Seismic reflection imaging of hydrostratigraphic facies in Boise: A tale of three scales

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Summary

We have acquired, processed and interpreted seismic reflection data from the Boise Valley at three scales to help build a hydrostratigraphic model for regional groundwater studies and to better understand the hydrostratigraphic significance of seismic boundaries. We use existing industry seismic reflection data to identify the structural and stratigraphic framework of the western Snake River Plain, a normal-fault bounded basin that contains more than 2 km of Neogene and younger sediments. To directly tie structure and stratigraphy to water well lithology and geophysical logs, we have acquired seismic reflection data throughout Boise to image near-surface sediments, where prograding delta and fluvial sediments control groundwater flow. To correlate seismic boundaries to hydrologic properties in Boise, we have also acquired seismic reflection data from a highly characterized wellfield. We find the seismic boundaries directly correspond to bulk changes in porosity at this site. Seismic reflection data from these three scales better define basin morphology and help map discrete hydrostratigraphic units necessary to understand hydraulic connectivity, groundwater flow directions, and aquifer capacity in the Boise Valley.

Introduction

Groundwater resources in the Boise Valley are limited. Mapping hydrostratigraphy and identifying hydraulic connectivity between and within sedimentary units is critical to assessing this valuable resource. Seismic methods are often used to assist with groundwater studies because large-scale permeability changes can occur at lithologic boundaries, and seismic velocity contrasts generally appear at these same boundaries.

The Boise Valley is part of the western Snake River Plain (WSRP), a fault-bounded extensional basin in southwest Idaho and eastern Oregon (Figure 1). The basin contains Neogene and younger fluvial and lacustrine sediments deposited from rising and falling lake levels of relic Lake Idaho (Figure 1). Sand layers and channels were deposited within deep-water mudstones (Wood, 1994). These sand units are targets for groundwater production in the valley. Unfortunately, the sands are often discontinuous and connectivity between aquifer units is poorly understood. In addition to the complex geometry of the sands, structural downwarping and faulting in the basin further complicate the stratigraphy. For example, a typical 4 degree dip shifts the stratigraphy approximately 70 m between wells spaced 1 km. Water wells rarely extend greater than 100 m depth and are often at greater distances. In addition, faults with greater than 200 m of vertical offset are observed in the basin (Wood, 1994; Liberty, 1998), suggesting lithology between water wells may be complex and that each well may record a unique stratigraphic sequence.

To address the problems of mapping complex stratigraphy and structures in the WSRP for groundwater resource assessment, we are compiling existing seismic reflection data and geophysical and lithologic logs to gain a regional understanding of the depositional style of the basin (Figure 2a). We are also acquiring and processing new seismic reflection data (Figure 3a) to better understand and map the subsurface stratigraphy in the upper 500 m below land surface (BLS) where groundwater resources are economically viable. Finally, we are conducting a series of surface and borehole seismic studies at a highly characterized research wellfield in Boise to better understand the significance of seismic boundaries for detailed hydrogeologic studies. By combining the geology and geophysics at these three scales, we are building a geologic framework to support planning for future groundwater needs for the growing Boise metropolitan area.

Basin-Scale Studies

Interest in the WSRP for petroleum and geothermal resources in the 1970s has yielded several hundred km of seismic reflection data and has provided great insight into the depositional and extensional history of the basin. In particular, a 1972 Chevron USA Vibroseis seismic reflection profile through Boise (Figure 2) provides a

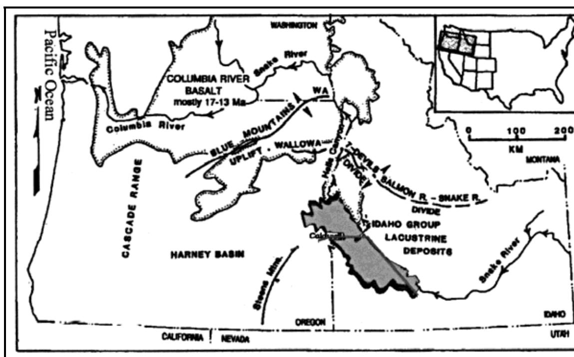

Figure 1. Regional map showing the location of the western Snake River Plain. We are acquiring new seismic reflection data primarily in the Boise metropolitan area.

concise picture of the basin structure and stratigraphy of the WSRP (Wood, 1994). The reflection data show a package of dipping and offset reflections that are typical of an extensional basin. Neogene and younger basin sediments appear in nearby wells with a prograding delta sequence that extends up to 1 km BLS. Numerous faults cut the basin sediments and may extend to the surface or very near surface. The steep dips, large-offset faults, and varying stratigraphy all complicate the groundwater models for the basin, but provide the necessary framework to characterize the groundwater aquifer system.

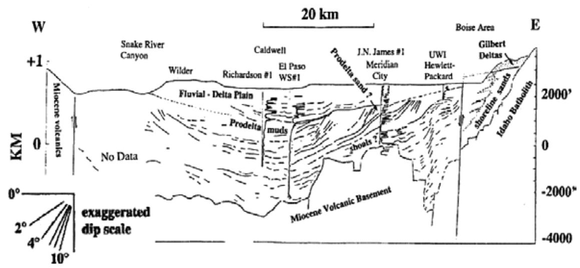

Figure 2a. Interpreted cross section of Chevron Line IB-2 profile across the western Snake River Plain (from Squires and Wood, 2001).

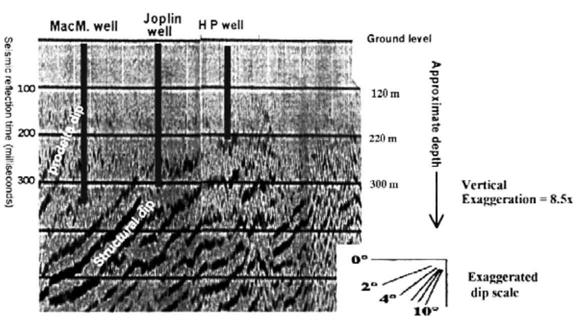

Figure 2b. A portion of profile IB-2 along the eastern front of the Boise basin. Note the absence of data above 300 m below land surface (from Squires and Wood, 2001).

The industry seismic data offer insights into ground water resources by helping to identify major structural boundaries that may inhibit lateral groundwater flow. The data also shed light into the depositional style and sequence of mudstones, silts, and sands that may extend to the surface in places (Squires and Wood, 2001). Unfortunately the basin-scale seismic data do not image the upper 300 m BLS (Figure 2b) due to the acquisition design and processing interests, and much of the seismic data are not available for reprocessing.

Aquifer-Scale Studies

In the past few years, we have acquired a series of seismic reflection profiles to image the structure and stratigraphy in Boise to map both the cold water aquifer (Barrash and Dougherty, 1997; Liberty, 1997; Liberty et al., 1999) and the underlying geothermal aquifer (Liberty, 1998). In addition, we have acquired seismic reflection data this past field season and have plans for additional campaigns. We are combining all seismic data to map the hydrostratigraphy in the valley and tie to lithologic and geophysical logs from nearby wells.

In the summer of 2000, we acquired a 10 km seismic reflection profile along the Union Pacific Railroad (UPRR) main line through Boise. This profile provides the opportunity to collect a straight seismic profile through an urban corridor in southwest Boise where data are needed to address hydrologic concerns. Access for seismic reflection studies is very challenging through urban areas (e.g., Liberty, 1998; Hemphill-Haley et al., 2000), where either expensive seismic sources (e.g., vibroseis, air gun, or explosives) are required to overwhelm cultural noise and operate on city streets, or else creative right-of-way access (e.g., railroad line, irrigation canal lines) must be employed to gain access and to minimize cultural noise. Since budgets are often limited when working with state and local agencies, we have thus far operated along large private property parcels (i.e., minimizing the number of land owners) and public property access (e.g., city and county parks, fairgounds, greenbelts, university campus). Although opportunities for unobstructed access may be limited as the urban areas continue to grow, we continue to pursue access on undeveloped lands.

We acquired the seismic reflection data along the UPRR using a trailer-mounted accelerated weight drop source. We used a 5-m source and receiver station spacing with a 120-channel Geometrics seismograph to produce a 60-fold seismic reflection section (Figure 3a). Railroads are often built up on a level grade to minimize topographic effects for rail traffic. Unfortunately the artificial grade can reduce source and receiver coupling in places and can produce significant near-surface lateral velocity contrasts. We compensate for poor coupling and busy street crossings (up to 5 lanes at 55 mph) with high fold and we also pay special attention to static corrections during processing to address the large near-surface lateral velocity changes.

The seismic data record a similar signature when compared to Chevron Profile IB-2 (Figure 2). However, we recorded reflections from approximately 20 m BLS and extending to at least 700 m depth. Although we acquired the seismic profile oblique to the primary dip direction in the basin, we observe reflections with depositional dips up to 5 degrees and numerous small-offset faults, likely due to a prograding delta sequence and basin extension. As suggested earlier, these steep dips and fault offsets preclude accurate hydrologic mapping of lithofacies with well logs alone.

The seismic reflection data show that the hydrostratigraphy cannot be mapped between major water wells more than 1 km apart (Figure 3) and that the seismic reflection data are critical to mapping hydrostratigraphic and structural detail relevant to groundwater management in Boise.

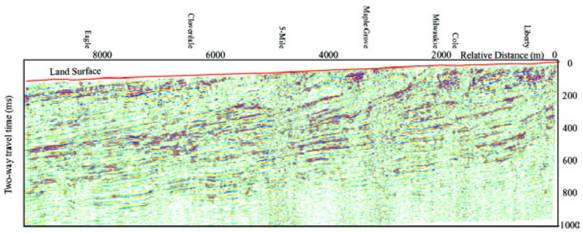

Figure 3a. Seismic reflection profile along the UPRR in southeast Boise. The profile parallels Chevron profile IB-2 further to the south.

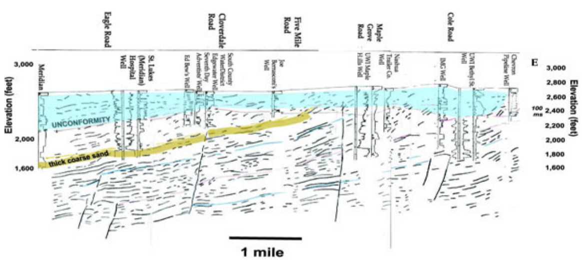

Figure 3b. Interpreted seismic reflection profile along the UPRR with well log information.

Meter-Scale Field Site

The Boise Hydrogeophysical Research Site (BHRS) is a research wellfield containing 18 cored wells which extend through a 17 m thick cobble-and-sand aquifer that is underlain by a continuous red clay layer. The BHRS is located on a gravel bar immediately adjacent to the Boise River where the river leaves a canyon and enters the WSRP. Ground penetrating radar (GPR) profiling indicates that the cobble-and-sand aquifer at the site consists of a sequence of deposits separated by subhorizontal bounding surfaces (Peretti et al., 1999). We established the BHRS to develop methods for mapping variations in permeability by combining information from hydrologic and non-invasive geophysical techniques (Barrash et. al, 1999; Clement et al., 1999). By identifying the seismic methods that can image lithologic boundaries in this difficult seismic environment, we can begin to map the three-dimensional distribution of lithologic and hydrologic properties at this site and better assess the role of seismic methods in mapping permeability in similar geologic environments.

To investigate the seismic character at the BHRS, we conducted a series of seismic experiments with a variety of source-receiver geometries, seismic sources, and receivers (Liberty et al., 1999; Liberty et al., 2000). Here we show a shot from a crosswell seismic survey at the BHRS (Figure 4) that correlates seismic velocities to borehole geophysical logs (e.g., neutron), and identifies the nature of reflectors that appear with both surface and borehole seismic studies.

Figure 4 shows an unprocessed and processed crosswell seismic shot from 21 m depth. We recorded shots at a 0.15 m depth spacing and receivers at a 0.10 m depth spacing below the water table (approximately 2.4 m below land surface) to the maximum depth in each well (approximately 20 m depth). Distinct first arrivals and reflections appear in the unprocessed shot from all downhole, source-receiver pairs (traces) below the water table. We picked all first arrivals for tomographic velocity analysis and used wave field separation techniques to separate upgoing and downgoing reflection energy for subsequent reflection processing.

The crosswell shot (Figure 4) shows three distinct reflections in the upper 5 m of the section, from the land surface, water table (at 2.4 m depth), and from approximately 4.5-5 m depth. Also, reflections appear later in the section at approximately 13 m, 17.5 m, and 21 m depth (reflection from 21 m correlates with the basal clay and does not appear on this shot gather due to source/receiver geometry). Each reflection is distinct and closely ties with hydrostratigraphic boundaries that appear on geophysical logs. For example, the transparent zone (no coherent reflections) that appears between 4.5-10 m depth corresponds to the high velocity/low porosity zone defined with the tomogram and the neutron-derived porosity logs (Figure 4). The zone between 10 and 21 m depth contains variable reflection quality that correlates with changes in porosity and the lithology of mostly cobbles with some sand lenses. When we invert the level run data set (source and receivers at the same depths between two wells), we see that seismic velocities strongly correlate with neutron-derived porosity values at this site (Figure 4).

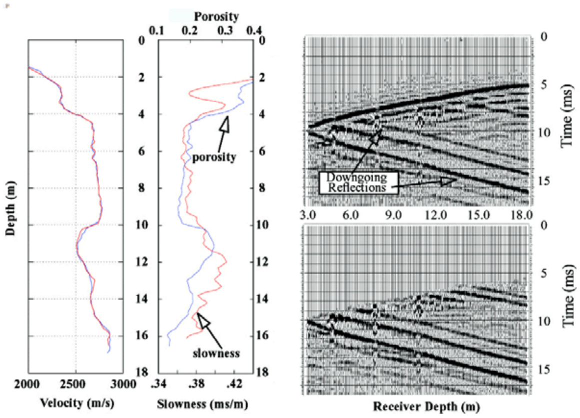

Figure 4. Results from a crosswell seismic reflection survey showing level run velocity logs, a comparison of slowness (1/velocity) vs. neutron-derived porosity values, and an unprocessed and processed (wavefield separation) shot gather from 21 m depth with 12.7 m borehole spacing. Note the strong correlation between seismic boundaries and porosity.

Conclusions

We show that seismic reflection methods are well suited for mapping hydrostratigraphy and structure on both a basin scale and aquifer scale to better understand the framework for groundwater flow in the WSRP. Also, we have successfully acquired seismic reflection data at the BHRS to map significant hydrostratigraphic boundaries in a shallow cobble-and-sand fluvial aquifer. The results of our study show that reflections are mainly controlled by changes in porosity. Although interbedded sands and mudstones dominate the deeper geology of the WSRP, this study shows that we can also map hydrostratigraphy at meter-scale at this shallow site.

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