PNNL-15386

Pacific Northwest National Laboratory
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Potential for Natural Gas Storage in Deep Basalt Formations at Canoe Ridge, Washington State: A Hydrogeologic Assessment

SP Reidel
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September 2005

Prepared for the U.S. Department of Energy
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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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Richland, Washington 99352

Summary

Between 1999 and 2002, Pacific Gas Transmission Company (now TransCanada Pipeline Company) and AVISTA Corporation, together with technical support provided by the Pacific Northwest National Laboratory and the U.S. Department of Energy (DOE) examined the feasibility of developing a subsurface, natural gas-storage facility in deep, underlying Columbia River basalt in south-central Washington State. As part of this project, the 100 Circles #1 well was drilled on Canoe Ridge and characterized in addition to surface studies. This report provides data and interpretations of the geology and hydrology collected specific to the Canoe Ridge site as part of the DOE funding to the Pacific Northwest National Laboratory in support of the project.

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1.0 Introduction

Between 1999 and 2002, Pacific Gas Transmission Company (PGT) (now TransCanada Pipeline Company) and AVISTA Corporation, together with technical support provided by the Pacific Northwest National Laboratory and the U.S. Department of Energy (DOE) examined the feasibility of developing a subsurface, natural gas-storage facility in deep Columbia River basalt in south-central Washington State. The natural gas-storage concept is similar to other numerous U.S. commercial subsurface aquifer storage facilities that temporarily store natural gas during non-peak power and low heating demand periods and then retrieve the stored natural gas as needed to meet immediate power generation and heating demands. The concept for storing natural gas within basalts requires the injection of natural gas within individual or multiple reservoir horizons (interflow zones) that are confined between deep (>700 meters), low-permeability basalt flow interiors (caprocks) of the Columbia River Basalt Group (CRBG). Of particular importance in evaluating the feasibility of basalt natural gas storage is characterizing the occurrence of candidate reservoir horizons having sufficient permeability, thickness, and storage capacity; geologic closure (structural/stratigraphic) for lateral containment of the stored natural gas; and presence of overlying low-permeability caprocks of sufficient thickness to minimize vertical leakage of the stored natural gas.

Methodologies and techniques for characterizing and evaluating Columbia River basalt for natural gas storage within the region were previously reported in Reidel et al. (2002), as part of Pacific Northwest National Laboratory's ongoing National Energy Technology research into unconventional natural gas-storage facilities. This report provides data and interpretations of the geology and hydrology collected specific to the Canoe Ridge site (Figure 1) as part of the DOE funding to the Pacific Northwest National Laboratory in support of the project.

2.0 Surface Geology

Initial characterization studies focused on detailed geologic mapping of Canoe Ridge to provide a quantitative understanding of the surface structure and stratigraphy of the site. Specific results associated with the detailed geologic mapping are summarized below.

2.1 Stratigraphy

Two basalt units are exposed at the surface on Canoe Ridge. The oldest exposed basalt unit is the 12 million year old Pomona Member (Figure 2) of the Saddle Mountains Basalt, which consists of only one flow at Canoe Ridge. It is readily identified by its characteristic tabular phenocrysts of plagioclase. The flow typically has a very thick entablature and thin colonnade (Figure 3). At Canoe Ridge, the flow can have a pillowed base that may reach thicknesses of up to 15 feet. The pillowed base results from basalt flows entering surface water. The top of the flow often has sediment imbedded within the basalt. This feature occurs where the basalt lava burrowed into underlying soft sediment.

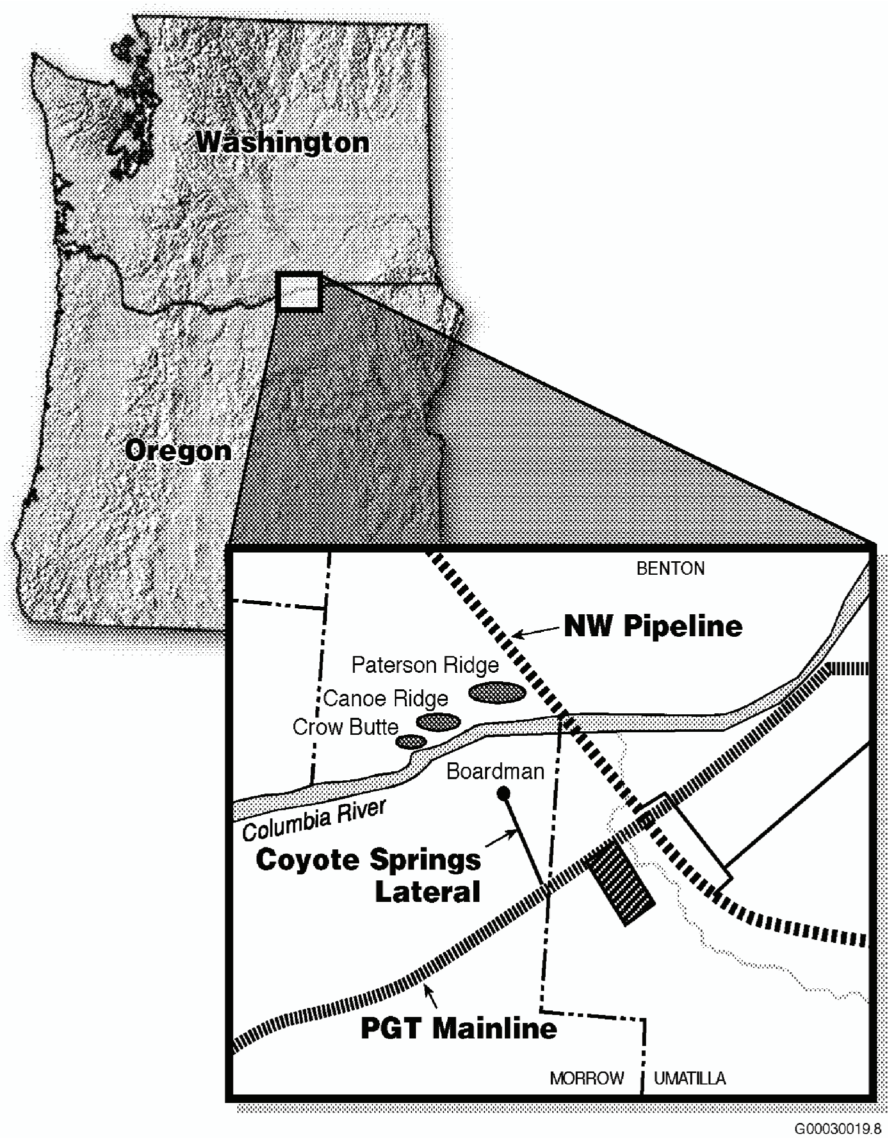

Figure 1. Location Map Showing Canoe Ridge and Nearby Natural Gas Pipelines

The youngest basalt exposed at Canoe Ridge is the 10.5 million year old Elephant Mountain Member (Figure 2) of the Saddle Mountains Basalt. The Elephant Mountain Member consists of two separate flows. The youngest, uppermost flow is not present everywhere on the Canoe Ridge structure. It appears to have pinched out on the flanks of the anticline. At the highest elevations on Canoe Ridge, there is only one thin (15 to 20 feet) Elephant Mountain flow. On the flanks of the ridge, however, two flows are present that reach an aggregate thickness of almost 150 feet.

Intercalated between the Elephant Mountain Member and the Pomona Member is the Rattlesnake Ridge sedimentary interbed. This sediment is a flood plain deposit with extensive paleosol development. It is gray with extensive bioturbation. The overlying Elephant Mountain Member has a pillowed base in contact with the Rattlesnake Ridge sediment.

Series		Group		Formation	Series	Isotopic Age (m.y)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	**Lower Monumental Member**	6	N
					Ice-Harbor Member	8.5	
					Basalt of Goose Island		N
					Basalt of Martindale		R
					Basalt of Basin City		N
					Buford Member		R
					Elephant Mountain Member	10.5	N, T
	Middle				**Pomona Member**	12	R
					Esquatzel Member	N	
					Weissenfels Ridge Member		
					Basalt of Slippery Creek		N
					Basalt of Tenmile Creek		N
					Basalt of Lewiston Orchards		N
					Basalt of Cloverland		N
					Asotin Member	13	
					Basalt of Huntzinger		N
					Wilbur Creek Member		
					Basalt of Lapwal		N
					Basalt of Wahluke		N
					Umatilla Member		
					Basalt of Sillusi		N
					Basalt of Umatilla		N
				Wanapum Basalt	**Priest Rapids Member**	14.5	
					Basalt of Lolo		R
					Basalt of Rosalia		R
					Roza Member		T, R
					Shumaker Creek Member		N
					Frenchman Springs Member		
					Basalt of Lyons Ferry		N
					Basalt of Sentinel Gap		N
					Basalt of Sand Hollow	15.3	N
					Basalt of Silver Falls		N, E
					Basalt of Ginkgo	15.6	E
					Basalt of Palouse Falls		E
					Eckler Mountain Member		
					Basalt of Dodge		N
					Basalt of Robinette Mountain		N
					Vantage Horizon		
				Grande Ronde Basalt	**Member of Sentinel Bluffs**	15.6	N_2
					Member of Slack Canyon		
					Member of Fields Spring		
					Member of Winter Water		
					Member of Umtanum		
					Member of Ortley		
					Member of Armstrong Canyon		
	Lower			Prineville Basalt	**Member of Meyer Ridge**		R_2
					Member of Grouse Creek		
					Member of Wapshilla Ridge		
					Member of Mt. Horrible		
					Member of China Creek		N_1
				Picture Gorge Basalt	**Member of Downy Gulch**		
					Member of Center Creek		R_1
					Member of Rogersburg		
					Teepee Butte Member		
					Member of Buckhorn Springs	16.5	
				Imnaha Basalt			R_1
							T
							N_0
						17.5	R_0

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Figure 2. Stratigraphic Nomenclature of the Columbia River Basalt Group

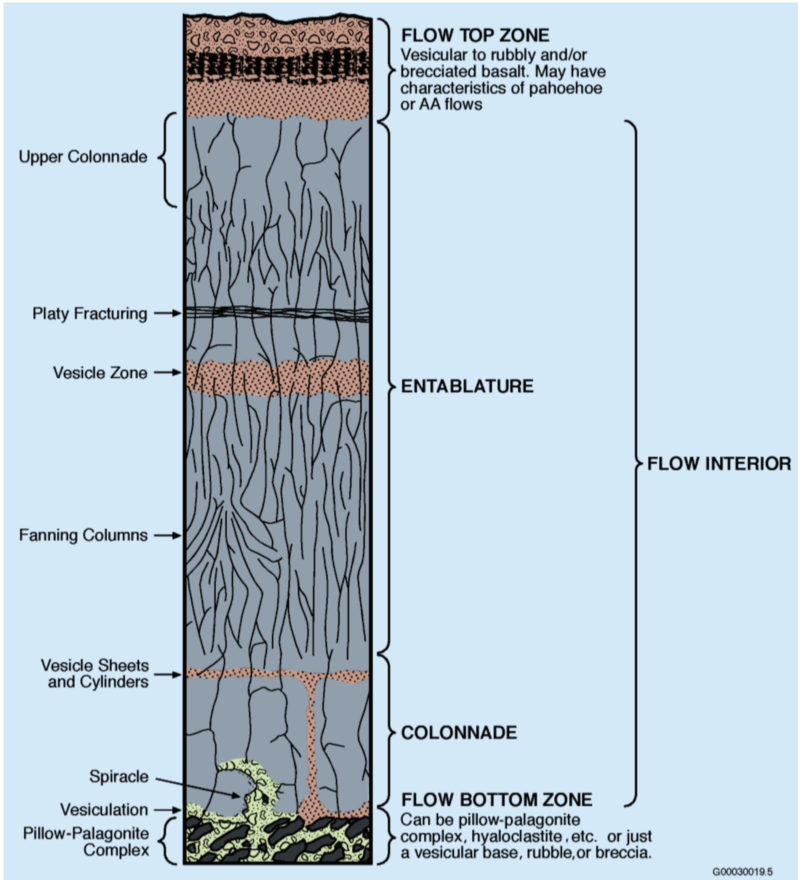


Figure 3. Generalized Internal Features of a Typical Lava Flow of the Columbia River Basalt Group

Overlying the CRBG lava flows are sands and gravels that were deposited by the Pleistocene age, glacial Missoula floods that occurred repeatedly between 770,000 and 10,000 years ago. Most of the deposits are associated with younger flood events. Localized surficial landslide deposits also occur on the southwest side of Canoe Ridge and appear to be the result of the Pomona and Elephant Mountain Members sliding on the Selah sedimentary interbed that underlies the Pomona Member (Figure 2). The localized landslide deposits appear to be concurrent in age with the Missoula floods. Regionally within the Columbia Basin, localized landslide deposits occur in similar geologic settings. Finally, there are also windblown deposits of reworked Missoula flood deposits locally deposited across Canoe Ridge.

2.2 Structure

Canoe Ridge is a doubly plunging anticline with a faulted south side. It is part of the Yakmia Fold Belt and Columbia Hills structural trend (Reidel et al. 1994). Crow Butte and an unnamed fold lie south of Canoe Ridge and form a series of small folds developed along the Columbia Hills anticline.

Canoe Ridge is a segmented anticlinal structure. The central segment reaches 950 feet above mean sea level (MSL); the western segment reaches about 800 feet above MSL; and the eastern segment reaches about 600 feet above MSL and has a gentle slope to the east. At the crest of the western and central segments, the basalt is folded with nearly horizontal basalt at the crest of the fold. The western part of the western segment plunges abruptly to the west.

There are no surface expressions of faults exposed on Canoe Ridge. Although exposure is not continuous, it is sufficient to show that no north to south trending faults occur at or cut across Canoe Ridge to define the segment boundaries. In the Dead Canyon area, the main access road on the west side of Canoe Ridge, the contact between the Elephant Mountain Member and Pomona Member shows no apparent structural offset that would define a fault. To the east of the drill site along the south side of Canoe Ridge, the Elephant Mountain Member can be traced at the surface from the drill-site elevation to the crest of the ridge. This suggests that there is no significant fault displacement (at least at the surface) that is responsible for the gain in elevation from the western segment to the central segment. This does not mean, however, that a blind thrust is not responsible for the higher segment of the ridge. Borehole drilling results discussed in a later section indicate there probably are blind thrust faults at depth.

3.0 Exploratory Borehole #1

3.1 Borehole History

Drilling of 100 Circles #1 borehole commenced on July 2, 1999, by Lang Exploratory Drilling (Salt Lake City, Utah), and continued to a total depth of 3,505 feet below ground surface (bgs), which was reached on July 29, 1999. The "flooded reverse" drilling technique was used to drill the borehole. Detailed hydrologic testing of selected Grande Ronde Basalt zones was conducted between July 29 and August 6, 1999, following termination of drilling activities. Figure 4 shows the well completion as-built for interim aquifer protection and location of bentonite seals. The borehole was plugged and abandoned in 2005.

3.2 Borehole Geology

The borehole stratigraphy is summarized in Figure 5 and Table 1. Identification of stratigraphic intervals was based on basalt chip lithology, X-ray fluorescence (XRF) chemical analysis of selected samples, geophysical log results, and knowledge of basalt stratigraphy of the area. Table 1 lists the depth intervals and associated unit assignments for the 100 Circles #1 borehole.

3.3 Basalt Chemistry to Identify Stratigraphy

Appendix A lists the XRF analytical results (GeoAnalytical Laboratory, Washington State University) for samples collected to identify and refine the basalt stratigraphy encountered in the borehole. The table includes the original compositions and totals, and compositions after the analyses were normalized to 100%. A total less than 100% is generally associated with volatiles that were "lost on ignition." This is due to sample preparation that involves fusing the basalt sample to a glass prior to analysis.

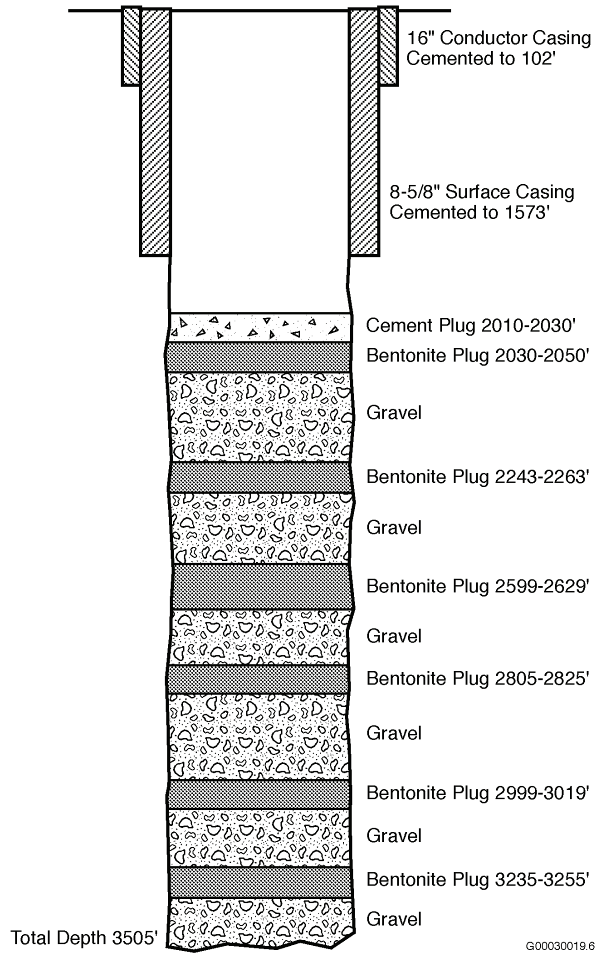


Figure 4. As-Built and Seal Design for the 100 Circles #1 Borehole Prior to Abandonment

3.4 Subsurface Stratigraphy

The stratigraphic units encountered in the borehole were those that were expected based on available regional geologic studies of the surrounding area. The youngest basalt flows are part of the Saddle Mountains Basalt, which is approximately 785 feet thick (860 feet if the Mabton sediments are included; Figure 5). Underlying the Saddle Mountains Basalt is the Wanapum Basalt, which is approximately 1,176 feet thick. The Vantage interbed represents a regional time-stratigraphic hiatus that separates the underlying Grande Ronde Basalt from the overlying Wanapum Basalt. Approximately 1,500 feet of Grande Ronde Basalt were penetrated in the borehole and the formational thickness probably exceeds 3,000 feet in this area (Reidel et al. 1989).

3.4.1 Saddle Mountains Basalt

The Saddle Mountains Basalt at Canoe Ridge includes (in descending stratigraphic order) the Elephant Mountain Member, the Pomona Member, and the Umatilla Member (Table 1; Figure 5; Appendix A). It consists of thick basalt flows with interbedded sediments of the Ellensburg Formation. Some Saddle Mountain Basalt flows appear to have invaded the underlying sediment as they were emplaced. This is very common in Columbia River basalt due to the incompetence and softness of the underlying, saturated, fine-grained sediment. Because of this invasive nature, the thickness of the sediments encountered by boreholes can be highly variable locally.

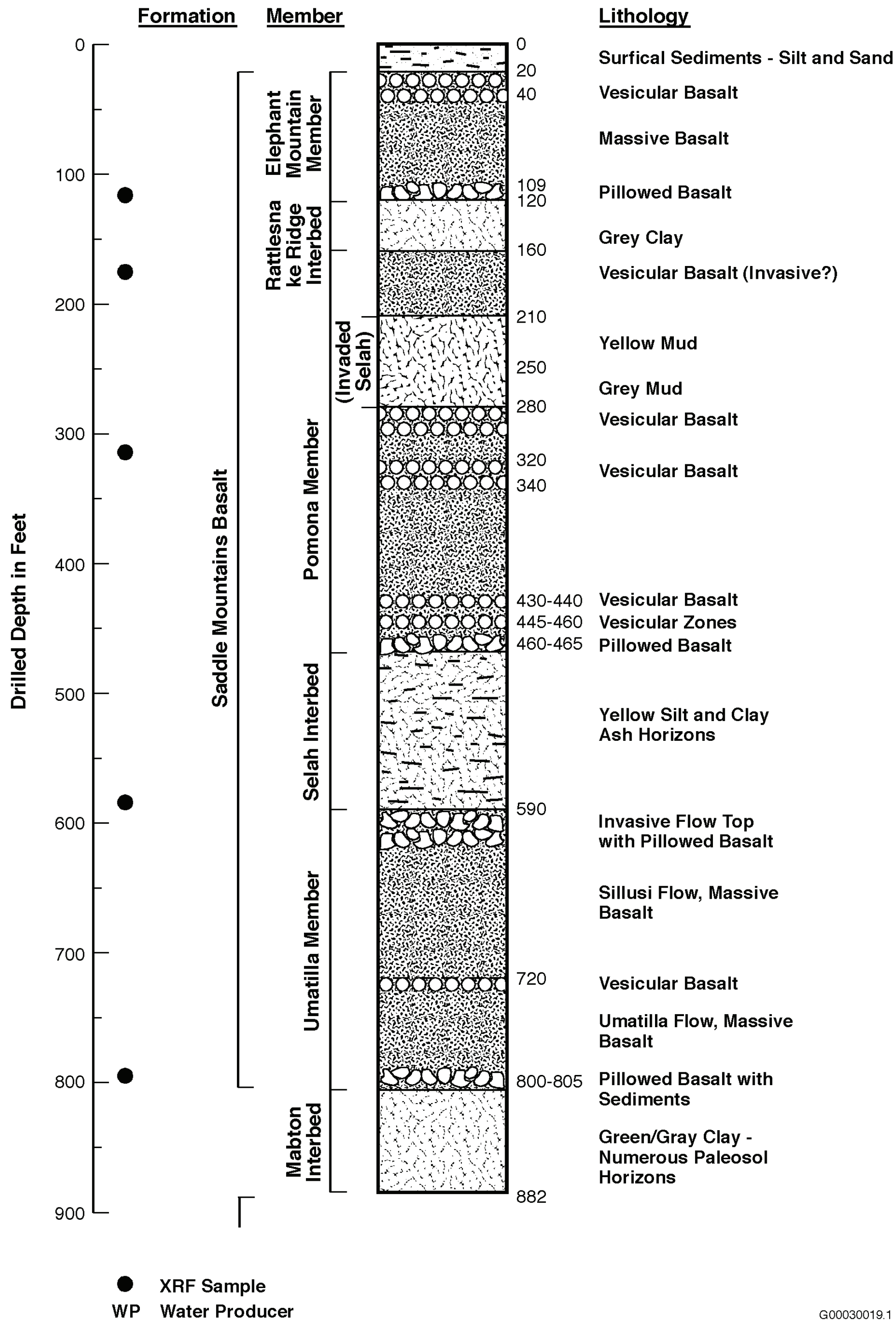


Figure 5. 100 Circles #1 Borehole Stratigraphy

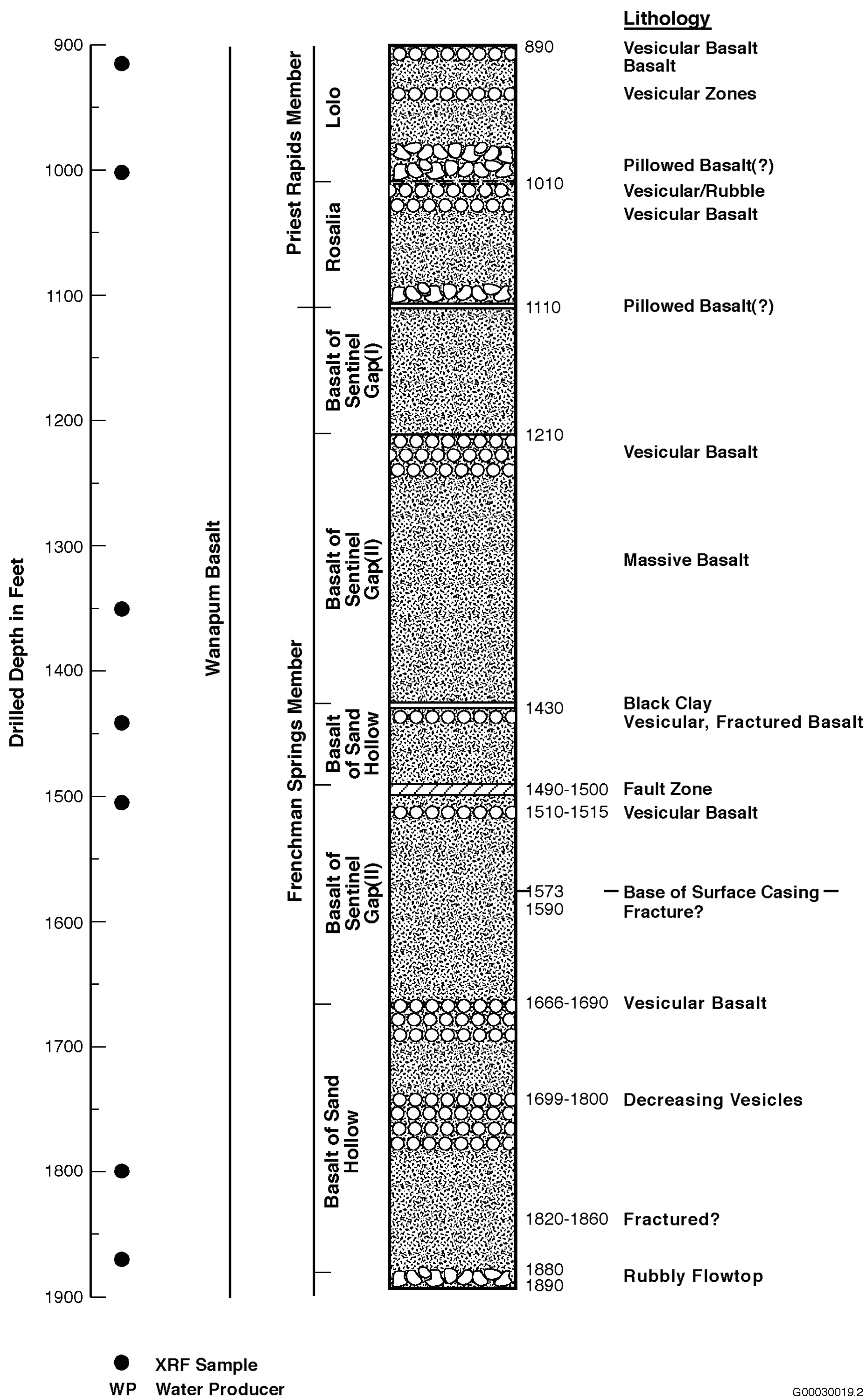
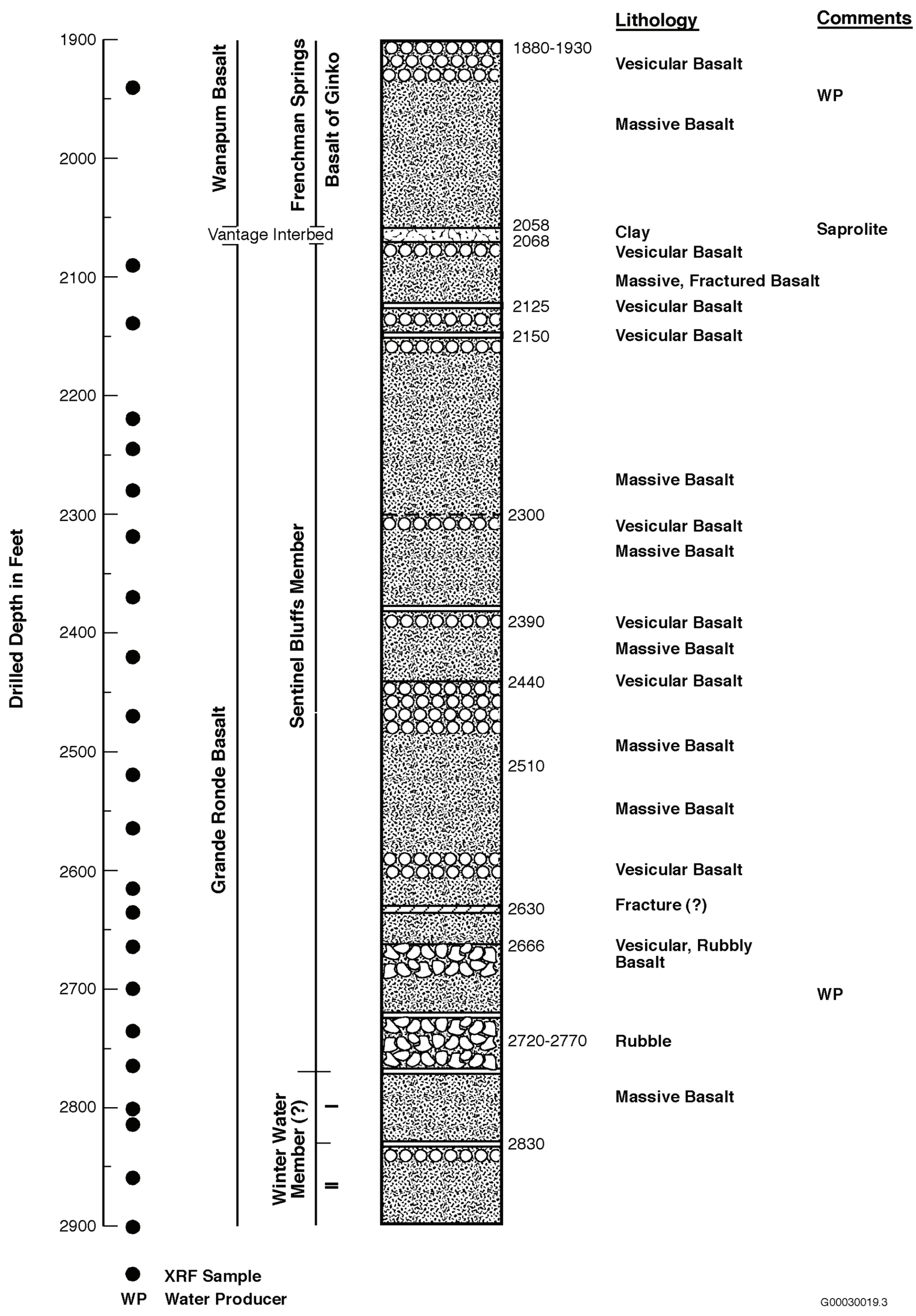


Figure 5. (contd)



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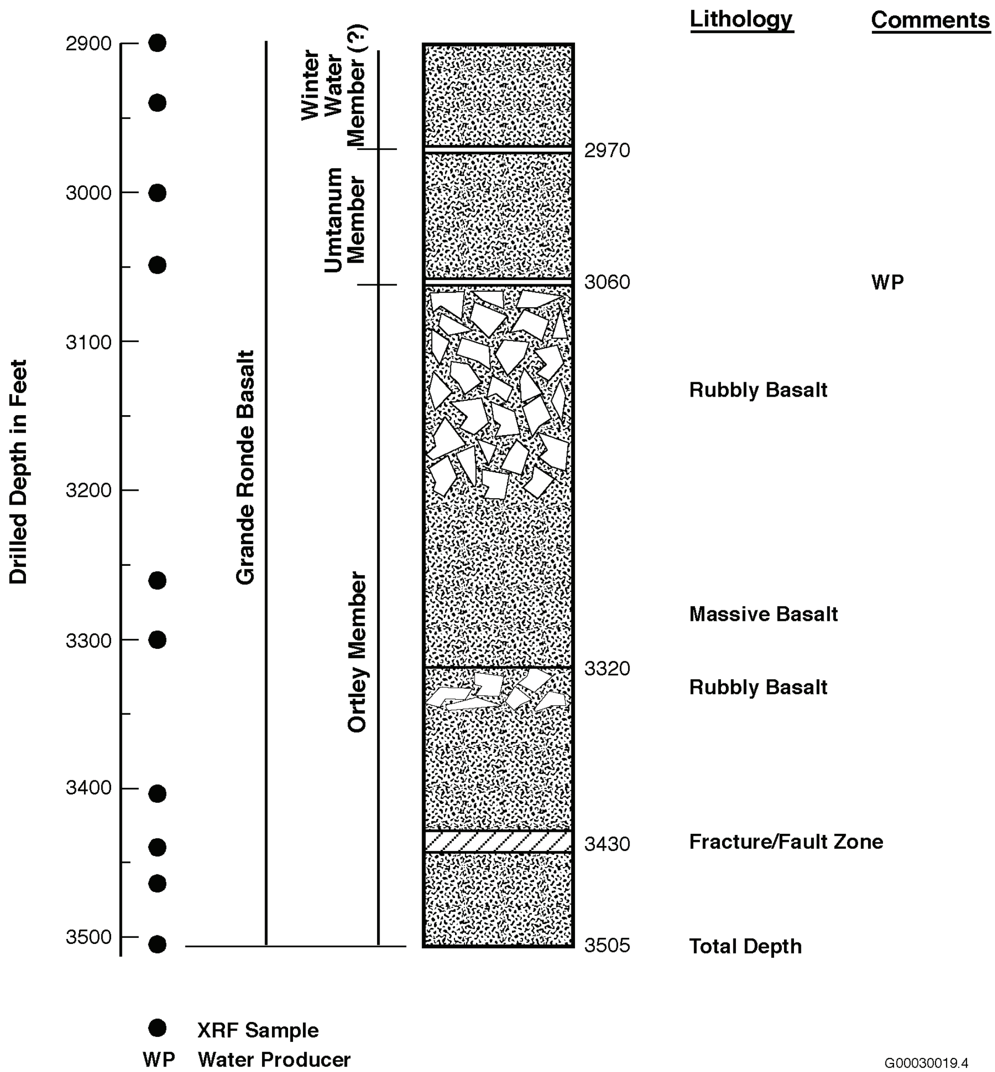

Figure 5. (contd)

3.4.2 Wanapum Basalt

The Wanapum Basalt consists of the Priest Rapids Member and the underlying Frenchman Springs Member (Table 1 and Figure 5). One geologically important feature is a fault zone that occurs at a depth 1,500 feet bgs in the borehole. Supporting the presence of the fault is a repeat geologic section that occurs below the fault contact. At this location, the Frenchman Springs (Table 1 and Figure 5) consists of two flows of the basalt of Sentinel Gap to a depth of 1,430 feet bgs. At this depth, there is a contact marked by black clay. The next flow below this contact is the basalt of Sand Hollow (sample 1440, Table A.1), which is the correct regional sequence. This flow is abruptly terminated by a fault and the next flow below the fault contact is a repeat section of the basalt of Sentinel Gap (sample 1505 [Table A.1]. At a depth of 1,666 feet, the Sentinel Gap/Sand Hollow contact occurs again (see samples 1800 and 1870). The basalt of Sentinel Gap and basalt of Sand Hollow can be difficult to distinguish based on visual drill-chip evaluation. For precise differentiation, XRF analyses were obtained. The compositions of the two flows are similar, but TiO_2 and P_2O_5 are the consistent discriminators. Note in

Table 1. 100 Circles #1 Borehole Stratigraphy

Depth Interval (feet)	Stratigraphic Unit	Lithology
0-20	Surficial Sediments	Eolian sands
20-3505 (TD)	Columbia River Basalt Group and intercalated Ellensburg Formation	Basalt and sediments
20-805	Saddle Mountains Basalt	Basalt interbedded with sediments
20-109	Elephant Mountain Member	Basalt, vesicular flow top
109-148	Ellensburg Formation (EF), Rattlesnake Ridge Interbed	Grey clay
160-465	Pomona Member	Basalt, vesicular flow top and pillowed base
210-280	Invaded Selah Interbed	Clay
280-465	Pomona Member	Basalt, invasive flow top
465-590	Selah Interbed, EF	Grey clay at top grading down into buff colored silty, sandy, clay
590-805	Umatilla Member	Basalt, mainly massive. Consists of two flows. Pillowed base
805-882	Mabton Interbed, EF	Green-grey clay
882-2058	Wanapum Basalt	
882-1,110	Priest Rapids Member	Consists of two basalt flows: Lolo and Rosalia; each with vesicular flow top. About 3 feet of Byron interbed between flows at 1,000 feet.
882-1,010	Basalt of Lolo, Priest Rapids Member	Basalt
1,010-1,110	Basalt of Rosalia, Priest Rapids Member	Basalt
1,110-2,058	Frenchman Springs Member	Basalt
1,110-1,430	Member of Sentinel Gap	Consists of two flows (I and II). Flow contact at 1,210 feet. Mainly massive basalt with thin, vesicular flow tops.
1,430-1,490	Basalt of Sand Hollow	Consists of one flow. Mainly massive basalt with vesicular flow top.
1,490-1,500	Fault zone	Ten feet of green breccia
1,500-1,666	Basalt of Sentinel Gap	Repeated above by fault
1,666-1,890	Basalt of Sand Hollow	Repeated above by fault
1,890-2,058	Basalt of Ginkgo	Consists of one flow. Mainly massive basalt with vesicular flow top.
2,058-2,068	Vantage Horizon	Black clay. Probably saprolite developed on Grande Ronde Basalt.
2,068-3,505	Grande Ronde Basalt	Upper normally magnetostratigraphic unit.
2,068-2,770	Member of Sentinel Bluffs	Consists of 5 flows. Contacts at 2,125, 2,150, 2,390, 2,440, and 2,666 feet. Upper portion is a deeply weathered saprolite.
2,770-2,970	Member of Winter Water	Consists of 2 flows.
2,970-3,060	Member of Umtanum	Consists of one flow with thick, rubbly flow top. Water producing zone.
3,060-3,505	Member of Ortley	Consists of 2 flows with contact at 3,320 feet. Breccia zone at 3430 feet. Upper flow top is water-producing zone as is breccia zone.

Table A.1 (normalized) that the basalt of Sentinel Gap has TiO_2 typically above 3.1 wt.%. Basalt of Sand Hollow has TiO_2 typically below 3.0 wt.%. In addition, P_2O_5 in the basalt of Sentinel Gap is typically above 0.62 wt.% while in the basalt of Sand Hollow P_2O_5 is typically below 0.60 wt.%. The analytical precision and accuracy of the laboratory analyses (Washington State University Geoanalytical Laboratory) is in the third decimal place. Although these differences appear small, they have been proven to be consistently significant for basalt flow discrimination across the Columbia Plateau (Beeson et al. 1985).

3.4.3 Grande Ronde Basalt

As a whole, Grande Ronde Basalt flows are difficult to distinguish visually in the field, because of their very similar appearance (Reidel et al. 1989; Reidel 2005). Because of this visual similarity and the need to be able to distinguish specific target reservoir and caprock horizons in the subsurface, flows were closely sampled for detailed XRF analysis (Table A.1) to develop a detailed stratigraphy for the 100 Circles #1 borehole. The resulting subdivisions are shown in Figure 5 and in Table1. The Grande Ronde Basalt subdivisions are consistent with regional stratigraphic relationships developed from other deep boreholes in the Columbia Plateau (Reidel et al. 1989). The member of Sentinel Bluffs stratigraphy follows the revisions by Reidel (2005). Because of this high-density sampling, a high level of reliability can be assigned to the Grande Ronde Basalt stratigraphy identified at the borehole. This stratigraphy can be used for detailed stratigraphic identification across the site at future borehole locations.

It should be noted that during drilling, chip sample logging also indicated that a second fault/fracture zone was encountered at 3,420 feet bgs. The Grande Ronde Basalt flows in this zone were examined for a repeated stratigraphy above or below the fracture. Although a slight increase in TiO_2 and P_2O_5 content occurs below the identified fracture/fault zone, no similar pattern is exhibited above the contact horizon. It is concluded that the fault zone does not exhibit significant vertical displacement; however, it cannot be classified as either a high angle reverse or normal fault due to insufficient data. However, a thrust fault would be consistent with the tectonic regime. An intraflow fault interpretation, however, would be consistent with other folded ridges within the Columbia Basin. Intraflow fault features usually are confined to only one flow. Typically, they occur as conjugate sets, which is probably the case with this local tectonic feature.

3.5 Structural Closure

Structural closure is one of the major characterization objectives to be addressed at the Canoe Ridge site. Surface geologic mapping indicates that there is about 300 to 400 feet of closure at the surface in the vicinity of the 100 Circles #1 borehole drill-site location (west segment) and as much as 500 feet of closure on the middle segment. Other geologic factors, however, suggest that closure may be much less at candidate storage depth horizons. The following discussion pertains to aspects relating to structural closure relationships at depth.

3.5.1 Closure Effect: Flow Thickening and Thinning

Based on geologic field-mapping, the Elephant Mountain Member thickens down the flanks of Canoe Ridge, 100 Circles #1 borehole drill site. This thickening indicates that the stratigraphy provides additional closure (at least for the Elephant Mountain Member). Analysis of surrounding well data, however, does not provide any additional stratigraphic control information on deeper basalt flows. If Canoe Ridge is similar to other anticlinal structures within the region where basalts flows are known to thin across the anticlinal crests, then added closure from additional flows thinning onto Canoe Ridge and thickening off the structural crest may be inferred.

3.5.2 Closure Effect: Fault at 1,500 Feet

The identified fault at 1,500 feet bgs repeats stratigraphy and, therefore, decreases the amount of structural closure below this fault contact depth. The amount of closure reduction is not known, because the data obtained from the 100 Circles #1 borehole provide only one control point, which is not sufficient to precisely determine the orientation and dip of the fault. However, it is estimated that this fault may have reduced the amount of closure by 50% or more. Borehole geophysical logs are helpful in evaluation fault characteristics, but do not provide definitive closure information.

3.5.3 Closure Effect: Fault/Fracture at 3,420 Feet

The refined stratigraphic characterization information indicates that the fault/fracture occurring at 3,420 ft bgs is either not a fault but a fracture zone, or is a reverse fault with very little vertical displacement. In either case, the fault/fracture appears to have little impact on closure reduction.

4.0 Hydrologic Characterization Results

Hydrologic characterization activities at Canoe Ridge focused on determining the hydraulic properties, hydraulic head, and hydrochemical characteristics of groundwater within selected basalt interflow zones of the Wanapum Basalt and Grande Ronde Basalt. The field testing program included the characterization of one lower Wanapum Basalt interflow zone (for comparison with Grande Ronde Basalt results), a composite Grande Ronde Basalt test (for selecting individual Grande Ronde zones for detailed characterization), and three Grande Ronde interflow zone tests. The three Grande Ronde Basalt interflow test interval zones selected for detailed hydrologic characterization were:

- The Member of Sentinel Bluffs Zone – 2,025 to 2,208 feet bgs
- The Member of Winter Water Zone – 2,625 to 2,805 feet bgs
- The Member of Ortley Zone – 3,025 to 3,240 feet bgs.

The results of the characterization activities are discussed below.

4.1 Hydraulic Properties

Hydraulic properties were determined from the analysis of monitored well responses associated with air-lift pumping tests. Analysis of the observed flow-rate variation during the air-lift pumping (drawdown) phase and analysis of the pressure recovery response following termination of the individual air-lift pumping tests provided the basis for determining the hydraulic properties for each zone tested. Downhole pressure readings were recorded at formation depth with a sensitive quartz transducer system for all Grande Ronde Basalt tests (Note: because a downhole pressure transducer system was not available, an electric water-level sensor was used for the initial lower Wanapum Basalt test). Surface flow rates were determined periodically during air-lifting, based on observed surface holding-tank volumetric readings.

The two test characterization methods provide a means of demonstrating the level of confidence for the hydraulic property estimates derived for individual test intervals; i.e., the two methods should provide consistent results if the test assumptions and inherent conceptual model (e.g., non-leaky aquifer) are valid. A brief discussion of the individual test methods is presented below. Since testing was limited to only single-well tests, transmissivity was the principal hydrologic parameter determined.

4.2 Constant-Drawdown (Pressure) Analysis

The air-lift testing procedure closely matches conditions of a constant-drawdown (pressure) test. For this test, the water-level within the well is lowered and maintained at a relatively uniform depth. The magnitude of the observed discharge for the given drawdown, and its decline with time provides a means of determining the transmissivity, T, of the test interval. The method used for analyzing these tests is based on the solution presented originally by Jacob and Lohman (1952). An example of a constant-drawdown analysis for one of the Grande Ronde Basalt test intervals (Ortley Zone) is presented in Figure 6. As shown, the predicted response using a T value of 250 ft^2/d provides a reasonable match for the observed flow-rate response pattern. As a measure of demonstrating the robustness of the flow-rate match, the best match value (solid line) and 1/2 the best-match value (dashed line) are shown for comparison purposes. The solution method is relatively insensitive to storativity, S, conditions. For the constant-drawdown analyses, an S value of 0.0001 was uniformly used. Constant-drawdown analysis results for all intervals tested are presented in Table 2.

4.3 Pressure Recovery Analysis

This method focuses on analysis of the observed pressure recovery following termination of the air-lift pumping test. The method requires that the discharge rate be relatively constant during the pumping period, and that no additional “complicating” factors occur. As mentioned above, discharge rates were not constant during the air-lift pumping test. When discharge variation is significant, special procedures, e.g., superposition/multi-rate analysis methods (see Earlougher 1977), must be used to obtain reliable analytical results. In addition, a number of “complicating” factors occurred or were imposed by the air-lift process (e.g., pre-test trends, additional well volume imposed by the annular air-line, etc.). Most of these complicating factors were of significance only for test intervals having lower transmissivities (e.g., member of Winter Water and member of Sentinel Bluff Zones), and should be accounted for in the recovery analyses. Pressure derivative analysis plots of the pressure recovery can also be used for identifying the presence of test interval leakage effects as discussed in Spane and Wurstner (1993) and Reidel et al. (2002). Diagnostic examination of derivative pressure recovery plots for all individual basalt interflow test intervals (not shown) indicate a non-leaky model response pattern.

For determining hydraulic properties for test intervals not exhibiting significant discharge variability or test complexities, recovery data collected after termination of the pumping test were analyzed using available analytical solutions for tests conducted in confined aquifer systems. These analytical approaches are described and summarized in Spane (1993) and Spane and Wurstner (1993). For hydraulic property determination, the standard Theis (1935) recovery method was employed in analysis of late-time recovery data collected following termination of the constant-rate test. Figure 7 shows the residual recovery (i.e., difference in observed recovery water level minus the pre-test static water-level reading) and associated data analysis for the same test interval examined in Figure 6. As indicated, a transmissivity of 280 ft^2/d was calculated for the member of Ortley Zone test interval based on the pressure recovery analysis. Pressure recovery analysis results are listed in Table 3 for all intervals tested. Transmissivity estimates from the recovery analysis were not possible for the member of Winter Water and the member of Sentinel Bluffs zones, due to the extended wellbore storage effects imposed during the recovery for these test intervals (i.e., lower T and greater drawdown equate to longer wellbore storage effect duration).

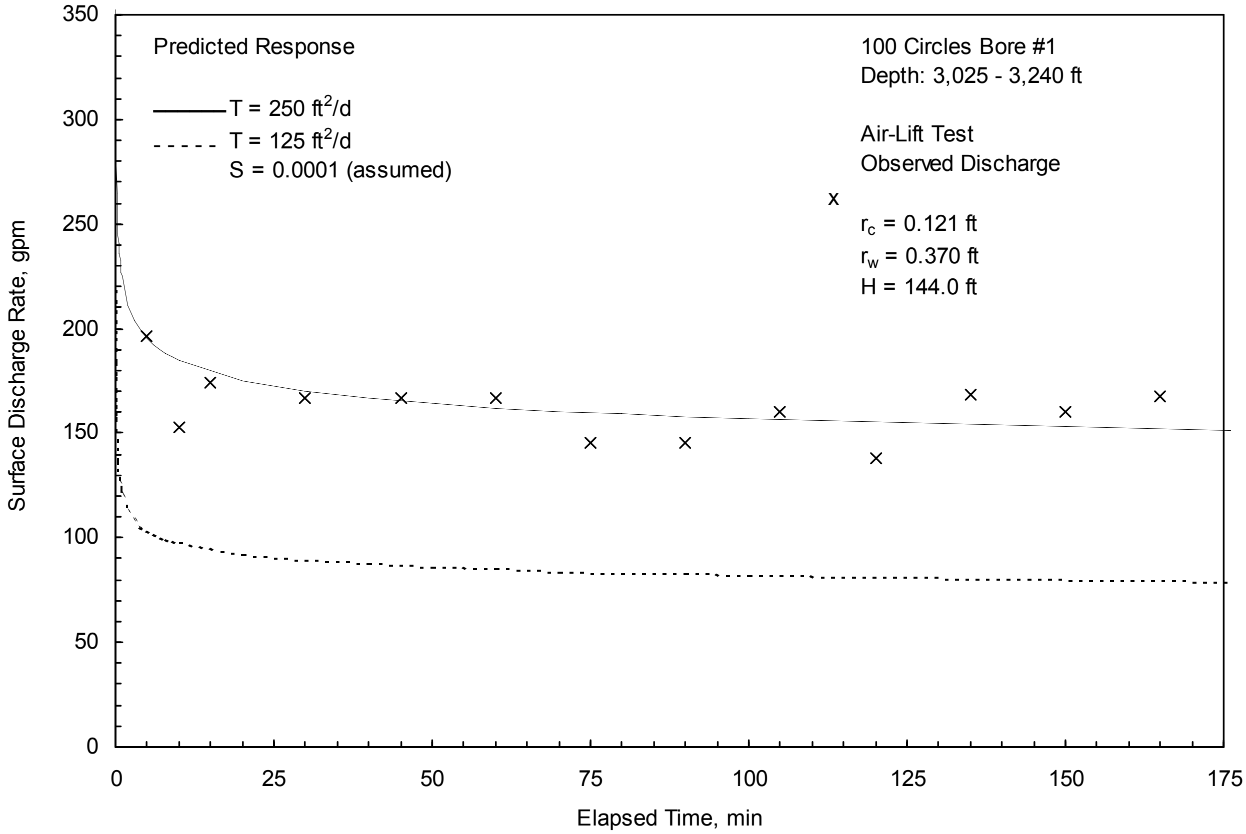

Figure 6. Air-Lift Pumping Test Constant-Drawdown Analysis for Grande Ronde Basalt, Member of Ortley Zone

For comparison purposes, Table 3 lists the transmissivity estimates obtained from constant-drawdown and pressure recovery analysis. As shown, good correspondence between analytical methods was exhibited for the one test interval having both analyzable results (i.e., Ortley Zone). It should be noted that most of the composite transmissivity value (2,800 ft^2/day) calculated for the entire Grande Ronde Basalt open borehole test interval (2,030 to 3,505 feet bgs) is reflective of the high permeability fracture zone located at a depth of approximately 3,420 and 3,440 feet bgs. This conclusion is based on the results of downhole flowmeter logging results conducted during the open borehole air-lift test. Because of the limited thickness and associated storage capacity of this fracture zone (i.e., ≤5 ft), this interval was not selected for detailed hydraulic characterization.

Table 2. Constant-Drawdown Air-Lift Test Analysis Summary, 100 Circles #1 Borehole

Test Interval	Test Date	Depth Interval (ft bgs)	Air-Lift Discharge/ Duration/Drawdown (gpm/minutes/ft)	Transmissivity Analysis (ft^2/d)
Lower Wanapum	7/21/99	1,573–1,725	62/60/[(a)]	NA
Grande Ronde Basalt Composite	7/31/99	2,030–3,505	141[(b)]/118/14	2,800
Grande Ronde Basalt, Member of Ortley Zone	8/4/99	3,025–3,240	160/165/144	280
Grande Ronde Basalt, Member of Winter Water Zone	8/5/99	2,625–2,805	76[(b)]/129/824	15
Grande Ronde Basalt, Member of Sentinel Bluffs Zone	8/6/99	2,025–2,208	150[(b)]/86/334	50

NOTE: All water from test zones was contained before disposal.
(a) Downhole pressure system unavailable.
(b) No drawdown measurement possible during testing for last air-lift flow period.
NA = Not applicable.

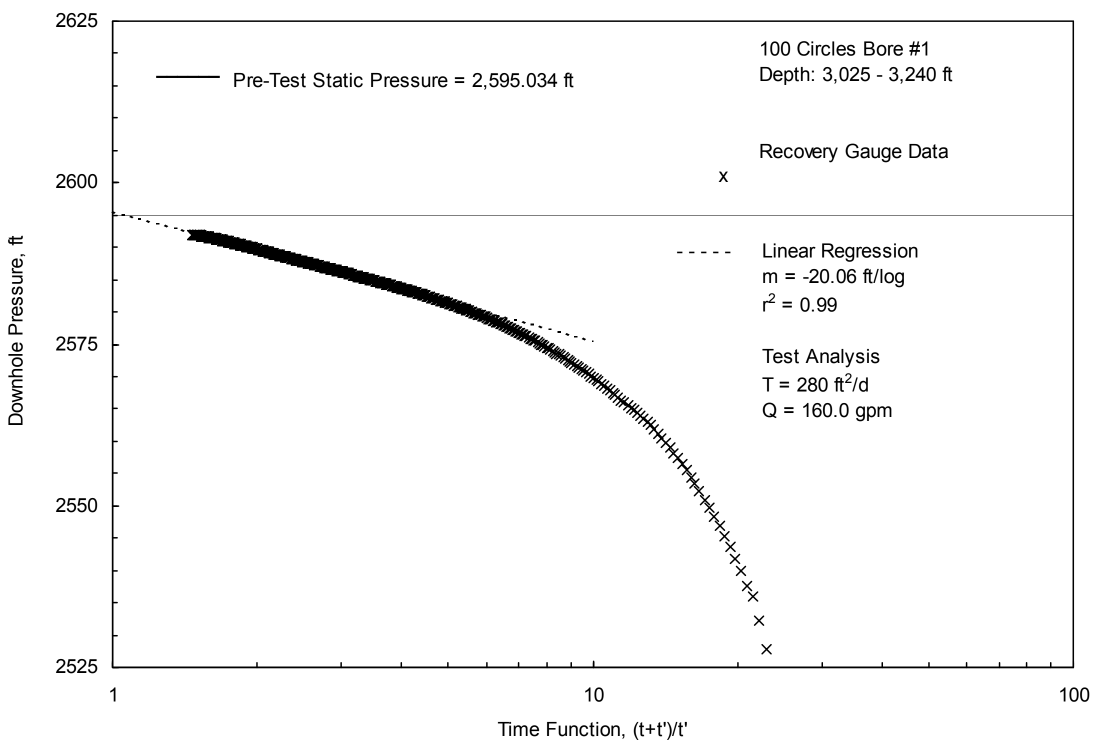

Figure 7. Air-Lift Pumping Test Pressure Recovery Analysis for Grande Ronde Basalt, Member of Ortley Zone

Table 3. Comparison of Analysis Results for Various Analytical Methods, for Hydrologic Tests Conducted Within 100 Circles #1 Borehole

Test Interval	Transmissivity (ft^2/d)		Best Estimate Transmissivity (ft^2/d)
	Pressure Recovery Analysis	Constant Drawdown Analysis	
Lower Wanapum Basalt	20	NA	20
Grande Ronde Basalt Composite	>800	2800	>800
Grande Ronde Basalt, Member of Ortley Zone	280	250	265
Grande Ronde Basalt, Member of Winter Water Zone	NA	15	≤15
Grande Ronde Basalt, Member of Sentinel Bluffs Zone	NA	50	50
NA = Test data not analyzable.			

4.4 Hydraulic Head

Observed static hydraulic head measurements for the three Grande Ronde Basalt and one lower Wanapum Basalt interflow zones tested are shown in Table 4. The hydraulic head values listed represent equilibrated measurements obtained at the end of extended recovery periods following air-lift pumping (Note: recovery time periods usually were twice that of the active air-lift pumping test phase). The hydraulic head values were calculated based on depth-to-water measurements (using an electric water-level sensor) from an assumed measurement datum (ground surface) elevation of 724 feet above MSL.

Table 4. Observed Hydraulic Measurements for 100 Circles #1 Borehole Test Intervals

Test Interval	Test Date	Depth Interval (ft bgs)	Static Hydraulic Head (ft MSL)[(a)]
Lower Wanapum Basalt	7/21/99	1,573–1,725	517
Grande Ronde Basalt Composite	7/31/99	2,030–3,505	524
Grande Ronde Basalt, Member of Ortley Zone	8/4/99	3,025–3,240	502
Grande Ronde Basalt, Member of Winter Water Zone	8/5/99	2,625–2,805	497
Grande Ronde Basalt, Member of Sentinel Bluffs Zone	8/6/99	2,025–2,208	493
(a) Measurement point reference = ground surface at an assumed elevation of 724 feet MSL.			

Figure 8 shows the vertical hydraulic head distribution relationship for intervals tested at the 100 Circles #1 well. Two major hydrologic relationships can be inferred from the vertical-head profile. The head profile pattern suggests a significant hydrologic discontinuity between the lower Wanapum Basalt and upper Grande Ronde Basalt, and a potential upward flow gradient within the Grande Ronde Basalt. The significant hydraulic head difference (~25 feet) between the lower Wanapum Basalt and the upper Grande Ronde Basalt zones is consistent with regional observations (DOE 1988) across this formational contact. The regional head difference is attributed to the low permeability conditions existing within the Vantage Horizon and/or an intensively weathered soil horizon development on the uppermost Grande Ronde Basalt. The presence of the Vantage interbed and upper Grande Ronde Basalt weathering zone (saprolite) comprises a regional aquitard of low permeability, which tends to separate groundwater within the two Columbia River Basalt Group formations. This is reflective also by the major hydro-chemical content differences that exist between the Wanapum Basalt and the Grande Ronde Basalt groundwater. These hydrochemical differences are discussed in the following subsection.

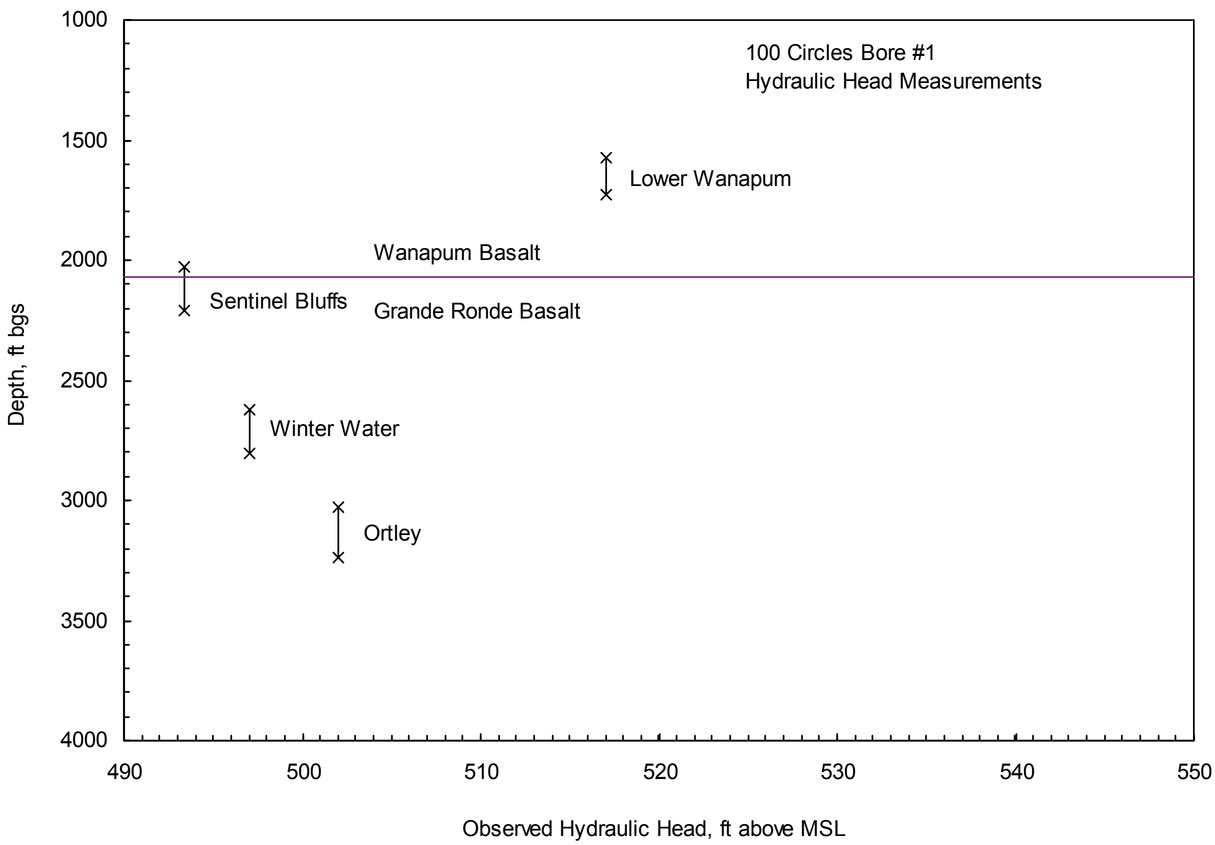

Figure 8. Vertical Hydraulic Head Relationship for 100 Circles #1 Well Test Intervals

The vertical head distribution also indicates that progressively higher hydraulic head conditions exist with depth within the Grande Ronde Basalt. This higher head with depth relationship is consistent with previously anticipated conditions for the area that are associated with a regional discharge area for Grande Ronde Basalt groundwater systems.

Based on the results from the 100 Circles #1 well and surrounding regional relationships, the following formational vertical hydraulic head depth profile conditions at Canoe Ridge are summarized below:

Saddle Mountains Basalt. Higher hydraulic head conditions than underlying Wanapum Basalt; hydraulic head decreasing with depth to the Saddle Mountains Basalt and Wanapum Basalt contact.

Wanapum Basalt. Lower hydraulic head conditions than overlying Saddle Mountains Basalt, but higher than underlying Grande Ronde Basalt; hydraulic head conditions relatively uniform in the upper Wanapum Basalt and slightly decreasing with depth.

Grande Ronde Basalt. Lower hydraulic head conditions in the upper Grande Ronde Basalt in comparison with the overlying Wanapum Basalt; hydraulic head conditions progressively increasing with depth.

4.5 Groundwater Chemistry

This section describes the composition of groundwater samples collected from test zones within the 100 Circles #1 borehole. One test interval within lower Wanapum Basalt was sampled before the Grande Ronde Basalt was penetrated to help evaluate groundwater isolation and caprock integrity between the two basalt formations. All other groundwater samples were obtained from Grande Ronde Basalt test intervals.

4.5.1 Wanapum Groundwater

On July 21, 1999, drilling was temporarily stopped and air-lift pumping initiated for the first Wanapum Basalt interflow zone (basalt of Sand Hollow flow top, Figure 5 and Table 1) encountered after well casing was set. Flow rates for the test interval (1,573 to 1,725 feet) during the 60-minute air-lift test steadily declined from an initial 106 gpm to 53 gpm at test termination. Electrical conductivity (EC), measured as specific conductance (µS/cm) was checked at ~5-minute time intervals on discrete samples collected during the air-lift test. EC declined rapidly from an initial ~8,000 µS/cm and appeared to stabilize at about 600 µS/cm after 40 minutes of air-lift pumping. One-liter grab samples for detailed laboratory analyses and final field determinations were collected at the end of the 60-minute pump test.

4.5.2 Grande Ronde Basalt Groundwater

Test Zones Sampled. Three individual Grande Ronde Basalt interflow zones and one composite Grande Ronde Basalt zone were sampled during air-lift pumping for hydrologic testing that was conducted between July 31 and August 6, 1999. Samples were collected near the end of the air-lift pumping period for 1) immediate analysis to assess compliance with wastewater discharge permit conditions and 2) for detailed laboratory analysis of major cations and anions. Specific conductance usually stabilized within 15 to 45 minutes from the start of pumping, depending on flow rate and interval tested.

4.5.3 Field Measurement Methods and Conditions

Permit-related parameters were measured with portable field testing equipment on discrete groundwater samples as they were collected during the course of pumping. The HACH Co. DR/2010 spectrophotometer was used for the fluoride measurements (SPADNS, method 8029) and for dissolved sulfide (HACH method 8131). EC values were measured with a temperature compensated conductivity meter (HACH Co. CO150, Model 50150) and pH with an Orion meter and probe. Chloride was determined using a HACH Co. digital titrator (Model 16900) with 2.22 M mercuric nitrate as the titrant.

Because fluoride is a characteristic parameter of deep basalt groundwater throughout the region, the fluoride method was checked in the field using a secondary standard consisting of a well-water sample of known fluoride concentration. The field-determined fluoride concentration of this standard sample was within 3% of the known value (2.9 mg/L).

Specific conductance was also checked in the field with an Oakton test solution (447 µS/cm at 25°C) and field determinations were within 5% of the known value. Nearly all collected samples were turbid and required filtration prior to analysis. Filtration through a 0.45-micron membrane filter was necessary to remove all the visible particulates prior to spectrophotometric analysis. A portable hand operated vacuum/Nalgene filter flask was used for filtering purposes. Except for the Wanapum Basalt sampled test interval (Table 5), all analyzed samples were filtered through a 0.45-micron filter. The Wanapum Basalt sample was filtered through a Whatman filter, which did not remove all particulate material.

Table 5. Field Hydrochemical Measurement Results

Date Sampled	Test Interval	Conductivity µS/cm	Fluoride (Mg/L)	Chloride (Mg/L)	pH	Sulfide (Mg/L)	Comment
Wanapum Basalt							
7/21/99	1,573-1,725 Basalt of Sand Hollow	585	1.3	8.9	10.1	0.2 (turbid)	No odor
Grande Ronde Basalt							
7/31/99	2,030-3,500 Composite *	2800	15	730	9.1	0.05	Slight H_2S odor
8/04/99	3,025-3,240 Member of Ortley	2100	15	650	8.9	--	No odor
8/05/99	2,625-2,805 Member of Winter Water	2220	11	620	8.7	--	No odor
8/06/99	2,035-2,208 Member of Sentinel Bluffs	1700	6.7	500	8.5	0.001	No odor

*Based on the preliminary analysis of the static and dynamic flowmeter survey test results, most of the water produced during the air-lift pumping of the composite Grande Ronde Basalt (2,030 to 3,500 feet) is believed to be derived from the fault/ fracture zone occurring between 3,420 to 3,440 feet.

Replicate 1-liter grab samples for the three Grande Ronde Basalt interflow test intervals were collected both at the mid-point and end of the air-lift pumping period. All individual Grande Ronde Basalt interflow zones yielded groundwater that was pale yellow to light brown in color. Samples collected from the entire composite Grande Ronde Basalt open borehole, on the other hand, were clear with no evidence of a suspended solid phase. The discoloration observed for individual Grande Ronde Basalt interflow zone water samples was attributed the presence of a colloidal iron phase (note: total iron concentration declined by nearly ten–fold for filtered versus unfiltered samples) that likely forms as a result of contact with air during the air-lift pumping process. The Grande Ronde Basalt composite samples were clear from the initial sampling and never showed any evidence of formation of a precipitate after even several weeks of storage.

4.5.4 Laboratory Measurements

The 1-liter grab samples collected during air-lift pumping were analyzed for detailed hydrochemical characterization at the Pacific Northwest National Laboratory in Richland, Washington. Analyses were performed on unfiltered (settled) samples that were kept in cold storage until analyzed. Major anions were analyzed by ion chromatography. All other cation and trace element analyses were made by inductively coupled plasma (ICP) emission spectroscopy. Carbonate alkalinity was computed from the elemental carbon ICP results. The latter was used for computing charge balance.

Depth intervals, collection time and date, and the corresponding laboratory results for the samples collected are summarized in Appendix B. Charge balance, or the percent difference in milliequivalents of cations and anions analyzed, was within acceptable limits (±5%) for all Grande Ronde Basalt groundwater samples. For the one Wanapum Basalt test zone, there was an excess of approximately 20% in negative charge balance. This suggests there was an unidentified anionic component. The elevated pH observed for this sampled test interval is attributed to the residual effects of recirculated drill cuttings slurry from cementing the permanent casing string. The presence of a high pH cement slurry component is believed to most likely account for the excess anionic charge not identified with laboratory analyses requested. (Note: alkalinity computed from the elemental carbon result, would not account for excess hydroxide present from the cement.) The lack of an acceptable charge balance for the Wanapum Basalt groundwater samples, however, should not impact interpretive use of the relative composition of the major anions and cations, as discussed in the following section. Since the same analytical methods yielded acceptable charge balance for the other Grande Ronde Basalt test zones, the results reported in Appendix B are expected to representative of in situ conditions.

In summary, the presence of residual cement-slurry can be carried down into underlying pervious zones at greater depth during subsequent drilling. The effect of recirculated cuttings slurry must be considered, if optimum conditions for obtaining representative groundwater samples for hydrochemical characterization is a primary test objective. For the initial, exploratory Canoe Ridge drilling campaign described in this report, obtaining high-quality samples for detailed formation hydrochemistry was a secondary test objective.

5.0 Groundwater Chemistry Results Discussion

The hydrochemical results shown in Table 5 and Appendix B illustrate the significant differences in water chemistry exhibited between the Wanapum Basalt and Grande Ronde Basalt groundwater collected from the 100 Circles #1 borehole site. The low specific conductance, low fluoride, and low chloride concentrations for the Wanapum Basalt, basalt of Sand Hollow test interval (1,573 to 1,725 feet) is in contrast to the high concentrations exhibited for sampled Grande Ronde Basalt interflow zones (2,030 to 3,500 feet). This significant difference or hydrochemical zonation between Wanapum Basalt and Grande Ronde Basalt groundwater is consistent with vertical hydrochemical profiles observed at other regional locations, and in particular to hydrochemical conditions exhibited beneath the central Pasco Basin located approximately 45 miles north-northeast of the Canoe Ridge site (DOE 1988, Johnson et al. 1993).

It should be noted that most of the water produced from the composite Grande Ronde Basalt interval is believed to have come from the fault/fracture zone occurring between 3,420 to 3,440 feet (based on dynamic flowmeter survey results). Also, based on color, odor, and high fluoride content, the Grande Ronde Basalt aquifers at this location would be undesirable for domestic or irrigation purposes.

The pH for basalt groundwater at Canoe Ridge ranged from 8.5 to 10 (Table 5). As noted previously, the slightly higher pH value for the Wanapum Basalt test interval is attributed to residual effects of the cement used to seal the borehole casing that was installed down to a depth of 1,573 feet. The slightly alkaline pH of the other samples is characteristic of deep basalt aquifers of the Columbia Basin (due to hydrolysis reactions involving dissolved silica).

The sharp contrast in hydrochemical composition between the Wanapum Basalt and the Grande Ronde Basalt groundwater (and supported by the vertical hydraulic head profile shown in Figure 8), is indicative of vertical isolation of these basalt formation aquifer systems. This lack of aquifer inter-communication has been noted previously to occur on a regional basis (DOE 1988). Even the small differences in hydrochemistry and hydraulic head between the discrete Grande Ronde Basalt zones tested suggest local vertical isolation of groundwater within individual Grande Ronde Basalt interflow zones (i.e., 2,040 to 3,507 feet) tested.

The contrasts in hydrochemical characteristics may be best exhibited by plotting selected anion ratios for the data listed in Appendix B, as a function of the chloride concentration. When presented in this fashion, distinct groupings and separations are evident as illustrated in Figures 9, 10, and 11. These plots show the distinct separation of the Wanapum Basalt from the Grande Ronde Basalt test zone group groundwater. Separation between individual Grande Ronde Basalt interflow groundwater is less dramatic, but still significant enough to suggest at least local isolation. (Note: if groundwater within the sampled Grand Ronde Basalt interflow zones were all in hydraulic communication, they would all have similar ratios and plot as one homogenous cluster rather than four distinct plot groupings.)

The distinct difference in the chemical composition of groundwater between the composite Grande Ronde Basalt and the other individual Grande Ronde Basalt test interflow zones is also illustrated in Figures 12 and 13. These plots show the concentration of magnesium and iron, respectively, plotted with increasing stratigraphic depth. As evident, the composite Grande Ronde Basalt groundwater sample (which is dominated by groundwater issuing from the fracture zone at a depth of 3,420 to 3.440 ft) is dramatically lower in concentration than the other Grande Ronde Basalt interflow zones. It should be noted, however, that the iron concentrations may be somewhat erratic, due to the effect of air injected into the discharge water during air-lift pumping. Nevertheless, it does show the same trend as for magnesium, which should not be influenced or subject to air oxidation effects. The depleted magnesium and iron for the composite Grande Ronde Basalt groundwater sample may suggest the formation of smectite clays (a common secondary mineral within basalts) at some point in the past evolutionary history of groundwater from this depth. Formation of iron rich smectite clays would deplete groundwater of iron and magnesium content. Quantitative geochemical modeling could be conducted to resolve and address the stoichiometry of the clay mineral formation from a non-Mg-Fe-depleted Grande Ronde Basalt groundwater (e.g., member of Sentinel Bluffs, member of Ortley, or member of Winter Water test zones).

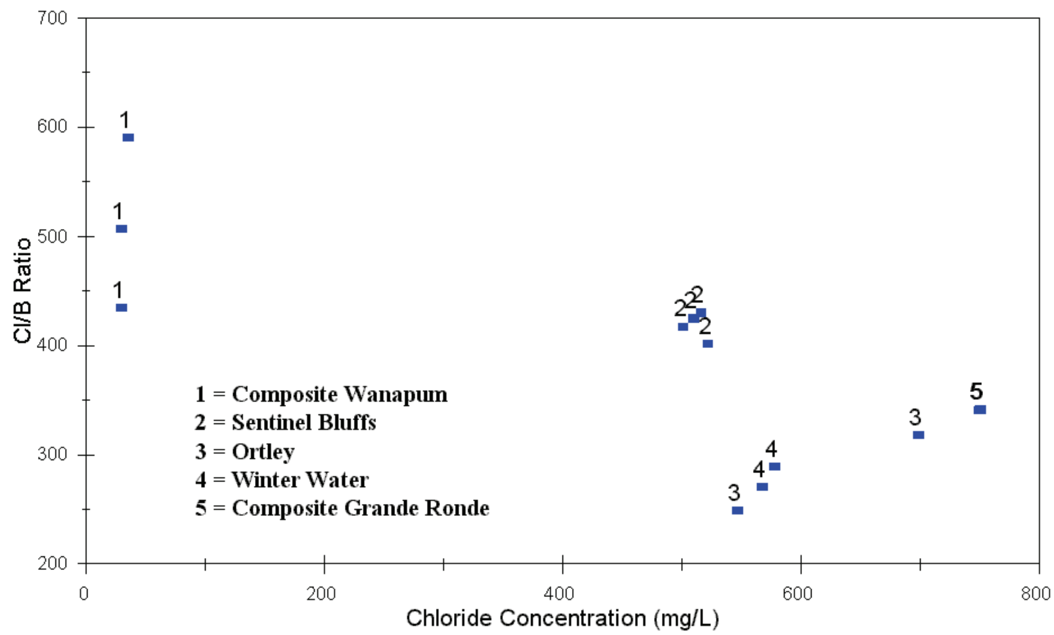

Figure 9. Cl/B Ratio versus Chloride Concentration

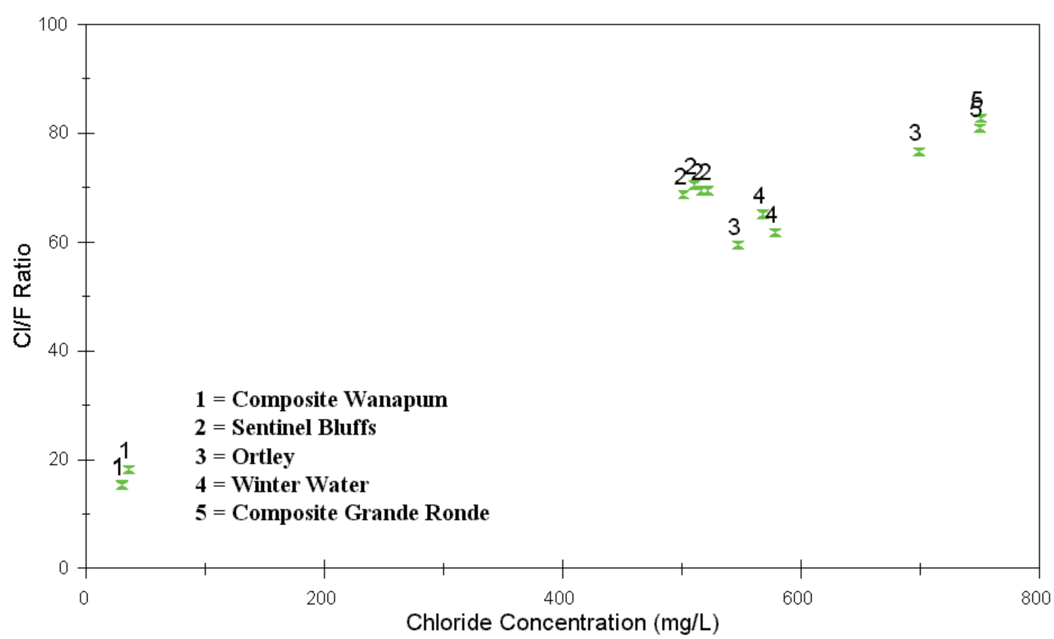

Figure 10. Cl/F Ratio versus Chloride Concentration

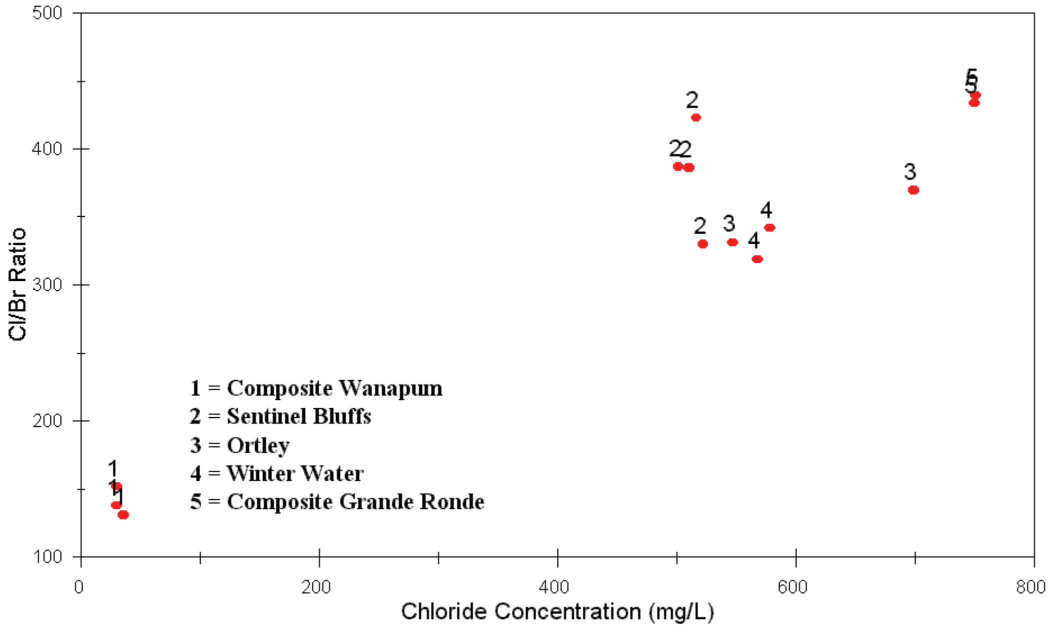

Figure 11. Cl/Br Ratio versus Chloride Concentration

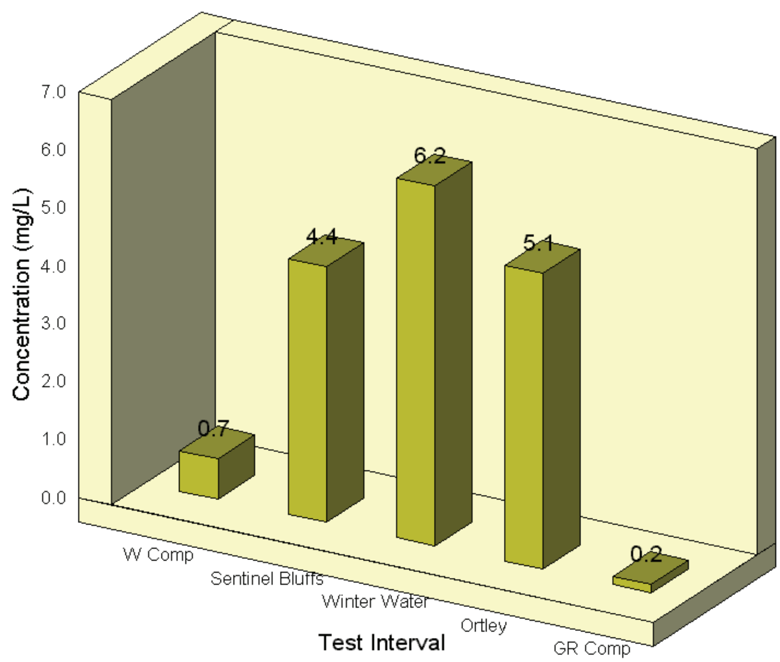

Figure 12. Magnesium Concentration

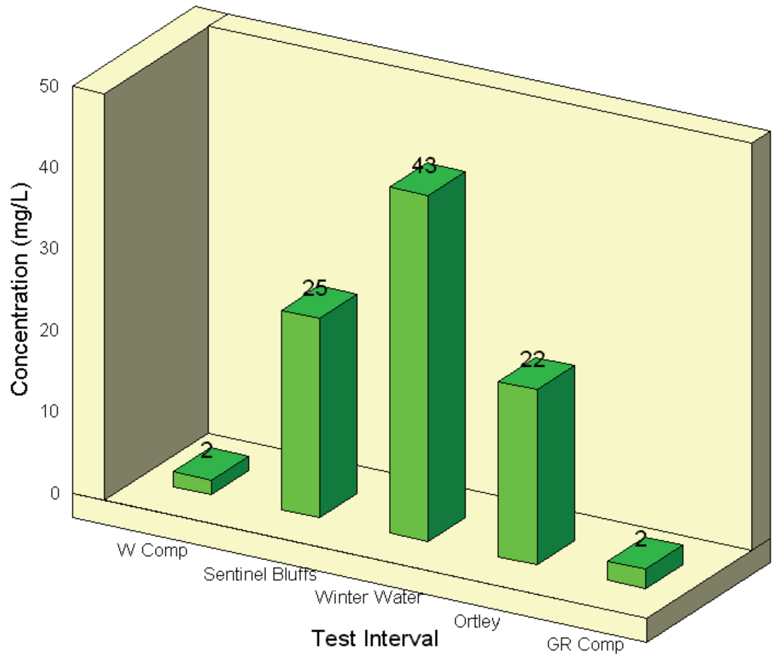

Figure 13. Iron Concentration

6.0 Conclusions

The subsurface geologic conditions, hydrologic test response characteristics (i.e., derivative plot analysis), vertical hydraulic head depth profile, and hydrochemical information comparisons from 100 Circles #1 well all suggest there is vertical isolation between the basalt interflow systems tested at the Canoe Ridge site. While there is lithologic and geophysical evidence of faulting and fracturing within the Grande Ronde Basalt sequence, the distinct differences in hydrochemical composition and vertical hydraulic head profile suggest there is little if any vertical mixing or communication between the two major groundwater flow systems (Wanapum Basalt and Grande Ronde Basalt) as a result of local fracture networks. There are also hydrochemical indications of vertical isolation between the deepest Grande Ronde Basalt zone (fracture zone at 3,420 to 3,440 ft) and the overlying Grande Ronde Basalt interflow zones tested.

The conditions noted above are favorable for the existence of multiple caprocks for containment of subsurface natural gas storage at the Canoe Ride site. Interpretation of the preliminary structural and stratigraphic data also suggests the possibility for sufficient closure within the central portion of the Canoe Ridge study area for enclosing subsurface natural gas storage. The confirmation of areal closure, however, is needed with additional drilling, and both vertical and areal seismic testing.

The U.S. Department of Energy participation in this project is leading to the acquisition of important new information with which to develop recognition criteria for viable subsurface natural gas-storage sites at other locations within the Columbia Basin region and in other geologically similar provinces.

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Appendix A

XRF Analyses for Columbia River Basalt Group Samples

Table A.1. X-Ray Fluorescence Analyses from the 100 Circles #1 Borehole

Depth	Flow	SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total
Feet	See Figure 5	**Unnormalized (wt. %)**										
110	SMB-Elephant Mountain Member	50.88	12.89	3.594	13.98	0.212	8.92	3.85	1.09	2.43	0.552	98.40
170	SMB-Pomona Member	52.15	15.06	1.704	9.50	0.172	11.08	6.10	0.57	2.49	0.233	99.06
310	SMB-Pomona Member	51.85	14.67	1.697	10.09	0.178	10.74	6.47	0.66	2.48	0.234	99.07
580	SMB-Umatilla Member,	52.72	13.81	2.711	12.10	0.303	6.34	1.85	2.13	2.85	1.056	95.87
790	SMB-Umatilla Member	53.73	13.45	2.714	11.96	0.252	6.26	2.56	2.70	3.22	0.979	97.83
910	W-PR Member-Basalt of Lolo	48.65	13.18	3.300	13.62	0.222	8.98	5.19	1.08	2.67	0.779	97.68
1,000	W-PR Member-Basalt of Rosalia	48.12	13.05	3.814	14.00	0.217	9.03	4.09	0.84	2.54	0.788	96.49
1,350	W-FS Member-Basalt of Sentinel Gap	51.38	13.12	3.078	13.99	0.230	8.23	4.05	1.40	2.80	0.630	98.91
1,440	W-FS Member-Basalt of Sand Hollow	50.54	13.30	*3.006*	13.40	0.240	8.56	4.06	1.03	2.90	*0.580*	97.62
1,505	W-FS Member-Basalt of Sentinel Gap	51.46	13.04	3.128	14.16	0.219	8.16	4.00	1.35	2.94	0.619	99.08
1,800	W-FS Member-Basalt of Sand Hollow	51.46	13.27	2.943	13.34	0.224	8.48	4.40	1.29	2.81	0.566	98.78
1,870	W-FS Member-Basalt of Sand Hollow	51.43	13.31	2.949	13.66	0.225	8.47	4.41	1.29	2.96	0.565	99.27
1,940	W-FS Member-Basalt of Ginkgo	50.95	13.14	3.144	13.55	0.227	8.41	3.96	1.19	3.01	0.708	98.29
2,090	GRB-Member of Sentinel Bluffs, Museum Flow(1)	53.99	14.25	1.792	11.05	0.201	8.26	4.68	1.26	3.06	0.314	98.85
2,140	GRB-Member of Sentinel Bluffs, Museum Flow(1)	53.28	14.18	1.802	11.08	0.219	8.86	4.90	1.04	2.92	0.316	98.60
2,220	GRB-Member of Sentinel Bluffs, Museum Flow(1)	54.23	14.19	1.784	10.74	0.193	8.37	4.72	1.25	3.19	0.326	99.00
2,240	GRB-Member of Sentinel Bluffs, Museum Flow(1)	54.20	14.23	1.763	10.56	0.201	8.65	4.81	1.27	2.99	0.323	98.99

Table A.1. (contd)

Depth	Flow	SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total
2,250	GRB-Member of Sentinel Bluffs, Museum Flow(1)	54.21	14.04	1.764	10.91	0.198	8.59	4.77	1.24	2.94	0.322	98.99
2,280	GRB-Member of Sentinel Bluffs, Museum Flow(1)	54.47	14.07	1.817	10.97	0.191	8.10	4.64	1.33	3.10	0.348	99.04
2,320	GRB-Member of Sentinel Bluffs, Spokane Falls Flow(1)	52.86	13.92	1.857	11.18	0.213	9.00	4.81	0.94	2.97	0.294	98.05
2,370	GRB-Member of Sentinel Bluffs, Spokane Falls Flow(1)	53.12	13.88	1.858	11.62	0.207	8.85	4.71	1.10	3.00	0.291	98.63
2,420	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.04	13.81	1.976	12.28	0.210	8.69	4.70	1.08	2.90	0.323	99.01
2,470	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.20	13.73	1.933	11.91	0.210	8.68	4.55	1.08	3.02	0.319	98.64
2,520	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.57	13.83	1.962	11.74	0.212	8.67	4.73	1.09	2.93	0.320	99.05
2,560	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.20	13.77	1.946	11.50	0.212	8.68	4.61	1.06	2.96	0.319	98.26
2,610	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.42	13.89	1.969	11.35	0.218	8.70	4.78	1.09	2.98	0.333	98.73
2,630	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.50	13.92	1.980	11.54	0.214	8.66	4.75	1.11	3.00	0.338	99.01
2,660	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	51.91	14.01	1.893	11.41	0.215	9.17	5.10	0.97	2.84	0.261	97.78

Table A.1. (contd)

Depth	Flow	SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total
2,700	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	52.90	14.07	1.907	10.86	0.211	9.17	5.19	0.93	2.96	0.269	98.47
2,730	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	51.24	14.10	1.930	12.06	0.209	9.00	5.16	0.72	2.89	0.248	97.56
2,760	GRB-Member of Winter Water	52.40	13.53	2.254	12.41	0.246	7.99	4.13	1.18	3.06	0.434	97.63
2,800	GRB-Member of Winter Water	54.18	13.66	2.107	11.45	0.220	8.18	4.23	1.27	3.18	0.363	98.84
2,810	GRB-Member of Winter Water	54.33	13.53	2.184	11.94	0.221	7.59	3.97	1.38	3.32	0.413	98.88
2,860	GRB-Member of Winter Water	55.36	13.35	2.125	11.77	0.207	7.21	3.37	1.57	3.29	0.359	98.61
2,900	GRB-Member of Winter Water	55.09	13.32	2.080	12.53	0.203	7.03	3.23	1.68	3.25	0.368	98.78
2,940	GRB-Member of Winter Water	55.48	13.40	2.137	11.92	0.210	7.19	3.37	1.54	3.53	0.362	99.14
3,000	GRB-Member of Umtanum	54.98	13.26	2.336	12.03	0.217	7.05	3.26	1.64	3.34	0.424	98.53
3,050	GRB-Member of Umtanum	55.56	13.21	2.532	11.84	0.218	6.67	2.97	1.70	3.46	0.470	98.63
3,260	GRB-Member of Ortley	56.38	13.85	1.775	10.93	0.183	7.13	3.50	1.40	3.49	0.309	98.95
3,300	GRB-Member of Ortley	56.51	13.79	1.817	10.97	0.174	6.83	3.56	1.74	3.48	0.311	99.18
3,400	GRB-Member of Ortley	56.19	13.88	1.822	10.65	0.194	7.24	3.51	1.59	3.21	0.309	98.60
3,440	GRB-Member of Ortley	53.67	14.11	1.973	11.34	0.204	7.79	3.63	1.44	3.25	0.340	97.75
3,460	GRB-Member of Ortley	55.86	13.76	1.894	11.18	0.198	7.18	3.46	1.48	3.38	0.330	98.72
3,460	GRB-Member of Ortley	56.14	13.80	1.900	10.93	0.197	7.20	3.51	1.48	3.40	0.330	98.89
3,460	GRB-Member of Ortley	55.86	13.76	1.894	11.18	0.198	7.18	3.46	1.48	3.38	0.330	98.72
3,505	GRB-Member of Ortley	55.85	13.86	1.874	11.12	0.198	7.28	3.55	1.36	3.42	0.324	98.84

Table A.1. (contd)

Depth	Flow	SiO_2	Al_2O_3	TiO_2	FeO*	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5
Feet	See Figure 5	**Normalized (wt. %)**									
110	SMB-Elephant Mountain Member	51.71	13.10	3.653	14.21	0.215	9.07	3.91	1.11	2.47	0.561
170	SMB-Pomona Member	52.64	15.20	1.720	9.59	0.174	11.19	6.16	0.58	2.51	0.235
310	SMB-Pomona Member	52.34	14.81	1.713	10.18	0.180	10.84	6.53	0.67	2.50	0.236
580	SMB-Umatilla Member	54.99	14.40	2.828	12.62	0.316	6.61	1.93	2.22	2.97	1.101
790	SMB-Umatilla Member	54.92	13.75	2.774	12.23	0.258	6.40	2.62	2.76	3.29	1.001
910	W-PR Member –Basalt of Lolo	49.81	13.49	3.379	13.95	0.227	9.19	5.31	1.11	2.73	0.798
1,000	W-PR Member –Basalt of Rosalia	49.87	13.52	3.953	14.51	0.225	9.36	4.24	0.87	2.63	0.817
1,350	W-FS Member-Basalt of Sentinel Gap	51.95	13.27	3.112	14.15	0.230	8.32	4.09	1.42	2.83	0.630
1,440	W-FS Member-Basalt of Sand Hollow	51.77	13.62	*3.079*	13.73	0.250	8.77	4.16	1.06	2.97	*0.593*
1,505	W-FS Member-Basalt of Sentinel Gap	51.94	13.16	3.157	14.30	0.221	8.24	4.04	1.36	2.97	0.625
1,800	W-FS Member-Basalt of Sand Hollow	52.10	13.43	2.979	13.50	0.227	8.58	4.45	1.31	2.84	0.573
1,870	W-FS Member-Basalt of Sand Hollow	51.81	13.41	2.971	13.76	0.227	8.53	4.44	1.30	2.98	0.569
1,940	W-FS Member-Basalt of Ginkgo	51.81	13.37	3.199	13.78	0.231	8.56	4.03	1.21	3.06	0.720
2,090	GRB-Member of Sentinel Bluffs, Museum Flow[(1)]	54.62	14.42	1.813	11.17	0.203	8.36	4.73	1.27	3.10	0.318
2,140	GRB-Member of Sentinel Bluffs, Museum Flow[(1)]	54.04	14.38	1.828	11.24	0.222	8.99	4.97	1.05	2.96	0.321
2,220	GRB-Member of Sentinel Bluffs, Museum Flow[(1)]	54.78	14.33	1.802	10.85	0.195	8.45	4.77	1.26	3.22	0.329
2,240	GRB-Member of Sentinel Bluffs, Museum Flow[(1)]	54.75	14.37	1.781	10.66	0.203	8.74	4.86	1.28	3.02	0.326
2,250	GRB-Member of Sentinel Bluffs, Museum Flow[(1)]	54.77	14.18	1.782	11.02	0.200	8.68	4.82	1.25	2.97	0.325
2,280	GRB-Member of Sentinel Bluffs, Museum Flow[(1)]	55.00	14.21	1.835	11.08	0.193	8.18	4.69	1.34	3.13	0.351

Table A.1. (contd)

Depth	Flow	SiO_2	Al_2O_3	TiO_2	FeO*	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5
2,320	GRB-Member of Sentinel Bluffs, Spokane Falls Flow(1)	53.91	14.20	1.894	11.40	0.217	9.18	4.91	0.96	3.03	0.300
2,370	GRB-Member of Sentinel Bluffs, Spokane Falls Flow(1)	53.86	14.07	1.884	11.78	0.210	8.97	4.78	1.12	3.04	0.295
2,420	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.57	13.95	1.996	12.40	0.212	8.78	4.75	1.09	2.93	0.326
2,470	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.94	13.92	1.960	12.08	0.213	8.80	4.61	1.09	3.06	0.323
2,520	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	54.08	13.96	1.981	11.85	0.214	8.75	4.78	1.10	2.96	0.323
2,560	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	54.14	14.01	1.981	11.70	0.216	8.83	4.69	1.08	3.01	0.325
2,610	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	54.11	14.07	1.994	11.49	0.221	8.81	4.84	1.10	3.02	0.337
2,630	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	54.03	14.06	2.000	11.65	0.216	8.75	4.80	1.12	3.03	0.341
2,660	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.09	14.33	1.936	11.67	0.220	9.38	5.22	0.99	2.90	0.267
2,700	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	53.72	14.29	1.937	11.03	0.214	9.31	5.27	0.94	3.01	0.273
2,730	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	52.52	14.45	1.978	12.36	0.214	9.23	5.29	0.74	2.96	0.254
2,760	GRB-Member of Winter Water	53.67	13.86	2.309	12.71	0.252	8.18	4.23	1.21	3.13	0.445
2,800	GRB-Member of Winter Water	54.82	13.82	2.132	11.58	0.223	8.28	4.28	1.28	3.22	0.367
2,810	GRB-Member of Winter Water	54.95	13.68	2.209	12.08	0.224	7.68	4.01	1.40	3.36	0.418
2,860	GRB-Member of Winter Water	56.14	13.54	2.155	11.93	0.210	7.31	3.42	1.59	3.34	0.364
2,900	GRB-Member of Winter Water	55.77	13.48	2.114	12.68	0.205	7.12	3.27	1.70	3.29	0.373

Table A.1. (contd)

Depth	Flow	SiO_2	Al_2O_3	TiO_2	FeO*	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5
2,940	GRB-Member of Winter Water	55.96	13.52	2.155	12.03	0.212	7.25	3.40	1.55	3.56	0.365
3,000	GRB-Member of Umtanum	55.80	13.46	2.371	12.20	0.220	7.16	3.31	1.66	3.39	0.430
3,050	GRB-Member of Umtanum	56.33	13.39	2.567	12.01	0.221	6.76	3.01	1.72	3.51	0.477
3,260	GRB-Member of Ortley	56.98	14.00	1.794	11.05	0.185	7.21	3.54	1.41	3.53	0.312
3,300	GRB-Member of Ortley	56.98	13.90	1.832	11.06	0.175	6.89	3.59	1.75	3.51	0.314
3,400	GRB-Member of Ortley	56.99	14.08	1.848	10.80	0.197	7.34	3.56	1.61	3.26	0.313
3,440	GRB-Member of Ortley	54.91	14.44	2.018	11.60	0.209	7.97	3.71	1.47	3.32	0.348
3,460	GRB-Member of Ortley	56.58	13.94	1.919	11.32	0.201	7.27	3.50	1.50	3.42	0.334
3,460	GRB-Member of Ortley	56.77	13.96	1.921	11.05	0.199	7.28	3.55	1.50	3.44	0.334
3,460	GRB-Member of Ortley	56.58	13.94	1.919	11.32	0.201	7.27	3.50	1.50	3.42	0.334
3,505	GRB-Member of Ortley	56.51	14.02	1.896	11.25	0.200	7.37	3.59	1.38	3.46	0.328

Table A.1. (contd)

Depth	Flow	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
Feet	See Figure 5	**Trace Elements (ppm)**																
110	SMB-Elephant Mountain Member	14	36	37	422	637	29	271	253	51	25.2	22	23	149	7	27	80	5
170	SMB-Pomona Member	47	107	38	291	279	13	245	136	32	12.5	17	49	94	0	12	45	1
310	SMB-Pomona Member	46	102	28	277	242	15	246	148	31	15.7	19	48	94	3	17	32	1
580	SMB-Umatilla Member	0	6	34	161	3520	36	314	528	50	23.7	22	9	132	9	45	76	8
790	SMB-Umatilla Member	1	4	27	173	3503	47	276	493	51	22.0	20	14	129	8	24	80	5
910	W-PR Member-Basalt of Lolo	39	100	41	359	538	20	283	180	46	15.4	17	39	137	5	19	46	3
1,000	W-PR Member-Basalt of Rosalia	12	32	39	476	491	24	304	220	50	18.6	20	18	140	6	22	60	4
1,350	W-FS Member-Basalt of Sentinel Gap	9	37	33	440	596	36	310	193	45	15.3	20	17	137	7	28	51	2
1,440	W-FS Member-Basalt of Sand Hollow	13	57	36	437	516	25	316	183	42	14.7	25	33	142	4	17	40	3
1,505	W-FS Member-Basalt of Sentinel Gap	13	41	36	439	580	35	299	194	45	15.8	25	22	143	8	8	47	6
1,800	W-FS Member-Basalt of Sand Hollow	16	60	35	434	548	32	311	176	42	14.9	22	45	146	5	19	58	6
1,870	W-FS Member-Basalt of Sand Hollow	20	68	37	429	545	33	309	178	40	14.3	21	33	134	4	25	53	3
1,940	W-FS Member-Basalt of Ginkgo	10	31	40	394	564	29	324	180	43	14.9	21	26	143	6	32	48	4
2,090	GRB-Member of Sentinel Bluffs, Museum Flow(1)	12	58	34	298	564	30	300	165	35	12.6	21	31	110	3	27	28	5

Table A.1. (contd)

Depth	Flow	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
2,140	GRB-Member of Sentinel Bluffs, Museum Flow(1)	10	48	40	313	460	27	312	159	35	11.2	22	31	115	7	18	45	4
2,220	GRB-Member of Sentinel Bluffs, Museum Flow(1)	13	50	34	298	536	32	301	156	34	11.2	21	33	120	3	15	28	8
2,240	GRB-Member of Sentinel Bluffs, Museum Flow(1)	10	49	38	304	536	32	304	155	33	11.4	21	26	115	7	20	39	2
2,250	GRB-Member of Sentinel Bluffs, Museum Flow(1)	13	50	35	297	547	31	307	156	33	10.9	19	26	110	6	20	47	4
2,280	GRB-Member of Sentinel Bluffs, Museum Flow(1)	10	46	36	305	570	35	303	162	34	11.8	19	27	115	7	24	32	5
2,320	GRB-Member of Sentinel Bluffs, Spokane Falls Flow(1)	12	49	36	322	427	27	305	150	34	11.8	21	29	113	6	26	58	4
2,370	GRB-Member of Sentinel Bluffs, Spokane Falls Flow(1)	10	51	41	320	487	35	303	148	36	11.3	24	37	114	4	22	38	3
2,420	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	12	50	44	327	482	28	308	158	36	13.1	21	30	120	4	11	44	6
2,470	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	10	46	36	323	499	27	307	158	35	12.4	21	33	118	2	26	39	2
2,520	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	10	45	36	336	500	29	307	156	35	12.0	21	34	132	2	3	27	5

Table A.1. (contd)

Depth	Flow	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
2,560	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	10	45	37	318	483	26	303	158	34	11.5	20	29	114	5	28	33	4
2,610	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	10	49	42	331	488	26	302	156	35	11.4	22	30	115	5	20	43	3
2,630	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	13	55	34	321	491	28	304	155	35	12.5	22	30	122	3	19	35	4
2,660	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	11	44	36	328	338	19	305	148	32	10.4	20	34	112	6	7	57	0
2,700	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	11	43	34	339	350	25	307	144	32	11.4	20	35	110	6	17	48	5
2,660	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	11	44	36	328	338	19	305	148	32	10.4	20	34	112	6	7	57	0
2,700	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	11	43	34	339	350	25	307	144	32	11.4	20	35	110	6	17	48	5
2,730	GRB-Member of Sentinel Bluffs, McCoy Canyon Flow(1)	11	40	38	343	381	13	320	148	31	11.9	21	35	113	3	22	34	7
2,760	GRB-Member of Winter Water	5	23	39	325	488	32	325	177	39	13.1	21	20	130	3	23	45	4
2,800	GRB-Member of Winter Water	6	32	37	340	538	31	310	161	36	14.1	21	24	124	4	22	53	4

Table A.1. (contd)

Depth	Flow	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
2,810	GRB-Member of Winter Water	4	23	39	331	589	36	308	171	39	12.8	22	20	124	5	25	51	6
2,860	GRB-Member of Winter Water	2	30	36	371	638	49	307	178	38	13.3	22	14	129	7	23	52	5
2,900	GRB-Member of Winter Water	4	22	35	353	631	47	312	182	38	13.9	22	15	128	5	28	38	5
2,940	GRB-basalt of Winter Water	4	25	37	360	627	46	305	178	39	14.3	24	21	130	8	34	64	5
3,000	GRB-Member of Umtanum	6	21	32	308	651	45	304	186	41	14.5	23	18	134	6	23	44	4
3,050	GRB-Member of Umtanum	1	15	36	261	681	47	301	192	41	15.3	23	17	138	9	30	67	9
3,260	GRB-Member of Ortley	4	20	28	294	683	51	304	177	35	12.7	20	16	116	8	28	64	5
3,300	GRB-Member of Ortley	4	22	29	287	688	49	294	177	35	12.7	21	16	114	12	22	56	7
3,400	GRB-Member of Ortley	2	19	32	304	638	42	298	175	34	11.7	22	13	120	6	19	59	4
3,440	GRB-Member of Ortley	3	20	41	326	760	34	331	184	36	12.4	19	16	119	10	21	51	6
3,460	GRB-Member of Ortley	4	17	28	296	691	38	305	179	36	13.1	21	16	119	11	11	51	5
3,460	GRB-Member of Ortley	4	22	32	322	689	39	307	178	37	12.6	20	17	120	7	25	57	7
3,460	GRB-Member of Ortley	4	17	28	296	691	38	305	179	36	13.1	21	16	119	11	11	51	5
3,505	GRB-Member of Ortley	4	18	35	307	679	38	313	176	36	13.3	25	19	118	5	24	41	7

(1) Member of Sentinel Bluffs nomenclature based on Reidel (2005).
All analyses performed by the GeoAnalytical Laboratory, Washington State University.
GRB = Grande Ronde Basalt.
SMB = Saddle Mountains Basalt.
WB = Wanapum Basalt.

Appendix B

Groundwater Analyses

Table B.1. Hydrochemical Data for 100 Circles #1 Well (all concentrations are in mg/L)

Sample ID	B	Ca	Fe	K	Mg	Na	Si	TIC	HCO_3	F	Cl	Br	SO_4
PGT-1[(a)]	0.07	2.7	1.8	11	0.71	98	46	23.4	119.0	1.98	30.4	0.22	18.40
PGT-2[(a)]	0.06	2.8	2.0	11	0.72	96	46	28.8	146.0	1.97	30.4	0.20	19.50
PGT-3[(a)]	0.06	3.1	1.5	17	0.64	96	44	27.9	142.0	1.94	35.4	0.27	20.10
PGT-4[(b)]	2.20	4.5	3.0	11	0.20	450	52	14.3	72.7	9.26	750.0	1.73	3.88
PGT-5[(c)]	2.20	4.2	1.7	11	0.10	440	52	12.3	62.5	9.07	751.0	1.71	3.47
PGT-6[(d)]	2.20	7.1	21.0	9	4.90	430	53	16.9	85.9	9.12	699.0	1.89	6.47
PGT-7[(e)]	2.20	7.3	22.0	14	5.30	430	56	16.3	82.9	9.20	547.0	1.65	5.37
PGT-8[(f)]	2.10	12.0	55.0	20	8.40	410	100	24.8	126.0	8.71	568.0	1.78	16.90
PGT-9[(g)]	2.00	8.5	30.0	21	4.00	400	58	20.9	106.0	9.36	578.0	1.69	8.74
PGT-10[(h)]	1.30	13.0	25.0	27	4.70	350	60	20.7	105.0	7.51	522.0	1.58	14.40
PGT-11[(i)]	1.20	13.0	24.0	27	4.40	340	56	21.0	107.0	7.42	516.0	1.22	13.00
PGT-12[(j)]	1.20	12.0	22.0	27	4.00	340	53	21.7	110.0	7.23	510.0	1.32	11.90
PGT-13[(j)]	1.20	12.0	27.0	27	4.50	340	59	22.3	113.0	7.29	501.0	1.30	12.20

(a) Depth interval 1,573 to 1,725 feet (date collected: July 21, 1999, 2:40 a.m.).
(b) Depth interval 2,030 to 3,505 feet (date collected: July 31, 1999, 2:30 p.m.).
(c) Depth interval 2,030 to 3,505 feet (date collected: July 31, 1999, 9:40 p.m.).
(d) Depth interval 3,025 to 3,240 feet (date collected: August 4, 1999, 1:10 a.m.).
(e) Depth interval 3,025 to 3,240 feet (date collected: August 4, 1999, 2:50 a.m.).
(f) Depth interval 2,625 to 2,805 feet (date collected: August 5, 1999, 2:00 p.m.).
(g) Depth interval 2,625 to 2,805 feet (date collected: August 5, 1999, 3:20 p.m.).
(h) Depth interval 2,025 to 2,208 feet (date collected: August 6, 1999, 8:50 a.m.).
(i) Depth interval 2,025 to 2,208 feet (date collected: August 6, 1999, 9:25 a.m.).
(j) Depth interval 2,025 to 2,208 feet (date collected: August 6, 1999, 9:55 a.m.).