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The Wallula Basalt Sequestration Pilot Project

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Abstract

The U.S. Department of Energy Big Sky Regional Carbon Sequestration Partnership completed drilling the world's first continental flood basalt sequestration pilot borehole to a total depth (TD) of 1253 m at a paper mill site near the town of Wallula located in Southeastern Washington State. Site suitability was assessed prior to drilling by acquisition, processing and analysis of a four-mile, five-line, three component seismic swath, which was processed as a single data-dense line. Analysis of the seismic survey data indicated absence of major geologic structures that would preclude CO_2 injection at the site. Drilling of Wallula pilot borehole was initiated on January 13, 2009 and reached TD on April 6, 2009. Hydrogeologic information was obtained primarily during borehole drilling/advancement utilizing a progressive drill-and-test characterization strategy. A general decreasing transmissivity trend with depth pattern was observed, which is consistent with results exhibited for Columbia River basalt interflow zones at a number of other deep wells in the region. Based on the comparative results from 10 test intervals, a candidate injection test zone was identified between the general depth interval of ~828 and 875 m bgs. Over this interval, three brecciated interflow zones were intersected and isolated for CO_2 injection. The flow tops have moderate permeability (75 to 150 millidarcies) and are bounded by thick flow interiors that have extremely low (microdarcy) permeability. The borehole configuration established at the Wallula pilot site provides a unique opportunity to scientifically study the reservoir behaviour of three connected reservoir intervals confined between primary and secondary caprock zones. The permitting process for the CO_2 injection has proceeded in accordance with formal rules for geologic sequestration projects enacted in June 2008 into the underground injection control program administered by the Washington State Department of Ecology. The permitting process is expected to conclude in October 2010 and injection would begin soon thereafter. Post-injection monitoring includes long-term sampling of water retrieved from the injection zone, shallow groundwater and soil gas monitoring, and PSInSAR.

Keywords: geologic sequestration; field pilot; basalt

1. Introduction

Continental flood basalts represent one of the largest geologic structures on the planet but have received comparatively little attention for geologic storage of CO_2. Because flood basalt formations exist in regions of the U.S. (and other countries such as India), where sedimentary basin storage capacity is limited [1], demonstration of commercial-scale storage in deep flood basalts is important in meeting global CO_2 emissions targets. That fact is now being increasingly realized. After the original concepts for CO_2 storage in basalts were proposed [2-3], interest has grown rapidly with laboratory [4-10] and two field trials [11-13] now underway around the world. Nevertheless, the field pilot study undertaken by the U.S. Department of Energy's Big Sky Carbon Sequestration Partnership (BSCSP) described in this paper remains unique in the world for confirming the feasibility of permanently and safely sequestering large quantities of supercritical CO_2 within deep flood basalt formations.

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2. Regional Setting

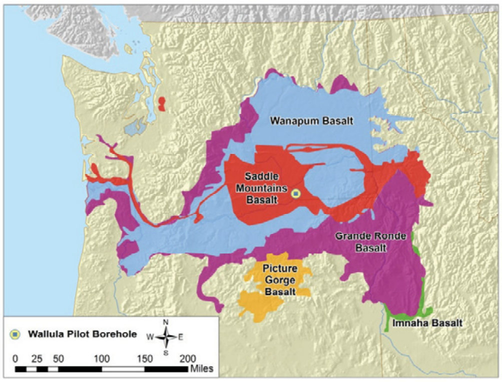

Figure 1. Surface Areal Extent of Basalt Formations of the Columbia River Basalt Group (modified from Reidel et al. 2002)

Southeastern Washington State, and indeed a large portion of the entire Pacific Northwest east of the Cascade Mountain Range belong to the Columbia Plateau Province, which hosts a world-class set of continental flood basalt deposits. The Miocene Columbia River Basalt Group (CRBG) covers over 77,200 mi^2 of portions of eastern Washington, northeastern Oregon and western Idaho (Figure 1), with a total estimated volume of more than 53,700 mi^3 [14]. Collectively, over 300 individual CRBG flows have been identified within the region, which attain a maximum composite thickness of greater than 5 km within the central portion of the Columbia Basin. Conservative estimates of CO_2 storage capacity in the CRBG are approximately 10 to 50 $GtCO_2$ [3]. Groundwater within the Grande Ronde Basalt and below in this region of the Columbia Basin is non-potable, brackish and sulfide-rich, with high concentrations of fluoride that exceed maximum concentration limits (MCL) as specified in U.S. National Primary Drinking Water Regulations (40 CFR 141.62). Injection of CO_2 for the purpose of permanent sequestration is permitted in Washington State under WAC 173-218-115[1] for formations containing non-potable water.

3. Site Selection

In April of 2007, Battelle Pacific Northwest Division (PNWD) and the BSCSP were invited by the Port of Walla Walla to conduct the field pilot study on Port-owned land in Walla Walla County. Following obtaining the necessary surrounding land owner permits, Battelle completed a seismic survey near Port-owned property in December 2007. Following completion of the seismic survey, it became necessary to shift the pilot project site to nearby private property at the Boise Whitepaper mill. This location ensured the pilot study could be carried out on private property but was still near enough to the seismic survey line to preserve relevance of the seismic survey. Negotiations for a Land Use Agreement were successfully concluded in August of 2008. PNWD staff surveyed the Boise mill site to identify a suitable location for the borehole. Site constraints, such as size of unobstructed areas, proximity to structures, access to electrical power and water dictated the final selected site.

4. Site Characterization

4.1. Soil Gas Monitoring Wells

Two soil gas probes were installed on Port property prior to the shift in the site location. The 1.9 cm diameter probes were spaced approximately 275 m apart and installed ~7.6 m deep and included a bottom screened interval of 2.54 m. Sand was used for packing around the probes and commercial dry granular bentonite was used for sealing. Above ground risers with pad locks were installed in concrete to protect the soil gas probes from adverse weather conditions.

Gas samples were collected using a Pulse Pump III (MiDan) and 1-L Tedlar® bags. A single air sample was collected near one of the wells and used as a background sample. Gas chromatography (GC) was utilized to measure concentrations of H_2, CO_2, C_2H_4, C_2H_6, O_2, N_2, CH_4, and CO in these gas samples. Results from the GC analysis show slightly elevated readings (above background) for N_2 and O_2. Concentrations of CO_2 in the wells were identical or lower than background levels. Remaining gas compounds of interest (especially methane) were below de-

[1] http://apps.leg.wa.gov/WAC/default.aspx?cite=173-218-115.

tectable limits in both wells and the air sample. Elevated methane concentrations in basalt systems can be indicative of faults or other geologic structures acting as conduits for vertical migration from deep methane sources [15]. Hence, the lack of elevated methane in the soil gas samples was suggestive that such high flux conduits were absent at the site.

4.2. Seismic Survey

An innovative three-component 2D surface seismic swath profile acquired near Wallula, Washington in December 2007 provided the framework for fault detection and first order characterization of subsurface stratigraphy and structure at the site of the proposed Big Sky CO_2 sequestration test. The results from this seismic acquisition and processing experiment greatly reduced uncertainty associated with site selection by showing that there are no deep seated surface or subsurface faults along the seismic line, and that a thick succession of basalt layers are present and undisturbed by large scale faulting. The seismic survey represents the first known success of surface-based seismic imaging of basalt that has a thin sediment cover. The results provide a critical key for subsurface characterization and monitoring of CO_2 sequestration in basalts. This experiment has important implications for sequestration not only in the Pacific Northwest but also in other basalt terrains, worldwide. Readers are referred to the paper by Sullivan et al. [16] in this volume for a more detailed discussion of the survey, data collected, and interpretation.

4.3. Borehole Drilling and Characterization

The Wallula pilot utilized the progressive "*drill-and-test*" characterization strategy that emphasizes the acquisition of detailed hydrogeologic characterization information concurrent with drilling and borehole advancement. This is in contrast to characterization strategies that are initiated after a borehole has reached the final well completion depth. As discussed in Reidel et al. [14], information acquired using a progressive *drill-and-test* strategy provides characterization information of higher quality, particularly for those hydrologic parameters that are sensitive or more significantly impacted by the borehole drilling process, (e.g., hydrochemistry, microbiology). This is also the preferred characterization strategy for boreholes such as the Wallula pilot that are drilled in areas not having significant subsurface information available from surrounding wells drilled to comparable depths. In the case of the Wallula pilot, the deepest well drilled within a 6-mile radius of the pilot borehole location is only 915 ft. Because of this lack of subsurface hydrogeologic information, characterization activities at the Wallula pilot borehole were more extensive than normally utilized at deep boreholes that are situated in more characterized areas. The Wallula pilot represents the first detailed-characterized, reconnaissance-level borehole for deep Columbia River basalt formations within this region of Washington State. Only the highlights of the characterization program are presented in this paper. Detailed characterization results are provided in a Topical Report [17].

4.3.1. Drilling Program and Well Construction

Drilling services for the Wallula pilot borehole were provided by Boart Longyear drilling services, based in Salt Lake City, Utah, utilizing a LM-140 rotary drilling rig constructed originally by Lang Drilling Company. It can employ standard or reverse-flood circulation methods, and utilize a variety of drilling fluids (polymer/bentonite, water, air, foam). Drilling was initiated on January 14, 2009 and continued to a depth of 56 ft utilizing a 24.0 in. drill-bit diameter. A 20-in. diameter surface conductor casing was set to this depth and an annular cement seal emplaced from depth to land surface utilizing a tremie-pipe delivery system. Cementing protocols followed recommended Washington State regulations specified for resource protection well construction/completions (WAC-173-160-420, -430, and -450).[2] The borehole was drilled below 56 ft utilizing a 19-in. bit, and continued to a depth of 1,108 ft. Conventional circulation using primarily a bentonite-based drilling fluid was utilized to a depth of 190 ft. Below 190 ft, the reverse-flood drilling method using primarily bentonite-based drilling fluid was employed. A 14-in. diameter casing was welded and installed from land surface to 1,108 ft, and the casing annulus sealed with neat cement and State approved additive accelerants (calcium chloride), using a tremie-pipe delivery system. The borehole was drilled below 1,108 ft utilizing a 12.25-in. drill bit, and advanced to a final depth of 4,110 ft.

[2]WAC-173-160-420, General Construction Requirements for Resource Protection Wells; WAC-173-160-430, Minimum Casing Standards; WAC-173-160-450, Well Sealing Requirements.

As part of the well completion design, the lower borehole section of the pilot borehole was cemented back to a targeted depth of 2,910 ft, utilizing a tremie-pipe delivery system. The top of the cement plug was tagged at a depth of 2,985 ft. Water was circulated in the borehole until clean and the lower borehole cement plug completed to a depth of 2,910 ft.

Following completion of the plug-back cementing from 2,910 to 4,110 ft, a protective sand/gravel layer was installed over the targeted open well completion depth interval 2,716 to 2,910 ft. Following installation of the protective sand/gravel layer, 7-in. diameter casing was installed from land surface to 2,716 ft. The 7-in. casing annulus was sealed with neat cement and State approved additive accelerants (calcium chloride), using a tremie-pipe delivery system. Following successful sealing of the 7-in. casing, the protective sand and gravel layer was removed using the air-lift method, and the 194-ft open well/test zone interval between 2,716 and 2,910 ft developed using the air-lift pumping technique. Figure 2 shows pertinent well completion details of the Wallula pilot borehole.

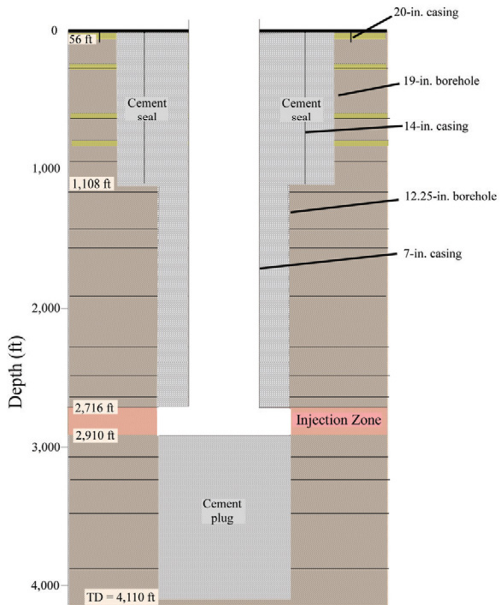

Figure 2. As-Built Completion for the Wallula Pilot Borehole

4.3.2. Stratigraphy and Geochemical Sampling

The reverse circulation drilling method produced optimal cuttings sizes for observation of important textural rock characteristics. Onsite geologists collected rock cuttings every 10 feet (more frequently in zones of interest), and following written, standardized procedures [18], recorded macroscopic and microscopic lithology descriptions, as well as degree of fracture surfaces observed. Basalt cutting samples taken at key points in drilling and sent to Eastern Washington University for XRF analyses provided whole rock geochemistry and stratigraphic control for the well. Interpretation of the wellbore data indicates that no faults were cut within the well, and that the stratigraphic level at total depth (4,110 feet) is within the Wapshilla Ridge 1 basalt flow.

Deviation surveys taken when total depth was at 1,800 feet and again from 4,110 to surface show that the wellbore remained vertical with a deviation of 0.52 degrees with an azimuth of 118.4 degrees (ESE) at 1,800 feet, and at a total depth of 4110 feet, the bottom hole location was at a distance of 50 feet from the top, with an azimuth of N50^{o}E.

Thirty two rotary sidewall cores were cut between 4,110 – 1,542 feet. The field print of the Formation Micro Imager (FMI) log (resolution about 1/8 inch) was used to determine precise intervals to be cored. This resulted in an increased success rate on retrieving cores, as we were able to avoid vugs, cavities and severe washouts. This technique also allowed us to more precisely sample a wide variety of basalt lithofacies. Depths of the cores in and proximal to the injection zone are shown in Figure 3. Preliminary petrographic analysis of thin sections from well cuttings indicates the basalt lithologies are dominated by plagioclase, augite, and glassy mesostasis. Hematite is one of the few accessory minerals. Vein, fracture, and vesicle filling materials include calcite and quartz (several crypto-, micro-, and mega crystalline forms). The most common alteration products, as determined from XRD and megascopic identification are illite, zeolites, clinoptilolite, and celadonite. Pyrite is also locally present.

Previous detailed study and mapping of the Columbia River flood basalts has resulted in the establishment of stratigraphic units that can be reliably identified and correlated on a regional basis [14]. The Columbia River Basalt Group (CRBG) has been divided into six formal formations in ascending stratigraphic order: the Imnaha, Grande Ronde, Prineville, Picture Gorge, Wanapum, and Saddle Mountains Basalts. CRBG units are identified and mapped in outcrop using a combination of lithology, paleomagnetic properties, and geochemical composition with regards to superposition, but borehole samples are not easily identified using only these techniques. Additional major and minor oxides, and trace and rare earth elements provide the key data, with TiO_2, P_2O_5, Cr, MgO, Zr, and Ba being the most diagnostic elements to consider. The most definitive identification technology of discrete basalt sub-groups, formations, members and individual flows is the high-precision, rapid analysis of major and trace elements by XRF (X-ray fluorescence analysis). The GeoAnalytical Laboratory at Washington State University-Pullman provided the high quality analyses that are the standard for identification of CRBG flows. The analytical and sample preparation techniques are described by Johnson et al. [19].

4.3.3. Wireline Geophysics

Two companies performed wireline logging activities at the pilot borehole. Stoller Inc., a local logging company that was able to accommodate the logging schedule driven by drilling and geologic conditions, conducted a sonic based cement bond log across the shallow 14 inch casing from 1108 feet to surface, as well as a cement bond log across the seven inch casing from 2720 feet to surface. Stoller also collected data in five logging runs in the deeper, 12 ¼ inch open borehole over separate logging intervals. Gamma, spontaneous potential (SP), four-arm caliper, dipole sonic, and resistivity data were acquired as needed to determine rock quality and select competent rock intervals for seating the down-hole packer tool for hydrologic tests. These logs were run from 1108 feet to borehole total depth (TD) of 4110 feet. An acoustic borehole imager was run from TD to 1108 feet to allow evaluation of data gathered through acoustic-based imaging and resistivity based imaging. All tools performed well; caliper, resistivity and sonic were especially helpful in picking unfractured intervals for seating the packer. To protect against aquifer cross-flow, and to prevent drilling complications from possible borehole instability, no open-hole wireline logs were acquired above 1100 feet.

The most important of the Stoller log data for moving ahead with permitting activities are the cement bond logs. Acoustic cement bond logs can be interpreted as percent of cement behind casing. Cement bond logs generated by Stoller indicate that in the shallow 14 inch casing, there is less than 50% cement bond over several of the sedimentary interbeds of the Ellensburg Formation. This is consistent with washout and some loss of circulation experienced while drilling these beds. The cement bond log indicates that these intervals are separated by intervals that have 95-100% bond. The bond is more consistently high below a depth of about 950 feet. The bond for the seven inch casing is consistently high, at or near 100% bond except in rare, isolated four to six foot intervals that have 95% bond. Only in one short isolated interval from 2,392-2,398 feet does the bond go below 90%. Thus, the sedimentary beds of the Ellensburg Formation appear to be isolated from each other and from the deeper basalts flow tops.

Schlumberger Wireline Services acquired the open-hole logs that required sealed source neutron logging and heavier tool strings of combined tools. Schlumberger open-hole caliper, gamma, SP, photoelectric cross-section, array induction, neutron, density, pulsed neutron sigma, and full waveform sonic logs were run from TD of 4,110 feet up into the shallow casing to a depth of 950 feet. The gamma, thermal neutron, and full waveform sonic logs were continued inside the 14 inch casing to the surface. The Formation Micro Imager (FMI) resistivity based image log was run from 4,110 feet to the base of the shallow casing and has been processed up to 2,000 feet.

Porosity was measured with the thermal neutron, density and sonic tools, and tied to basalt lithofacies and structure through image logs. All porosity and permeability displays on these preliminary logs are uncalibrated, and were not used in calculating injectivity, transmissivity, or storage capacity within the targeted composite injection zone. The matrix values for density, neutron and sonic porosity will be calibrated with laboratory data from the rotary sidewall cores or from core material from equivalent formations at the Hanford site. However, even in this early stage of evaluation, the log signatures provide important clues for identification of basalt lithofacies. Both uncalibrated cross-plot density/neutron porosity and sonic porosity are essentially zero in the massive basalt flow interiors, and range from zero to 3% in the entablature zones (Figure 3). In zones of washout in the brecciated flow tops, the neutron-density porosity will be less reliable, even when calibrated to core. Uncalibrated sonic porosities are from 15 to 30% in the brecciated flow tops; and from 15 to 25% in the proposed injection zones.

The logging data combined with XRF stratigraphy indicate that there are no major faults in the well. In particular, image log analysis indicates that dip reversals are stratigraphic rather than due to faults. Regional structural dip, as interpreted by Schlumberger is two degrees to the northwest; stratigraphic dips are commonly 10-30°, vary considerably in azimuth and magnitude, and appear to be related to basalt emplacement.

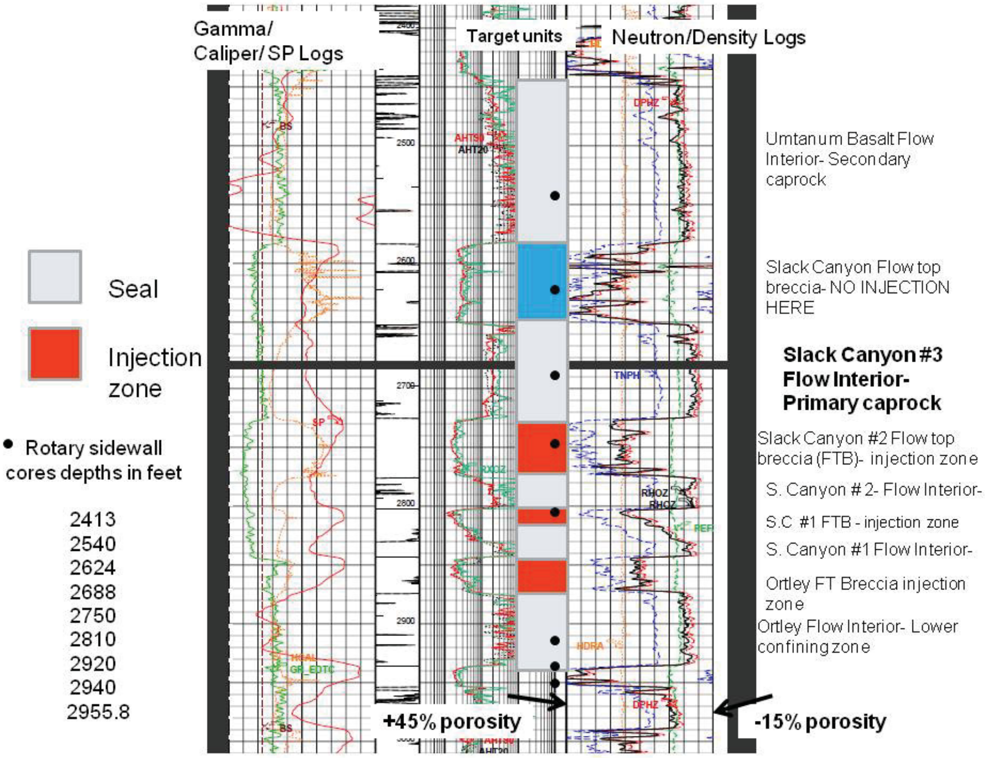

Figure 3. Schlumberger Platform Express Logs through the Proposed Injection Zone. Note on this display, porosity increases to the left. The thermal neutron curve is TNPHI and the density porosity is DPHZ.

4.3.4. Hydrologic Testing

The primary objectives of the borehole test characterization program were to identify and characterize a suitable basalt interflow zone for a subsequent CO_2 injection. General hydraulic property criteria for injection zone selection include Grande Ronde basalt interflow zones below ~2,400 ft, having sufficient: thickness (≥30 ft), permeability (k ≥ approximately 500 millidarcy), effective porosity (n_e ≥ approximately 0.1), and composite, overlying caprock thicknesses (≥ approximately 100 ft). The depth selection criteria (i.e., shallowest acceptable reservoir horizon) is based on facilitating the possible geophysical monitoring/ imaging of the CO_2 injected as a supercritical fluid, as part of the field test pilot study. In addition, groundwater within the targeted interval is required to meet definitions for non-potable water established in Washington State (WAC 173-200-020).

As previously discussed, hydrogeologic information was obtained primarily during borehole drilling/advancement utilizing the progressive *drill-and-test* characterization strategy. This requires use of a downhole packer test system conveyed by a test tubing string to isolate the underlying test zone from the overlying open borehole section. Test data was collected during testing utilizing manufacturer provided software and observed and stored on a field lap top computer. Hydrologic stresses imposed as part of the characterization process were produced using a downhole submersible pump within a cross-over, expanded section of the test tubing string. Isolation integrity of the test zone was evaluated by loading the annular zone above the inflated packer and between the test tubing string and 14-in. diameter casing with water at the beginning and end of each test zone characterization period, and observing test interval response with the real-time downhole pressure probe system. Hydraulic communication was detected only once following packer inflation for test zone isolation. This was remedied by repositioning the packer seat location a short distance along the borehole.

In all, 6 interflow test zone characterizations were conducted during active borehole advancement (Zones 1 through 5B). Immediately following completion of drilling activities, 4 additional interflow zones were characterized (Zones 6A, 6B, 6C, and 7) using the same downhole test system deployment used during borehole advancement. This was accomplished by simply repositioning the packer test system and sequentially characterizing different composite test sections within the lower section of the borehole. Transmissivity generally declined with increasing depth, attributed to compaction (i.e., increasing effective stress), increased secondary mineral formation with depth, and, in some basinal geologic settings, increasing horizontal to vertical stress-field conditions [20]. Based on the comparative results of these 10 test interval characterizations, a candidate injection test zone was identified between the general depth interval of ~2,716 and 2,870 ft. Two test sections were characterized sequentially within this identified, candidate injection zone depth interval by repositioning the overlying downhole test system (Zone 8A: 2,790 - 2,913 ft; Zone 8B: 2,688 - 2,913 ft). Preliminary analysis for individual hydraulic characterization tests have provided the following hydrologic property estimate ranges for the target injection zone: transmissivity, T = 9.8 to 19.8 ft^2/day; hydraulic conductivity, K = 0.108 to 0.218 ft/day; intrinsic permeability, k = 44 to 90 millidarcies. The majority of the composite transmissivity (i.e., ~90%) occurs within the 48-ft flow top of the Slack Canyon flow # 2 (2,720.5 - 2,768.5 ft). In addition to the 12 basalt interflow zone tests, three low-permeability caprock test intervals (Zones 9, 10A, and 10B) were also characterized above the candidate injection zone 8B. Preliminary analysis results provided average K estimates for the three caprock intervals ranging between ~$1.0E^{-12}$ to $1.0E^{-13}$ m/sec (i.e., ~0.01 to ~0.1 micro-darcies). [21]. These extremely low-permeability values suggest that overlying thick basalt flow interior sections (≥50 ft) represent an effective caprock for isolating CO_2 injected into underlying Wallula completion zone flow tops.

Groundwater samples were collected from six Wallula borehole test zones prior to final well completion. The samples were collected at the end of long-duration, constant-rate pumping or cyclical pumping characterization periods primarily using a downhole submersible pump. Collection of the samples at the end of the pumping periods provided for maximum test zone development and removal/minimization of potential antecedent drilling or open borehole conditions. Results from major and trace metal inorganic analyses indicates that all Wallula pilot sampled test zones are of similar hydrochemical character and can be classified as a relatively dilute, sodium-bicarbonate chemical water-type. Primary drinking water standards are exceeded in the isolated injection zone for pH (9.68), fluoride (4.98 mg/L), and iron (962 µg/L).

5. Injection Simulation Analysis

Simulations of a pilot-scale CO_2 injection into the flow tops of individual basalt flows in the Grande Ronde Basalt at Wallula, Washington were performed using the STOMP-H2O-CO2-NaCl model simulator [22]. The model for the CO_2 injection simulations included three injection horizons: the Ortley flow top (OFT), the Slack Canyon #1 flow top (SCFT1) and the Slack Canyon #2 flow top (SCFT2). The injection zone flow top intervals possess moderately high permeabilities and are overlain by two thick flow interior/caprock intervals (i.e., the Umtanum and Slack Canyon #3) exhibiting low-permeability, confining-layer conditions. Separating the individual injection zone flow tops are relatively thin, intervening flow interiors have expected low permeability conditions.

The total mass of CO_2 modeled for the injection simulations was 1000 metric tons (MT), which was injected over a time period of either 14 or 30 days. The radius of the injected supercritical CO_2 from the Wallula pilot well increases from 100 ft after the active two weeks of injection, to 180 ft one year after the start of injection. The simulated increase in downhole pressure within the injection zone/well bore is less than 110 psi. Hence, sufficient permeability exists within the target injection interval to complete the CO_2 injection with very modest overpressure from the prevailing hydrostatic head. One year after the start of injection, 18% of the injected CO_2 has dissolved into the aqueous-groundwater phase. The dissolved CO_2 in addition to reactions of the basalt directly with the water-wet supercritical CO_2 phase [23-24] provides ample opportunity to track in situ mineralization during a relatively short monitoring time period.

6. Conclusion

Drilling and characterization of the Wallula pilot borehole has resulted in the world's first deep basalt CO_2 injection well with three basalt breccia zones between the depth interval of 2,716 and 2,910 feet isolated for a subsequent CO_2 injection pilot study. The targeted injection reservoir lies stratigraphically below the massive Umtanum Member of the Grande Ronde Basalt, whose flow-interior section possesses regionally recognized extremely low-permeability characteristics. The identified composite injection zone provides a unique and attractive opportunity to scientifically study CO_2 migration and chemical reaction behavior of three inter-connected reservoir intervals below primary and secondary caprock confining zones.

The permitting process for the CO_2 injection is underway in accordance with formal rules for geologic sequestration projects in Washington State. The permitting process is expected to conclude in October 2010 and injection to begin soon thereafter. Post-injection monitoring includes long-term sampling of water retrieved from the injection zone, shallow groundwater and soil gas monitoring, and satellite imaging (PSInSAR).

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