U.S. DEPARTMENT OF ENERGY

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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Preliminary Analysis of Grande Ronde Basalt Formation Flow Top Transmissivity as it Relates to Assessment and Site Selection Applications for Fluid/Energy Storage and Sequestration Projects

FA Spane

April 2013

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Pacific Northwest National Laboratory
Richland, Washington 99352

Date:	**April 17, 2013**		
To:	**Pete McGrail and Casie Davidson**	Internal Distribution:	**D. Bacon** **M. Chamness** **C. Murray** **S.R. Reidel** **File/LB**
From:	**Frank Spane**		
Subject:	**Preliminary Analysis of Grande Ronde Basalt Formation Flow Top Transmissivity as it Relates to Assessment and Site Selection Applications for Fluid/Energy Storage and Sequestration Projects**		

Note: The following was an internal memorandum originally prepared and distributed on June 21, 2012, as part of the Department of Energy/Bonneville Power Administration-funded Compressed Air and Thermal Energy Storage in Columbia River Basalt (Project 1918-1546). It was updated with an appendix section of pertinent data utilized in the assessment, two additional figures (Figures 10 and 11) and with minor editing of the text discussion, following an internal technical review provided by Christopher Murray (PNNL).

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Summary

The following summary comments pertain to a preliminary assessment of transmissivity conditions within the Grande Ronde Basalt Formation flow tops (i.e., interflow zones), as they may relate to a variety of fluid/energy storage or sequestration projects within deep Columbia River Basalt formations. Transmissivity is the principal hydraulic parameter controlling well/reservoir injectivity and/or extraction of fluids within subsurface formations. In this regard, the preliminary findings and statistical relationships developed herein regarding Grande Ronde Basalt flow-top transmissivity are considered relevant for feasibility assessments and site selection applications within deep basalts. Salient findings include:

1. Grande Ronde Basalt flow tops exhibit a wide transmissivity range (i.e., 8 orders of magnitude, 10^{-4} to 10^{4} ft^2/day), and display log-normal (random) distribution behavior.

2. Standard statistical analysis of the regional data set indicates a geometric mean value for Grande Ronde flow top transmissivity of 2.03 ft^2/day (50% percentile probability plot). The Hanford Site sub-data set yields slightly higher transmissivity results and relationships with a geometric mean of 3.25 ft^2/day.

3. Probability percentage distribution plots for flow-top transmissivity were developed and can be utilized to assess probabilities that an intersected Grande Ronde Basalt flow top will possess required hydraulic properties to support various storage/extraction or sequestration applications. For example, probability analysis for the regional data set indicates a ~20% probability that an individual Grande Ronde flow top intersected within a borehole will exhibit a transmissivity value of 36 ft^2/day (i.e., K = 1.2 ft/day, b = 30 ft, k = 0.50 darcies) or higher, which was the value utilized in recent PNNL compressed air energy storage simulations.

4. Dykstra-Parsons variation plot analysis indicates that Grande Ronde Basalt flow-top transmissivities are reflective of highly heterogeneous formation conditions (Dykstra-Parson Coefficient $C_v > 0.9$), with a "maximum expected" transmissivity value (i.e., 2 percentile projection) of 3,950 ft^2/day for an individual Grande Ronde flow top at a well site location.

5. On a collective regional basis, transmissivity-vs.-depth plots for Grande Ronde Basalt flow tops do not exhibit an obvious depth dependency relationship (i.e., an associated transmissivity reduction with depth). At a few individual borehole locations, however, a consistent, generally decreasing transmissivity pattern with depth (e.g., Hanford Site borehole DC-15, and the Wallula pilot borehole). Statistical boxplot comparisons for the regional dataset, however, suggest a possible weak association for a possible reduction in the transmissivity geometric mean with depth (i.e., to a depth of ~4,000 ft). The lack of a predominant general transmissivity/depth dependency suggests that the transmissivity probability relationships developed for the regional data set are also applicable for Grande Ronde Basalt flow tops at individual borehole locations for depths to 6,000 ft.

6. No significant visual differences in transmissivity-versus-depth pattern relationships were exhibited for various, selected stratigraphic members of the Grande Ronde Basalt. Stratigraphic members examined include (in chronological order, youngest to oldest): the Sentinel Bluffs,

Winterwater/Umtanum, Slack Canyon, Ortley, Grouse Creek, and Wapshilla Ridge members. Visual examination of stratigraphic results suggest a randomness in the flow top results for the various stratigraphic members, although a wider range in flow-top transmissivity was exhibited for Grande Ronde flow tops within the Umtanum through Ortley basalt members. Statistical boxplot comparisons for the regional dataset, however, suggest that basalt flow tops within the uppermost Grande Ronde Basalt member (Sentinel Bluffs) may exhibit slightly higher transmissivities (i.e., a higher geometric mean) than flow tops within underlying Grande Ronde Basalts (i.e., for basalt flow tops through the Wapshilla Ridge member).

Discussion

This memorandum contains preliminary statistical analysis plots and discussion of transmissivity relationships for Grande Ronde Basalt flow tops obtained from hydrologic packer tests conducted within deep characterization boreholes. Packer tests provide a definitive means for isolating and characterizing individual and/or composite adjoining Grande Ronde Basalt flow tops during testing. Results from packer tests are considered to be superior to open borehole/well tests, which test large composite basalt sections that commonly contain numerous/multiple contributing flow top intervals. The compiled data set of test results examined in this memorandum is mainly reflective of Hanford Site borehole tests conducted as part of the Basalt Waste Isolation Project (BWIP), but also includes surrounding regional borehole test results that were obtained as part of natural gas storage, carbon sequestration, and natural gas exploration investigation studies, and are reflective of borehole test depths between 1,760 and 5,960 ft. Available Grand Ronde test data for BWIP/Hanford Site boreholes include: DC-1, DC-4/5, DC-6, DC-7/8, DC-12, DC-14, DC-15, RRL-2, and RRL-14, while non-Hanford Site test boreholes having reported Grande Ronde flow top results include: Canoe Ridge (natural gas storage), Wallula (carbon sequestration), and RSH-1 (natural gas exploration). Supporting reports and documents that were utilized in the compilation of the Grande Ronde flow-top transmissivity data set are listed in the Reference section of the memo. In total, the initial data set includes transmissivity results for 67 Grande Ronde flow top intervals: 48

Hanford Site and 19 test results for boreholes outside the Hanford Site. The data set that was compiled and analyzed for this memorandum is considered to be preliminary, and will be updated periodically with additional regional basalt borehole transmissivity data from other scientific characterization borehole test results. The statistical analysis results presented in this internal memo are useful in assessing injectivity or productivity of Grande Ronde Basalt flow tops within surrounding regions of the Columbia Basin, particularly as it may relate to evaluating the feasibility for compressed air or thermal energy storage, natural gas storage, and carbon sequestration projects.

Figure 1 shows a histogram plot of the log transmissivity and a normal distribution plot for the 67 Grande Ronde flow-top test results within the Columbia Basin region. As indicated in the figure, regional Grande Ronde transmissivity values appear to be log-normally distributed, varying over a wide range (i.e., 8 orders of magnitude), and visually conform to a normal distribution, with a log geometric mean value of 0.3072 (i.e., transmissivity = 2.03 ft^2/day).

Figure 2 shows a log-normal probability plot of the same regional Grande Ronde transmissivity data set, indicating the cumulative percent probability of encountering a Grande Ronde Basalt flow top having a specific transmissivity value or higher. For example, based on the compiled data set, there is 50% probability that a Grande Ronde Basalt flow top encountered during drilling over the depth interval of ~1,800 to 6,000 ft, will exhibit a transmissivity of 2.03 ft^2/day or greater (95% confidence range = 0.8 to 4.9 ft^2/day). Additionally, if the transmissivity requirements are known for a particular storage/sequestration (injection) or pumping/retrieval activity, then Figure 2 can be used to assess the probability that an individual Grande Ronde Basalt flow top will possess those transmissivity characteristics. For example, a recently completed simulation by PNNL of the performance of a compressed air energy storage/retrieval project required a flow-top transmissivity of 36 ft^2/day (i.e., transmissivity, T, = Kb; and hydraulic conductivity, K, = $(\gamma_w k)/\mu_w$; where intrinsic permeability, k, = 0.5 darcies; K = 1.2 ft/day and flow-top thickness, b, = 30 ft; for the reference values for the specific weight, γ_w, and dynamic viscosity, μ_w, of water at standard pressure and temperature conditions). The cumulative probability percentage plot shown in Figure 2 indicates that there is an

~80% probability that an encountered Grande Ronde Basalt flow top will exhibit a transmissivity less than the required 36 ft^2/day (or correspondingly a ~20% probability that the flow top will equal or exceed the required value).

Figure 3 shows a log-normal probability plot comparison for the total regional data set (67 data points) shown in Figure 2, along with the probability plot for the predominant Hanford Site sub-data set (48 data points). As indicated, the Hanford Site data set exhibits slightly more variability (as indicated by the lower P-value), and indicates slightly higher transmissivity values for given probability percentages (e.g., 50% probability: Hanford Site sub-data set = 3.25 ft^2/day vs. total regional data set = 2.03 ft^2/day). The underlying reason for the slightly greater variability and higher transmissivities exhibited by the Hanford sub-data set is currently unknown, but may be attributed, in part, to the relatively smaller sample size.

Figures 4 and 5 show standard Dykstra-Parsons coefficient-of-variability plots for flow-top transmissivity for the total regional data set and the Hanford Site sub-data set, respectively. Dykstra-Parsons statistical plot analysis is commonly utilized in the oil industry for assessing reservoir permeability variation and for assessing potential resource development (e.g., Stell and Fischer, 1997). Results from this type of statistical variation plot analysis (shown in Figure 4) indicate that regional Grande Ronde flow-top transmissivities are reflective of highly heterogeneous formation conditions (Dykstra-Parson Coefficient $C_v > 0.9$), and with a "maximum expected" transmissivity value of 3,950 ft^2/day for an individual Grande Ronde flow top. Figure 5 presents the results for the same variability analysis as applied solely to the Hanford Site sub-data set. As shown, the same highly heterogeneous formation condition is indicated, but with a higher "maximum expected" transmissivity of 4,975 ft^2/day

A series of depth and stratigraphic vs. transmissivity plots were developed to visually examine the possibility of any significant relationship dependency in the transmissivity data. Figure 6 shows a comparison of regional and Hanford Site Grande Ronde Basalt flow-top transmissivity versus depth. As indicated in the figure, on a collective basis, Grande Ronde Basalt flow-top transmissivity does not exhibit a depth dependency (i.e., an associated reduction-with-depth relationship). A few individual boreholes, however, do appear to exhibit a general decreasing transmissivity pattern with depth (e.g., Hanford Site borehole DC-15, and the Wallula pilot borehole). Figure 7 shows this apparent decreasing transmissivity-versus-depth pattern for the Wallula pilot borehole, superimposed with the collective Hanford Site sub-data set. The vast majority of the individual borehole locations, however, exhibit a random transmissivity-vs.-depth relationship (not shown). The lack of a general transmissivity depth dependency suggests that the transmissivity probability relationships developed for the regional data set are also applicable for Grande Ronde Basalt flow tops at individual borehole locations for depths to 6,000 ft.

In addition to depth, no significant differences in the transmissivity pattern relationships were exhibited for the various stratigraphic members of the Grande Ronde Basalt. Stratigraphic members examined include (in chronological order, youngest to oldest): the Sentinel Bluffs, Winterwater/Umtanum, Slack Canyon, Ortley, Grouse Creek, and Wapshilla Ridge members. Figure 8 shows a comparison of transmissivity versus depth for Sentinel Bluffs basalt flow tops (uppermost Grande Ronde member) versus the collective flow-top transmissivities for basalts within the directly underlying Umtanum, Slack Canyon and Ortley basalt members. Figure 9 shows the Sentinel Bluffs transmissivity results in comparison to deeper basalt flow tops below the Ortley member (i.e., Grouse Creek and Wapshilla Ridge members). Visual examination of the figures suggest a randomness in the flow top results for the various stratigraphic members, although a wider range in flow-top transmissivity was exhibited for Grande Ronde flow tops within the Umtanum through Ortley basalt members (Figure 8).

As was the case for the lack of depth dependence, the lack of a general transmissivity/stratigraphic member dependency suggests that the transmissivity probability relationships developed for the regional data set are also applicable for Grande Ronde Basalt flow tops at individual borehole locations for basalt flow tops down through the Wapshilla Ridge member.

Figures 10 and 11 show statistical boxplot comparisons for the regional flow-top transmissivity dataset as a function of depth ~500-ft intervals) and based on the previous stratigraphic association groupings shown in Figures 6 through 9. As indicated, only a weak association with respect to decreasing flow-top transmissivity (i.e., geometric mean) with depth and for older Grande Ronde basalts is suggested.

Acknowledgments

The author wishes to acknowledge the technical review comments and suggestions provided by Chris Murray of Pacific Northwest National Laboratory.

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Figure 1. Log Transmissivity Histogram and Normal Distribution Plot for Regional Grande Ronde Basalt Flow Tops within the Columbia Basin

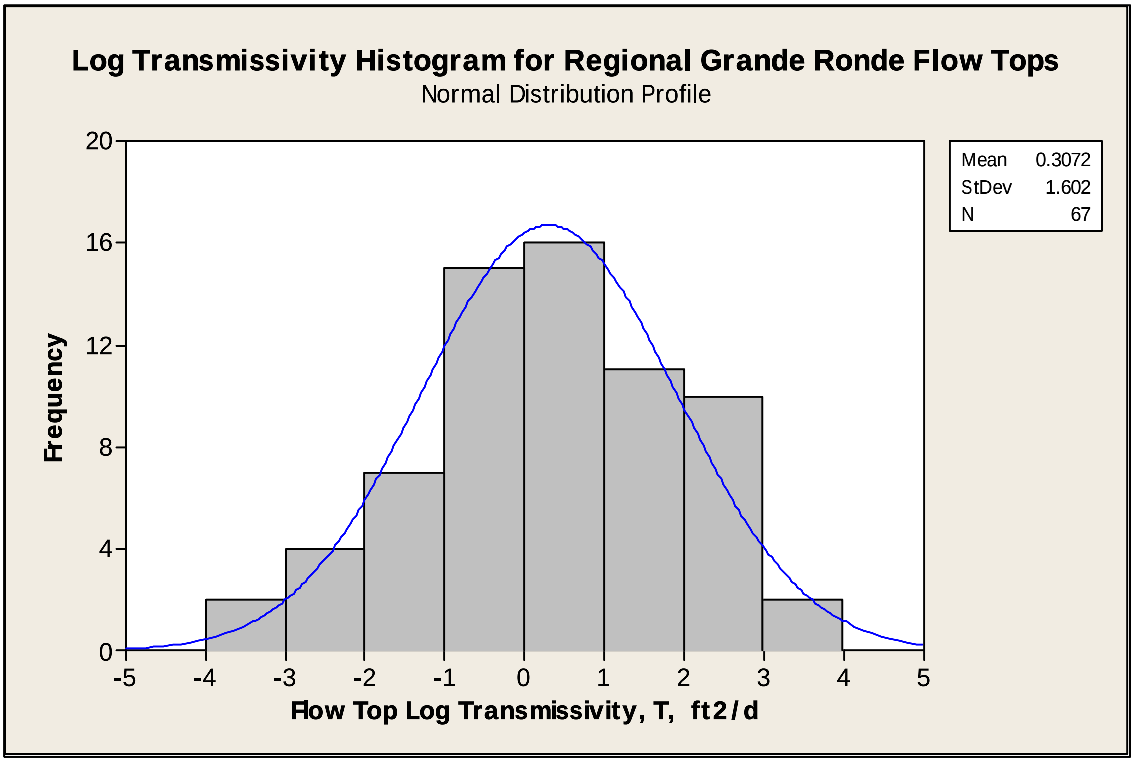


Figure 2. Probability Plot of Regional Grande Ronde Basalt Flow-Top Transmissivity

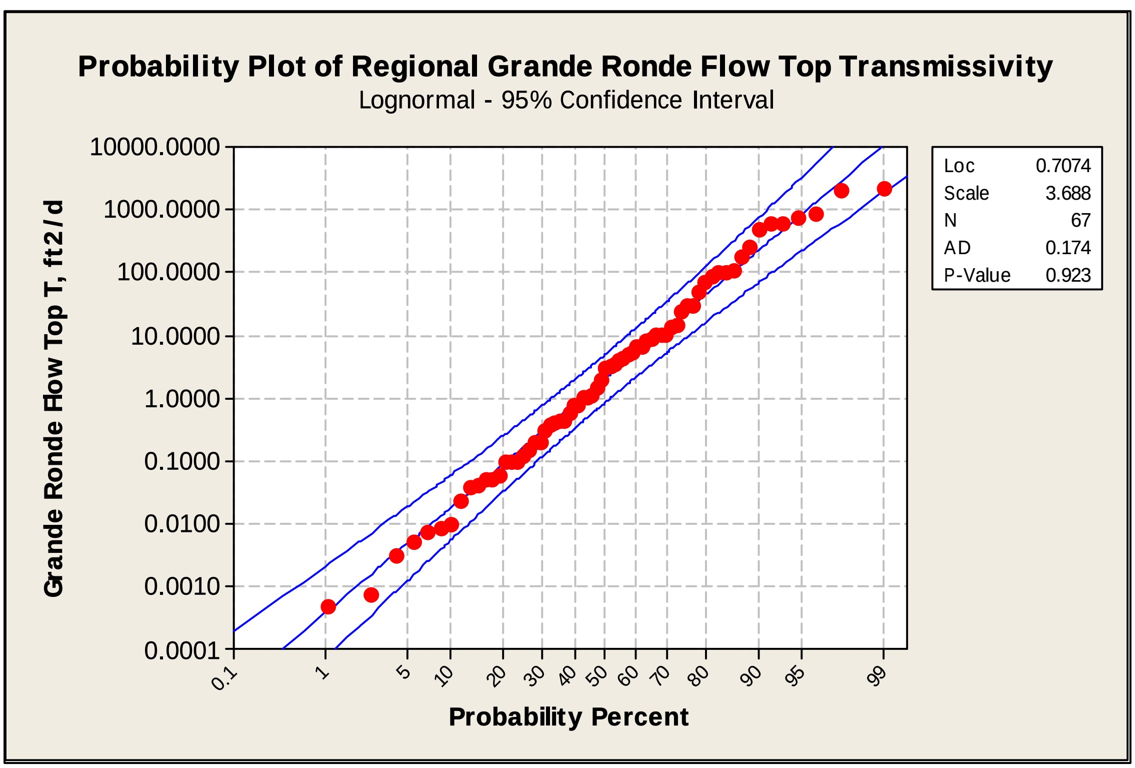


Figure 3. Probability Plot Comparison of Grande Ronde Flow-Top Transmissivity: Total Data Set and Hanford Site Sub-Data Set

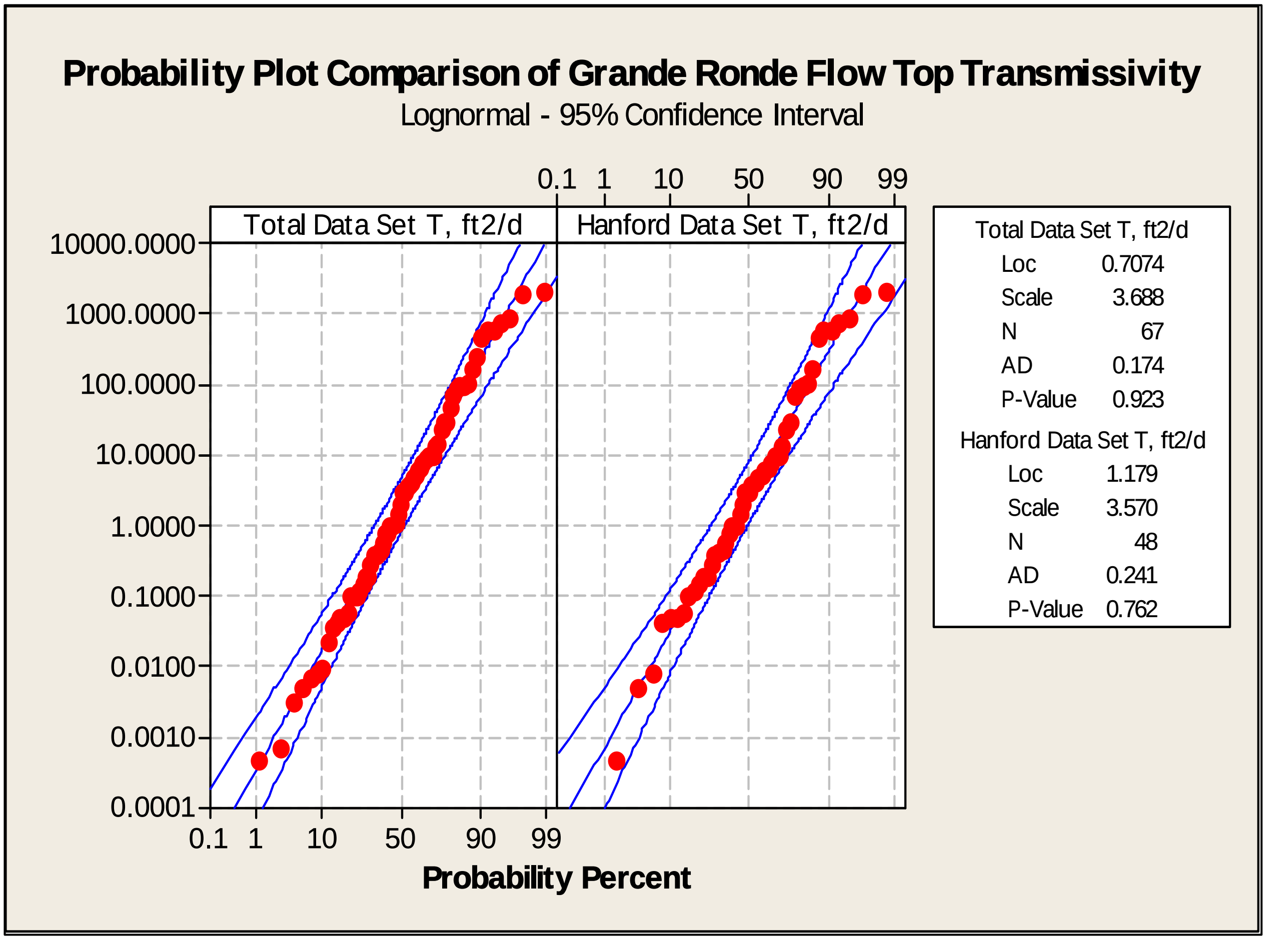


Figure 4. Regional Grande Ronde Flow-Top Transmissivity: Dykstra-Parsons Coefficient-of-Variation

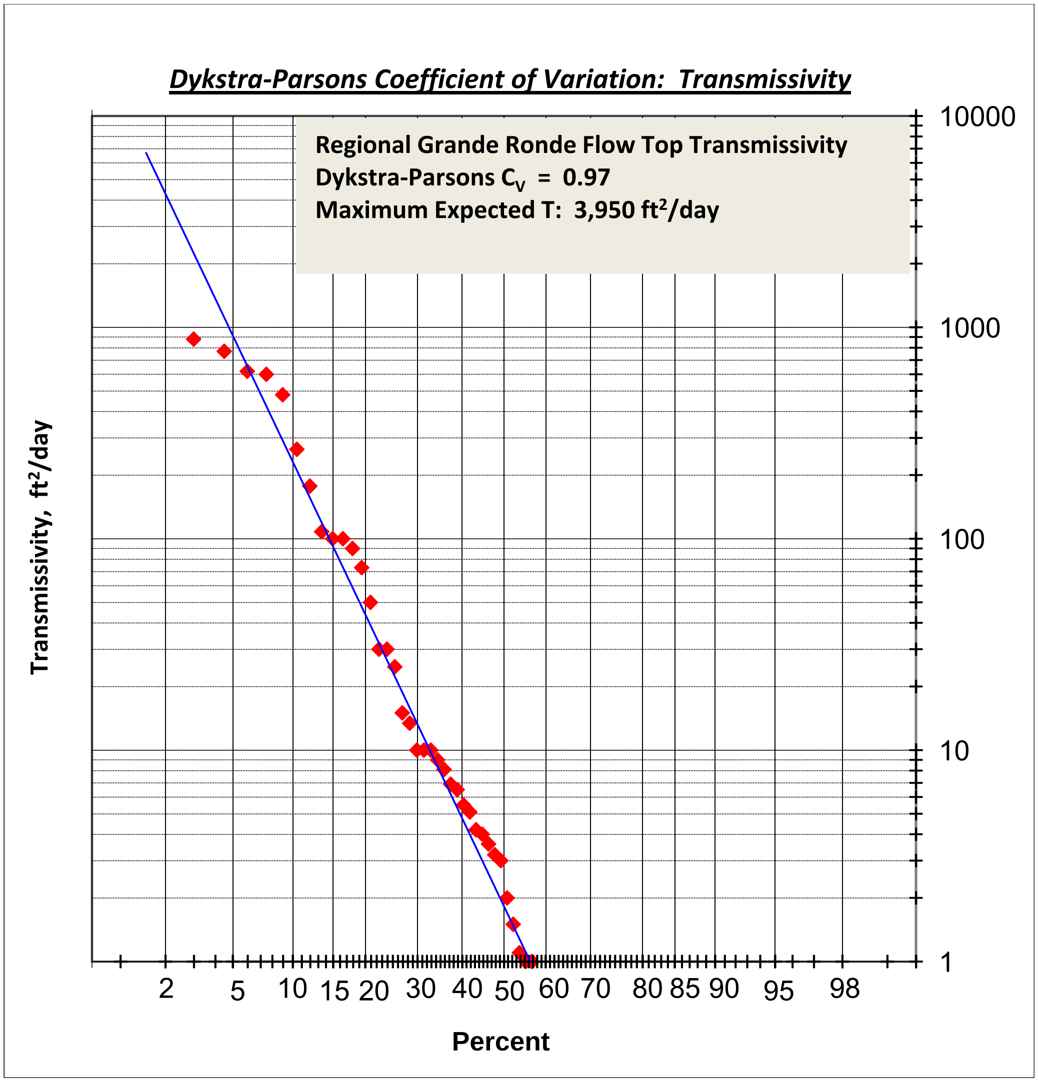


Figure 5. Hanford Site Grande Ronde Flow-Top Transmissivity: Dykstra-Parsons Coefficient-of-Variation

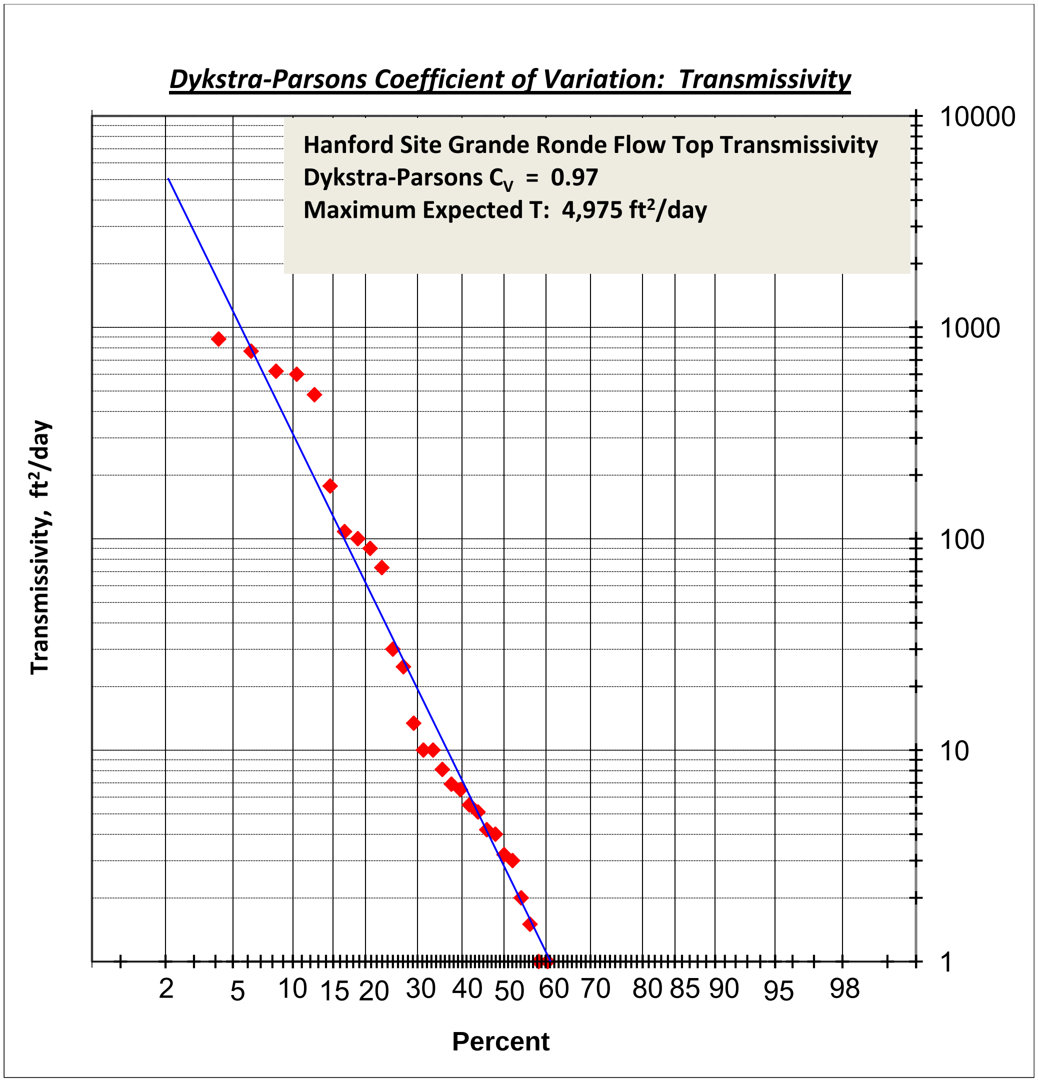


Figure 6. Regional and Hanford Site Grande Ronde Flow-Top Transmissivity vs. Depth

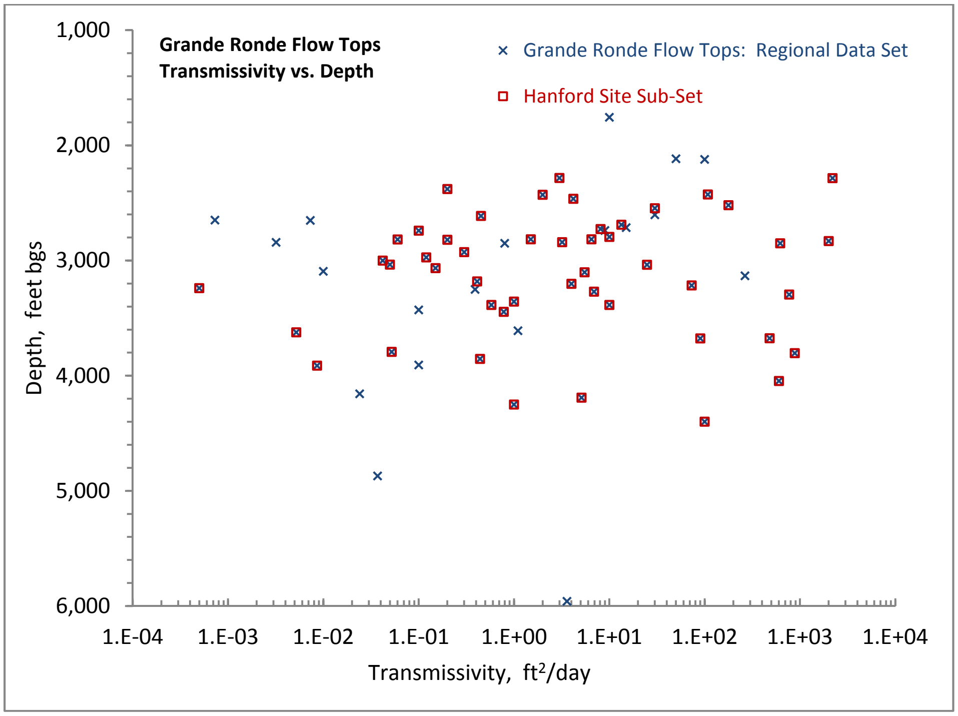


Figure 7. Wallula Grande Ronde Flow-Top Transmissivity vs. Depth

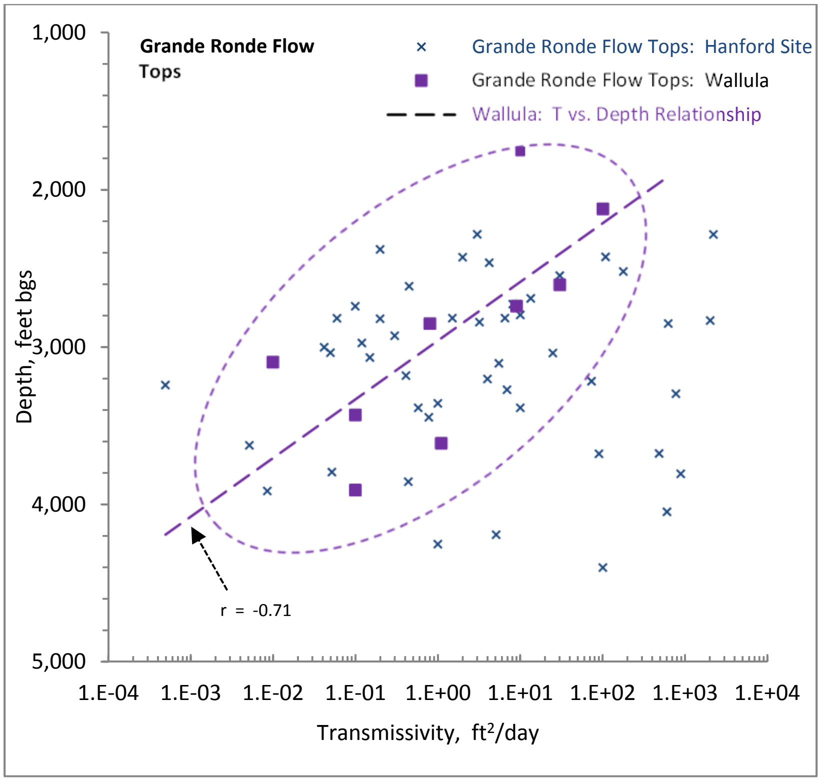


Figure 8. Comparison of Sentinel Bluffs and Umtanum through Ortley Member Flow-Top Transmissivity vs. Depth

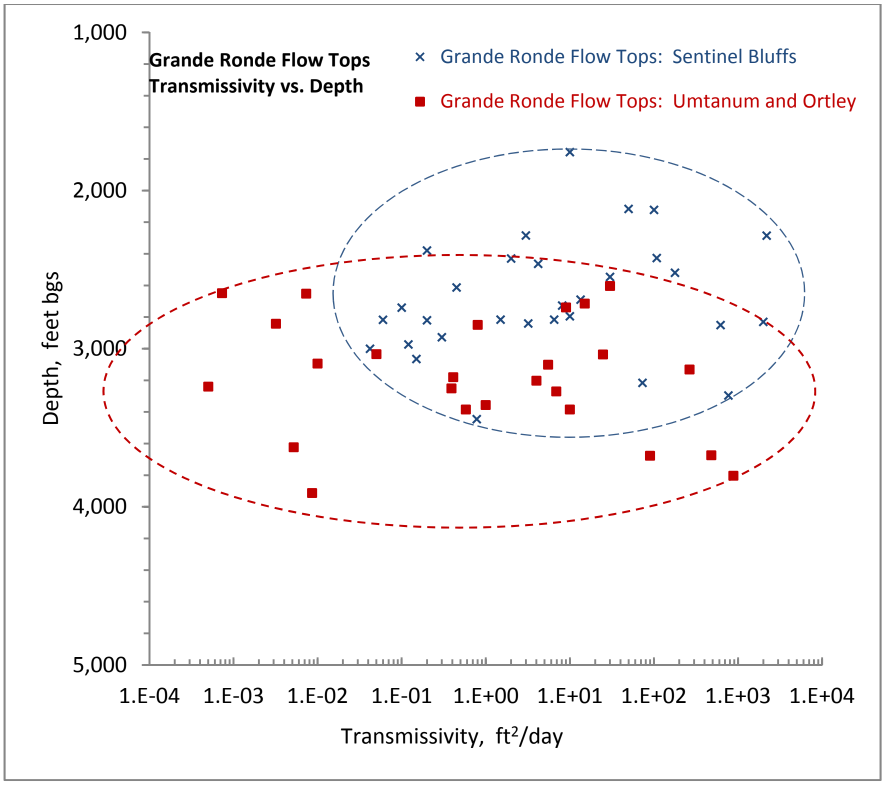


Figure 9. Comparison of Sentinel Bluffs and Below Ortley Member Flow-Top Transmissivity vs. Depth

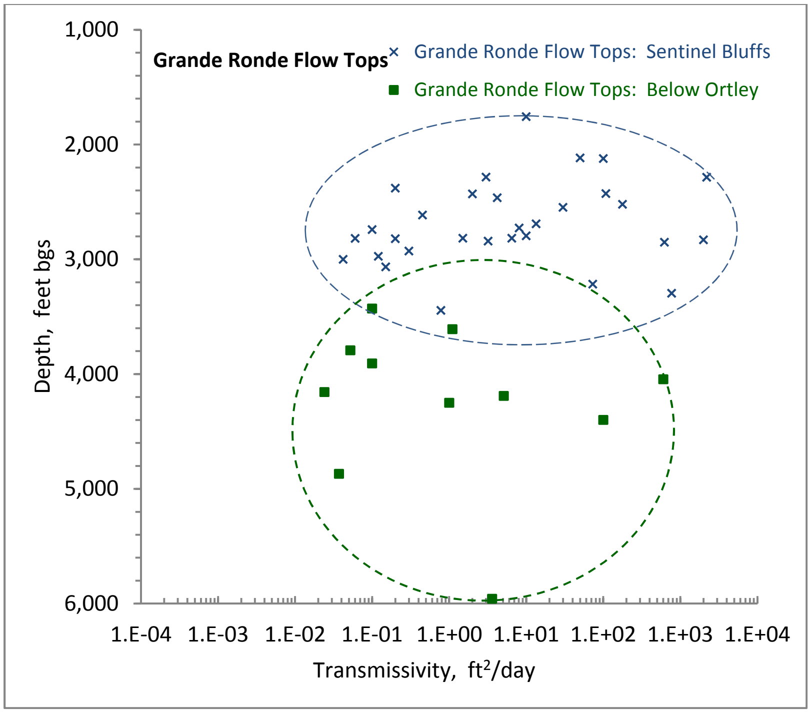


Figure 10. Boxplot Comparison for Selected Grande Ronde Basalt Member Flow-Top Transmissivity

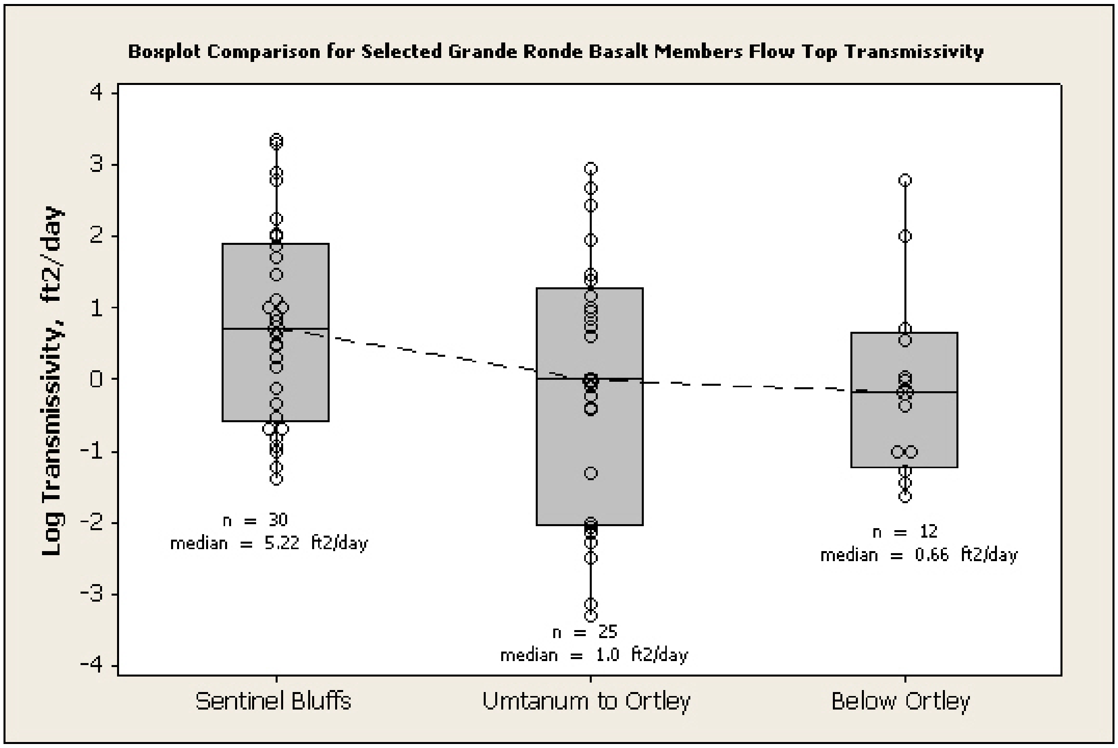
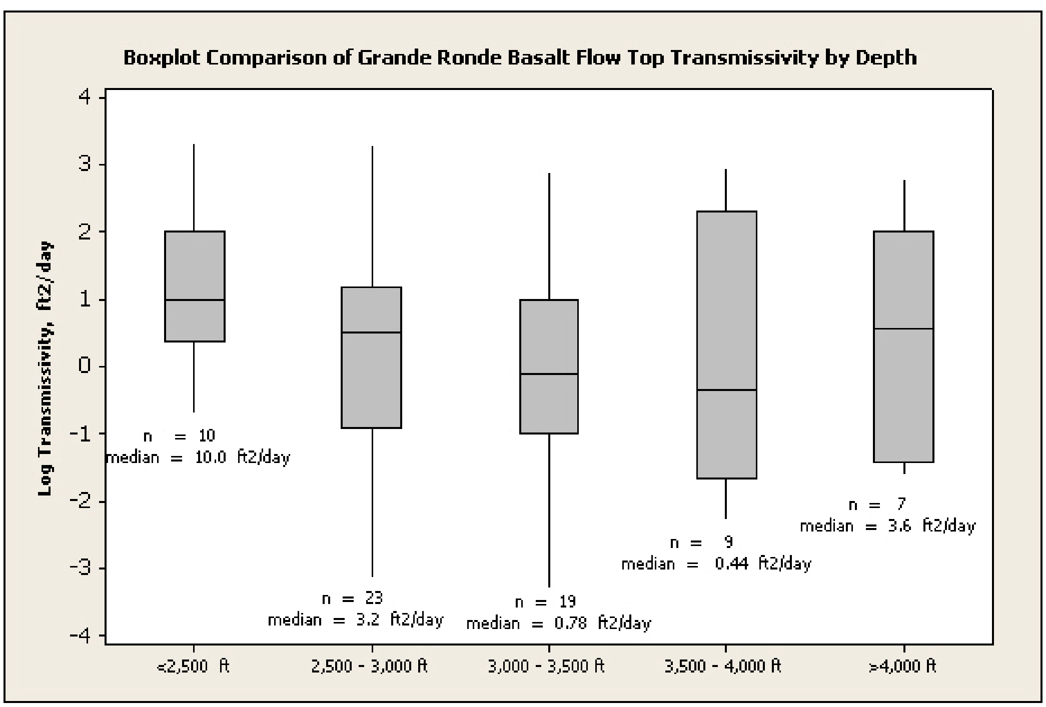


Figure 11. Boxplot Comparison for Grande Ronde Basalt Flow-Top Transmissivity by Depth



Appendix

Grande Ronde Data Used in the Assessment

Table A.1. Grande Ronde Data Used in the Assessment

Well	Location (Township/Range -Section)	Ground Elevation, ft MSL	Hydrologic Test Reference	Hydrogeologic Unit*	Top Depth, ft	Bot. Depth, ft	Mid-Depth, ft	T, ft^2/day
DC-6	T13N/R27E-S26G4	402.2	Bruce (1981)	Rocky Coulee FB + Composite Cohassett FT	2396	2697	2546.5	30
DC-6	T13N/R27E-S26G4	402.2	Bruce (1981)	Cohassett FB + Composite	2697	2893	2795.0	10
DC-6	T13N/R27E-S26G4	402.2	Bruce (1981)	Umtanum FT	2992	3078	3035.0	0.05
DC-6	T13N/R27E-S26G4	402.2	Bruce (1981)	Umtanum FB + SLC+Ortley FT	3242	3529	3385.5	10
DC-6	T13N/R27E-S26G4	402.2	Bruce (1981)	Ortley + GCM	3530	3824	3677.0	90
DC-6	T13N/R27E-S26G4	402.2	Bruce (1981)	GCM	4169	4333	4251.0	1
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	Top of Grande Ronde	2267	2301	2284.0	3
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	Rocky Coulee FT	2408	2446	2427.0	108
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	Rocky Coulee FB + Cohassett FT	2565	2661.5	2613.3	0.45
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	Cohassett FB	2818	2843	2830.5	2000
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	Below Cohassett	2838	2863	2850.5	620
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	McCoy Canyon FT	2978	3153	3065.5	0.15
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	Umtanum FT	3199	3282	3240.5	0.0005
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	GCM	4021	4070	4045.5	600
DC-12	T11N/R26E-S3G2	516.0	Bruce (1981)	GCM	4344	4455	4399.5	100
DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	Rocky Coulee FB	2368	2390	2379.0	0.2
DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	Cohassett FT	2451	2476	2463.5	4.2
DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	Cohassett FB	2657	2824	2740.5	0.1
DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	Below Cohassett	2760	2874	2817.0	0.06

DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	McCoy Canyon FT	2880	2975	2927.5	0.3
DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	Umtanum FT	3060	3144	3102.0	5.5
DC-14	T14N/R27E-S29K1	393.9	Bruce (1981)	Umtanum FB	3180	3225	3202.5	4
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Rocky Coulee FT	2227	2343	2285.0	2192
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Rocky Coulee FB	2372	2487	2429.5	2
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Cohassett FT	2492	2548	2520.0	177.6
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Composite Below Cohassett	2692	2763	2727.5	8.1
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	above McCoy Canyon	2813	2868	2840.5	3.2
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	McCoy FB + Umtanum FT	2961	3113	3037.0	24.8
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Umtanum FB	3245	3296	3270.5	6.9
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	SLC	3301	3412	3356.5	1
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Ortley	3611	3636	3623.5	0.0052
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	Ortley & N2/R2 + GCM	3741	3845	3793.0	0.052
DC-15	T11N/R28E-S35L1	402.0	Ron Jackson DC-15 Hydrologic Testing Notebook (1980 - 1981)	GCM	4138	4243	4190.5	5.1
DC-1	T13N/R26E-S35H	571.9	La Sala and Doty (1971)	Cohassett FB + Composite	2600	2780	2690.0	13.4
DC-1	T13N/R26E-S35H	571.9	La Sala and Doty (1971)	McCoy Canyon FT + Composite above	2730	2910	2820.0	0.2
DC-1	T13N/R26E-S35H	571.9	La Sala and Doty (1971)	Superposition: Very High Mg	3196	3236	3216.0	73
DC-1	T13N/R26E-S35H	571.9	La Sala and Doty (1971)	Umtanum FB	3166	3196	3181.0	0.41
DC-1	T13N/R26E-S35H	571.9	La Sala and Doty (1971)	Ortley	3320	3451	3385.5	0.58

DC-1	T13N/R26E-S35H	571.9	La Sala and Doty (1971)	Composite Below Ortley	3774	3934	3854.0	0.44
DC-4/5	T13N/R25E-S34A2	745.66/744.47	Spane, Thorne, and Riggsbee (1983)	Cohassett FT	2966	2981	2973.5	0.12
DC7-8	T12N/R27E-S35J6	543.82/544.31	Jackson (1982)	McCoy Canyon FT	3410.2	3480.4	3445.3	0.78
RRL-2A	T12N/R25E-S10B	635.1	Strait and Spane (1983a)	Rocky Coulee FB	2981	3020	3000.5	4.20E-02
RRL-2A	T12N/R25E-S10B	635.1	Strait and Spane (1982a)	Cohassett FB	3247	3344	3295.5	770
RRL-2A	T12N/R25E-S10B	635.1	Strait and Spane (1982b)	McCoy Canyon FB + Umtanum FT	3568	3781	3674.5	480
RRL-2A	T12N/R25E-S10B	635.1	Strait and Spane (1983b)	Umtanum FB/Fracture Zone (Winterwater Contact	3781	3827	3804.0	880
RRL-2B/2A	T12N/R25E-S3R/T12N/R25-S10B	636.19/635.05	Stone (1985)	Rocky Coulee FT	2799	2833	2816.0	6.5
RRL-2B/2C	T12N/R25E-S3R/T12N/R25E-S2N1	636.19/636.71	Stone (1985)	Rocky Coulee FT	2799	2833	2816.0	1.5
RRL-14	T12N/R25E-S4K1	652.7	Brown and Spane (1983)	Umtanum FB	3874	3952	3913.0	0.0086
RSH-1	T11N/R24E-S15R1	2881.9	Raymond and Tillson (1968)	Umtanum FT	2614	2690	2652.0	0.0073
RSH-1	T11N/R24E-S15R1	2881.9	Raymond and Tillson (1968)	Ortley	3213	3289	3251.0	0.39
RSH-1	T11N/R24E-S15R1	2881.9	Raymond and Tillson (1968)	Grouse Creek	4119	4195	4157.0	0.024
RSH-1	T11N/R24E-S15R1	2881.9	Raymond and Tillson (1968)	Wapshilla	4832	4908	4870.0	0.037
RSH-1	T11N/R24E-S15R1	2881.9	Raymond and Tillson (1968)	Wapshilla	5921	5997	5959.0	3.6
RSH-1	T11N/R24E-S15R1	2881.9	Gephart, Deju and Eddy (1979)	Umtanum FT	2622	2676	2649.0	7.30E-04
RSH-1	T11N/R24E-S15R1	2881.9	Gephart, Deju and Eddy (1979)	Umtanum FB	2825	2860	2842.5	3.20E-03
Canoe Ridge	T5N/R24E-S34	774.0	Reidel, Spane and Johnson (2005)	Sentinel Bluffs	2025	2208	2116.5	50
Canoe	T5N/R24E-S34	774.0	Reidel, Spane and Johnson (2005)	Winterwater	2625	2805	2715.0	15

Ridge								
Canoe Ridge	T5N/R24E-S34	774.0	Reidel, Spane and Johnson (2005)	Ortley	3025	3240	3132.5	265
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	Upper Grande Ronde	1700	1814	1757.0	10
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	Sentinel Bluffs+ Winterwater	1899	2345	2122.0	100
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	Umtanum FB + Slack Canyon	2519	2688	2603.5	30
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009); Spane et al. (2012)	Slack Canyon	2688	2790	2739.0	9
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009) ; Spane et al. (2012)	Slack Canyon + Ortley	2790	2910	2850.0	0.8
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	Ortley	2910	3279	3094.5	0.01
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	Ortley + GCM	3344	3515	3429.5	0.1
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	GCM	3515	3704	3609.5	1.1
Wallula	T7N/R31E-S10	364.0	McGrail et al. (2009)	GCM + Wapshilla Ridge	3704	4110	3907.0	0.1

*note:

FB = Flow Bottom

FT = Flow Top

GCM = Grouse Creek Member

SLC = Slack Canyon Member

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