below 14 m (300 ns).

A number of reflectors below the water table are evident at several scales or frequencies (Fig. 2); we use supporting information from core and porosity logs (e.g., Clement et al., 1999) and from surrounding reflection character to give preliminary interpretations of these reflectors in terms of fluvial stratigraphy. For reference, the water table was 2.2 m below land surface at well B1when the GPR data were collected; the strong reflector at the water table is labeled in Figures 2a and 2b. Reflector 1 is evident at all frequencies and is the bounding surface between a sand unit above and a cobble-dominated unit below. The bounding surface dips toward the Boise River and is interpreted to be the bottom of a paleochannel. Both core and porosity logs corroborate the different lithologies and the bounding surface's depth in wells B5 and B6 (and C4 and C5 - see Fig. 1); the portion of this sand below the water table pinches out between wells B6 and B1. Apparent crossbedding within the sand channel may be seen just above the bounding surface in the 200 and 100 MHz images; this crossbedding is not recognizable in porosity logs and generally is not recognizable in the unconsolidated core.

Reflectors 2 (~3.5 m depth) and 3 (~5.3 m depth) are evident in the 200, 100 and 50 MHz images and may be associated with the top and bottom of a sandy high porosity lens within a cobble-dominated unit, as indicated in the porosity log for well C1 (not shown here). Reflector 4 is evident in the 100, 50, and 25 MHz images and occurs at about the limit of penetration with the 200 MHz antennas. The reflection pattern below reflector 4 is more hummocky than above; porosity logs indicate laterally variable cobble-dominated units in this zone. The unmigrated 25

Inline Data

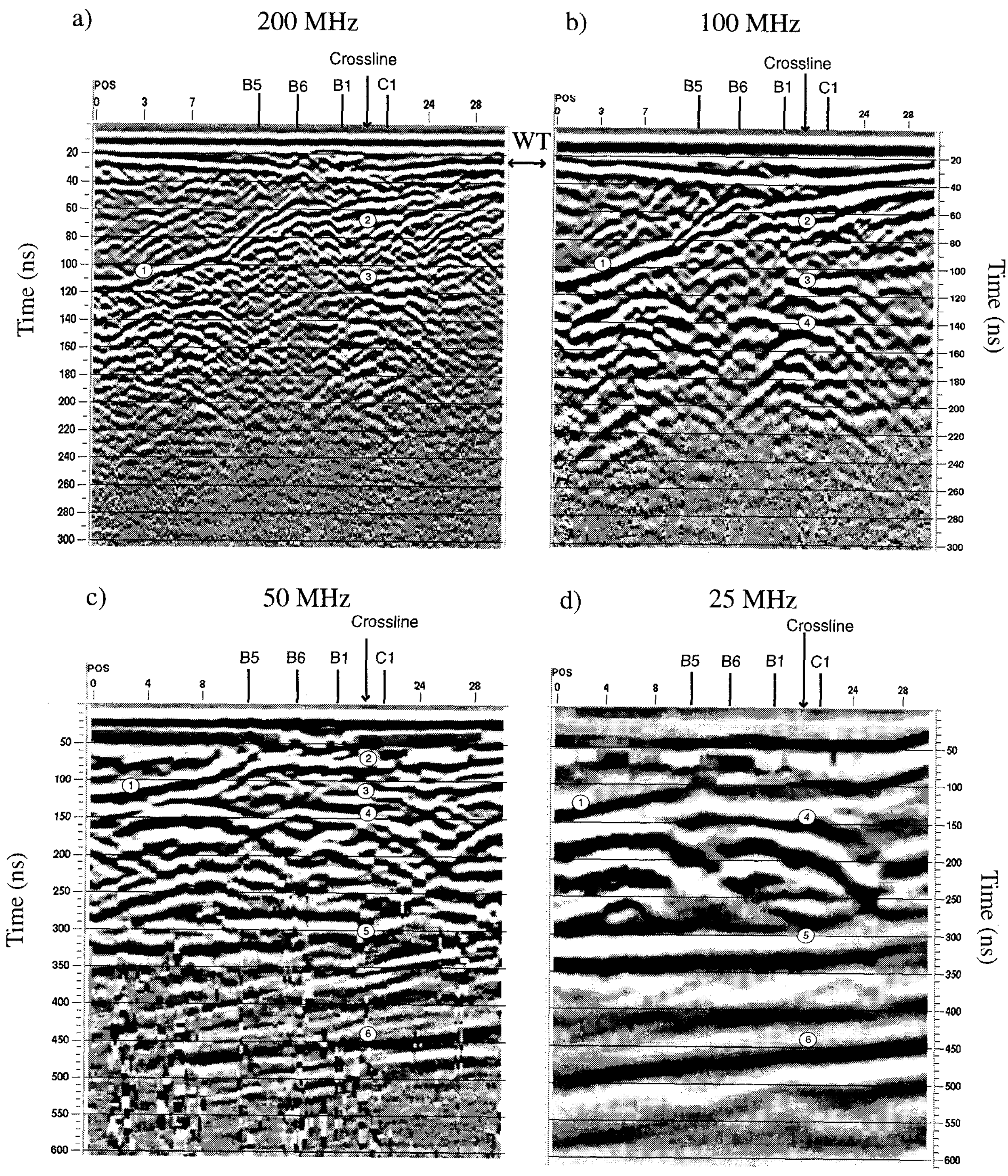

Figure 2. GPR profiles for Line 6.0 at four different frequencies. (a) 200 MHz data, (b) 100 MHz data, (c) 50 MHz data, and (d) 25 MHz data. The water table reflection is labelled WT on the 100 MHz and 200 MHz data. Numbers in circles are used to identify reflections off important stratigraphic features (e.g., bounding surfaces) as discussed in text.

Crossline Data

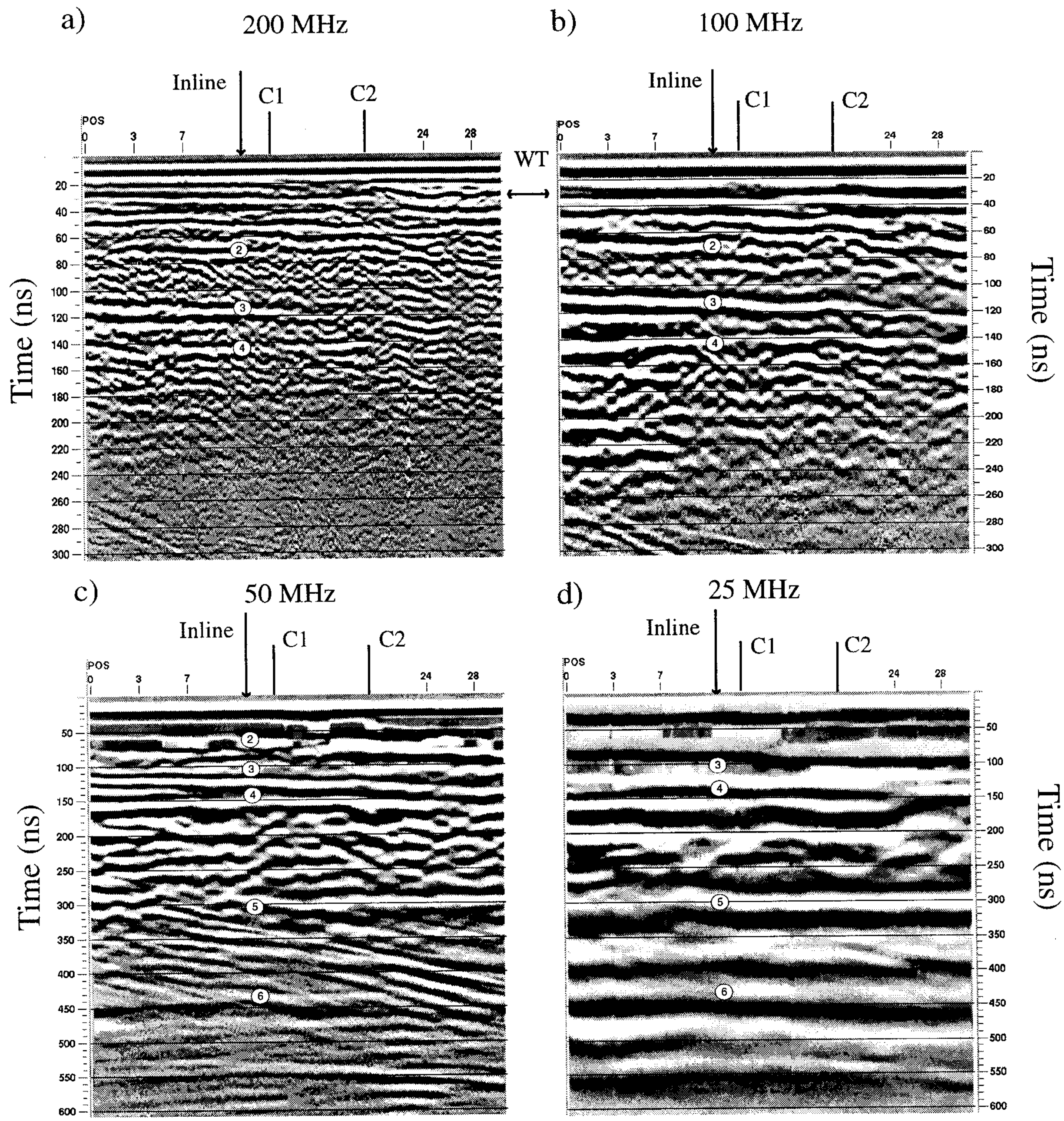

Figure 3. GPR profiles for Crossline 20.0 at four different frequencies. (a) 200 MHz data, (2) 100 MHz data, (c) 50 MHz data, and (d) 25 MHz data. Reflection labels are the same as in Figure 2.

MHz and 50 MHz data have at least two channel or trough features occurring in the region between reflectors 4 and 5 and are best seen at 150 and 250 ns depth as bowtie structures.

Reflector 5 (~14 m depth) is clearly visible around 300 ns in both the 50 and 25 MHz data. This reflector occurs at the base of a couplet of thin sandy lenses within a thicker cobble-dominated unit as interpreted from porosity logs for wells B5, B6 and B1. Resolution is lost below this level, but Reflector 6 is very strong and shows clearly through the noise between 470 ns (~21.3 m depth) to the left (toward the river) and 400 ns (~18.3 m depth) on the right in the 50 and 25 MHz data (Fig. 2). This reflector corresponds with the top of the clay layer that extends beneath the BHRS; both coring data and GPR images indicate that this horizon deepens from the center of the wellfield toward the Boise River (Fig. 1).

Example 3-D block and chair images from 200 MHz data (Figs. 4 and 5) show line (vertical) and time (~horizontal) slices to ~200 ns (~9.6 m depth). Major bounding surfaces and many internal reflectors can be traced laterally and vertically to provide 3-D control on locations, dimensions, and orientations of radar facies and architectural elements; similar examples can be found in Beres (1998). Also, local regions with characteristics such as crossbedding, subhorizontal layering, high attenuation and scattering (Figs. 4-5) can be recognized in lines with most-favorable orientations relative to the characteristics, and then traced laterally and vertically. This is what makes 3-D data so valuable for detailed characterization.

CONCLUDING DISCUSSION

Images such as Figures 4 and 5, in combination with additional site data to assist with interpretation (e.g., core data, well logs, VRPs and VSPs, crosshole radar and seismic tomography, TEM soundings), are being used to build a 3-D model of lithologic and geophysical zonation at the BHRS. This intermediate-scale zonation will be characterized using architectural element analysis (Miall, 1985; Pratt and Miall, 1993) and various geostatistical methods such as traditional variogram analysis (Journel and Huijbregts, 1978), indicator geostatistics (Ritzi et al., 1994), and facies transition-probability geostatistics (Carle et al., 1998). Particular attention will be focussed on the role of bounding surfaces in determining permeability correlation structure (Davis et al., 1997). Hydraulic parameter values (porosity and permeability) will be associated with intermediate- and fine-scale zones using both direct measurements of hydraulic parameters at wells (hard data), and indirect petrophysical transforms, empirical statistical relationships, and stochastic methods (soft data) between wells (Poeter et al., 1997). The reliability of the soft data will be assessed at control points where hard data are available.

Although we are in the early stages of this research, it is clear that 3-D GPR will play a major role in our efforts to characterize the permeability distribution at the BHRS. As shown in this paper, 3-D GPR can image important hydrostratigraphic boundaries and provide indirect information about the nature of the sediments within these boundaries. With this information, heterogeneous fluvial deposits can be subdivided laterally and vertically into distinct units or radar architectural elements. Descriptive features about each unit's character, such as size, shape, orientation, bedding style, indications of scattering and attenuation, and associations with adjacent units, are helpful indicators for classifying and characterizing different units and sedimentary deposits. 3-D volume visualization, time/depth slices, and vertical cuts all give valuable information about the location, scale and geometry of different hydrostratigraphic units, information that is needed to construct hydrogeologic models of fluid flow and contaminant transport. In this way, we hope to make fundamental contributions to the problem of quantitatively characterizing heterogeneous alluvial aquifers.

ACKNOWLEDGMENTS

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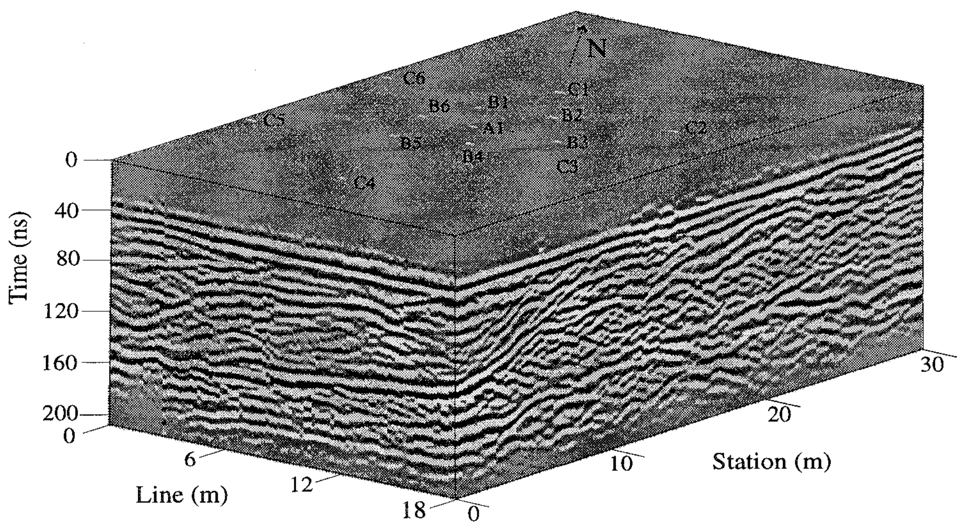

Figure 4. 3-D GPR image (200 MHz) of hydrostratigraphy at the BHRS. The continuous horizontal reflector at ~32 ns is the water table (2.2 m depth at well B1). Numerous bounding surfaces separating different radar architectural units are clearly visible. The depth corresponding to 200 ns is ~9.6 m.

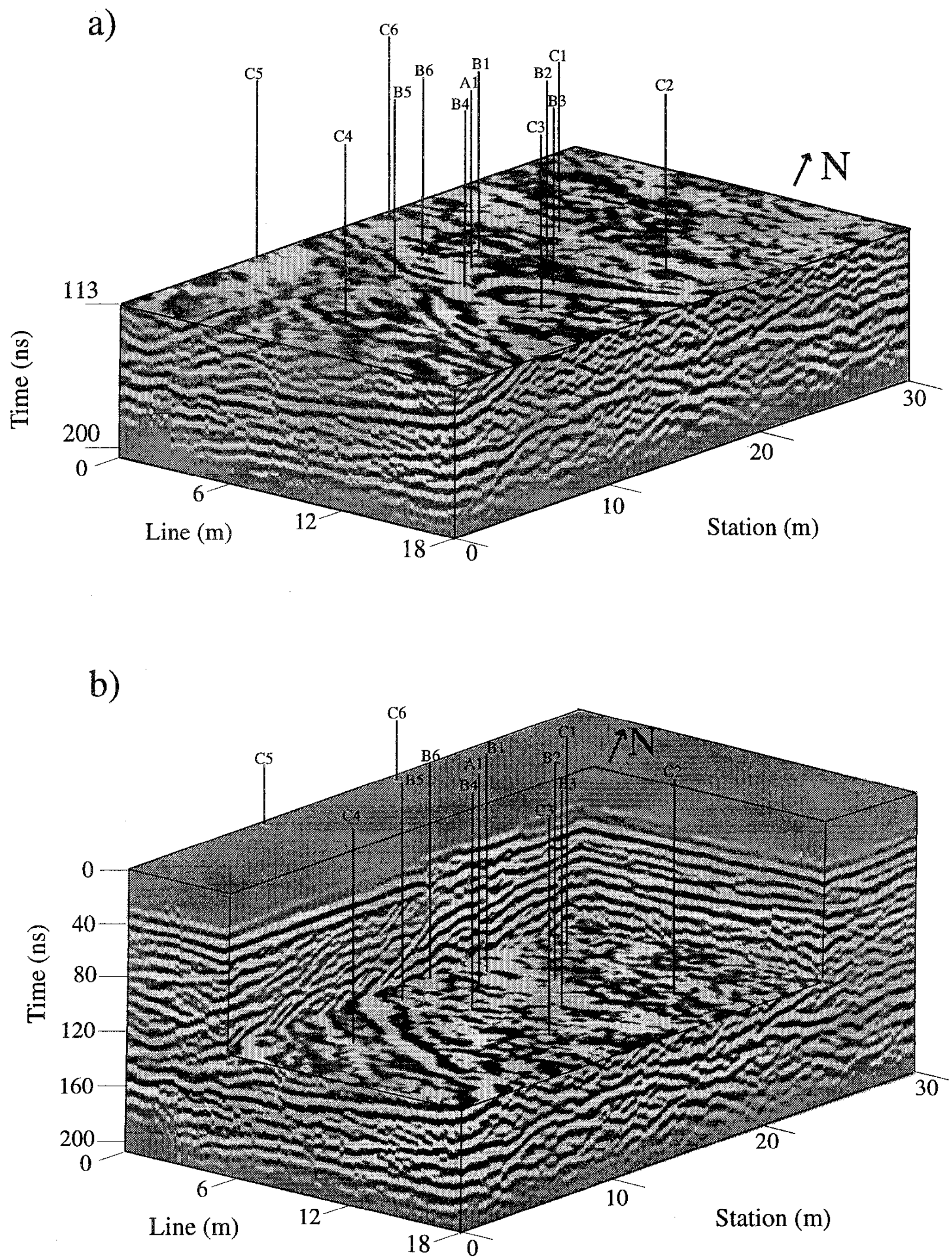

Figure 5. Two composite images of the interior of the 200 MHz GPR data cube. (a) Block image showing time slice at 113 ns (~5.9 m depth). (b) Chair image showing time slice at 134 ns (~6.8 m depth), and vertical sections along the 5.6 m inline and the 24.0 m crossline. Note how major bounding surfaces have different local strikes and dips, and how sediment bodies are more continuous in the crossline direction than in the inline direction. Views such as these are being used to map apparent hydrostratigraphic units between wells and to characterize the zonation and anisotropy of the aquifer.