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Breakthroughs in Seismic and Borehole Characterization of Basalt Sequestration Targets

EC Sullivan[1], BA Hardage[2], BP McGrail[1], and KN Davis[3]

[1]*Pacific Northwest National Laboratory, Richland, Washington, USA*
[2]*University of Texas, Austin , Texas, USA*
[3]*Washington State University, Pullman, Washington, USA*

Abstract

Mafic continental flood basalts form a globally important, but under-characterized CO_2 sequestration target. The Columbia River Basalt Group (CRBG) in the northwestern U.S. is up to 5 km thick and covers over 168,000 km^2. In India, flood basalts are 3 km thick and cover greater than 500,000 km^2. Laboratory experiments demonstrate that the CRBG and other basalts react with formation water and super critical (sc) CO_2 to precipitate carbonates, thus adding a potential mineral trapping mechanism to the standard trapping mechanisms of most other types of CO_2 sequestration reservoirs.

Brecciated tops of individual basalt flows in the CRBG form regional aquifers that locally have greater than 30% porosity and three Darcies of permeability. Porous flow tops are potential sites for sequestration of gigatons of $scCO_2$ in areas where the basalts contain unpotable water and are at depths greater than 800 m. In this paper we report on the U.S. DOE Big Sky Regional Carbon Sequestration Partnership surface seismic and borehole geophysical characterization that supports a field test of capacity, integrity, and geochemical reactivity of CRBG reservoirs in eastern Washington, U.S.A.

Traditional surface seismic methods have had little success in imaging basalt features in on-shore areas where the basalt is thinly covered by sediment. Processing of the experimental 6.5 km, 5 line 3C seismic swath included constructing an elastic wavefield model, identifying and separating seismic wave modes, and processing the swath as a single 2D line. Important findings include: 1) a wide variety of shear wave energy modes swamp the P-wave seismic records; 2) except at very short geophone offsets, ground roll overprints P-wave signal; and 3) because of extreme velocity contrasts, P-wave events are refracted at incidence angles greater than 7-15 degrees. Subsequent removal of S-wave and other noise during processing resulted in tremendous improvement in image quality.

The application of wireline logging to onshore basalts is underexploited. Full waveform sonic logs and resistivity-based image logs acquired in the 1250 m basalt pilot borehole provide powerful tools for evaluating geomechanics and lithofacies. The azimuth of the fast shear wave is parallel to S_H and records the changes through geologic time in basalt flow and tectonic stress tensors. Combined with image log data, azimuthal S-wave data provide a borehole technique for assessing basalt emplacement and cooling history that is related to the development of reservoirs and seals, as well as the orientation of tectonic stresses and fracture systems that could affect CO_2 transport or containment. Reservoir and seal properties are controlled by basalt lithofacies, and rescaled P- and S-wave slowness curves, integrated with image logs, provide a tool for improved recognition of subsurface lithofacies.

Keywords: CO_2; flood basalts; carbon sequestration

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1. Introduction

Southeastern Washington State and a large portion of the entire U.S. Pacific Northwest east of the Cascade Mountain Range belong to the Columbia Plateau Province, which hosts world-class continental flood basalts. The Miocene Columbia River Basalt Group (CRBG) covers over 168,000 km^2 of eastern Washington, northeastern Oregon and western Idaho [1]. Collectively, over 300 individual flows have been mapped within the region, with a maximum composite thickness of greater than 5 km within the central portion of the Pasco Basin (Figure 1).

The Columbia River flood basalts are grouped into five basalt formations, of which the Grande Ronde flows are the most voluminous, comprising some 148,600 km^3 and extending from eastern Idaho to the Pacific Ocean [2] (Figure 1). Younger flows cover more limited areas, and commonly fill paleo-canyons cut into older flows [3]. Sedimentary and volcaniclastic interbed layers are thinner and less common between older flows than between younger flows.

The Columbia River basalts are quartz tholeiites, dominated by plagioclase, augite and glassy, noncrystalline mesostasis material [4]. The flows are mapped in outcrop using a combination of lithology, paleomagnetic properties, and geochemical composition. Borehole samples may require additional oxides for identification, along with trace and rare earth elements. Abundances of TiO_2, P_2O_5, Cr, MgO, Zr, and Ba provide the most diagnostic data for distinguishing flows. The basalts and associated shallow sedimentary interbeds of the CRBG have been mapped and studied for almost a century, primarily in relation to aquifer usage, repository potential at the DOE Hanford Nuclear Reservation, and more recently for natural gas exploration [5-7]. Regional aquifer studies include data on storage capacity, injectivity and production, zonal containment and lateral continuity. Nuclear repository studies of the 1980's added geomechanical information (in-situ stresses, minimum threshold fracture pressures, and fracture reopening pressures) for basalts in the Pasco Basin.

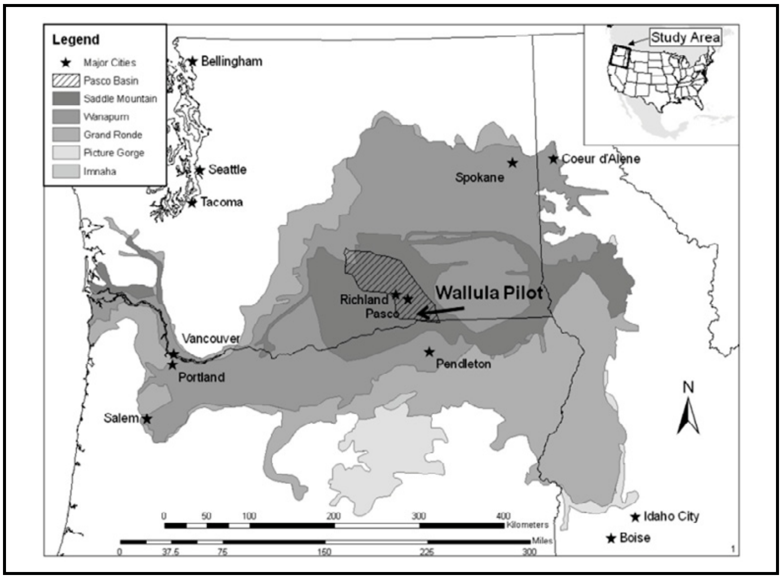

Figure 1. Geographic Extent of the Miocene Columbia River Basalt Group.

Basalt flow tops form layered regional aquifers with local development of 30% porosity and three Darcies of permeability. Hydrologic aquifer studies [8-9] and wellbore studies of the Hanford nuclear site basalts [6] demonstrate sealing capacity of CRBG flow interiors. Ground waters within and below the Grande Ronde Basalt in the central Columbia Basin have high pH and contain concentrations of fluoride that exceed the Federal primary drinking water standards as well as the standard adopted in Washington State for permitting geologic sequestration projects. Porous basalt flow tops are thus potential targets for sequestration of anthropogenic supercritical (sc) CO_2 in areas where the basalts contain non-potable water and are at depths greater than 800 m. Conservative estimates of CO_2 storage capacity in the CRBG are approximately 10 to 50 $GtCO_2$ [10].

Basalt reservoir and seal development are strongly controlled by lithofacies related to mode of emplacement and thermal cooling history. In outcrop, CRBG basalts are typically smooth to blocky pahoehoe flows with brecciated and heavily vesiculated flow tops, a massive base, and columnar joints at right angles to the cooling surfaces (Figure 2). An upper and lower colonnade may be present; both upper and lower colonnade may contain zones of platy fracturing. Vesiculation in colonnade zones is generally sparse with small vesicles in occasional isolated tracts and cylinders [11-12].

The entablature lithofacies is a zone of rubbly irregular horizontal fractures, and may occur directly below the flow top or between the upper and lower colonnade. Fanning columns or bands of vesicles may separate entablature from upper or lower colonnades [11-14] or may result from flow over irregular topography. Basal portions of older CRBG flows are generally massive; younger flows in the northeastern part of the Columbia Basin locally contain basal pillow palagonite complexes, spiracles, and shattered-glass peperites that reflect flow of basaltic lava into water or onto saturated substrates. Vesicles may be present in thin sheets associated with glassy flow bases or in pipes and cylinders [11-13], or in flow interiors as vesicle sheets. Mega vesicles appear in lower portions of some flow crusts [14] and commonly record flow shear. The accurate identification of subsurface basalt lithofacies is challenging, but is important in constructing robust static and dynamic reservoir models.

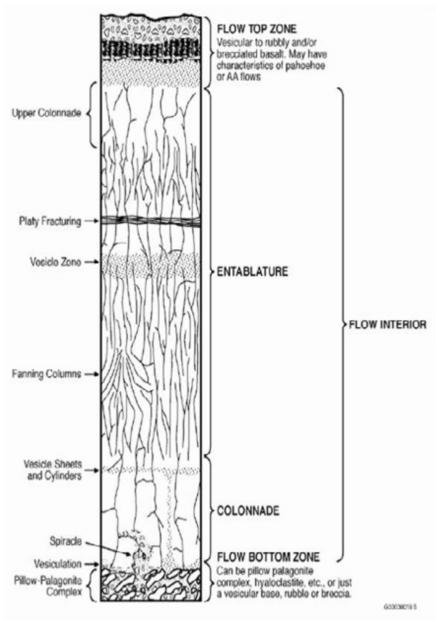

Figure 2. Basalt Lithofacies. After Reidel 2002.

The geologic characterization activities associated with the Big Sky Regional Carbon Sequestration Partnership multi-year field test of the capacity, integrity, and geochemical reactivity of continental flood basalts include 1) acquisition and processing of an innovative 3C surface seismic swath near Wallula, Washington in 2007, and 2) drilling, logging, and hydrologically testing an associated 1250 m pilot borehole in 2009. Injection of 1000 metric tons of supercritical CO_2 is scheduled for the first quarter of 2011. In this paper we summarize the acquisition and processing of the multi-component seismic swath, and present observations on the integration of P- and S- waveform sonic logs with information from resistivity-based image logs to determine regional and local stress tensors and to improve identification of subsurface basalt lithofacies.

2. Seismic Methods and Results

Continental flood basalts are some of the largest geologic structures on the planet and are present in regions of the U.S., China, India, Siberia, and elsewhere where sedimentary basin storage capacity may be limited. Consequently, demonstration of commercial-scale storage in deep flood basalts is important in meeting global CO_2 emissions targets. Because of extensive prior characterization of the flood basalts in southeastern Washington State, this region has been the focus of these first field studies.

The surface seismic acquisition method, which utilized advanced multi-component sensors, two 60,800 pound truck-mounted vibroseis sources, and a 5-line receiver swath layout, is the first of its kind to be used on continental flood basalts. The 2007 survey was designed to greatly enhance acoustic signal preservation, and to allow the identification and removal of converted wave or other noise that traditionally results in extremely poor seismic images of on-shore basalt layers that have a thin sediment cover. The 6.5 km reflection survey used a seismic signal generated by two large vibrator trucks. Approximately 3000 receivers simultaneously recorded various modes of compression and shear waves, including waves that are mode converted as they encounter sharp boundaries of subsurface rock layers. Three-component receivers, consisting of one vertical compression wave sensor and two orientations of shear wave sensors, were arranged in a five-line (168 m wide) swath (**Error! Reference source not found.**) that extended north-south, near the proposed CO_2 pilot injection site. The vibrator trucks generated a synchronized seismic signal at closely spaced stations along each of the long sides of the rectangular swath. Prior to acquiring the survey data, the vibrators were tested to ensure the electronics and control systems preformed within specifications. Finally, acquisition tests were conducted to determine the optimal combination of vibration frequency, length of vibration time ("sweep") and number of sweeps that created the strongest reflections of the basalt layers below about 800 m that were targeted for detailed sequestration characterization.

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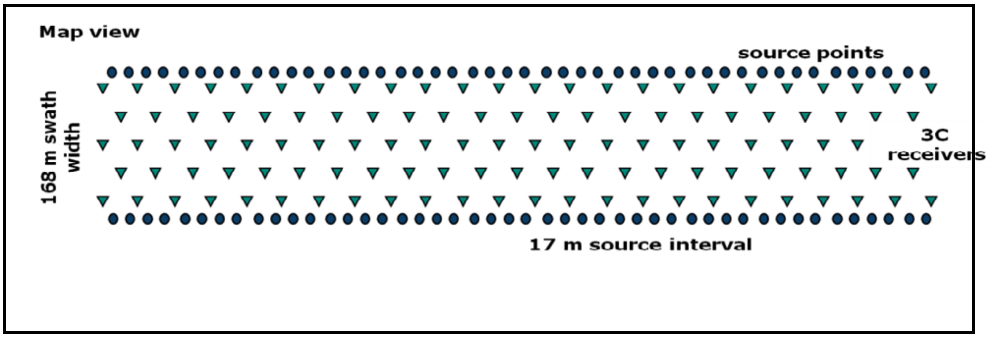

Figure 3. Plan View of the Wallula 6.5 km, 3C Seismic Receiver Swath Design

Processing of the Wallula multi-component data set included more than 30 individual processing steps, many of which were iterative. Seismic processing addresses six main functions: database building, editing and basic corrections, signal-to-noise optimization, and enhancement of resolution in time and space. Finally, processing involves producing images that allow easier detection of specific geologic features, such as faults or fracture zones. Because the survey was designed to allow for identification of converted waves that can behave as noise and can obscure the seismic image, full elastic numerical modeling of seismic wave behavior was required. Results of the numerical modeling allowed the identification and removal of converted wave noise, and identified causes of loss of P wave signal at shallow depths and at basalt flow interfaces. To enhance signal to noise, the data were processed as a single 2D line. An intermediate processing image (Figure 4) shows the migrated P-wave section with a 12-16-36-48hz filter applied. The dotted horizons are isovelocity lines taken from the velocity-depth profile computed by a tomographic refraction static algorithm. The image indicates that in the subsurface geology intersected by the seismic swath, a thick succession of basalts (about 2450 m) is present, with no indications of major faulting. At this stage, the data in the zone of interest (approximately 0.5 sec two-way time) are relatively low frequency, about 15 hertz (Hz). Figure 5 shows the final vendor-produced P-P image with higher dominant frequency data of about 30 Hz. Although these data have relatively low resolution compared with many sedimentary data sets, they represent higher signal to noise ratio than has been previously obtained for basalt layers that have a thin sediment cover.

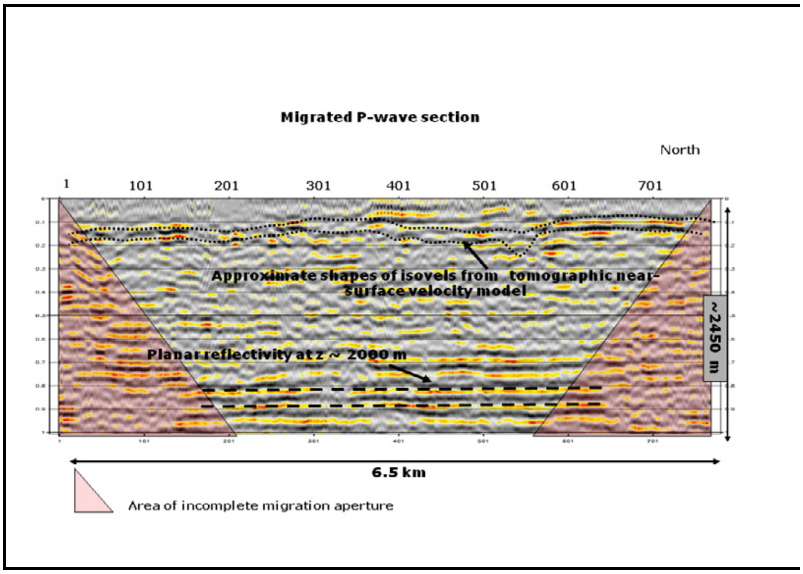

Figure 4. Intermediate Processing Product of the Wallula Seismic Data

With a dominant frequency of about 30 Hz, the data are sufficient to determine there are no large vertical offsets in the subsurface along the seismic line. As with images generated during the intermediate processing stages, the final migrated P-wave images indicate that no east-west striking faults disrupt the deep basalt interval along the seismic swath, and thus no major deep-seated breaks are likely to penetrate the shallower basalt section. Because the dominant wavelength of the data is approximately 200 m, there could be small-throw faults with vertical displacements of 15 or 20 m (0.1 λdom) that cannot be recognized on the currently processed two-dimensional images. In addition, faults parallel to the seismic swath would not be imaged by this transect.

Data gaps near the surface and underlying disruption of the seismic image resulted from avoidance of irrigation waterlines and surface infrastructure. Data interpreted from this seismic line do not eliminate risk of a fault being present near the pilot well site, but do reduce uncertainty associated with existence of hidden east-west striking faults associated with major compressional structures in the Pasco Basin.

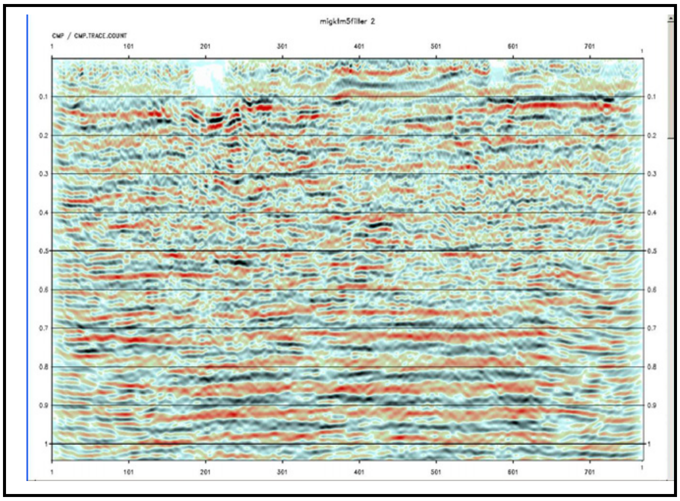

Figure 5. Final P-Wave Vendor-Produced Processing Product of the Wallula Seismic Data. Field of view is 6.5 km; North is to the left.

The insights gained during acquisition and processing of the experimental three-component swath have resulted in a breakthrough in application of seismic imaging to basalt geology. Identification of the specific causes of poor data quality allow the development of processing steps to remove unwanted energy modes, improve the signal-to-noise ratio, and increase resolution. Our most important findings include: 1) a wide variety of shear wave energy modes swamp the P-wave seismic records; 2) except at very short geophone offsets, ground roll overprints P-wave signal; 3) because of extreme velocity contrasts, P-wave events are refracted at incidence angles greater than about 7-15 degrees; and 4) conversion of down-going P-wave energy at very shallow depths to down-going S waves generates a shear source and a shear wave (SV-SV) volume, which has yet to be interpreted. Analyses of these shear-wave data may potentially lead to new techniques for evaluating azimuthal seismic anisotropy, fractures, and stratigraphic heterogeneity. The surface seismic data and wellbore synthetic seismogram (not shown) will be calibrated with a vertical multi-component seismic profile, scheduled to be acquired in the pilot well near the end of 2010.

Wireline Logs Methods and Results

The Wallula pilot borehole represents the first detailed borehole characterization of deep Columbia River basalt formations within this region of the State. The closest well penetrating the Grande Ronde interval of interest is a natural gas exploratory well 60 km distant. The carefully selected suite of conventional open and cased wireline logs included a pulsed neutron reservoir saturation log that was run in the Sigma Saturation mode for comparison with post-injection saturation signatures. Open-hole wireline caliper, gamma, SP, photoelectric cross-section, array induction, neutron, density, pulsed neutron sigma, full waveform sonic, and resistivity-based image logs were run from total depth of 1250 m into the shallow casing to a depth of 259 m. Gamma, thermal neutron, and full waveform sonic log acquisition continued inside the shallow casing to the surface.

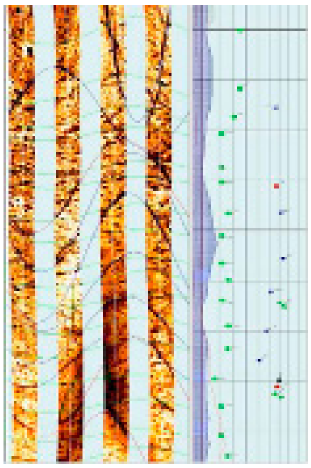

Figure 6. Vesicular Texture and Fractures in the Wallula Pilot Image Log. Vertical scale is marked in .3m increments. Colored tadpoles show dip and dip azimuth of flow structures and fractures.

Two types of wireline logs are especially useful in the interpretation of basalts. Resistivity-based image logs provide a rich data set that allows interpretation of dip and azimuth of basalt cooling features, tectonic fractures, and stratigraphic and structural dip, as well as basalt lithofacies textures that are related to reservoir and seal development (**Error! Reference source not found.**). In addition, image logs permit determination of stress tensors near the borehole through analysis of borehole breakout and drilling induced fractures. Full waveform sonic logs are also rich in azimuthal data. At Wallula, analysis of the P- and S- modes of the full waveform sonic log data were integrated with the pilot well image log data to yield information on Young's modulus, Poisson's ratio and other geomechanical properties of the basalts. Of particular interest is the azimuth of the fast shear mode, which is parallel to the horizontal component of the maximum compressive stress tensor (**Error! Reference source not found.**). An integrated interpretation of the image log and shear mode data yields a bed by bed record of basalt flow orientation as well as changes in tectonic stress regimes. This integration provides a new borehole application for assessing basalt emplacement and cooling events that are related to the development of reservoirs and seals, as well as better mapping of tectonic stresses and fracture systems that could affect CO_2 transport or containment.

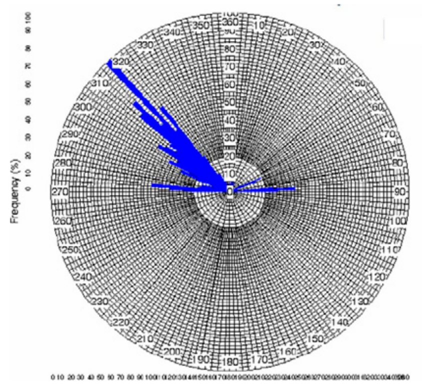

Figure 7. Rose Plot of Fast Shear Azimuth from the Full Waveform Sonic. North (zero degrees) is at the top of the circle. Observed east-west azimuth may be related to basalt flow emplacement.

Log Identification of Basalt Lithofacies

The lithology responses of conventional resistivity, neutron – density, gamma, and SP logs provide a first order means to distinguish potential flow top reservoirs from potential flow interior seals. In addition, sonic logs and resistivity-based image logs provide important geomechanical information and signatures for open fractures that could compromise seal integrity. We follow the suggested methodology of Boldreel [13] to investigate the use of rescaled sonic P- and S-slowness curves to further refine our ability to distinguish basalt lithofacies as determined from a combination of well cuttings, rotary sidewall cores and image logs.

We find that when sonic slowness curves are graphed on a single track but with different scales (P-wave slowness from left to right, 130-10 µs/ft and S-wave slowness plotted at 170-50 µs/ft) large separation of P- and S-curves is a good indication of sedimentary interbeds while intermediate separation is typical of flow top crust (Figure 8). Similar to the study by Boldreel [13], we note that logged intervals within massive flow interiors, as recognized on image logs, are characterized by overlap of the two sonic curves, or by curve separation of less than five units. Log separations between five and 30 µs/ft coincide with regions of vesicular, heavily fractured and/or brecciated basalts. Heavily weathered basalts with visible authigenic clay components occur in wellbore intervals where the P- and S- sonic curve separation is 30 to 80 units. Logged intervals with greater than 80 units of curve separation contain interbeds of sedimentary siliciclastics and rhyolitic volcaniclastics sourced from Cascade volcanoes west of the flood basalts.

P-wave slowness curves that plot to the left of the S-wave curve are usually associated with zones of low permeability fractures. When the separation is less than 5µs/ft, the basalt tends to be vesicular, with little connectivity between vesicles and largely impermeable. In well cuttings, vesicles in these zones may or not be coated with clay minerals. Large separation of the curves, particularly in cases where the unscaled P-sonic values are close to or equal to the S-sonic values, is indicative of non vesicular zones with low permeability fractures. These fractures may be filled with clays or healed with other secondary minerals.

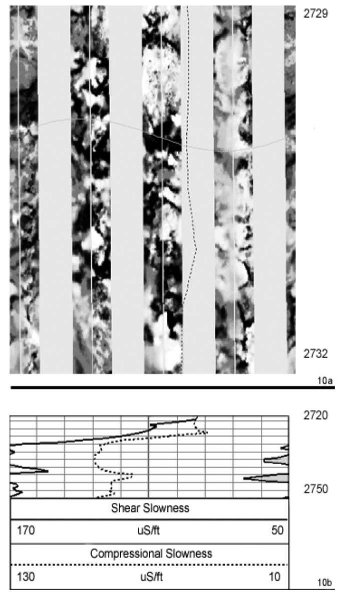

Figure 8. Rescaled Sonic Slowness P- and S- Curves over a Basalt Flow Top, as Identified in Image log and Well Cuttings. Note depth scales in feet.

These observed empirical relations between sonic curve signatures and basalt lithofacies reflect basic lithofacies differences in sonic velocities. When we generate lithofacies grouped histograms of the P-wave sonic log velocities from the Wallula well, we find that sedimentary interbeds (as confirmed with well cuttings) show a wide range of low velocity peaks but have the strongest peak around 3.5 km/s; flow tops exhibit a much wider spread with the greatest concentration of velocities between 3.25 and 3.75 km/s; and flow interior zones are tightly clustered around 5.5 km/s.

3. Discussion

In outcrop and well cuttings, the Columbia River basalts appear to consist of pahoehoe flows with few a'a flow characteristics. Differences in well log signatures reflect differences in position of rubble/breccia zones relative to the massive flow interiors: both a'a flows and pahoehoe flows with palagonite or pillow basalts are characterized by rubble at the bottom of a flow, grading upward into massive flow interiors. Within the deeper CRBG of easternmost Washington, basal rubble or breccia zones are extremely rare, and no true a'a textures were observed in outcrop. Slabby pahoehoe flow top lithofacies are present in Grande Ronde outcrops and appear to provide the maximum target for thickness and porosity. Environmental or compositional controls on the thickness and lateral extent of flow top breccias are poorly understood. Prolific basalt potable-water aquifers are generally developed in younger, shallower basalts, and often consist of interconnected flow tops of thin flows. Older deeper flows with greater relevance to sequestration tend to be thicker, with thinner flow tops. Computer generated logs of lithofacies that incorporate dip data appear to show stacking patterns in the basalt flows. Future investigation of these data may reveal stratigraphic patterns that favor development of flow top breccias.

4. Conclusion

Our work provides a breakthrough in the seismic imaging of subsurface geologic features of the Columbia River Basalt Group of the northwest U.S. and illustrates the potential of multi-component seismic technology for imaging flood basalts or other near surface, fast velocity rocks- crystalline or sedimentary. This success supports seismic potential for subsurface basalt characterization and a path forward for developing seismic and wireline monitoring technology for commercial-scale CO_2 sequestration in basalts, where appropriate geological conditions exist.

Many of the conventional wireline logging tools are applicable to the characterization of subsurface basalts. Rescaled sonic P-wave and S-wave slowness curves, when calibrated with rock and image log data provide a robust tool for identifying an array of subsurface basalt textures and structures that are of relevance to the safe and permanent sequestration of anthropogenic carbon dioxide in continental flood basalts. The capability to define wire-line log signatures for flow interior, entablature, flow bases and tops, and various vesiculated and fractured lithofacies, and the ability to determine the relative abundance of the different lithofacies has important implications for mapping and evaluating reservoirs and seals for long-term carbon dioxide sequestration in basalts of the northwestern U.S. and elsewhere. Exploring for basalt reservoirs will be challenging, but now has a path forward with tools and technologies similar to those demonstrated on the CRBG flood basalts.

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