# VERTICAL RADAR PROFILING TO DETERMINE DIELECTRIC CONSTANT, WATER CONTENT AND POROSITY VALUES AT WELL LOCATIONS

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## ABSTRACT

A vertical radar profiling (VRP) experiment was conducted at the Boise Hydrogeophysical Research Site to determine if direct arrivals and reflections can be recorded using the surface-to-borehole survey geometry. The receiving antenna was deployed downhole to insulate it from cultural noise. The transmitting antenna was located on the surface near the wellhead and oriented radially to the well axis. Although the antenna polarizations are perpendicular, we were able to record radar direct-arrivals and reflections. Picked first-arrival traveltimes were inverted to determine layer interval velocities. The VRP-derived velocity estimates fall in the same range as velocity estimates determined from crosshole radar tomography at the site; average velocities for the unsaturated and saturated zones are 0.140 m/ns and 0.080 m/ns, respectively. Resolution of the VRP-derived velocity estimates is significantly better than the resolution of CMP-derived velocity estimates. Dielectric constant and porosity estimates were also derived from the VRP data using a simple petrophysical model, and compared to porosity estimates derived from neutron logging. Correlation between the two porosity estimates is encouraging. While the VRP method has not been widely used in site investigations to date, the results of this study suggest that VRPs provide an accurate, high-resolution, and cost-effective means of obtaining dielectric constant, EM velocity, volumetric moisture content and porosity values at well locations.

## INTRODUCTION

Ground-penetrating radar (GPR) is widely used to image and characterize the shallow subsurface. Most GPR surveys are conducted using surface-based antennas to collect common offset reflection profiles (Davis and Annan, 1989). Reflection profiles can provide valuable information about subsurface structure and stratigraphy (e.g., Peretti et al., 1999), but they provide little direct information about material properties (e.g., dielectric or hydrogeologic parameter values). In addition, reflection profiles record the traveltime to an interface, not the depth of that boundary. To determine the depth to a given reflector, or to convert time sections to depth sections, information about electromagnetic (EM) velocities is required. Analysis of common midpoint (CMP) data can determine average and interval velocities (e.g., Greaves et al., 1996), however CMP-derived velocity estimates are generally characterized by low resolution and high uncertainty (Tillard and Dubois, 1995). For applications such as detailed hydrogeologic site characterization, better methods are needed to estimate EM velocity distributions.

Tomographic inversion of crosshole radar traveltime data is one method to obtain better velocity estimates. A description of crosshole radar tomography can be found in Olsson et al. (1992). Tomography can provide reliable, high-resolution, velocity estimates correctly located in space; thus tomography is a valuable imaging and characterization tool. However, tomography also has its limitations. For instance, because EM waves attenuate rapidly with distance, closely spaced wells are necessary. Also, the resolution and accuracy of the method are dependent upon ray coverage, so zones with limited coverage have lower resolution and higher uncertainty. These zones typically include source and receiver well locations. Unfortunately, we would especially like to have accurate velocity estimates at well locations. With accurate estimates, we could test petrophysical models and develop site-specific empirical relationships between dielectric properties and other material properties, such as porosity and permeability, determined from geophysical logs and hydraulic well tests. These limitations have motivated us to consider surface-to-borehole measurements, or vertical radar profiling (VRP), as a means of acquiring accurate, high-resolution, EM velocity information at well locations.

Vertical radar profiling is similar to vertical seismic profiling (VSP). VSP techniques have been used successfully for many years in the petroleum industry, primarily to calibrate surface seismic reflection data (Hardage, 1985). VSP has also been used for high-resolution imaging in near-surface environments (Milligan et al., 1997). Despite the benefits of VSP techniques, few VRP studies exist. Two factors cause this. Until recently, the cost of borehole radar instrumentation has been prohibitive. However, in the past two years, commercial manufacturers have introduced low-cost borehole radar antennas. Additionally, antenna theory suggests that detecting the direct wave in VRP data is difficult due to polarization mismatch of the antennas. Recently, Lu et al. (1996) demonstrated that both co-polarized and cross-polarized antenna orientations can record data in VRP surveys.

In this paper, we demonstrate the VRP method using data collected at the Boise Hydrogeophysical Research Site (BHRS). We record direct arrivals and reflections using transmitting and receiving antennas located on the surface and in boreholes, respectively. The traveltimes of the direct arrivals are analyzed to estimate interval velocity values as a function of depth. We then estimate dielectric constant and porosity values from the derived interval velocities using a set of simple petrophysical relationships. To assess the potential value of these material property estimates, we compare the VRP-derived porosity estimates to porosity values determined from neutron logging. Our results suggest that the VRP method can provide accurate, high-resolution, electromagnetic and hydrogeologic property information at well locations.

## BOISE HYDROGEOPHYSICAL RESEARCH SITE

We conducted the VRP survey in the Fall of 1998 at the BHRS. At this site, we are undertaking an intensive, multidisciplinary, research effort to characterize the three-dimensional distribution of lithologic, hydrologic and geophysical parameters within a control volume (~20 m x 20 m x 20 m) of a heterogeneous alluvial aquifer (Barrash et al., 1999), with the overall goal of developing methods for mapping variations in permeability by combining information from hydrologic and geophysical techniques. The VRP method is one of many geophysical and hydrogeological techniques being used to characterize the control volume. For an overview of some of the other techniques, see Clement et al. (1999) and the references contained therein.

The wellfield at the BHRS presently consists of 18 wells completed with 4-inch ID PVC screen (see Barrash and Knoll, in press, for more details). The wells were "drilled" by continuous coring with a split-spoon sampler, beyond the end of drive casing, to a depth of 20 - 23 m. The wells penetrate a heterogeneous, cobble and sand, unconfined aquifer that is underlain by a continuous clay layer at 18.5 – 21.5 m depth that is >3 m thick. We conducted multi-offset VRPs in 14 of the wells, as well as a series of polarization tests, ambient noise tests and duplicate experiments. For the purposes of this paper, however, we limit our discussion to one VRP data set: the near-offset VRP collected in well X4. For a map of the wellfield, see Figure 1 in the companion GPR paper by Peretti et al. (1999).



### Well X4

We selected well X4 because it penetrates a thick zone (3.5 m) of well-sorted sand at the top of the aquifer, in addition to several cobble-dominated units. Well-sorted sands are believed to be among the most permeable material in the control volume, although they comprise only a small fraction of the aquifer's volume and typically occur only as thin (<0.5 m) units. The thick sand in X4 provides the opportunity to define the geophysical signature of this important material under both saturated and unsaturated conditions since the depth to water at the time of the VRP was 1.69 m below land surface. Below this upper sand, X4 is dominated by cobbles with varying amounts of intergranular sand. Because cobble "cobbles" are impermeable, the pore-filling sand controls the permeability response of this material. We believe that the cobble deposits at the BHRS can be subdivided into several different classes with characteristic grain-size distributions, packing styles and pore-filling material, and that these classes can be recognized and distinguished in different types of geophysical data (Barrash and Morin, 1997). The VRP from well X4 presents an opportunity to test this hypothesis for GPR.

## DATA ACQUISITION

The VRP was acquired using a Mala RAMAC/GPR system with 250 MHz borehole antennas. (Although not shown in this paper, we also collected VRP data using a Sensors and Software, Inc., PulseEKKO 100 GPR system with both 100 MHz and 200 MHz borehole antennas. The processed results are similar.) The Mala system employs fiber optic cables to connect the antennas with the control unit. We placed the transmitting antenna on the surface and oriented it radially to the well axis to minimize polarization mismatch with the receiving antenna. The transmitting antenna was not moved during the course of the experiment. The center (feedpoint) of this antenna was 0.85 m from the well axis; the length of the antenna element itself is 0.62 m. The receiving antenna was located downhole to insulate it from sources of cultural noise. Depths are referenced to the feedpoint of the antenna. We lowered the receiving antenna down the well in 5-cm steps. At each depth, stacked 32 traces. Using a surface walkaway experiment, we determined timezero by observing the airwave at different offsets and extrapolating the time of this arrival to zero offset. The timebase was calibrated before the survey, and then checked after the survey; no time drift was detected. The total elapsed time to complete the survey (i.e., one VRP with two surface walkaways) was about 15 minutes.

## PROCESSING

We processed the data minimally to maintain its field character. We editted trace headers to insure correct positioning, removed the dc bias on a trace-by-trace basis (using data before first arrivals to estimate the mean amplitude bias of each trace), applied a dewow filter using a 25-point residual median filter, and AGCed the data to improve the display of the first arrivals. We used a residual median filter to dewow the data to preserve the causal nature of the wavelet (i.e., to avoid introducing precursors to the first arrivals) (Gerlitz et al., 1993). Careful processing is important to preserve the true arrival times in the data for later velocity analysis.

## RESULTS

The processed VRP data (Figure 1) show remarkably strong and clean first arrivals to a depth of ~14 m; this suggests that antenna polarization mismatch is not a serious impediment to collecting quality VRP data. We see several changes in the slope of the first arrivals. For instance, a large change in slope occurs at a depth of 1.85 m, another occurs at 3.50 m, and a third change occurs at 5.0 m. These slope changes mark the locations (depths) of boundaries between materials with different EM velocity (or dielectric constant) values. We also see reflections from these boundaries. The slope of the reflections is opposite that of the first arrivals. Although difficult to see, slope changes and reflections also occur deeper in the section at ~9 m and 11 m. The reflections are more apparent when the downgoing energy is attenuated by dip filtering (e.g., Liberty et al., 1999).

The waveforms of the first arrivals are relatively constant to a depth of ~11 m, but change significantly between 11 m and 14 m where the transmitted wave is lost in the noise. EM theory predicts that phase should vary continuously with propagation distance as a result of dispersion caused by non-zero conductivity (Hollender and Tillard, 1998). We do not have a good explanation for the observed phase behavior yet. It is clear, however, that one should pick first arrivals, instead of peaks or troughs, in VRP and other GPR transmission data. To avoid problems associated with polarity reversals, we picked the first arrivals from amplitude envelope plots; this made it easier to pick the data between 11 m and 14 m.

The apparent lengthening of the wave train or coda after the first arrival is also interesting. One might be tempted to explain this lengthening by dispersion, however this would not be correct. All downgoing energy after the first arrivals in VRPs is observed as short-period multiple reflections. Dispersion will affect the waveform of the multiples somewhat, but it is not the primary cause of the coda. Multiples contain valuable information about layer thicknesses and properties that possibly could be extracted by full-waveform inversion. We mention this as an important topic for future research.

### EM Velocity and Dielectric Constant Estimates

The traveltimes of the first arrivals were used to estimate interval velocities (Figure 2) and dielectric constant values (Figure 3) as a function of depth. We computed interval velocities in two ways. First, we computed interval velocity by dividing the difference in offset by the difference in traveltime for measurements taken 10 cm apart, and plotted the result at the midpoint of the measurements; we refer to these data as the central difference estimates. These estimates fall in the range of expected values for EM velocities (0.05 m/ns – 0.3 m/ns). However the estimates fluctuate over small depth intervals because the central difference method is sensitive to small errors in the traveltime and offset measurements.

To provide a better estimate of interval velocities, we developed a least-squares inversion method. We assume that the subsurface consists of thin (0.25 m) horizontal layers and compute the ray paths between the transmitter and the receiver. To linearize the problem, we approximate the ray paths with straight rays. We then use singular value decomposition to find the inverse of

## Vertical Radar Profile

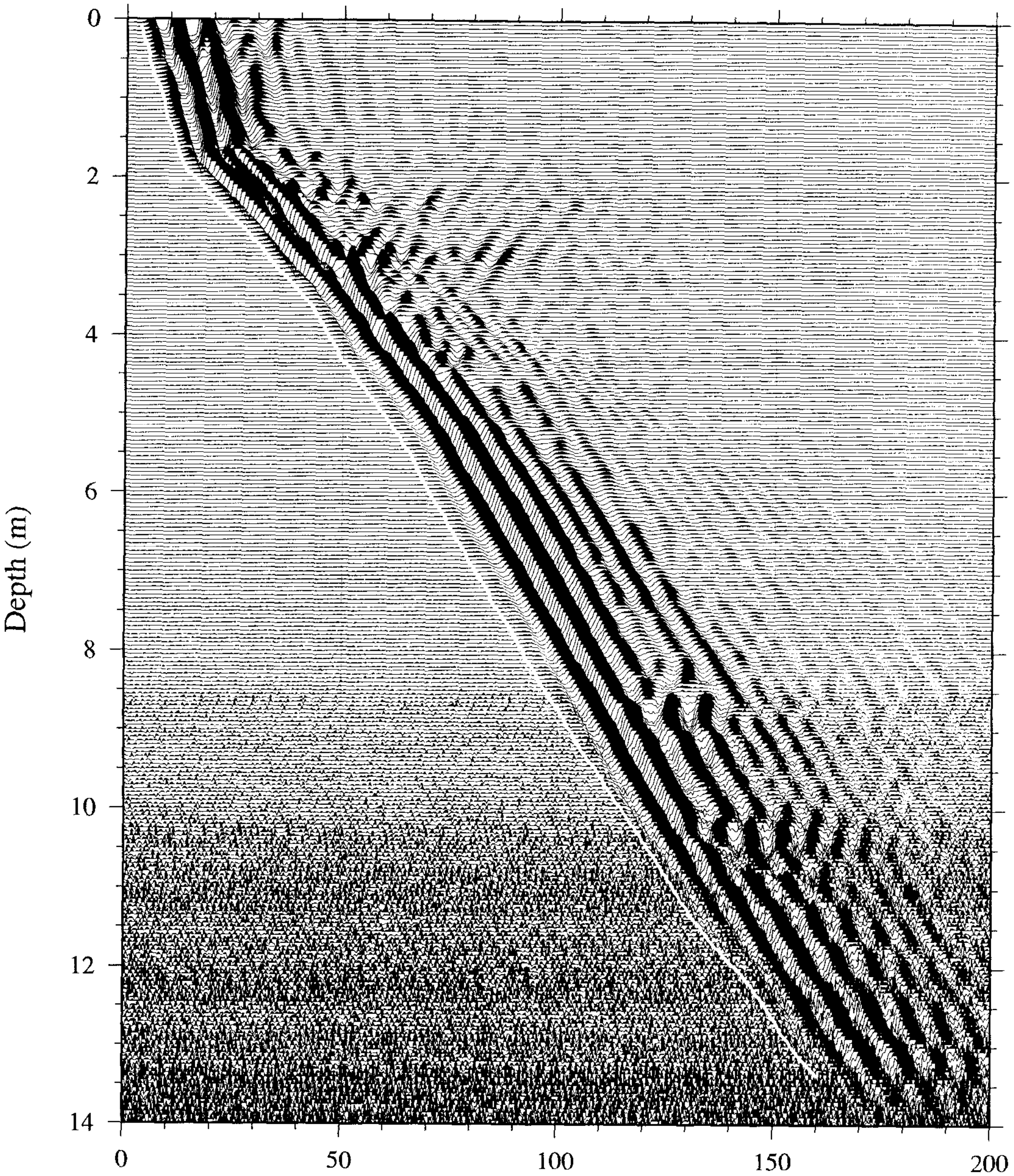


Figure 1. Near-offset VRP from well X4. The vertical axis is depth of the feedpoint of the receiving antenna below land surface and the horizontal axis is travel time. The transmitting antenna was located 0.85 m from the well axis. Note the changes in slope of the first arrivals and the reflections which dip in the opposite direction.

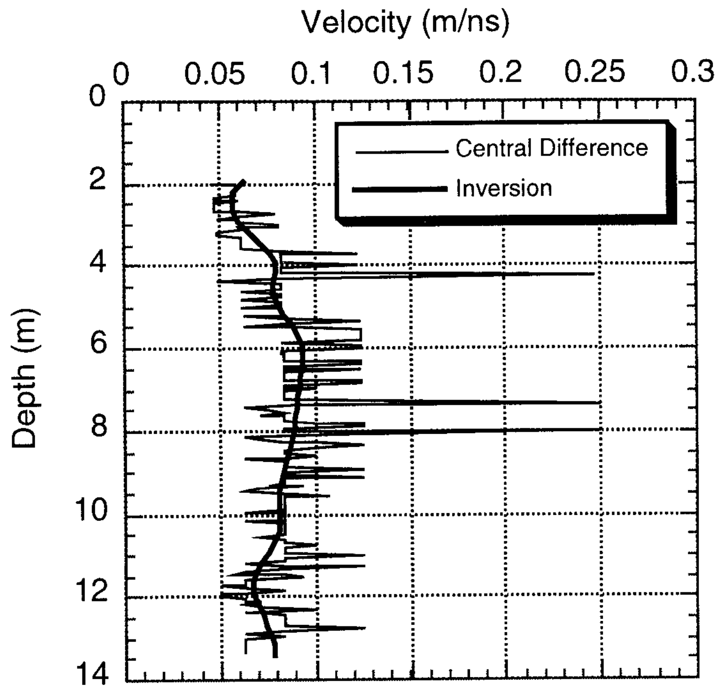


Figure 2. Interval velocity versus depth, derived from first-arrival traveltimes.

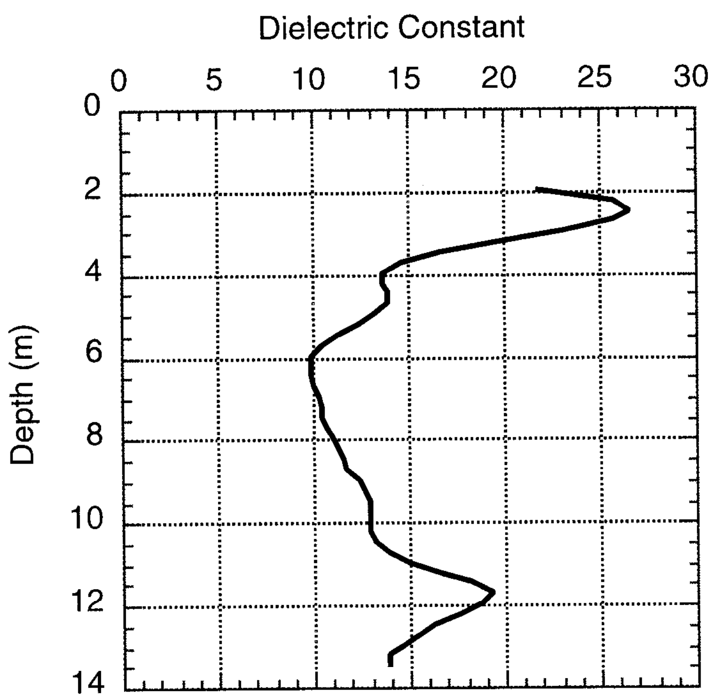


Figure 3. Dielectric constant versus depth, derived from interval velocities.

the overdetermined system of equations. We discard the small singular values to ensure solution stability. Using the first ten singular values, we determined the velocity model that best fits the observed data in a least-squares sense.

The result of the traveltime inversion is shown in Figure 2. The estimates appear to be quite reasonable. The mean interval velocity for the saturated zone below 2 m at well X4 is 0.080 m/ns. This compares quite favorably with velocity values determined by crosshole radar tomography at the site. For instance, Peterson et al. (1999) determined an average velocity of 0.86 m/ns for the saturated zone between wells B1, B2 and C1. Because the water table at X4 was near the surface when the VRP data were collected, reliable estimates of the interval velocity of the unsaturated zone could not be determined. However, other VRPs conducted at the site reliably record direct arrivals through the unsaturated zone indicating that the zone has a velocity ~0.14 m/ns. Linear regression analysis of the direct ground-wave arrival observed in surface CMP data from the site gives the same velocity for the unsaturated zone.

Calculations show that if the velocity of the unsaturated zone is ~0.14 m/ns, then the depth to the receiving antenna must be greater than twice the distance from the transmitting antenna to the well axis before direct arrivals are the first arrivals; otherwise surface refractions are the first arrivals. Also, it should be noted that our velocity estimates assume that the antennas respond when the direct wave reaches the feedpoint. However, when the antennas are close together in a VRP experiment, energy can propagate between the ends of the antennas faster than it can between the feedpoints of the antennas. This will introduce some error into velocity estimates.

We compute dielectric constant $\kappa$ values directly from velocity estimates using the approximation: $\kappa = (c/v)^2$ where $c$ is the speed of light in a vacuum, and $v$ is the measured velocity for the material. For electrically resistive materials such as the cobbles and sands at the BHRS, this is a good approximation. The results are shown in Figure 3. Dielectric constant values in the saturated zone at X4 range from 10.0 to 26.7, with an average dielectric constant of 14.8.

## Porosity Estimates

A number of petrophysical models have been proposed to relate dielectric properties to hydrogeologic properties such as volumetric moisture content, porosity, water saturation and permeability (see Knoll, 1996, for a review). We use the Time Propagation equation (Knoll et al., 1995) to estimate porosity values for the saturated zone from the VRP-derived dielectric constant values. We use effective dielectric constant values of 4.60 and 83.95 for the matrix material (cobbles and sand), and water (very low conductance, 10 degrees C), respectively. The results of the petrophysical modeling are shown in Figure 4, along with porosity estimates derived from neutron logging in X4.

Overall, a good correlation between the VRP and neutron-derived porosity estimates exists. The minimum and maximum porosity values are similar, and occur at about the same depths. Some of the large changes in porosity also occur at the same depths in both methods. For instance, both the VRP-derived porosity estimates and the neutron porosity estimates show a high porosity unit above 3.5 m depth. In the core from well X4, a clean well-sorted sand exists from 1 to 3.5 m. By correlating dielectric measurements to lithologic data from cores, we can determine the dielectric signature of the important units at the BHRS. The derived porosity values between 5 and 9 m correlate well. The core and porosity logs indicate that a tight cobble-dominated unit with relatively little internal variability exists at these depths.

The large decrease in porosity values around 5 m corresponds to a major bounding surface observed in surface radar data from the BHRS (reflector 1 of Peretti et al, 1999); this bounding surface dips toward the Boise River and is interpreted to be the bottom of a paleochannel. Above this bounding surface, however, there are some differences between the VRP-derived and neutron log-derived porosity estimates. At depths between 3 and 4 m, the neutron log and core indicate a tight cobble stringer in an otherwise porous unit that the VRP poorly resolves, although the VRP detects a change to an intermediate level of porosity at that depth. Differences between the VRP-derived porosity estimates and the neutron porosity estimates exist below 9 m. This depth corresponds to the location of another bounding surface observed in the surface GPR data (reflector 4 in Peretti et al, 1999). Some of the porosity differences between the two data types at greater depths could be due to errors in picking the first arrival in the VRP data. Below 9 m, the data quality of the VRP deteriorates and confidently picking the first arrivals is difficult. Overall, the porosity estimates from the two different methods agree well.

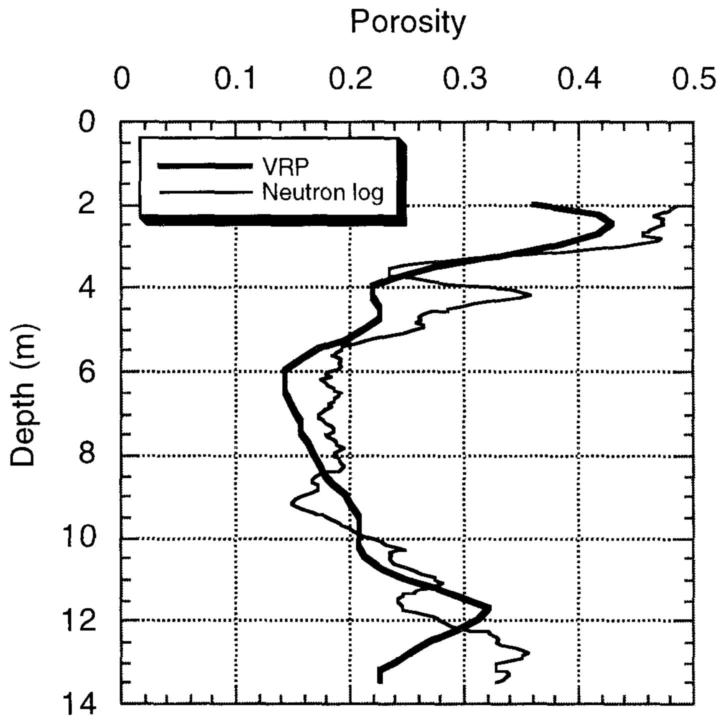


Figure 4. Porosity estimates derived from VRP data and Neutron log data.

## CONCLUSION

The VRP data acquired at the Boise Hydrogeophysical Research Site show that recording direct arrivals and reflections with the surface-to-borehole acquisition geometry is possible. Polarization mismatch between co-polarized antennas does not preclude acquiring useful VRP data. Inversion of first-arrival traveltimes leads to estimates of interval velocities. The least-squares method of inverting the data provides reliable velocity estimates that are resolved on a scale of about a meter. This resolution is significantly better than the resolution from CMP velocity analysis methods. The interval velocity changes are useful for identifying boundaries between different units. We can also transform the data to porosity values using petrophysical relationships. At the X4 well, the VRP identifies four zones with different porosity characteristics that correlate well with neutron logs, core data and surface GPR data. While the VRP method has not been widely used in site investigations, our results suggest that VRPs are an accurate, high-resolution, and cost-effective means of obtaining dielectric constant, EM velocity and porosity information at well locations.

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