Miocene Evolution of the Moscow-Pullman Basin, Idaho and Washington

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ABSTRACT

The Moscow-Pullman basin, located on the eastern margin of the Columbia River flood basalt province, consists of a subsurface mosaic of Miocene sediments of the Latah Formation and lava flows of the Columbia River Basalt Group. At least 25 flows emplaced into the basin disrupted westward drainages at Pullman, Washington, and caused sedimentation along flow edges and steep mountain fronts to the east near Moscow, Idaho. Approximately 2,700 ft (823 m) of basalt and sediment filled the basin, but only the uppermost units occur in rare outcrops. Rock-chip chemistry from ten wells greater than 700 ft (213 m) in depth was used to form a stratigraphic framework for the Grande Ronde, Wanapum, and Saddle Mountains basalts and associated Latah sediments. Domestic well reports, test wells, outcrops, and regional comparisons were used to determine approximate time lines and develop paleogeographic reconstructions from early Grande Ronde to late Saddle Mountains time. Our intent in this investigation is to use these constraints to create a series of realistic paleogeographic reconstructions consistent with the eruptive and depositional history of the Moscow-Pullman basin and areas immediately north and west of the basin. Reconstructions include the distribution of basalt flows and the disruptions, obliterations, and reversals of drainages. The ancestral Palouse River, believed to have flowed southwest from Pullman, was overwhelmed by the advancing lavas numerous times, eventually reversing its direction to flow north toward the area of Palouse, Washington, and then northwestward away from the basin. Interbedded sediments are primarily fluvial and representative of a low energy environment; they are clay rich with poorly sorted, coarse-grained channel lag deposits. Overall the low energy environment was caused by rapid rises in base levels both regionally and locally with each basalt emplacement. Stream development out of the basin was also slowed by the formation of a small, northwest-trending anticline in the Columbia River Basalt Group near Pullman across the western edge of the basin. Folding began at least as early as the Grande Ronde R_2 interval and continued after emplacement of the last Saddle Mountains flow. At times the anticline restricted access to lava flows entering into the basin from the west. The Lolo flow of the Wanapum Basalt covered the entire basin and the anticline. Clastic sediments prograded away from mountain fronts across the basalt plains in early Saddle Mountains time. Continued anticlinal growth and local basalt flows slowed erosion. Modern stream development is still adjusting to the volcanic and folding events.

INTRODUCTION

The Moscow-Pullman basin (MPB) is located on the eastern margin of the Columbia River flood basalt province where it straddles the Idaho-Washington border (Figure 1). The basin was filled by Miocene emplacement of Columbia River Basalt Group (CRBG) basaltic lavas and associated siliciclastic sediments into steep mountainous terrains along the western edge of the Rocky Mountains. Pre-CRBG drainage in the MPB was part of the ancestral Columbia River system. The ancestral Palouse River likely flowed westward across a low-relief paleoslope from Pullman, Washington, to the Columbia River or to the southwest to the ancestral Salmon-Clearwater River. The ancestral Columbia and Salmon-Clearwater rivers are believed to have joined near the central part of the Columbia Basin (Reidel and Tolan, 2013b).

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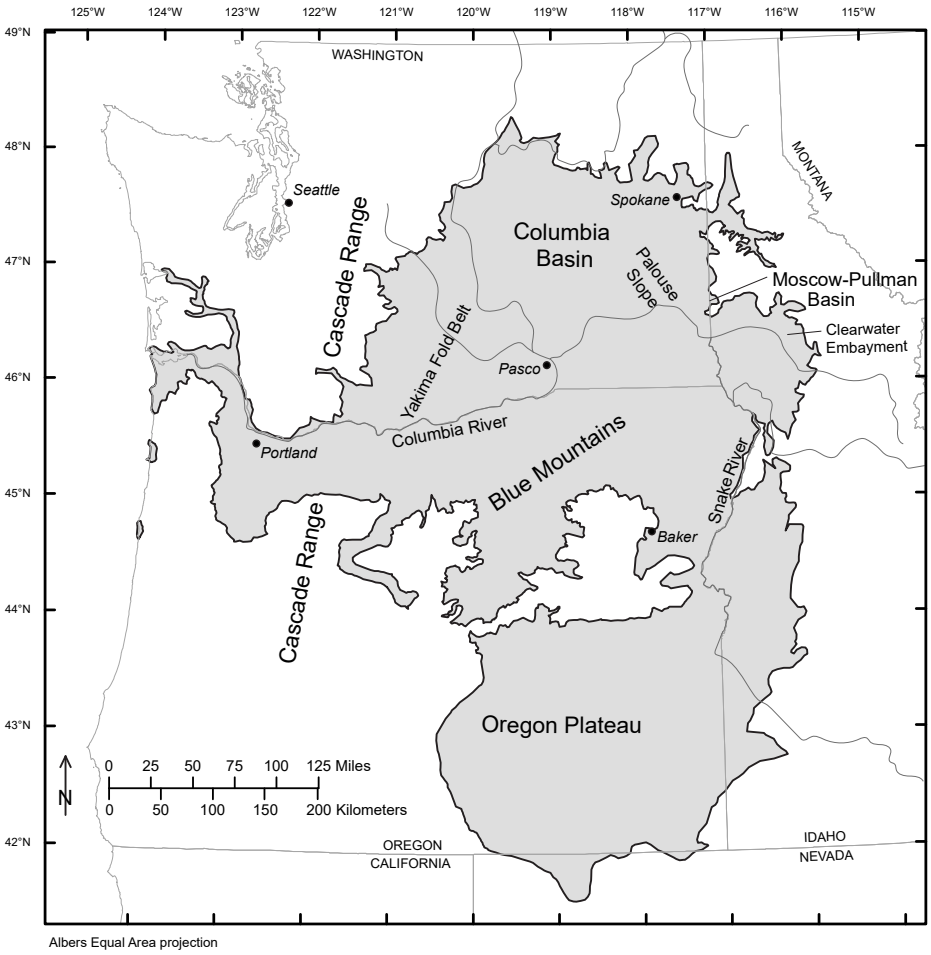

Figure 1. Map showing the Columbia River flood basalt province and areal extent of the Columbia River Basalt Group (gray, modified from Reidel and others, 2013b, and Ludington and others, 2006 [2007]) and other major physiographic features.

The northwestern and northern edges of the MPB are delineated by steptoes of Precambrian–Cambrian(?) quartzite (Lewis and others, 2005) representing island-like tops of the prebasalt terrain rising above younger basalts. The southern and eastern edges of the basin are bounded primarily by Cretaceous granitic and Precambrian–Cambrian(?) quartzitic rocks that rise above the uppermost Miocene basalts and sediments (Figure 2). Most CRBG flows were emplaced into the basin from the west, across Pullman toward Moscow, partially filling it while allowing for deposition of Latah Formation interbedded units along its eastern edge. In Moscow, the Miocene sequence exceeds 1,800 ft (549 m) in thickness and is dominated by Latah sediments. Beneath Pullman, the sequence totals at least 2,250 ft (686 m) in thickness and is dominated by basalt flows. The composite thickness of the basalts and sediments in the MPB exceeds 2,700 ft (823 m).

Grande Ronde Basalt flows comprise about 72 percent of the CRBG (Reidel and others, 2013b), are greater than 3 km (1.9 mi) in thickness in central Washington (Reidel and Tolan, 2013a), and according to Barry and others (2013), erupted between ca. 16 Ma and ca. 15.6 Ma. Webb (2017) provided evidence that the main phase of the CRBG, including the Grande Ronde Basalt, was erupted between 16.7 Ma and 16.0 Ma. These massive volcanic events obliterated drainages of the ancestral Columbia, Salmon-Clearwater (Riedel and Tolan, 2013b), and Palouse rivers (Bush and others, 2016). Reidel and Tolan (2013b) noted that drainages of the ancestral Columbia River were pushed northward and westward until the river reestablished itself around the

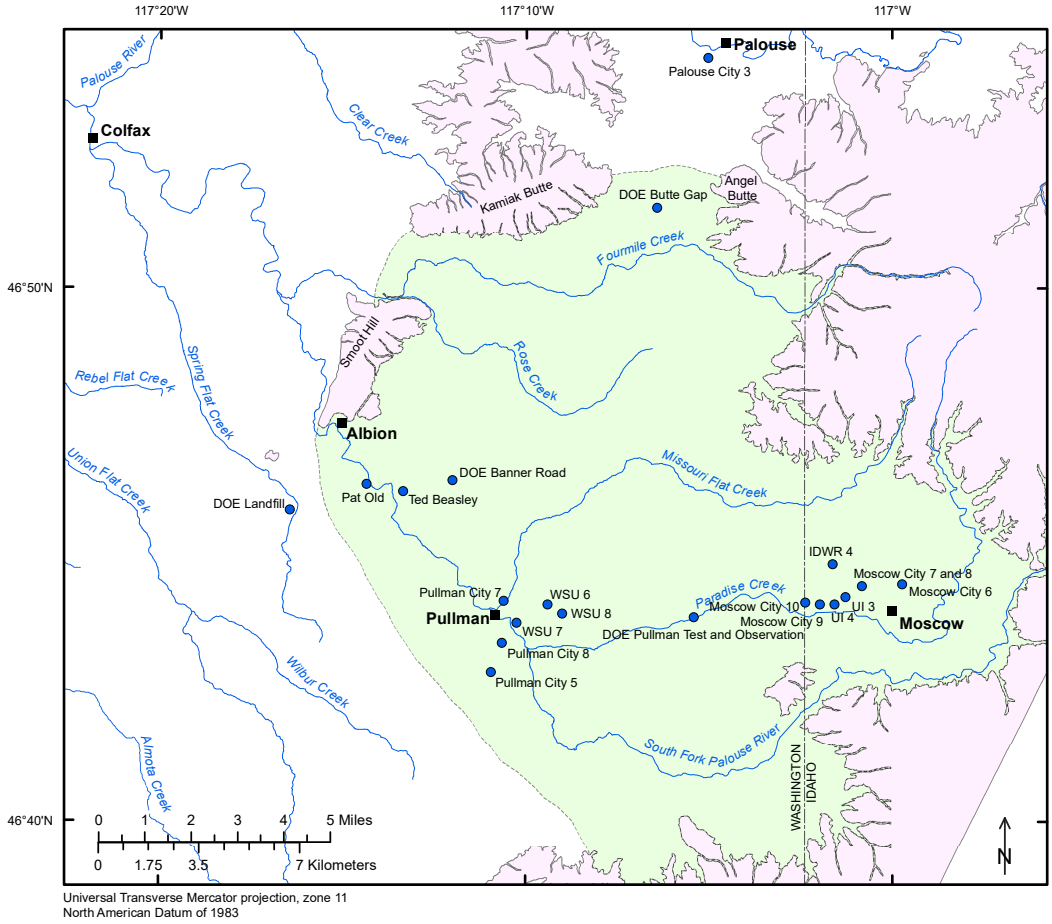

Figure 2. Map showing Moscow-Pullman Basin (green), select wells (blue filled circles), and pre-Columbia River Group Basalt basement rocks (pink).

northern and northwestern edges of the Columbia River flood basalt province. Bush and others (2016) provided evidence that the ancestral Palouse River drainage was reversed and flowed northward out of the MPB by the end of Grande Ronde time. Today, a thick mantle of Pleistocene loess covers much of the MPB, and erosion has exposed only a limited number of outcrops of the CRBG. Our understanding of the structure, drainage disruptions, and evolution of the basin is therefore based primarily on subsurface information obtained from more than 500 water- and test-well reports. Figure 2 illustrates the location of specific wells that are referred to in this paper.

Comparisons of rock-chip chemistry from several of these wells have established stratigraphic correlations of basalt flows between Moscow and Pullman (Brown, 1976; Bush and Garwood, 2005; Conrey and Wolff, 2010; Conrey and Crow, 2014). Washington State University (WSU) well 7 (2,250 ft [686 m] deep) in Pullman is the only well installed to date that can provide information about the early CRBG flows. In other parts of the basin, due to the lack of deep wells, the presence of lower units of the Grande Ronde Basalt only can be estimated. However, geologic maps, outcrops, test well data (Conrey and others, 2013) and water-well reports have been used to determine stratigraphic and structural relations for the upper Grande Ronde and overlying Wanapum Basalt over the entire basin (Bush and others, 2016).

To date, eighteen members of the CRBG consisting of at least 25 flows have been identified in the Moscow-Pullman area (Conrey and Wolff, 2010; Conrey and others, 2013; Conrey and Crow, 2014; Bush and others, 2016). These local units fall within the regional

stratigraphic framework for the CRBG (e.g., Reidel and others, 2013b), thus providing time-stratigraphic constraints for most of the lavas and interbedded sediments in the MPB. Our intent in this investigation is to use these constraints to create a series of realistic paleogeographic reconstructions consistent with the eruptive and depositional history of the MPB and areas immediately north and west of the basin.

STRATIGRAPHIC FRAMEWORK AND PREVIOUS WORK

Decades of research have produced a regional stratigraphic framework for the CRGB (Reidel and others, 2013b). Most large exposures in the Columbia River flood basalt province have been identified as individual flows and (or) members. Now, with proper sampling followed by chemical analysis and comparative studies, nearly any basalt outcrop or unit encountered in a well can be placed into its proper stratigraphic position. Associated sediments have been described, named in places, and correlated primarily by their position to identifiable basalt units. Rock-chip chemistry from ten deep wells (712–2250 ft [217–686 m] in depth) in the MPB was the primary method used to place basalt units into the established regional stratigraphic framework (Table 1). The terminology for the CRBG and associated sediments in the MPB is illustrated in Figure 3.

COLUMBIA RIVER BASALT GROUP	LATAH FORMATION
SADDLE MOUNTAINS BASALT	
Weissenfels Ridge Member (F)	Sediments of Bovill
Basalt of Tenmile Creek (I)	
Basalt of Lewiston Orchards (I)	
Asotin Member (F)	
WANAPUM BASALT	
Priest Rapids Member (F)	
Basalt of Lolo(I)	----------
Roza Member (F)	
GRANDE RONDE BASALT	
N_2 MAGNETOSTRATIGRAPHIC UNIT	*Vantage Member (F)
Sentinel Bluffs Member (F)	
Basalt of Spokane Falls(I)	
Basalt of McCoy Canyon(I)	
Winter Water Member (F)	----------
R_2 MAGNETOSTRATIGRAPHIC UNIT	
Meyer Ridge Member (F)	
Grouse Creek member (I)	
Wapshilla Ridge Member (F)	
Mount Horrible member (I)	
N_1 MAGNETOSTRATIGRAPHIC UNIT	Sediments of Moscow
Cold Spring Ridge Member (F)	
Frye Point member (I)	
Downey Gulch member (I)	
Brady Gulch member (I)	
R_1 MAGNETOSTRATIGRAPHIC UNIT	
Brady Gulch member (I)	
Kendrick Grade member (I)	
Teepee Butte Member (F)	
Basalt of Joseph Creek (I)	
Buckhorn Springs Member (F)	

Figure 3. Stratigraphic nomenclature of the Columbia River Basalt Group and Latah Formation in the Moscow-Pullman area, Idaho and Washington; (F), formal unit; (I), informal unit (as defined by Reidel and others, 2013b, and Reidel and Tolan, 2013a); N, normal polarity; R, reverse polarity; *The Vantage Member of the Latah Formation in the Moscow-Pullman area consists of sediments between the uppermost Grande Ronde Basalt and lowermost Wanapum Basalt units at any one locality (Bush and Provant, 1998; Bush and others, 1998a, b, 2000; Duncan and Bush, 1999).

Table 1. Composition of Columbia River Basalt Group units in deep wells.

[All samples analyzed by Peter Hooper GeoAnalytical Laboratory, WSU, Pullman, Wash., with the exception of Moscow city well 10, analyzed by Hamilton Analytical Laboratory, Hamilton College, Clinton, N.Y.; GRB, Grande Ronde Basalt; WB, Wanapum Basalt; *, total Fe expressed as FeO]

Unit	Depth (ft)	Elevation (ft)	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Idaho Department of Water Resources Well 4—Major oxides (weight percent)													
WB-Priest Rapids-Lolo flow	75	2549	50.55	3.33	13.99	13.11	0.230	4.64	9.52	2.70	1.14	0.780	100.00
WB-Priest Rapids-Lolo flow	245	2379	49.61	3.37	14.24	12.99	0.230	5.40	9.57	2.70	1.08	0.810	100.00
WB-Priest Rapids-Lolo flow	270	2354	50.23	3.16	13.70	13.66	0.230	5.23	9.20	2.72	1.13	0.740	100.00
GRB-Meyer Ridge	510	2114	55.30	1.77	14.77	9.91	0.210	4.40	9.13	2.82	1.39	0.290	100.00
GRB-Meyer Ridge	545	2079	54.26	1.72	14.52	10.95	0.200	4.87	8.97	2.83	1.38	0.300	100.00
GRB-Wapshilla Ridge	730	1894	55.59	2.78	14.84	10.12	0.190	3.16	7.74	3.14	1.68	0.770	100.00
GRB-Wapshilla Ridge	735	1889	55.94	2.71	14.57	10.59	0.190	2.98	7.47	3.17	1.89	0.500	100.00
Moscow City Well 9—Major oxides (weight percent)													
WB-Priest Rapids-Lolo flow	0–10	2555–2545	49.67	3.32	13.66	14.38	0.24	4.67	9.44	2.73	1.10	0.79	100.00
WB-Priest Rapids-Lolo flow	70–80	2485–2475	49.75	3.47	13.03	14.60	0.25	4.98	9.27	2.74	1.08	0.83	100.00
WB-Priest Rapids-Lolo flow	180–190	2375–2365	49.18	3.36	14.41	14.28	0.26	3.86	9.62	3.05	1.16	0.81	100.00
GRB-Meyer Ridge	430–440	2125–2115	55.48	1.99	15.05	9.98	0.17	3.95	8.77	2.91	1.30	0.40	100.00
GRB-Meyer Ridge	520–530	2035–2025	54.17	1.68	14.42	10.74	0.19	5.16	9.17	2.89	1.29	0.29	100.00
GRB-Meyer Ridge	590–600	1965–1955	53.76	1.73	14.39	11.50	0.220	4.92	8.89	2.95	1.35	0.298	100.00
GRB-Mount Horrible	677–687	1878–1868	54.83	2.19	14.11	11.98	0.198	3.64	7.97	3.31	1.39	0.378	100.00
GRB-Mount Horrible	737–747	1818–1808	54.85	2.15	13.88	12.04	0.203	3.88	7.96	3.11	1.54	0.378	100.00
GRB-Cold Spring Ridge	797–807	1758–1748	55.23	1.92	14.45	10.82	0.193	3.96	8.44	3.12	1.46	0.408	100.00
GRB-Cold Spring Ridge	937–947	1618–1608	57.29	1.77	15.55	9.82	0.163	3.72	6.82	3.13	1.44	0.281	100.00
GRB-Cold Spring Ridge	973–983	1582–1572	55.83	1.78	14.14	11.05	0.193	4.21	7.86	3.22	1.47	0.251	100.00
GRB-Cold Spring Ridge	1033–1043	1522–1512	55.73	1.78	14.08	11.34	0.193	4.17	7.83	3.20	1.43	0.252	100.00
GRB-Cold Spring Ridge	1093–1103	1462–1452	55.84	1.77	14.09	11.16	0.192	4.19	7.85	3.19	1.47	0.249	100.00
GRB-Cold Spring Ridge	1153–1163	1402–1392	56.15	1.76	14.04	10.92	0.192	4.21	7.84	3.18	1.47	0.249	100.00
GRB-Cold Spring Ridge	1203–1213	1352–1342	55.55	1.80	14.10	11.35	0.200	4.18	7.90	3.17	1.50	0.271	100.00
GRB-Cold Spring Ridge	1243–1253	1312–1302	55.85	1.76	14.24	11.52	0.179	4.05	7.48	3.25	1.41	0.250	100.00
Moscow City Well 10—Major oxides (weight percent)													
Contaminated or bad analysis(?)	490–500	2118–2108	55.32	2.14	15.32	9.76	0.166	3.45	8.35	2.99	1.50	0.391	99.39
Contaminated or bad analysis(?)	500–515	2108–2093	55.15	2.09	14.74	10.26	0.182	3.80	8.63	2.91	1.51	0.389	99.66
GRB-Meyer Ridge	565–575	2043–2033	54.54	1.74	14.76	9.96	0.182	4.71	9.23	2.89	1.40	0.295	99.71
GRB-Meyer Ridge	570–580	2038–2028	54.09	1.72	14.66	10.51	0.204	4.73	9.22	2.83	1.42	0.296	99.68
GRB-Wapshilla Ridge	700–710	1908–1898	55.44	2.22	14.42	10.72	0.189	3.59	8.07	3.14	1.44	0.443	99.66
GRB-Mount Horrible	711–716	1897–1892	54.40	2.12	13.75	12.39	0.243	3.97	7.93	2.95	1.57	0.373	99.69
GRB-Mount Horrible	730	1878	54	2.16	14.00	12.31	0.238	3.59	8.10	3.02	1.39	0.475	99.68
GRB-Mount Horrible	750	1858	55	2.16	13.96	11.86	0.203	3.70	8.01	3.05	1.51	0.393	99.72
GRB-Mount Horrible	770	1838	55	2.16	13.90	11.94	0.196	3.61	8.32	3.04	1.49	0.388	99.68
GRB-Mount Horrible	790	1818	55	2.14	13.91	12.02	0.196	3.66	8.00	3.04	1.45	0.379	99.67
GRB-Mount Horrible	810	1798	54	2.09	14.31	12.00	0.198	3.85	8.15	2.98	1.27	0.380	99.70
GRB-Cold Spring Ridge	830	1778	55	1.93	14.19	11.77	0.199	3.92	8.24	3.02	1.38	0.429	99.72

Unit	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd	U
Idaho Department of Water Resources Well 4—Trace elements (parts per million, ppm)																			
WB-Priest Rapids-Lolo flow	45	101	39	376	620	28	290	190	43	14.4	23	42	146	7	29	63	4	36	--
WB-Priest Rapids-Lolo flow	49	102	40	379	677	24	295	180	45	15.8	23	43	150	7	30	65	4	42	--
WB-Priest Rapids-Lolo flow	49	97	38	366	531	28	281	182	42	14.7	21	42	141	9	30	55	4	33	--
GRB-Meyer Ridge	34	107	37	330	641	35	305	147	30	10.1	21	58	110	7	19	41	4	25	--
GRB-Meyer Ridge	38	109	36	318	512	34	292	145	30	10.0	20	65	121	37	17	38	3	22	--
GRB-Wapshilla Ridge	22	17	35	420	1087	45	362	206	43	13.1	24	31	130	11	28	66	5	37	--
GRB-Wapshilla Ridge	14	13	34	425	971	49	349	202	41	13.3	22	29	141	10	27	54	5	33	--
Moscow City Well 9—Trace elements (parts per million, ppm)																			
WB-Priest Rapids-Lolo flow	45	99	39	378	526	25	293	192	47	16.5	21	49	146	6	25	60	3	34	1
WB-Priest Rapids-Lolo flow	39	82	41	391	560	25	285	203	49	17.2	21	46	150	6	27	63	3	38	2
WB-Priest Rapids-Lolo flow	43	97	40	371	551	30	303	202	48	16.9	22	47	147	6	24	63	4	38	2
GRB-Meyer Ridge	28	81	37	340	711	38	331	166	36	11.7	21	56	125	7	23	49	4	28	2
GRB-Meyer Ridge	35	115	38	322	506	32	307	147	33	11.1	19	73	117	7	15	40	5	20	1
GRB-Meyer Ridge	30	92	37	322	516	35	299	150	33	10.8	20	56	113	7	22	42	3	24	3
GRB-Mount Horrible	10	14	36	370	603	36	338	172	37	10.9	22	24	132	8	21	47	4	27	2
GRB-Mount Horrible	11	11	36	372	578	37	330	171	36	11.4	21	23	129	7	23	45	4	26	1
GRB-Cold Spring Ridge	9	15	38	361	584	37	337	166	38	10.4	20	42	128	7	26	52	5	29	0
GRB-Cold Spring Ridge	8	9	32	306	597	47	329	186	35	13.0	21	22	119	10	21	49	5	25	1
GRB-Cold Spring Ridge	7	6	34	320	531	42	318	161	33	11.6	20	19	116	7	20	43	4	21	1
GRB-Cold Spring Ridge	7	6	34	325	527	42	319	163	33	11.3	21	20	125	8	19	43	5	23	3
GRB-Cold Spring Ridge	7	6	35	327	522	42	320	163	33	11.0	21	20	115	6	21	44	4	22	3
GRB-Cold Spring Ridge	6	5	32	321	530	42	321	162	31	11.4	20	19	114	6	22	45	5	23	1
GRB-Cold Spring Ridge	8	7	34	321	518	42	318	164	33	11.5	21	20	134	7	19	41	5	24	3
GRB-Cold Spring Ridge	7	7	33	316	534	43	320	165	33	11.3	20	20	116	7	16	40	5	20	3
Moscow City Well 10—Trace elements (parts per million, ppm)																			
Contaminated or bad analysis(?)	27	70	36	364	815	44	351	179	40	14	21	59	136	10	24	48	5	28	1
Contaminated or bad analysis(?)	28	65	36	370	738	42	334	171	37	13	20	50	128	7	22	46	5	28	2
GRB-Meyer Ridge	36	106	36	330	563	34	316	150	33	11	20	57	110	6	19	39	4	21	0
GRB-Meyer Ridge	37	103	35	326	513	35	314	148	32	11	21	58	110	6	22	40	6	22	3
GRB-Wapshilla Ridge	21	19	35	386	781	38	356	172	38	11	23	22	136	8	23	44	3	28	2
GRB-Mount Horrible	21	20	32	372	572	38	331	167	37	12	22	19	126	7	19	44	5	26	1
GRB-Mount Horrible	18	19	35	381	610	36	344	169	40	11	22	22	131	7	20	41	5	24	3
GRB-Mount Horrible	18	19	34	379	581	38	338	168	37	11	22	23	129	7	20	43	4	26	2
GRB-Mount Horrible	19	21	34	378	629	40	364	171	39	12	23	24	130	6	18	47	5	28	1
GRB-Mount Horrible	17	20	33	377	599	39	340	169	39	11	21	22	129	6	17	43	4	26	0
GRB-Mount Horrible	19	20	36	377	588	34	338	170	40	11	22	30	129	6	24	43	3	27	3
GRB-Cold Spring Ridge	17	18	35	358	547	36	332	164	39	11	21	36	123	6	25	42	5	28	2

Table 1 continued.

Unit	Depth (ft)	Elevation (ft)	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd	U
GRB-Cold Spring Ridge	850	1758	55	1.93	14.09	11.73	0.196	4.02	8.13	3.03	1.44	0.384	99.73	17	19	36	355	554	36	331	164	37	12	23	34	127	8	23	43	3	26	1
			Pullman City Well 5—Major oxides (weight percent)											Pullman City Well 5—Trace elements (parts per million, ppm)																		
WB-Priest Rapids-Lolo flow	10	2436	49.64	3.33	13.16	14.32	0.248	5.31	9.12	2.67	1.16	0.790	99.74	45	102	41	372	543	30	289	197	48	19	21	43	155	6	29	60	3	37	3
WB-Priest Rapids-Lolo flow	33	2413	49.27	3.53	12.59	15.08	0.255	5.48	8.87	2.58	1.27	0.794	99.72	52	110	41	404	557	34	267	213	50	20	21	51	155	129	31	66	3	37	2
WB-Priest Rapids-Lolo flow	63	2383	49.40	3.25	13.40	14.40	0.232	5.35	9.17	2.73	1.01	0.752	99.70	49	108	39	372	536	24	291	193	46	17	22	382	190	8	27	62	4	35	1
WB-Priest Rapids-Lolo flow	72	2374	49.59	3.31	13.38	14.30	0.244	5.06	9.22	2.70	1.17	0.767	99.74	47	108	38	378	543	31	289	199	47	19	22	49	151	8	30	59	4	37	1
GRB-Sentinel Bluffs-McCoy Canyon flow	112	2334	53.18	2.01	14.31	12.00	0.209	4.89	8.97	2.79	1.07	0.340	99.77	22	63	39	332	494	29	318	162	36	13	21	35	127	6	17	43	3	24	2
GRB-Sentinel Bluffs-Spokane Falls flow	117	2329	53.61	1.84	14.20	11.67	0.214	4.93	9.01	2.83	1.17	0.297	99.78	20	53	38	328	468	29	318	160	35	14	20	39	121	7	17	44	3	25	1
GRB-Sentinel Bluffs-Spokane Falls flow	133	2313	53.92	1.80	14.42	10.93	0.222	5.06	9.24	2.83	1.09	0.275	99.78	23	59	38	330	454	27	315	152	34	13	21	40	118	19	20	37	3	21	1
GRB-Sentinel Bluffs-Spokane Falls flow	153	2293	53.24	1.81	14.35	11.63	0.203	5.24	9.16	2.89	0.98	0.277	99.78	20	55	39	327	472	24	319	153	34	13	20	36	124	9	18	39	3	25	2
GRB-Sentinel Bluffs-Spokane Falls flow	167	2279	53.88	1.82	14.45	11.14	0.199	5.10	9.07	2.86	0.98	0.280	99.78	21	54	39	335	462	24	313	152	33	12	20	38	119	7	20	40	2	23	1
GRB-Sentinel Bluffs-Spokane Falls flow	183	2263	51.79	1.99	16.22	13.71	0.183	4.58	8.38	2.25	0.34	0.303	99.76	36	108	44	347	495	15	318	158	37	12	22	59	130	16	19	48	5	27	2
GRB-Sentinel Bluffs-Spokane Falls flow	197	2249	52.76	1.81	15.09	11.83	0.183	4.86	9.49	2.75	0.70	0.294	99.77	34	91	41	338	446	22	330	148	38	12	21	63	121	7	18	49	3	26	1
GRB-Meyer Ridge	218	2228	53.88	1.76	14.58	11.38	0.180	4.62	9.28	2.83	0.96	0.310	99.77	31	89	39	331	482	27	321	145	35	12	18	57	116	6	15	45	3	23	1
GRB-Meyer Ridge	227	2219	54.00	1.74	14.51	11.56	0.179	4.56	9.04	2.92	0.96	0.291	99.77	27	84	39	326	509	25	317	145	34	13	20	51	114	59	19	44	3	24	1
GRB-Meyer Ridge	248	2198	53.54	1.73	14.32	11.45	0.189	5.13	9.18	2.93	1.04	0.280	99.78	25	90	39	331	471	27	314	142	33	13	19	63	121	7	17	40	3	21	1
GRB-Meyer Ridge	267	2179	53.41	1.70	14.34	11.27	0.179	5.49	9.17	2.93	1.03	0.260	99.78	31	108	39	331	447	26	307	138	31	13	18	70	112	7	19	41	2	21	1
GRB-Meyer Ridge	283	2163	53.64	1.69	14.36	11.27	0.179	5.20	9.17	2.97	1.02	0.268	99.78	29	101	39	333	455	26	311	138	32	12	19	68	111	18	12	39	3	22	2
GRB-Meyer Ridge	302	2144	53.93	1.74	14.29	11.45	0.178	4.84	8.94	3.02	1.09	0.281	99.77	27	82	39	333	475	28	311	146	33	14	20	64	114	11	19	39	3	22	2
GRB-Meyer Ridge	318	2128	53.98	1.71	14.71	10.76	0.173	4.85	9.33	2.87	1.09	0.301	99.77	30	118	39	331	466	29	316	142	34	12	20	64	113	8	21	38	4	22	1
GRB-Meyer Ridge	338	2108	53.70	1.72	14.40	11.16	0.178	5.16	9.22	2.91	1.05	0.276	99.77	32	122	38	331	465	27	308	141	33	12	19	66	116	6	21	38	3	25	2
GRB-Meyer Ridge	353	2093	54.00	1.77	14.23	11.30	0.174	5.10	8.77	3.01	1.16	0.270	99.77	30	113	39	341	484	32	301	146	32	12	18	58	116	7	18	37	3	20	3
GRB-Meyer Ridge	372	2074	54.05	1.76	14.28	11.37	0.185	4.94	8.70	3.03	1.18	0.278	99.77	31	102	38	333	499	31	302	148	33	13	20	57	116	6	21	41	2	23	0
GRB-Wapshilla Ridge	388	2058	54.02	2.21	13.89	12.60	0.192	3.92	7.94	3.06	1.52	0.382	99.74	25	30	37	436	640	40	339	178	38	15	21	50	136	11	21	55	5	28	1
GRB-Wapshilla Ridge	407	2039	53.64	2.23	13.56	13.29	0.239	3.93	7.78	3.07	1.60	0.385	99.73	26	26	36	442	648	42	334	177	38	15	20	50	134	11	25	52	5	28	1
GRB-Wapshilla Ridge	428	2018	52.93	2.67	14.35	13.65	0.194	3.68	7.53	2.86	1.34	0.514	99.72	19	16	37	441	739	40	345	210	44	16	22	36	150	16	25	62	6	34	2
GRB-Wapshilla Ridge	428	2018	52.95	2.67	14.43	13.42	0.194	3.75	7.53	2.92	1.35	0.514	99.72	19	16	36	442	737	39	345	208	45	16	23	36	153	14	31	56	5	33	3
GRB-Wapshilla Ridge	447	1999	54.15	2.57	13.89	12.83	0.197	3.41	7.42	3.04	1.73	0.485	99.73	14	13	34	418	710	50	332	204	43	16	21	34	145	10	29	60	5	33	3
GRB-Wapshilla Ridge	447	1999	54.04	2.57	13.85	13.02	0.195	3.39	7.42	3.03	1.72	0.486	99.73	13	14	34	414	708	50	332	204	43	15	20	34	141	10	31	59	5	32	2
GRB-Wapshilla Ridge	468	1978	54.09	2.56	13.76	12.94	0.197	3.55	7.35	3.10	1.72	0.456	99.73	14	16	34	416	724	48	326	202	43	16	21	33	142	10	27	61	6	34	1
GRB-Wapshilla Ridge	487	1959	54.21	2.55	13.69	12.86	0.198	3.58	7.33	3.10	1.74	0.459	99.73	14	15	32	418	719	49	324	201	41	15	21	33	146	10	34	58	5	31	1
GRB-Wapshilla Ridge	487	1959	54.24	2.57	13.75	12.56	0.200	3.66	7.39	3.16	1.74	0.461	99.73	15	14	33	417	737	49	328	201	41	15	21	33	146	12	25	56	5	30	5
GRB-Wapshilla Ridge	508	1938	54.39	2.53	13.85	12.71	0.224	3.44	7.26	3.16	1.69	0.474	99.73	13	16	33	397	722	48	334	204	45	16	22	34	152	10	31	61	6	35	3
GRB-Wapshilla Ridge	522	1924	54.11	2.49	14.11	13.36	0.199	3.43	7.16	3.05	1.35	0.466	99.73	9	13	34	358	731	40	352	210	47	15	22	29	157	9	29	65	5	34	3
GRB-Wapshilla Ridge	543	1903	54.29	2.44	13.92	13.25	0.200	3.35	7.14	3.15	1.51	0.493	99.73	7	15	33	356	744	47	346	208	46	16	23	22	153	11	27	62	5	35	1
GRB-Wapshilla Ridge	563	1883	54.77	2.37	13.49	12.81	0.205	3.37	7.09	3.08	2.08	0.482	99.74	10	16	33	343	715	56	329	205	43	15	22	20	145	11	26	58	6	31	2
GRB-Wapshilla Ridge	587	1859	54.95	2.37	13.58	12.61	0.207	3.38	7.03	3.17	1.96	0.480	99.74	6	13	33	341	737	51	330	210	44	17	21	22	147	11	27	63	5	36	2
GRB-Cold Spring Ridge	612	1834	53.54	2.20	14.23	12.77	0.208	4.08	8.18	3.04	1.09	0.397	99.75	12	21	37	383	597	33	347	173	43	14	22	27	136	8	17	51	4	27	3
GRB-Cold Spring Ridge	633	1813	53.96	2.17	14.21	12.43	0.203	3.92	8.16	3.13	1.18	0.384	99.75	18	18	37	380	596	34	346	170	43	14	23	28	140	11	22	49	3	26	2
GRB-Cold Spring Ridge	652	1794	53.62	1.97	14.44	12.43	0.216	4.24	8.36	3.12	1.03	0.355	99.76	14	20	38	375	531	28	340	168	39	13	22	40	132	9	22	48	4	27	2

Table 1 continued.

Unit	Depth (ft)	Elevation (ft)	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd	U
GRB-Cold Spring Ridge	673	1773	52.92	2.07	14.89	12.84	0.196	4.29	8.30	3.03	0.89	0.337	99.76	14	18	39	376	548	22	348	170	40	13	24	36	136	11	23	40	4	27	2
GRB-Cold Spring Ridge	692	1754	54.59	2.03	13.96	11.99	0.201	4.00	8.00	3.10	1.53	0.373	99.77	13	16	37	355	567	40	324	167	38	13	21	33	129	10	22	47	4	25	3
GRB-Cold Spring Ridge	707	1739	54.26	2.08	14.15	12.10	0.200	3.84	8.22	3.13	1.33	0.443	99.76	15	15	38	368	574	37	335	169	41	13	21	33	135	12	23	48	5	27	2
Pullman City Well 7—Major oxides (weight percent)														Pullman City Well 7—Trace elements (parts per million, ppm)																		
WB-Priest Rapids-Lolo flow	25	2320	50.28	3.25	13.54	13.55	0.230	5.05	9.22	2.75	1.11	0.768	99.75	44	96	39	374	544	27	290	194	45	16	19	45	148	8	28	57	7	36	1
GRB-Sentinel Bluffs-Spokane Falls flow	95	2250	52.77	1.98	14.75	12.34	0.207	4.98	9.04	2.64	0.75	0.314	99.78	18	51	38	342	473	21	319	166	35	11	21	39	120	8	25	49	6	24	0
GRB-Sentinel Bluffs-McCoy Canyon flow	135	2210	52.43	2.29	14.36	12.23	0.212	5.01	9.09	2.74	0.97	0.434	99.77	26	65	38	349	515	24	306	170	36	13	21	40	127	8	24	48	5	28	2
GRB-Meyer Ridge	160	2185	53.70	1.82	14.11	11.57	0.249	5.05	8.90	2.94	1.14	0.301	99.78	16	44	37	324	501	28	312	158	32	11	19	35	115	6	19	44	4	26	2
GRB-Meyer Ridge	180	2165	53.17	1.96	15.56	12.34	0.190	4.67	8.23	2.58	0.77	0.302	99.77	19	70	42	339	538	22	302	167	35	12	20	43	124	8	24	41	6	23	2
GRB-Meyer Ridge	210	2135	53.87	1.75	14.47	11.02	0.195	5.08	9.14	2.94	1.03	0.275	99.77	29	82	39	337	489	27	314	146	31	11	19	56	110	8	22	40	5	21	2
GRB-Meyer Ridge	235	2110	53.90	1.71	14.40	10.76	0.195	5.21	9.29	2.94	1.08	0.271	99.78	29	89	39	332	468	27	314	144	31	11	19	58	109	8	23	38	6	21	2
GRB-Meyer Ridge	265	2080	53.77	1.70	14.29	11.05	0.198	5.32	9.14	2.94	1.10	0.271	99.78	30	85	39	330	471	28	308	142	31	10	19	61	109	8	23	35	6	22	3
GRB-Meyer Ridge	285	2060	54.31	1.77	14.67	10.69	0.184	4.62	9.13	2.89	1.20	0.295	99.77	29	96	38	338	493	34	315	151	33	11	20	59	114	8	19	40	5	22	3
GRB-Meyer Ridge	300	2045	54.11	1.73	14.36	11.07	0.201	4.95	9.02	2.88	1.19	0.277	99.77	30	95	37	336	502	31	310	148	32	11	17	54	110	8	20	38	6	21	1
GRB-Meyer Ridge	320	2025	54.35	1.73	14.53	10.80	0.169	4.95	8.80	3.01	1.14	0.274	99.77	29	103	39	329	508	30	312	148	31	11	18	57	104	8	23	37	5	21	1
GRB-Meyer Ridge	340	2005	54.35	1.75	14.41	10.93	0.183	4.85	8.83	3.02	1.17	0.279	99.77	31	92	38	332	515	29	311	151	31	12	19	53	110	8	24	39	5	22	0
GRB-Wapshilla Ridge	350	1995	54.02	2.21	13.93	12.59	0.202	3.91	8.01	3.01	1.48	0.381	99.74	25	27	38	429	645	40	339	176	36	12	20	45	133	9	27	52	5	26	2
GRB-Wapshilla Ridge	365	1980	54.19	2.25	13.79	12.57	0.201	3.82	7.86	3.13	1.53	0.386	99.73	24	19	37	448	684	38	343	180	37	13	22	43	136	9	29	52	5	27	2
GRB-Wapshilla Ridge	395	1950	54.30	2.25	13.88	12.39	0.195	3.81	7.86	3.19	1.47	0.386	99.73	24	18	36	445	681	37	344	181	36	13	21	45	131	11	29	53	6	27	2
GRB-Wapshilla Ridge	425	1920	54.06	2.57	14.00	12.96	0.208	3.46	7.39	2.98	1.66	0.439	99.73	17	11	34	425	707	46	331	205	41	14	21	34	138	10	31	56	7	31	1
GRB-Wapshilla Ridge	450	1895	54.24	2.53	13.73	12.67	0.214	3.62	7.32	3.04	1.91	0.453	99.73	16	10	34	410	728	48	325	205	40	13	22	31	146	10	29	62	8	32	1
GRB-Wapshilla Ridge	478	1867	54.59	2.56	13.74	12.53	0.201	3.44	7.35	3.09	1.77	0.457	99.73	16	10	33	414	746	48	325	203	41	13	21	32	137	10	28	60	8	32	3
GRB-Wapshilla Ridge	500	1845	54.60	2.56	13.79	12.44	0.203	3.40	7.35	3.11	1.80	0.461	99.73	14	10	33	414	742	48	327	205	40	13	22	31	141	10	31	62	6	33	2
GRB-Wapshilla Ridge	520	1825	54.83	2.46	13.71	12.51	0.214	3.41	7.23	3.09	1.83	0.454	99.73	12	9	34	383	737	49	329	205	40	14	20	24	139	10	36	65	7	33	1
GRB-Wapshilla Ridge	540	1805	55.28	2.35	13.58	12.32	0.215	3.37	7.07	3.13	1.96	0.459	99.74	9	11	32	345	733	52	327	207	40	13	20	20	138	10	28	64	8	36	1
GRB-Wapshilla Ridge	550	1795	55.38	2.35	13.65	12.28	0.213	3.33	7.07	3.15	1.85	0.466	99.74	9	13	32	343	747	51	328	208	40	13	22	19	137	9	28	53	7	31	3
GRB-Wapshilla Ridge	565	1780	55.40	2.38	13.68	12.20	0.216	3.32	7.06	3.18	1.83	0.477	99.74	8	7	33	350	762	50	332	210	41	14	21	18	138	9	32	57	7	34	2
GRB-Wapshilla Ridge	595	1750	54.14	2.19	14.08	12.37	0.211	4.03	8.11	3.02	1.20	0.401	99.75	12	14	38	382	629	33	343	174	42	11	20	25	136	8	27	53	5	30	1
GRB-Wapshilla Ridge	615	1730	54.64	2.21	14.01	11.81	0.210	3.90	8.06	3.15	1.41	0.369	99.76	10	14	36	388	608	36	338	173	38	11	21	24	133	9	24	46	6	26	2
GRB-Wapshilla Ridge	635	1710	54.44	2.23	14.15	11.97	0.213	3.89	8.04	3.10	1.34	0.378	99.75	11	13	37	388	619	34	342	177	40	11	21	25	137	8	22	51	6	28	1
GRB-Mount Horrible	655	1690	54.86	2.19	14.02	11.63	0.208	3.82	8.03	3.14	1.49	0.362	99.76	10	12	37	385	599	37	337	172	38	11	21	22	134	10	22	48	5	27	2
GRB-Mount Horrible	695	1650	53.55	2.14	14.76	12.34	0.202	4.02	8.35	3.06	0.97	0.363	99.77	8	12	39	377	550	26	345	173	37	11	22	27	131	9	24	51	6	27	2
GRB-Mount Horrible	710	1635	54.69	2.04	14.13	11.62	0.207	3.99	8.16	3.10	1.45	0.385	99.77	8	12	37	361	574	37	328	166	36	11	20	28	127	9	26	49	6	28	3
Pullman City Well 8—Major oxides (weight percent)														Pullman City Well 8—Trace elements (parts per million, ppm)																		
WB-Priest Rapids-Lolo flow	170	2343	49.94	3.27	13.89	13.24	0.236	5.15	9.37	2.74	1.13	0.779	99.74	48	101	38	375	556	27	295	194	46	14	22	44	148	3	30	61	4	37	0
WB-Priest Rapids-Lolo flow	255	2258	52.05	2.37	15.41	12.76	0.202	4.69	8.56	2.52	0.74	0.451	99.76	21	67	41	365	537	21	293	185	38	13	21	43	134	5	28	52	4	27	2
GRB-Sentinel Bluffs-McCoy Canyon flow	268	2245	52.24	2.09	15.36	13.14	0.208	4.83	8.44	2.52	0.61	0.334	99.77	16	59	41	352	500	18	301	174	36	12	21	42	128	6	23	46	4	27	1
GRB-Meyer Ridge	305	2208	53.51	1.83	14.26	11.69	0.231	5.11	8.95	2.91	1.01	0.289	99.78	13	47	38	327	492	24	312	156	32	10	19	36	115	5	23	41	3	23	2
GRB-Meyer Ridge	360	2153	53.66	1.74	14.53	11.21	0.193	5.03	9.25	2.90	1.00	0.269	99.78	26	84	39	326	467	25	314	145	31	9	19	58	109	5	23	38	2	22	0
GRB-Meyer Ridge	410	2103	53.92	1.72	14.63	10.70	0.177	5.11	9.30	2.94	1.02	0.272	99.78	28	95	38	331	469	24	315	142	31	9	19	67	109	4	17	37	3	22	2
GRB-Meyer Ridge	465	2048	53.76	1.70	14.60	10.71	0.225	5.10	9.41	2.89	1.08	0.281	99.77	29	119	39	327	478	27	312	141	30	9	19	63	107	5	18	37	3	21	1
GRB-Meyer Ridge	515	1998	54.15	1.75	14.39	11.17	0.210	4.81	8.83	3.00	1.17	0.283	99.77	26	92	37	331	510	29	308	148	31	9	19	56	106	6	18	39	3	23	1

Table 1 continued.

Unit	Depth (ft)	Elevation (ft)	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd	U
GRB-Wapshilla Ridge	545	1968	54.38	2.24	13.85	12.76	0.206	3.54	7.77	3.15	1.46	0.387	99.74	20	22	36	437	670	36	340	181	36	13	21	46	128	8	24	54	5	28	2
GRB-Wapshilla Ridge	575	1938	54.28	2.57	13.77	12.78	0.202	3.61	7.38	3.00	1.70	0.447	99.73	14	10	34	417	740	47	329	203	40	12	19	33	137	8	31	57	4	32	2
GRB-Wapshilla Ridge	620	1893	54.43	2.54	13.74	12.62	0.201	3.56	7.38	3.09	1.73	0.445	99.73	13	11	33	416	725	46	326	201	40	12	21	33	138	9	27	59	5	33	0
GRB-Wapshilla Ridge	685	1828	54.92	2.34	13.60	12.87	0.249	3.29	6.98	3.23	1.81	0.456	99.74	6	10	33	358	725	47	328	205	39	12	21	20	136	8	33	60	5	31	3
GRB-Wapshilla Ridge	715	1798	55.67	2.37	13.72	11.81	0.201	3.26	6.96	3.39	1.88	0.474	99.74	4	9	32	346	736	49	327	209	40	13	21	17	141	8	31	63	5	35	1
GRB-Cold Spring Ridge	745	1768	55.05	1.95	14.17	11.28	0.204	4.00	8.14	3.14	1.47	0.345	99.77	6	15	37	364	591	35	330	165	37	9	20	35	124	6	21	43	4	27	0
GRB-Cold Spring Ridge	755	1758	54.76	2.11	14.03	11.90	0.205	3.91	8.04	3.08	1.36	0.375	99.76	8	13	37	377	617	36	337	169	39	9	21	27	131	6	24	52	4	29	2
GRB-Cold Spring Ridge	775	1738	54.55	2.03	14.08	11.88	0.275	3.91	8.17	3.11	1.40	0.360	99.77	8	13	37	366	567	35	331	166	36	10	20	33	125	7	26	46	3	28	2
GRB-Cold Spring Ridge	795	1718	54.65	2.08	13.99	11.88	0.206	4.00	8.02	3.16	1.43	0.353	99.77	7	13	36	372	578	35	330	168	36	10	19	30	124	5	23	46	4	27	1
			University of Idaho Well 3—Major oxides (weight percent)											University of Idaho Well 3—Trace elements (parts per million, ppm)																		
WB-Priest Rapids-Lolo flow	35	2532	52.00	3.73	15.89	10.55	0.14	2.86	9.65	2.97	1.08	0.85	99.72	28	121	42	390	624	30	353	222	51	18	24	52	151	7	32	62	7	40	1
WB-Priest Rapids-Lolo flow	55	2512	51.75	3.70	15.72	10.75	0.18	3.32	9.71	2.83	0.87	0.88	99.71	27	118	43	400	640	23	345	210	54	17	23	44	164	7	33	71	7	42	2
WB-Priest Rapids-Lolo flow	65	2502	51.65	3.67	15.62	11.68	0.17	2.68	9.59	2.79	1.01	0.86	99.71	25	116	43	400	659	28	343	217	54	18	22	48	163	9	38	75	7	42	4
WB-Priest Rapids-Lolo flow	95	2472	51.59	3.54	15.08	10.91	0.19	3.64	9.95	2.95	1.19	0.69	99.72	26	113	43	402	632	30	327	208	46	18	22	47	146	8	27	59	7	35	2
WB-Priest Rapids-Lolo flow	125	2442	50.64	3.43	14.68	11.80	0.22	4.17	9.85	2.86	1.27	0.81	99.73	35	113	40	394	583	32	315	206	48	16	22	52	153	7	30	63	7	37	3
WB-Priest Rapids-Lolo flow	145	2422	49.87	3.31	13.85	13.73	0.24	4.77	9.34	2.70	1.16	0.78	99.74	41	104	39	375	583	28	296	198	45	15	21	49	151	7	35	60	6	36	1
WB-Priest Rapids-Lolo flow	145	2422	49.93	3.30	13.80	13.73	0.24	4.77	9.36	2.70	1.15	0.77	99.74	40	104	39	374	571	29	295	196	46	16	21	49	149	6	28	62	3	37	2
WB-Priest Rapids-Lolo flow	155	2412	50.78	3.48	14.65	11.77	0.21	3.99	9.87	2.86	1.30	0.82	99.73	33	108	41	397	584	33	314	210	48	17	21	51	153	7	31	67	6	40	1
WB-Priest Rapids-Lolo flow	155	2412	50.76	3.47	14.60	11.86	0.21	3.99	9.86	2.85	1.31	0.82	99.73	34	109	41	397	582	33	315	210	49	17	21	52	152	8	31	61	6	38	2
WB-Priest Rapids-Lolo flow	180	2387	50.05	3.24	13.70	13.59	0.224	5.30	9.16	2.62	1.10	0.759	99.74	45	98	38	370	540	27	296	197	45	16	20	51	149	9	34	60	6	37	1
GRB-Meyer Ridge	505	2062	54.25	1.71	14.43	10.72	0.169	5.07	8.91	3.05	1.18	0.273	99.76	31	114	40	327	569	31	297	141	30	16	18	66	120	9	26	42	4	23	2
GRB-Meyer Ridge	555	2012	53.61	1.73	14.30	11.20	0.236	5.05	9.09	2.88	1.39	0.289	99.77	29	104	38	334	532	32	304	146	31	11	18	58	111	7	21	36	3	20	2
GRB-Meyer Ridge	580	1987	53.91	1.74	14.60	11.51	0.228	4.21	8.99	2.95	1.30	0.319	99.76	26	102	37	332	571	35	308	155	32	11	18	57	113	7	23	42	5	24	1
GRB-Meyer Ridge	580	1987	53.89	1.74	14.53	11.59	0.229	4.21	8.99	2.95	1.30	0.321	99.76	25	101	38	329	577	35	308	154	32	11	19	56	113	6	24	44	2	27	2
GRB-Wapshilla Ridge	625	1942	55.14	2.59	14.10	11.78	0.194	3.17	7.38	2.90	1.90	0.524	99.70	15	18	33	402	938	81	352	207	43	15	22	32	146	8	31	62	4	33	1
GRB-Wapshilla Ridge	625	1942	55.17	2.59	14.11	11.74	0.193	3.17	7.38	2.91	1.92	0.524	99.70	15	16	33	406	931	81	351	208	43	14	20	34	146	9	35	67	5	35	2
GRB-Mount Horrible	665	1902	55.14	2.21	13.82	11.67	0.215	3.72	7.95	3.14	1.50	0.393	99.76	11	20	35	379	620	38	331	174	37	11	21	27	136	8	23	48	3	29	1
GRB-Mount Horrible	675	1892	55.05	2.23	13.92	11.63	0.207	3.71	8.01	3.11	1.50	0.392	99.75	10	21	35	380	629	39	336	174	37	11	21	27	133	7	25	49	3	28	1
GRB-Mount Horrible	725	1842	55.19	2.20	14.14	11.31	0.200	3.68	8.06	3.13	1.46	0.379	99.75	10	20	35	382	694	38	343	172	39	12	21	24	138	8	26	44	3	26	1
GRB-Mount Horrible	725	1842	55.27	2.20	14.14	11.22	0.200	3.70	8.06	3.12	1.45	0.380	99.75	12	20	37	377	684	38	339	171	38	11	20	25	138	6	26	51	3	30	2
GRB-Cold Spring Ridge	765	1802	55.01	1.95	14.29	10.81	0.197	4.01	8.45	3.10	1.42	0.507	99.75	10	20	38	365	658	36	342	167	37	10	21	40	137	8	23	45	4	27	2
GRB-Cold Spring Ridge	895	1672	55.57	1.76	14.12	10.98	0.208	4.25	8.03	3.16	1.46	0.246	99.78	6	11	33	323	573	40	330	158	31	11	19	21	117	8	21	41	3	24	2
GRB-Cold Spring Ridge	925	1642	55.70	1.76	14.12	10.98	0.195	4.16	7.87	3.16	1.58	0.251	99.78	6	13	34	323	559	41	323	162	31	11	19	22	117	8	23	42	3	23	2
GRB-Cold Spring Ridge	1015	1552	55.48	1.77	14.03	11.32	0.199	4.20	7.88	3.18	1.46	0.252	99.78	10	21	34	326	544	40	317	158	32	11	19	31	115	8	24	41	4	22	2
GRB-Cold Spring Ridge	1045	1522	55.39	1.83	13.86	11.75	0.202	4.08	7.75	3.22	1.44	0.258	99.78	9	15	33	324	579	42	315	164	32	13	20	33	119	10	22	40	5	25	2
GRB-Cold Spring Ridge	1115	1452	55.71	1.77	14.14	10.99	0.195	4.22	7.89	3.22	1.39	0.250	99.78	7	14	35	328	558	40	321	159	31	13	20	22	119	8	19	38	4	23	1
GRB-Cold Spring Ridge	1175	1392	55.55	1.84	14.41	11.34	0.165	3.90	7.49	3.39	1.44	0.255	99.78	9	15	34	343	557	42	330	165	31	11	20	27	118	9	21	43	6	24	1
			Washington State University Well 6—Major oxides (weight percent)											Washington State University Well 6—Trace elements (parts per million, ppm)																		
WB-Priest Rapids-Lolo flow	156	2379	50.70	3.54	15.03	11.43	0.191	3.97	9.77	3.08	1.19	0.829	99.72	48	110	40	402	589	29	322	211	50	17	22	62	163	31	31	69	4	41	1

Table 1 continued.

Unit	Depth (ft)	Elevation (ft)	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd	U
GRB-Sentinel Bluffs-Spokane Falls flow	185	2350	53.75	1.83	14.23	11.26	0.206	5.16	8.91	3.02	1.12	0.301	99.78	15	50	38	324	494	26	310	158	33	14	20	45	121	7	21	45	4	25	1
GRB-Sentinel Bluffs-Spokane Falls flow	200	2335	53.65	1.86	14.43	11.48	0.204	4.96	9.06	2.77	1.04	0.318	99.78	17	47	39	334	485	29	317	157	33	11	19	41	121	7	23	40	8	24	3
GRB-Sentinel Bluffs-Spokane Falls flow	200	2335	53.47	1.86	14.37	11.78	0.203	4.95	9.02	2.77	1.04	0.317	99.78	17	50	38	329	484	28	318	159	33	11	19	40	119	6	21	41	2	24	1
GRB-Sentinel Bluffs-Spokane Falls flow	215	2320	52.73	1.89	15.07	11.78	0.205	5.19	9.22	2.67	0.75	0.284	99.78	18	54	39	346	469	23	320	158	33	11	20	42	120	6	20	40	3	25	3
GRB-Sentinel Bluffs-Spokane Falls flow	270	2265	52.67	1.89	15.02	11.94	0.205	5.16	9.19	2.67	0.74	0.283	99.78	17	54	37	342	470	22	321	159	33	11	20	43	119	6	21	40	3	26	2
GRB-Sentinel Bluffs-Spokane Falls flow	270	2265	53.54	1.83	14.20	11.57	0.210	5.19	8.87	2.96	1.12	0.292	99.78	16	50	39	325	485	27	309	156	31	13	21	39	119	6	24	41	3	25	0
GRB-Sentinel Bluffs-Spokane Falls flow	300	2235	52.37	1.88	15.58	11.74	0.196	4.92	9.56	2.67	0.57	0.274	99.77	29	99	43	354	446	16	333	151	38	11	21	66	122	5	21	43	3	24	1
GRB-Sentinel Bluffs-Spokane Falls flow	320	2215	52.46	1.98	16.56	12.02	0.156	4.34	8.97	2.67	0.38	0.210	99.75	30	112	45	331	509	16	351	163	37	12	21	70	138	5	23	48	3	29	2
GRB-Meyer Ridge	390	2145	53.14	1.65	14.51	11.46	0.179	5.38	9.31	2.91	0.97	0.265	99.77	40	129	39	324	435	25	309	134	29	10	17	90	154	15	18	33	3	23	2
GRB-Meyer Ridge	420	2115	53.72	1.71	14.35	11.26	0.182	5.26	8.95	2.97	1.08	0.271	99.78	29	85	39	335	464	28	305	143	32	11	18	68	117	6	22	37	3	23	2
GRB-Meyer Ridge	430	2105	50.41	1.63	13.32	16.87	0.250	4.75	8.36	2.68	1.12	0.267	99.67	47	92	35	330	449	28	279	137	29	10	19	215	436	450	18	43	3	22	1
GRB-Meyer Ridge	445	2090	54.65	2.00	14.42	12.07	0.193	3.99	7.72	2.97	1.41	0.333	99.75	16	40	34	332	648	40	332	174	35	13	21	41	135	14	26	45	5	24	1
GRB-Meyer Ridge	470	2065	55.97	1.98	13.99	11.56	0.195	3.59	7.16	3.14	1.85	0.333	99.75	7	14	32	325	728	50	325	181	34	13	20	23	124	9	26	52	6	28	2
GRB-Grouse Creek	490	2045	56.68	2.03	14.13	11.63	0.162	3.26	6.36	3.36	1.79	0.347	99.75	6	11	33	324	745	53	329	184	34	12	21	17	123	10	27	51	5	28	2
GRB-Grouse Creek	505	2030	55.85	2.06	13.69	12.25	0.200	3.40	6.93	3.06	1.94	0.374	99.75	12	13	31	318	746	51	317	189	36	14	20	29	131	10	30	54	6	27	2
GRB-Wapshilla Ridge	525	2010	52.09	2.92	15.89	13.85	0.154	3.26	7.33	2.94	0.70	0.548	99.69	18	18	37	482	808	22	377	229	57	15	24	50	150	12	40	84	6	44	2
GRB-Wapshilla Ridge	550	1985	54.18	2.54	13.77	12.86	0.201	3.59	7.33	3.02	1.80	0.447	99.73	16	13	33	421	711	48	328	203	40	14	20	35	139	10	32	60	4	32	3
GRB-Wapshilla Ridge	575	1960	54.23	2.54	13.70	12.73	0.203	3.63	7.26	3.05	1.93	0.450	99.73	15	13	33	413	718	49	321	203	40	15	20	33	137	8	29	61	5	34	2
GRB-Wapshilla Ridge	610	1925	54.79	2.59	13.89	12.08	0.205	3.51	7.37	3.06	1.76	0.460	99.73	15	13	34	420	740	46	325	204	43	14	20	34	142	8	30	59	5	33	0
GRB-Wapshilla Ridge	610	1925	54.79	2.59	13.92	12.06	0.205	3.51	7.37	3.06	1.76	0.460	99.73	16	11	34	421	737	47	325	202	42	14	19	33	143	9	32	67	6	35	1
GRB-Wapshilla Ridge	625	1910	54.61	2.59	13.92	12.21	0.204	3.52	7.41	3.06	1.74	0.463	99.73	15	11	35	421	732	46	327	203	43	14	21	33	142	10	31	60	6	35	1
GRB-Wapshilla Ridge	650	1885	54.73	2.53	13.86	12.58	0.203	3.49	7.17	2.99	1.74	0.450	99.73	13	12	32	397	752	47	324	207	42	15	20	32	147	14	28	58	6	35	2
GRB-Wapshilla Ridge	665	1870	54.26	2.56	14.50	12.78	0.212	3.41	7.13	3.11	1.27	0.488	99.72	10	13	35	357	820	37	358	221	47	15	22	22	150	11	36	64	6	37	3
			Washington State University Well 7—Major oxides (weight percent)											Washington State University Well 7—Trace elements (parts per million, ppm)																		
WB-Priest Rapids-Lolo flow	80	2334	50.36	3.29	13.86	13.32	0.223	4.89	9.33	2.68	1.02	0.766	99.74	47	108	38	377	561	28	302	193	45	15	20	49	150	7	32	62	7	37	1
GRB-Sentinel Bluffs-Spokane Falls flow	240	2174	52.61	1.91	14.91	12.30	0.207	5.00	8.96	2.82	0.77	0.279	99.77	21	51	39	340	466	20	325	163	33	10	20	43	123	94	20	44	6	23	2
GRB-Sentinel Bluffs-Spokane Falls flow	300	2114	52.73	1.88	15.06	12.36	0.194	4.86	8.96	2.74	0.71	0.277	99.77	24	78	41	342	475	18	329	158	35	10	19	53	121	18	21	44	5	26	0
GRB-Winter Water	340	2074	53.33	2.29	14.55	13.67	0.193	3.70	7.82	2.79	1.01	0.393	99.73	25	32	37	436	645	31	343	181	40	12	21	54	137	10	28	56	6	31	2
GRB-Meyer Ridge	410	2004	54.13	1.71	14.42	11.08	0.177	5.13	8.70	2.99	1.17	0.272	99.77	29	98	37	329	491	32	304	146	29	10	19	56	111	10	21	42	6	19	2
GRB-Grouse Creek	450	1964	53.86	2.19	13.96	12.61	0.212	3.94	8.04	3.04	1.50	0.377	99.74	24	30	35	433	648	38	339	174	35	11	19	48	131	11	27	53	6	31	2
GRB-Wapshilla Ridge	540	1874	54.28	2.54	13.60	12.83	0.207	3.61	7.36	3.00	1.85	0.455	99.73	14	10	33	410	724	50	326	203	40	12	23	34	141	11	30	60	6	32	3
GRB-Wapshilla Ridge	590	1824	55.20	2.39	13.68	12.45	0.205	3.40	7.03	3.05	1.87	0.455	99.74	8	11	33	356	734	50	328	210	40	13	21	20	141	11	30	61	7	34	2
GRB-Wapshilla Ridge	640	1774	55.24	2.38	13.62	12.40	0.206	3.39	7.02	3.18	1.84	0.467	99.74	7	9	33	350	730	50	327	209	41	13	21	24	142	12	35	60	8	34	2
GRB-Wapshilla Ridge	670	1744	55.31	2.38	13.58	12.35	0.206	3.35	6.97	3.15	1.99	0.463	99.74	7	10	32	349	737	51	324	209	41	12	19	20	140	10	27	59	8	33	3
GRB-Wapshilla Ridge	720	1694	53.87	2.20	14.17	12.36	0.217	4.24	8.18	3.03	1.13	0.358	99.76	10	14	38	392	605	29	344	173	40	11	21	29	135	9	26	49	6	28	1
GRB-Mount Horrible	790	1624	54.16	2.11	14.12	12.14	0.212	4.13	8.18	3.04	1.30	0.373	99.77	9	14	39	371	565	34	335	170	37	10	20	31	131	9	24	43	7	28	2
GRB-Mount Horrible	820	1594	54.58	2.07	14.16	12.25	0.201	3.97	7.90	2.97	1.31	0.364	99.77	9	14	37	359	598	35	326	169	35	10	19	31	127	10	25	47	6	28	3
GRB-Cold Spring Ridge	920	1494	54.59	2.06	13.79	12.23	0.213	4.14	7.81	3.03	1.50	0.395	99.76	8	11	37	370	628	38	327	167	36	10	19	33	130	10	25	47	6	27	0
GRB-Cold Spring Ridge	950	1464	54.55	2.08	13.73	12.39	0.213	4.05	7.82	3.03	1.49	0.407	99.76	10	11	38	365	616	38	324	167	36	11	21	34	129	10	25	41	6	23	2

Table 1 continued.

Unit	Depth (ft)	Elevation (ft)	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd	U
GRB-Cold Spring Ridge	1014	1400	55.90	1.82	14.13	10.96	0.201	4.23	7.84	3.03	1.44	0.237	99.77	9	10	34	332	605	39	322	164	32	11	20	24	120	11	23	39	7	25	2
GRB-Frye Point	1060	1354	55.70	2.07	13.79	11.81	0.209	3.72	7.38	3.14	1.59	0.339	99.76	8	3	33	360	640	42	320	197	38	12	22	34	130	9	27	51	7	26	1
GRB-Frye Point	1080	1334	55.75	2.05	13.76	11.76	0.209	3.77	7.38	3.09	1.66	0.328	99.76	8	4	33	355	636	42	319	194	38	11	20	34	128	9	28	49	6	30	2
GRB-Frye Point	1130	1284	55.69	2.16	14.10	11.97	0.186	4.00	7.35	2.71	1.32	0.270	99.76	10	9	35	346	643	38	314	191	38	11	20	45	133	23	28	52	7	29	2
GRB-Frye Point	1180	1234	55.64	2.10	13.92	11.73	0.195	3.95	7.50	2.96	1.46	0.296	99.76	10	15	35	346	648	42	318	191	37	12	20	45	127	10	24	45	6	23	3
GRB-Frye Point	1230	1184	55.74	2.07	13.70	11.68	0.192	3.91	7.56	3.06	1.55	0.302	99.76	9	9	32	337	626	44	316	187	35	11	21	45	123	12	20	46	7	25	3
GRB-Frye Point	1250	1164	55.72	2.07	13.70	11.56	0.194	3.95	7.61	3.09	1.58	0.299	99.76	9	8	33	341	625	44	317	185	35	12	20	44	122	9	28	48	6	28	1
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1280	1134	56.65	2.20	13.46	11.91	0.193	3.22	6.77	3.23	1.80	0.320	99.74	7	10	31	355	722	51	319	207	37	13	21	24	132	12	29	55	7	31	4
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1310	1104	56.39	2.21	13.48	12.04	0.200	3.26	6.84	3.24	1.76	0.328	99.74	8	15	31	355	744	49	320	208	39	13	22	25	133	13	31	55	7	28	3
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1380	1034	56.86	2.23	13.42	11.89	0.195	3.06	6.64	3.24	1.87	0.329	99.74	4	7	31	358	746	53	318	211	38	13	21	22	134	12	31	51	7	30	3
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1410	1004	56.91	2.22	13.43	11.84	0.192	3.07	6.62	3.26	1.87	0.326	99.74	3	8	31	361	734	54	319	210	37	12	23	21	133	12	25	55	7	30	4
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1460	954	56.36	2.26	13.64	12.32	0.195	3.18	6.67	3.11	1.66	0.331	99.74	3	8	32	362	719	47	323	211	38	13	23	21	161	12	28	51	8	28	3
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1490	924	56.78	2.22	13.37	12.02	0.194	3.07	6.63	3.26	1.86	0.333	99.74	3	7	31	358	734	53	316	212	38	14	22	23	136	12	24	55	9	29	2
GRB-Downey Gulch/Brady Gulch/Kendrick Grade	1540	874	53.90	2.76	15.27	13.16	0.190	3.32	6.45	3.08	1.10	0.472	99.72	8	16	35	398	664	30	407	242	43	15	24	41	152	16	34	64	7	34	0
GRB-Teepee Butte-Joseph Creek flow	1620	794	54.23	2.33	14.11	11.89	0.189	4.73	8.09	2.74	1.09	0.328	99.75	31	84	35	349	548	28	351	197	36	13	20	78	127	15	27	49	6	29	1
GRB-Teepee Butte-Joseph Creek flow	1730	684	52.36	2.36	14.24	11.85	0.188	5.25	9.07	2.98	1.13	0.333	99.75	43	113	38	355	444	30	347	187	34	13	19	93	125	8	26	48	6	27	2
GRB-Teepee Butte-Joseph Creek flow	1770	644	52.49	2.39	14.55	11.11	0.287	4.82	9.62	2.94	1.13	0.405	99.75	45	121	37	358	439	29	365	185	35	13	21	98	124	9	22	42	5	26	1
GRB-Teepee Butte-Joseph Creek flow	1800	614	52.06	2.40	14.54	11.58	0.397	4.69	9.54	3.01	1.13	0.411	99.75	42	121	37	354	438	30	363	187	35	13	21	90	124	7	23	43	6	27	2
GRB-Teepee Butte-Joseph Creek flow	1830	584	52.51	2.37	14.35	11.62	0.184	5.03	9.34	2.93	1.05	0.336	99.72	44	118	38	355	435	27	356	184	34	12	20	97	166	220	19	48	5	27	2
GRB-Buckhorn Springs	1945	469	52.94	2.61	13.92	12.35	0.206	4.54	8.75	3.05	0.99	0.394	99.75	34	74	39	377	441	22	303	219	40	15	21	136	130	13	24	44	4	26	1
GRB-Buckhorn Springs	1955	459	52.44	2.58	13.97	12.67	0.215	4.73	8.86	2.91	0.98	0.399	99.75	35	70	38	370	419	24	309	221	42	15	19	138	134	8	25	49	5	31	1
GRB-Buckhorn Springs	1965	449	52.17	2.62	13.90	12.92	0.216	4.73	8.85	2.95	1.00	0.405	99.75	34	69	38	380	440	26	306	221	43	16	20	139	129	8	24	48	6	30	2
GRB-Buckhorn Springs	1980	434	52.28	2.59	13.75	13.08	0.216	4.74	8.74	2.91	1.04	0.405	99.75	41	71	37	376	414	27	299	220	43	15	21	144	132	8	25	46	6	28	2
GRB-Buckhorn Springs	1995	419	52.03	2.60	13.85	12.98	0.217	4.84	8.88	2.94	1.02	0.396	99.75	36	73	38	377	400	25	298	215	42	15	20	143	132	7	27	47	4	29	2
GRB-Buckhorn Springs	2015	399	52.37	2.60	13.69	12.99	0.225	4.79	8.77	2.87	1.07	0.396	99.75	35	74	38	374	413	26	297	218	42	15	21	140	132	9	26	45	6	30	2
GRB-Buckhorn Springs	2020	394	52.38	2.61	13.59	13.09	0.226	4.74	8.71	2.93	1.09	0.395	99.75	34	70	38	376	420	28	295	219	42	15	21	142	135	11	24	45	5	30	2
GRB-Buckhorn Springs	2100	314	52.26	2.61	13.73	12.99	0.219	4.79	8.77	2.92	1.08	0.390	99.75	31	72	38	378	420	27	295	218	42	15	21	143	133	9	23	49	6	29	0
GRB-Buckhorn Springs	2130	284	53.41	2.57	13.43	12.86	0.218	4.62	8.31	2.81	1.12	0.390	99.75	32	67	37	367	425	29	290	220	43	15	20	140	128	8	26	49	5	31	2
GRB-Buckhorn Springs	2195	219	52.54	2.62	13.61	13.05	0.221	4.77	8.51	3.01	1.05	0.385	99.75	33	64	37	375	434	28	292	219	43	15	19	145	128	11	24	45	6	29	1
GRB-Buckhorn Springs	2210	204	51.93	2.67	13.58	13.41	0.227	4.78	8.62	3.12	1.01	0.393	99.75	35	67	37	383	437	25	288	219	43	14	19	149	134	9	21	46	5	29	1
			Washington State University Well 8—Major oxides (weight percent)											Washington State University Well 8—Trace elements (parts per million, ppm)																		
GRB-Cold Spring Ridge	755	1851	54.55	2.10	14.05	11.94	0.21	4.05	8.04	3.09	1.36	0.37	99.76	10	15	36	376	601	34	334	170	37	12	21	27	131	7	25	42	6	26	1
GRB-Cold Spring Ridge	765	1841	54.46	2.17	14.07	11.92	0.22	4.02	8.06	3.15	1.32	0.37	99.76	8	15	37	381	627	34	341	172	38	10	22	25	134	7	29	50	6	30	0
GRB-Cold Spring Ridge	775	1831	54.68	2.18	14.00	11.81	0.21	3.85	8.04	3.22	1.42	0.36	99.76	8	13	35	383	590	36	336	171	38	10	22	24	131	7	27	45	5	29	3
GRB-Cold Spring Ridge	785	1821	54.85	1.86	14.21	11.13	0.21	4.41	8.25	3.09	1.45	0.31	99.77	10	17	37	358	541	34	327	160	35	9	20	40	121	6	56	42	6	22	1

HISTORY OF REGIONAL STRATIGRAPHIC FRAMEWORK

Early pioneers in establishing a CRBG stratigraphy include Mackin (1961) and Waters (1961). Present-day terminology evolved over the following decades based on geologic mapping, measured sections, geochemical analyses, geophysical logging, and magnetic polarity studies. Tolan and others (1989) discussed the historical development of stratigraphic contributions up to 1989. The subdivision of the Grande Ronde Basalt by Reidel and others (1989b) is of major importance. Reidel and others (2013b) and Reidel and Tolan (2013a) discussed continuing refinements and acknowledge many of the researchers involved.

Swanson and others (1979) formalized five formations in the CRBG as follows (from oldest to youngest): Imnaha Basalt, Grande Ronde Basalt, Picture Gorge Basalt, Wanapum Basalt, and Saddle Mountains Basalt. The Steens Basalt (Camp and others, 2013) and the Prineville Basalt have since been adopted as the sixth and seventh formations in the CRBG (Reidel and others, 2013b). The Picture Gorge, Steens, and Prineville Basalts do not occur within the MPB. Bush and Hayden (1987), Bush and Garwood (2005), Conrey and Wolff (2010), and Bush and others (2016) reported the presence of the Imnaha Basalt in the lowermost part of WSU well 7. A review of rock-chip chemistry indicates that those basalt units belong to the Buckhorn Springs Member of the Grande Ronde Basalt (see Appendix A). We now include all of the identified basalt flows in the MPB, from base upward, into the Grande Ronde, Wanapum and Saddle Mountains Basalt.

PREVIOUS WORK IN THE MOSCOW-PULLMAN AREA

Bingham and Walters (1965) were first to suggest a term (Roza) for an individual flow in Whitman County, Washington. Walters and Glancy (1969) used the plagioclase phenocryst rich Roza flow as a stratigraphic marker to produce a geologic map of the county. Wright and others (1973) reported that the flow above the Roza in Colfax, Washington, had a similar chemistry to the Lolo Creek flow of Bond (1963) in the Clearwater embayment southeast of Moscow, Idaho. Siems and others (1974) correlated the Vantage Member of the Ellensburg Formation eastward across the Columbia Plateau into Pullman where sediments occur between the Wanapum Basalt (basalt of Lolo) and the underlying Grande Ronde Basalt. Brown (1976) made the first attempt of subsurface correlations from Pullman to Moscow using chemistry of well chips. Swanson and others (1980) produced a geologic map of southeastern Washington in which they subdivided the Grande Ronde into four magnetic polarity units, named from base upward as the R_1, N_1, R_2, and N_2 magnetostratigraphic units (MSUs). Swanson and others (1980) also noted that a saprolite on top of the Grande Ronde correlates, in part, to the Vantage Member. Hooper and Webster (1982) placed basalt outcrops in the Moscow-Pullman area into a stratigraphic framework and identified sediments between the Grande Ronde and Wanapum Basalts.

Four geologic maps extending over much of the eastern edge of the MPB described and discussed nomenclature for the associated sediments (Bush and Provant, 1998; Bush and others, 1998a, b, 2000). Well reports on IDWR well 4 (Bush, 2006) and Pullman city wells 7 and 8 (Bush and others, 2001b; Bush, 2008) provided rock-chip chemistry and suggested correlations to other wells. Bush and Garwood (2005) constructed an east-west geologic cross section from Moscow to Pullman using all rock-chip analyses then available.

Conrey and Wolff (2010) reanalyzed stored beads and chips from several wells and produced a stratigraphic cross section from Pullman to eastern Moscow. Conrey and others (2013) determined the stratigraphic sequences for several Washington Department of Ecology (DOE) observation wells drilled along the western and northern edges of the MPB. Conrey and Crow (2014) obtained stored chips for wells in Moscow and reported on the determined sequences. Bush and others (2016) utilized portions of Conrey and others (2013) work to illustrate stratigraphic relations of the upper Grande Ronde and Wanapum Basalts and associated sediments. Several geologic cross sections have been completed utilizing all data available (Bush and others, 2018).

WELL CHIPS AND COLUMBIA RIVER BASALT GROUP STRATIGRAPHY

Determination of the stratigraphic position of a CRBG basalt flow often requires a combination of geologic mapping, section measurement, magnetic polarity data, and geochemical analyses. Identification of a particular flow or member from well chips depends mainly on the geochemical data. There are a few flows or members

where the chemistry is so distinctive that it alone can be used to place the basalt sample into the proper stratigraphic position. One such example is the basalt of Lolo (Priest Rapids Member of the Wanapum Basalt). This unit occurs as a single flow in the MPB and is herein referred to as the Lolo flow. For the majority of the flows in the CRBG, determination of stratigraphic position only requires geochemical comparisons to a regional database. One such example is the determination of the Buckhorn Springs Member of the Grande Ronde Basalt, formerly believed to be the older Imnaha Basalt in WSU well 7, as discussed in the Appendix A.

Determination of the precise boundary between flows and members from well chips can be difficult depending on the nature of the drilling method, sampling technique, and the accuracy of the driller's log. Generally, a rock chip from one basalt flow can look similar to that from another basalt flow, and contamination by one chip can cause misleading results. Different methods of collecting samples vary considerably, and the collectors of the samples differ in experience. Therefore, caution must be used in the final determination of a boundary between units using chemistry from well chips. Some boundaries can also be naturally transitional due to mixing of lavas. In this paper the thicknesses and boundaries reported were, in places, adjusted after review of drill logs and well reports in conjunction with the geochemical data.

The samples reported in this paper were collected over a period of more than five decades by numerous individuals. However, the sequential chemistry from the Cold Spring Ridge Member of the Grande Ronde Basalt upward is consistent from well to well, and the very upper units (upper R_2 to the basalt of Lolo) also match nearby outcrops and available shallow well chemistry. Below the Cold Spring Ridge Member stratigraphic determinations were made from samples collected for WSU well 7, and designations are based primarily on comparisons of the chemistry to a regional data base (Appendix A).

LATAH FORMATION

Sedimentary units associated with the CRBG occur throughout the Columbia River flood basalt province but are generally thicker at the edges. They consist of a wide range of lithologies, grain sizes, and thicknesses; numerous names for these units exist in the literature. In general, sediments along the western edges of the Columbia River flood basalt province are ash rich with volcanic clasts and are referred to as the Ellensburg Formation (Swanson and others, 1979). Along the eastern margins, equivalent sediments are siliciclastic with clasts of continental basement rock and are referred to as the Latah Formation (Figure 3). Reidel and Tolan (2013b) noted that the sediments in the Columbia River flood basalt province have been studied for over a century and provided numerous references.

In the Moscow-Pullman area lavas of the CRBG overlie, are interlayered with and, in places, are overlain by sediments of the Latah Formation (Figure 4). These sediments consist of unconsolidated and partially consolidated gravel, sand, silt, and clay. Beneath Moscow the Latah Formation comprises more than 60 percent (>1,100 ft [335 m]) of the sequence, but these units thin and (or) pinch out toward Pullman where they comprise less than 10 percent (<160 ft [49 m]). The Latah Formation in the Moscow area is subdivided, from the base upward, into the sediments of Moscow, the Vantage Member, and the sediments of Bovill (Figure 3) (Bush and Provant, 1998; Bush and others, 1998a, b, 2000; Duncan and Bush, 1999).

The sediments of Moscow unit is laterally equivalent to the Grande Ronde Basalt and ranges from a total of about 550 ft (168 m) in Moscow (in Moscow city wells 6 and 8) to less than 140 ft (43 m) in Pullman (in WSU well 7) due to west-to-east pinching out of basalt flows (Figure 4). The sediments consist of sand, silt, and clay with minor gravel. Sands consist primarily of coarse- to very coarse grained, subrounded quartz, feldspar, and rock fragments. Muscovite, biotite, and minor amounts of amphibole and pyroxene are also present. Sediments in the uppermost part of the unit are overall finer in size than lower parts, but sphericity, roundness, and sorting of coarse-grained sediments are similar throughout the sequence (Cavin, 1964).

The Vantage Member in the MPB overlies various Grande Ronde Basalt flows (Conrey and Wolff, 2010; Conrey and others, 2013; Bush and others, 2016). The Lolo flow overlies the Vantage throughout much of the basin, and where basalt chemistry data are lacking, the Vantage has been used as a marker bed between wells in close proximity. The member ranges from more than 325 ft (99 m) beneath Moscow to less than a few feet (<3 m) in places beneath Pullman. At a few localities in the western part of the MPB it is absent. Sand, silt, and clay

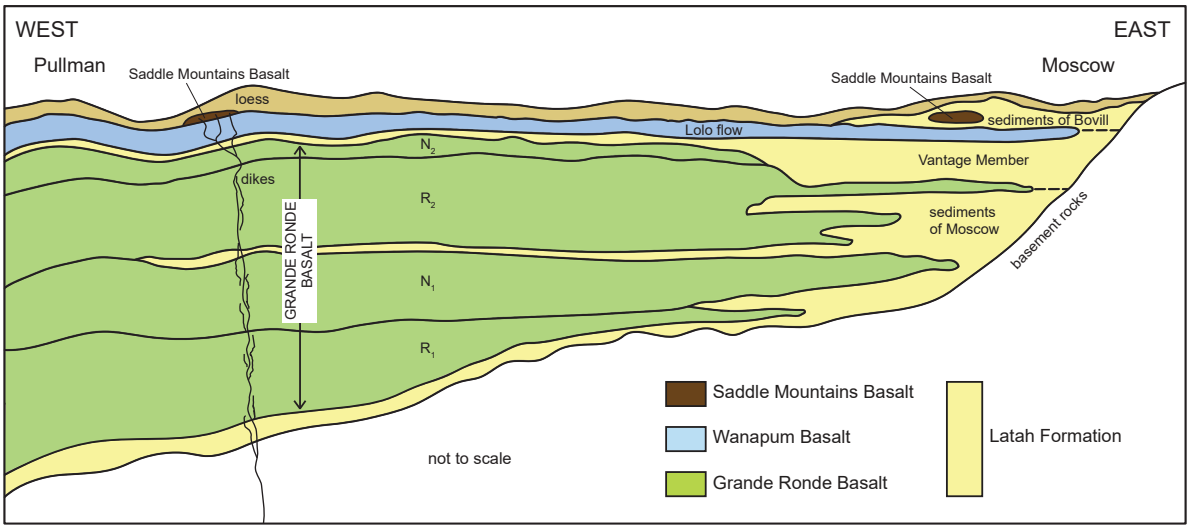

Figure 4. Generalized west-to-east geologic cross section from Pullman, Washington, to Moscow, Idaho; N, normal polarity; R, reverse polarity. Loess is a Quaternary deposit, all other formations are Miocene.

dominate the sediments with locally abundant gravel beds. Similar to the lower portions of the sediments of Moscow, the sand consists primarily of coarse-grained, poorly rounded, and poorly sorted quartz and feldspar. Overall, drillers' reports for wells throughout the basin indicate that the Vantage contains more silt and clay than the underlying sediments of Moscow, but less clay than the overlying sediments of Bovill.

The sediments of Bovill unit overlies the uppermost flow of the Wanapum Basalt (basalt of Lolo, Priest Rapids Member) in Moscow and other areas in Latah County, Idaho (Bush and Provant, 1998; Bush and others, 2000; Lewis and others, 2005). Locally in Moscow the sediments are interbedded with the basalt of Lewiston Orchards of the Saddle Mountains Basalt. These sediments exceed 300 ft (91 m) in thickness in Moscow and, for the most part, thin rapidly westward until pinching out at locations near the Washington-Idaho border. Erosional remnants occur as far west as the DOE Banner Road well 3 mi (4.8 km) northwest of Pullman (Figure 2), where 65 ft (20 m) of silt are overlain by 8 ft (2.4 m) of the basalt of Tenmile Creek of the Saddle Mountains Basalt (Conrey and others, 2013). Grader (2011) noted Bovill sediments occurring as high as 2,800 ft (853 m) in elevation which suggests that these deposits may have been as thick as 500 ft (152 m) prior to erosion. The unit consists primarily of clay and silt; layers, pockets, and lenses of sand and gravel are not uncommon.

The uppermost part of the sediments of Bovill unit was studied for its potential as a clay and aluminum resource (Hubbard, 1956; Hosterman and others, 1960). Studies by Fairley and others (2006) and Grader (2011) characterized parts of these sediments from shallow test wells and small exposures. Foundation excavations provided additional information. The clays are yellow, white, brown, and kaolinite rich; the sands and gravels consist of poorly sorted, subangular quartz with minor basalt and feldspar. Cross-bedding and upward-fining cycles are common in exposures. Overall, there is an east-to-west fining. Of interest is the fact that the coarser sand and gravel components contain poorly sorted, subangular to angular quartz grains similar to those in the earlier Vantage Member and sediments of Moscow units.

Grader (2011) noted that parts of areas previously mapped as sediments of Bovill are in fact Quaternary and modern channel deposits. Othberg and Breckenridge (2001) noted Quaternary terraces 60 ft (18 m) above the flood plain floor in the Moscow area. The inability to consistently recognize and separate these units, along with a fundamental problem of distinguishing weathered granite from locally transported sediments in well cuttings, prohibits the generation of accurate lithofacies maps for the sediments of Bovill (Grader, 2011).

The Latah sediments owe their origin to the emplacement of the CRBG into the rugged pre-Tertiary topography of

the Moscow-Pullman area. Alluvial fan, braided stream, and meandering stream environments dominated, with local lake, pond, and swamp settings. Consistent poor sorting and rounding of the coarse grains, along with high kaolinite content, indicate rapid deposition and burial in a low-energy regional system close to a weathered, granitic source area. A sudden rise in base level near steep, mountainous topography to the east caused rapid sedimentation. The lack of high-energy stream development out of the MPB was responsible for the general absence of mature and well-sorted sediments. The coarse-grained portions are considered to be reworked channel lag deposits.

STRUCTURAL SETTING

The Miocene and post-Miocene structural setting within the MPB is not complex. Basal contacts of basalt flows between Moscow and Pullman are generally horizontal north of Pullman is outside the basin proper but projects eastward into the gap between Smoot Hill and Kamiak Butte (Figure 5). The fault of Moscow (Conrey and Crow, 2014), interpreted from stratigraphic correlations, may be a northern extension of the Cottonwood Creek fault of Bond (1963) mapped southeast of Moscow by Bush and others (2001a) and Bush and others (2007). The fault of South Fork in Pullman was identified by minor offset of basalt units between closely spaced wells (Conrey and Wolff, 2010). Overall these faults, along with the folds and dikes, produce a northwest fabric to the area, in particular on the Palouse Slope along the basin's western edge at Pullman.

The Columbia Basin in central Washington was continuously subsiding during and after basalt eruptions (Reidel and others, 2013b) while the MPB, situated on continental rocks, remained relativity stable. An angular unconformity between the R_1 and N_1 MSUs at the northern border of the Lewiston Basin (Alloway

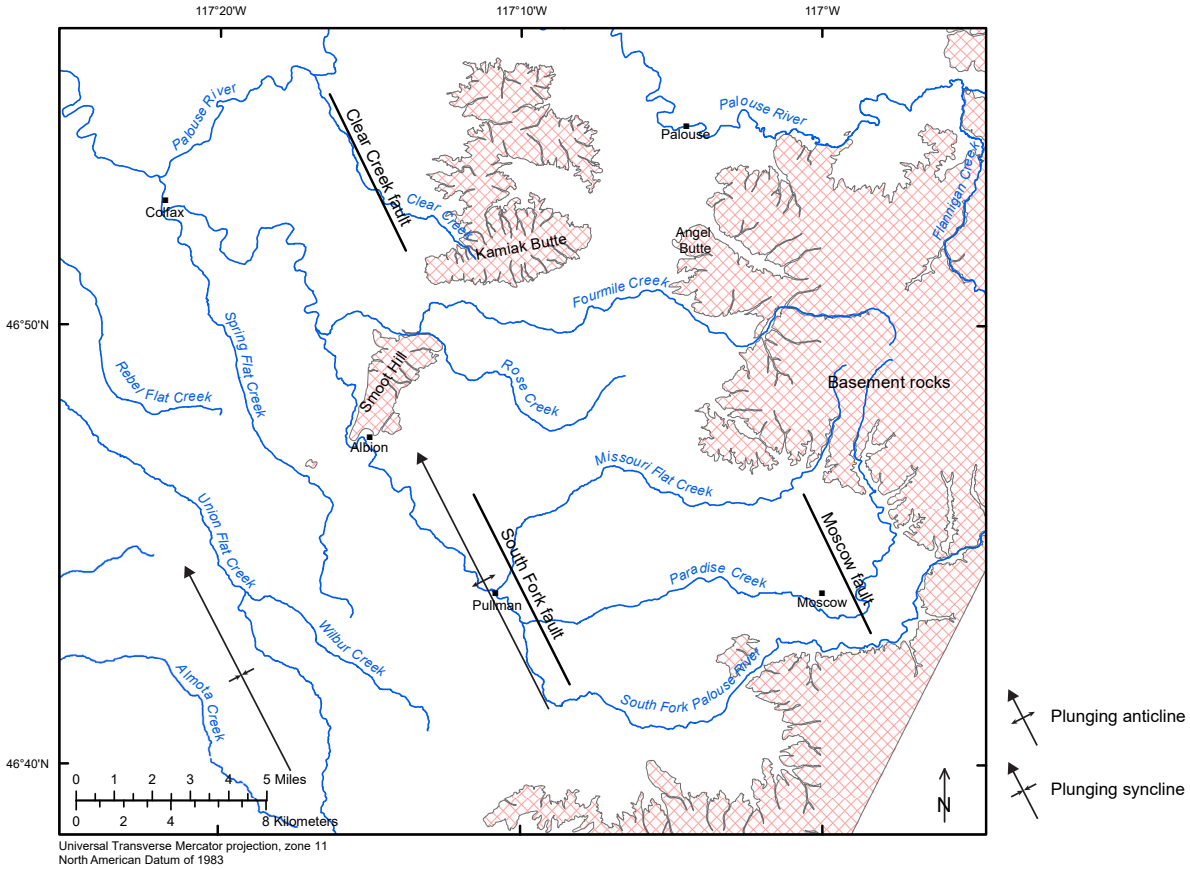

Figure 5. Map showing approximate locations of major structures in the Moscow-Pullman area (from Bush and others, 2016, Figure 5).

and others, 2013; Reidel and others, 2013a) 20 mi (32 km) south-southeast of Pullman indicates some nearby tectonic activity during early Grande Ronde eruptions. Northwest-trending folds occur at the western edge of the MPB. Stratigraphic relations in and west of Pullman document minor folding began at least as early as R_2 Grande Ronde time (Conrey and others, 2013; Bush and others, 2016). Folding continued until at least middle Saddle Mountains time. The anticline along western edges of the basin at Pullman was an impediment to western drainage development out of Pullman. In addition, the same anticline at times prohibited flows from entering the MPB, caused sedimentation within the basin, and was responsible for the northwest trend of the South Fork Palouse River. Figure 6 illustrates the nature of this fold in a west-to-east geologic cross-section across the northern extent of the anticline near Albion.

PALEOGEOGRAPHY

INTRODUCTION AND PRE-BASALT TOPOGRAPHY

Stratigraphic correlations determined from the rock-chip chemistry are the primary basis for the paleogeographic reconstructions. Data for the Grande Ronde Basalt R_1 and the lower N_1 are based entirely on chips from WSU well 7, the only well deep enough to encounter units below the upper N_1 (Cold Spring Ridge Member). In addition to the deep water wells (Table 1), the upper Grande Ronde Basalt (R_2–N_2 intervals), Vantage Member, Wanapum Basalt, and Saddle Mountains Basalt reconstructions were determined from numerous deep (300–600 ft [91–183 m]) domestic water wells, rock-chip chemistry from seven DOE test wells (Conrey

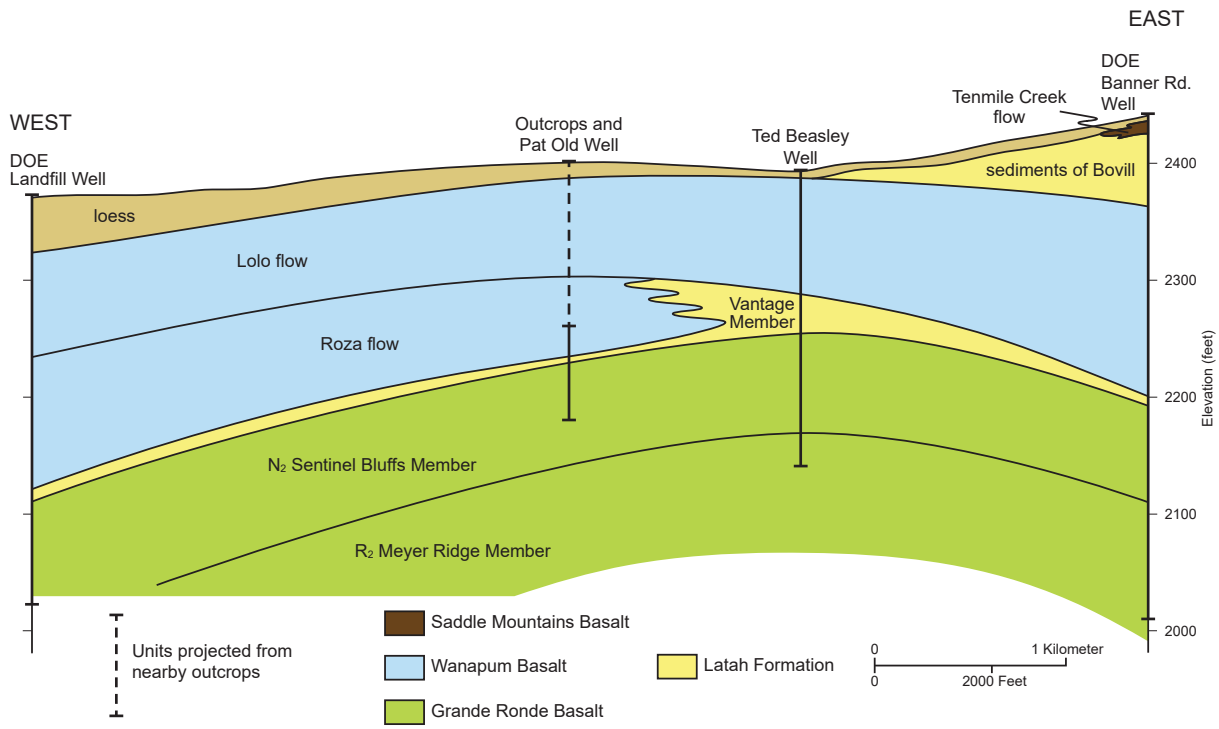

Figure 6. West-to-east geologic cross section across the northwest end of the anticline, from DOE Landfill well to DOE Banner Road well (Figure 2), Whitman County, Washington. Loess is a Quaternary deposit, all other formations are Miocene.

and others, 2013), and outcrop identifications (Hooper and Webster, 1982; Bush and others, 2016). Regional distribution diagrams and discussions by Reidel and Tolan (2013a) were used for comparisons. A structure contour map on the upper Grande Ronde surface (Bush and Dunlap, 2018) and several geologic cross sections (Bush and others, 2018) constructed from a well and outcrop database of 333 sites (Bush and Dunlap, 2017) were also useful. Each paleogeographic reconstruction required projection of known thicknesses and thickness trends into unknown parts of the basin.

CRBG correlations are very useful for paleogeographic reconstructions in that flow and member contacts can be used for approximations of time lines. Eruption and emplacement rates for flows are controversial and range from centuries (Keszthelyi and Self, 1998; Thordarson and Self, 1998) to a few years (Reidel and Tolan, 1992; Reidel and others, 1994; and Reidel, 1998, 2005) to as short as weeks (Shaw and Swanson, 1970). In any case, correlation of the base of a flow or member over several miles is very close to a time line within the MPB. The paleogeographic reconstructions shown and discussed herein are selected time intervals deducted from local and regional stratigraphic correlations and comparisons.

A conceptual model of the pre-CRBG basin topography for the MPB (Figure 7) was prepared using geophysical studies, slope modeling, water-well reports, basalt correlations, and geologic mapping. The geophysical studies included those by Cavin and Crosby (1966), Jackson (1975), Klein and others (1987), Holom (2006), and Piersol and Sprenke (2014). The overall subsurface shape of the basin is irregular with at least two elongated paleovalleys that are now infilled with thick sequences of basalt and associated sediments of the CRBG. The east-west paleovalley between Moscow and Pullman is well documented by available deep well

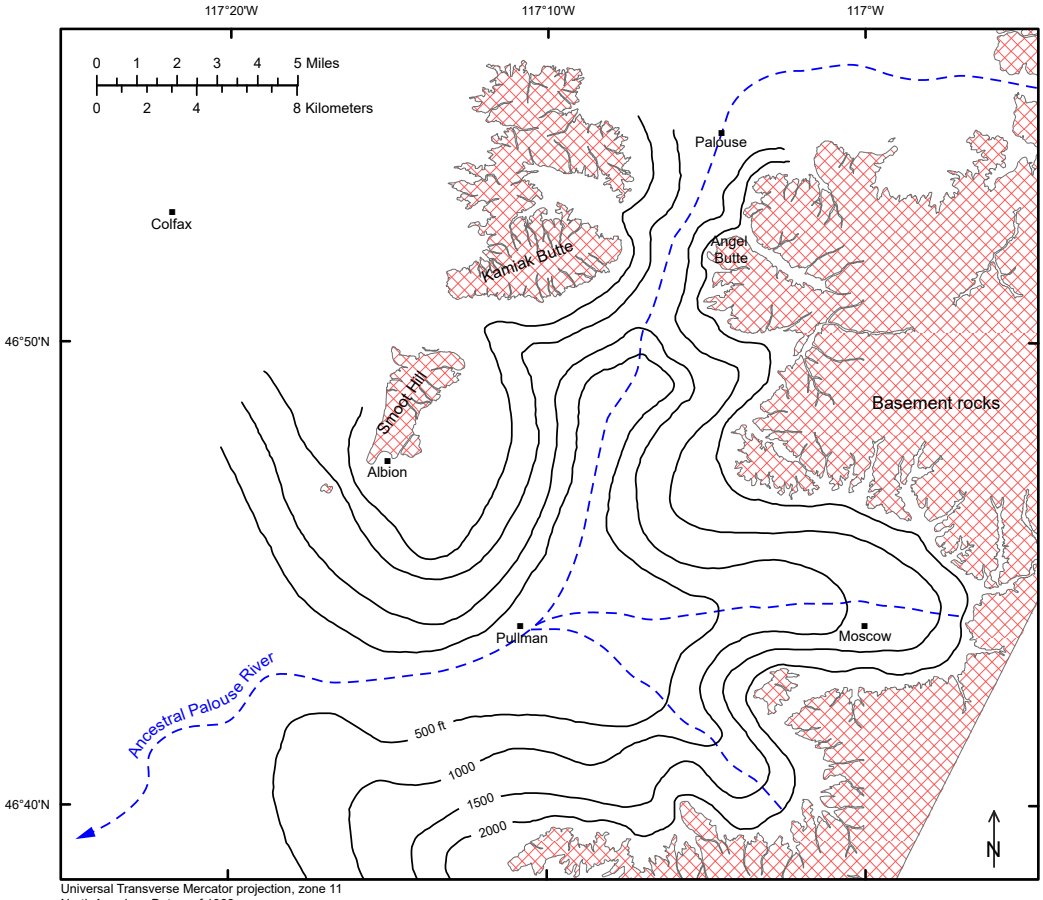

Figure 7. A topographic model of the Moscow-Pullman Basin prior to emplacement of the Columbia River Basalt Group; contours on top of basement rock, in feet.

data. The second paleovalley is believed to occur in a north-northeast elongated area extending from Pullman toward the city of Palouse. Klein and others (1987) reported that a thick sequence of basalt occurs northeast of Pullman, and Piersol and Sprenke (2014) suggested that the CRBG sequence is at least 600 ft (183 m) thick in the gap between Kamiak and Angel Buttes (Figure 7). This north-northeast buried canyon is believed to have been occupied by the ancestral Palouse River.

Most CRGB flows sourced from dikes of the Chief Joseph system south, southwest, west and northwest of the MPB. These flows moved across the Palouse Slope toward a subsiding Columbia Basin in central Washington. The most voluminous flows entered the canyon of the ancestral Palouse River from the west overwhelming and disrupting drainages in the MPB numerous times.

Early Wanapum Basalt flows in the central part of the Columbia Basin did not reach Pullman, because subsidence in central Washington near Pasco exceeded flow volume. Later Wanapum flows onlapped toward Pullman as subsidence slowed and (or) volume increased. In late Wanapum time a Roza flow reached the western edge of the MPB. All of the Wanapum Basalt flows impaired western drainage development. Emplacement of the last Wanapum flow (basalt of Lolo) covered the MPB and completely obliterated all drainages. Later local Saddle Mountains Basalt flows also disrupted drainage development.

GRANDE RONDE BASALT R_1 INTERVAL

The oldest flows (in early R_1 time) of the Grande Ronde Basalt belong to the Buckhorn Springs Member (Reidel and Tolan, 2013a), and the lowermost basalt sequence (358 ft [109 m] in thickness) encountered at the bottom of WSU well 7 is assigned to this member. The driller's report, well-chip descriptions, and the neutron-neutron log all suggest that the unit consists of one dense flow with a flow top 30–40 ft (9–12 m) thick (Bush and Hayden, 1987). This Buckhorn Springs flow would have blocked the ancestral Palouse River drainage and caused deposition of sediments in the deep canyons. The top of the Buckhorn Springs in WSU well 7 projects to 700 ft (213 m) below basement rocks in Moscow city well 6 where the sediments of Moscow separate basement rocks and younger flows of the N_1 basalt interval.

The lowermost portions of the sediments of Moscow contain intervals that consist of coarse-grained, subangular, poorly sorted quartz and feldspar (Cavin, 1964), indicating rapid burial with little reworking. However, it is not possible to determine if these early Latah sediments were deposited during the R_1 interval.

The Buckhorn Springs Member in WSU well 7 is overlain by 34 ft (10 m) of coarse-grained, poorly sorted sand with angular grains of quartz. This sand indicates that there was reestablishment of a drainage extending across the basalt in Pullman from surrounding basement rocks. The lack of lateral data prohibits determination of the size and extent of the stream and (or) streams. A possible paleogeographic reconstruction for early R_1 time is illustrated in Figure 8. Overlying this sandy interbed is 253 ft (77 m) of the basalt of Joseph Creek of the Teepee Butte Member (Reidel and Tolan, 2013a) that consists of two flow units which are in turn overlain by 20 ft (6 m) of coarse-grained sand.

Late R_1 flows (295 ft [90 m] in thickness) encountered in WSU well 7 belong, from base upward, to the Kendrick Grade, Downey Gulch, and Brady Gulch members, undivided. The Brady Gulch member is believed to occur at the transition between the R_1 and N_1 boundary (Reidel and Tolan, 2013a). Rock-chip chemistry, the driller's report, and downhole geophysical information suggest that the three members consist of less than seven flows. None of these flows have been identified in the deep wells to the east in Moscow. At end of the R_1 about 735 ft (224 m) of basalt and sediment were emplaced into the western portion of the MPB beneath Pullman. Basement rocks in Moscow would have been about 250 ft (76 m) above the R_1 basalts in Pullman.

Reidel and Tolan (2013a) reported that at least 3,300 ft (1,006 m) of R_1 basalt were emplaced in the central part of the Columbia Basin. These flows obliterated the drainages of the ancestral Salmon-Clearwater and Columbia rivers and raised base levels all around the Columbia River flood basalt province. The Palouse River was likely disconnected and forced northward and (or) northwestward around flow edges. Sedimentation would have occurred around flow edges, filling up the deep canyons in the northwestern, northern, and eastern parts of the basin. Figure 9 illustrates a possible paleogeographic setting at the end of R_1 time.

GRANDE RONDE BASALT N_1 INTERVAL

In WSU well 7 the Brady Gulch member is overlain

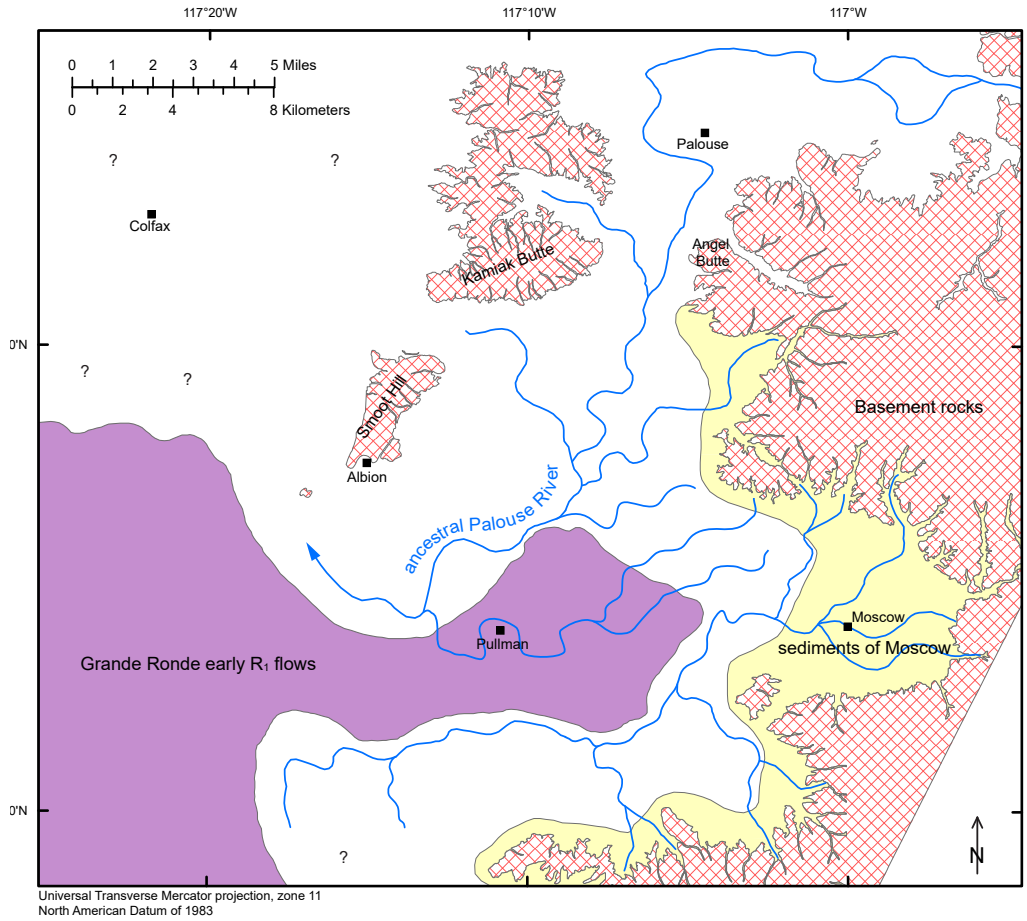

Figure 8. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of early R_1 flows of the Grande Ronde Basalt.

by basalts of the Frye Point member (231 ft [70 m] in thickness). Emplacement of basalts across the R_1–N_1 boundary appears continuous and it is difficult, from the data available, to identify the contact between the Kendrick Grade, Brady Gulch, and Frye Point members. There are a number of alternating dense and soft zones, but the basalts are consistently fine grained and dense. No distinctive flow boundaries were noted (Bush and Hayden, 1987).

Basalts of the Frye Point member are separated by a coarse-grained, basalt and quartz sand 45 ft (14 m) thick. Similar to the sands in the R_1, the grains are subangular and poorly sorted suggesting rapid deposition and (or) little reworking. The number of early N_1 flows is difficult to interpret from the data available, but there were probably at least 2–3 flows or flow units. These early N_1 basalts would have continued to disrupt drainages and caused sedimentation around the edges of the flows in the MPB. Figure 10 illustrates a possible paleogeographic setting near the end of early N_1 time. The uppermost Frye Point is also overlain by a sand unit (24 ft [7 m] in thickness) with subangular quartz, basalt, and muscovite grains, which indicate drainages once again were reestablished and sourced from surrounding basement rocks. These sands on top of the Frye Point member were probably deposited by short-lived streams before being overrun by flows of the overlying Cold Spring Ridge Member.

The youngest N_1 basalt unit in WSU well 7 is the Cold Spring Ridge Member which is 260 ft (79 m) thick with a 100 ft (30 m)-thick vesicular top. This unit is in turn overlain by about 30 ft (9 m) of a vesicular glass and clay zone that is interpreted as a hyaloclastite and (or) pillow lava unit. The flow and (or) flow units of the Cold

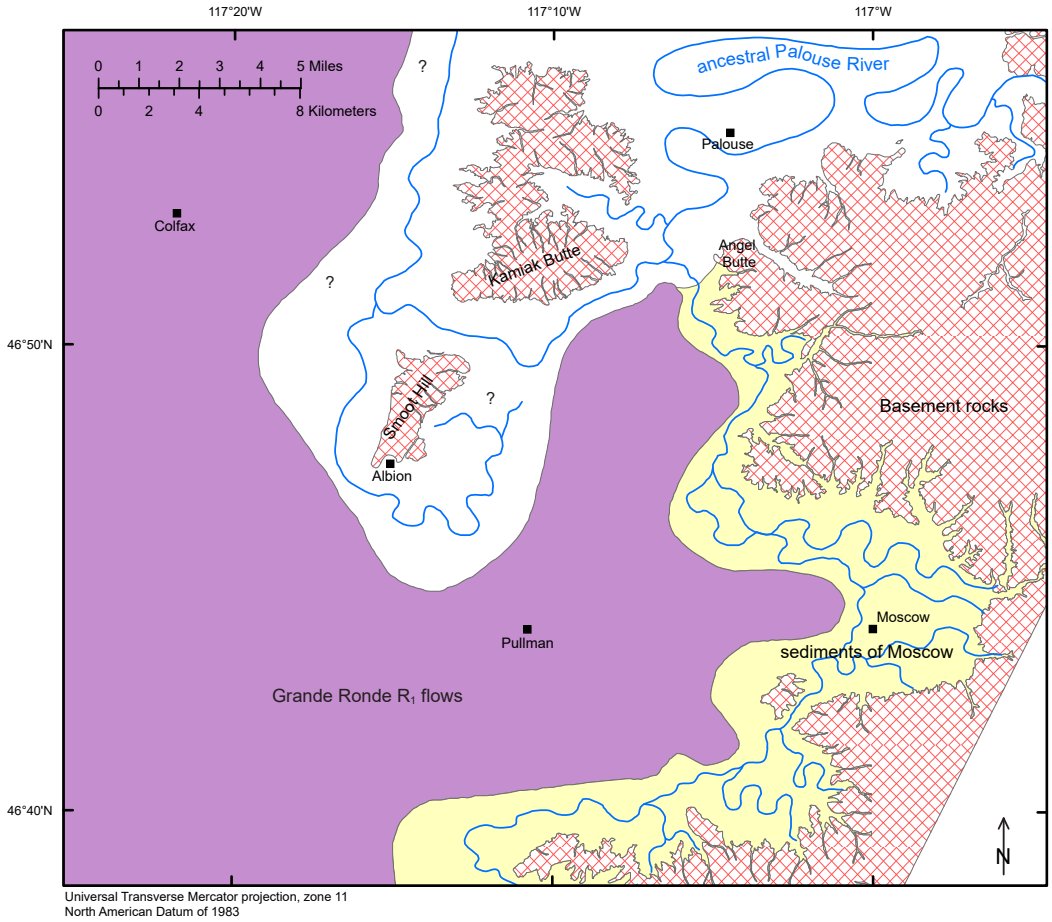

Figure 9. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the late R_1 flows of the Grande Ronde Basalt.

Spring Ridge Member onlap earlier N_1 flows and were encountered in several wells in Moscow and in the DOE Pullman Test and Observation (PTO) well between the two cities. In these eastern wells the vesicular zone is absent, with the exception of Moscow city well 10. The same basalt occurs in the five other deep wells in Pullman where it is overlain and interbedded with sediments. The top of the Cold Spring Ridge Member is interpreted to be near the N_1–R_2 boundary.

Of particular interest are the sedimentary clasts within the N_1–R_2 interval in Pullman city well 8 and WSU well 8. These clasts consist of rounded granules, pebbles, and cobbles that are primarily basaltic in composition with a very small percentage of quartzite and granitic pebbles. Seven pebbles and cobbles of basalt from the two wells were analyzed for chemical content (Table 1). Six of the seven samples have similar chemical attributes indicating that they were derived from the same unit, the underlying Cold Spring Ridge Member. The other four deep wells in Pullman intersected interbeds of sand, clay, silt, and hyaloclastite at the same interval. The interpretation is that a major drainage was attempting to reestablish itself at the western edge of the MPB near the end of the N_1 before being overrun by later R_2 flows. The drainage may have flowed northwest toward Colfax around the advancing edges of the N_1 basalt and the southern end of Smoot Hill (Figure 11). This suggestion is based, in part, on the general lack of sediments between exposures of the N_1–R_2 contact along the Snake River southwest of Pullman and the presence of gravels (37 ft [11 m] in thickness) encountered about 300 ft (91 m) below the top of the Grande Ronde in a Colfax city well (Walters and Glancy, 1969). Unfortunately, the Grande Ronde stratigraphy beneath Colfax is unknown,

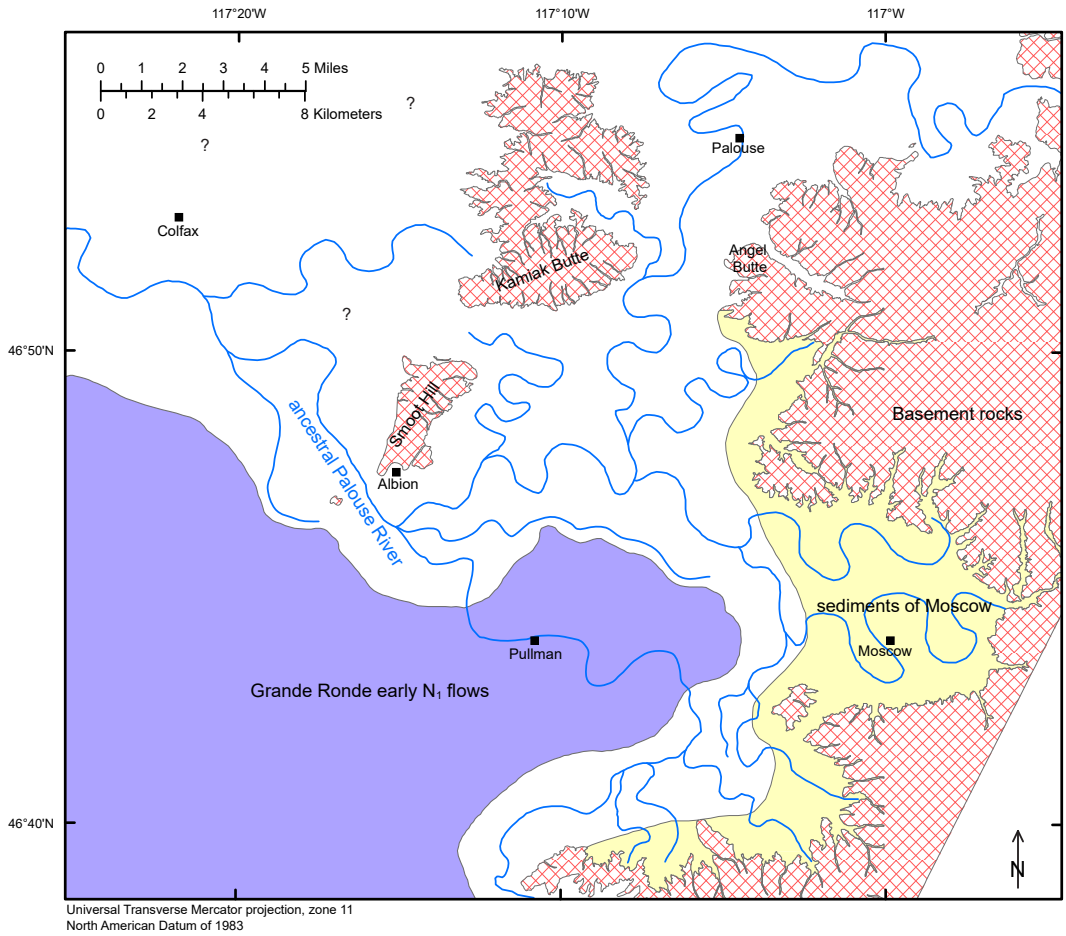

Figure 10. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the early N_1 flows of the Grande Ronde Basalt.

and there are no known deep wells in the Grande Ronde Basalt between Pullman and Colfax.

In the bottom of the PTO well, an interval of the Cold Spring Ridge Member 55 ft (17 m) thick occurs as a glassy and dense basalt interbedded with and overlain by sediments of Moscow (139 ft [42 m] in thickness). The sediments are predominately clay and silt with lesser sand and a thin (2 ft [0.6 m] thick) basalt gravel unit at the top. In Moscow, the Cold Spring Ridge Member is greater than 300 ft [91 m] thickness in UI well 3. The basalt is dense, has a glassy top, and contains few vesicular zones suggesting that much of the unit along the eastern edge of the basin is invasive (Figure 11). The top and bottom of this unit can be correlated to Moscow city wells 6, 8, and 9. In Moscow city well 6 the Cold Spring Ridge Member is reported to have few vesicular zones and is overlain by 193 ft [59 m] of a predominately clay unit of the sediments of Moscow. Overall the data suggest a clay-dominated environment existed in Moscow near the end of the N_1, while a major stream or river had established itself in Pullman.

GRANDE RONDE BASALT R_2 INTERVAL

The R_2 sequence in WSU well 7 is 320 ft (98 m) thick, does not contain any interbeds, and thickens eastward to 450 ft (137 m) in the PTO well (Conrey and Wolff, 2010) where it contains four interbeds totaling 78 ft (24 m) in thickness. The R_2 basalts rapidly thin eastward from the PTO well to less than 47 ft (14 m) in Moscow city well 6 where they are underlain by and interbedded with the sediments of Moscow and overlain by sediments of the Vantage Member. Separation of flow units from flows

is difficult to determine from the data available, and the total number of flows can only be estimated to be six or seven. It is evident that R_2 basalts overwhelmed all stream development in Pullman, but eastward they became mixed with sediments as they thinned and pinched out near the Idaho-Washington state boundary. Subdivision of the R_2 sequence (discussed below) provides more paleogeographic information.

Reidel and Tolan (2013a), from base upward, divided the R_2 into the Mount Horrible member, Wapshilla Ridge Member, Grouse Creek member, and Meyer Ridge Member. Conrey and Wolff (2010) noted that flows from all four members of the R_2 have been identified or tentatively identified in the MPB. Correlations show that the lowermost Mount Horrible member extends into Moscow. The overlying Wapshilla Ridge Member is over 200 ft (61 m) in thickness at the PTO well, but it thins eastward to less than 50 ft (15 m) before pinching out beneath Moscow.

The Grouse Creek member is present in WSU wells 6 and 7, Pullman city well 7, the PTO well, and the DOE Butte Gap well but has not been detected in any deep Moscow well (Conrey and Wolff, 2010; Conrey and Crow, 2014). The overlying Meyer Ridge Member is believed to occur in most Pullman and Moscow wells that are deep enough. The Meyer Ridge is 80 ft (24 m) in thickness in WSU well 7 but thickens eastward to 275 ft (84 m) in the PTO well and then rapidly thins toward the Idaho-Washington state line to less than 80 ft (24 m) beneath Moscow where it is overlain by thick sediments of the Vantage Member of the Latah Formation. The thinning over Pullman is believed to have been caused by growth of an anticline; the thinning into Moscow was caused by the uppermost Meyer Ridge

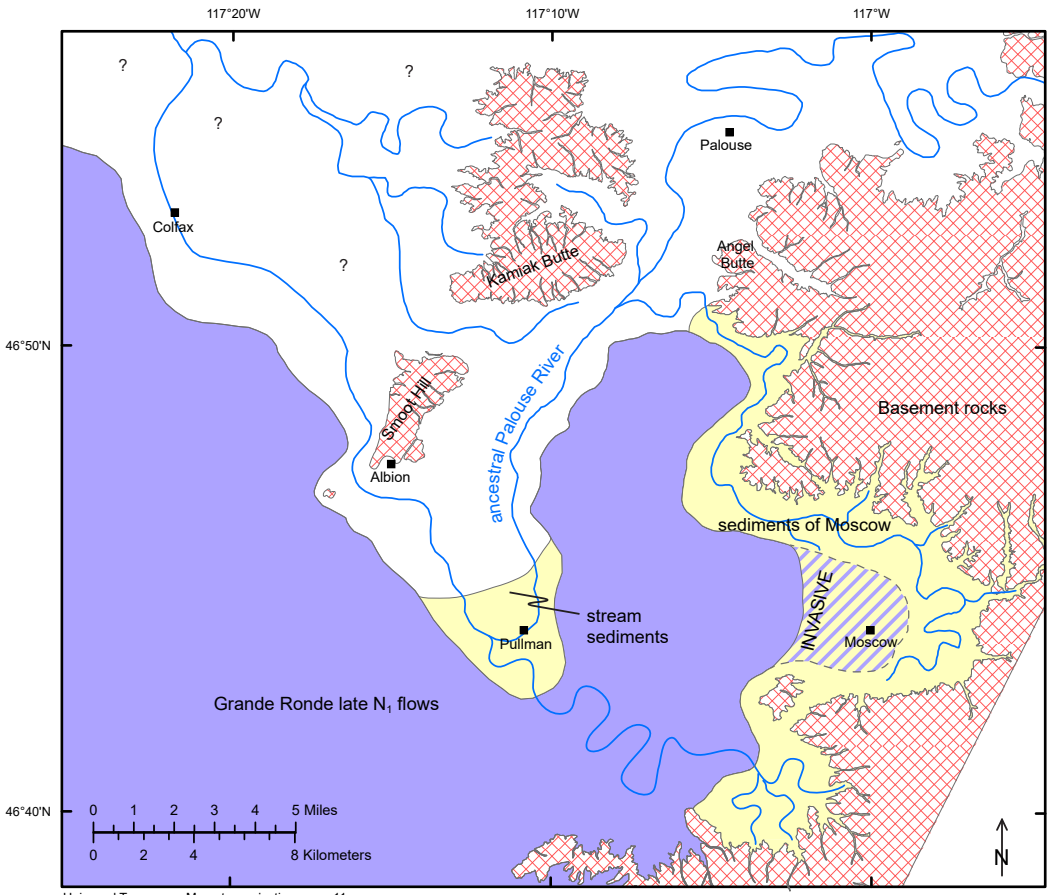

Figure 11. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the late N_1 flows of the Grande Ronde Basalt.

flows not having enough volume to reach Moscow. Thinning over developing anticlines in the CRBG has been documented in the eastern part of the Columbia River flood basalt province (Garwood and Bush, 2005; Alloway and others, 2013; Reidel and others, 2013b). The Meyer Ridge Member can be correlated from domestic well data northward toward the DOE Butte Gap well where it thins to 138 ft (42 m) and is overlain by a thick Vantage Member (113 ft [34 m] in thickness).

The R_2 flows in the MPB were part of a sequence of regional events that covered a slightly larger area than the older Grande Ronde flows; they are the most voluminous attaining a thickness of more than 4,500 ft (1.37 km) in the central Columbia Basin (Reidel and Tolan, 2013a). This huge volume of R_2 eruptions in such a short time onto the Palouse Slope and into the Columbia Basin overran and pushed the westward-flowing drainages of the ancestral Columbia River farther westward and northwestward to the edges of the Columbia River flood basalt province (Reidel and Tolan, 2013a). In the MPB these flows again obliterated streams at Pullman in early R_2 time (Figure 12), and it is unlikely that there was any major westward drainage out of the basin at Pullman. Continued emplacement of R_2 flows is believed to have covered much of the basin (Figure 13).

The latest R_2 flows of the uppermost Meyer Ridge Member offlap earlier R_2 flows and set the stage for a new setting in the MPB. The rapid thinning and offlap of Meyer Ridge flows near the Idaho-Washington state line began the construction of an eastward-facing edge of a basalt plateau that extended more than 7 mi (11 km) north-northwest toward the DOE Butte Gap well. The anticline along the western margin of the basin

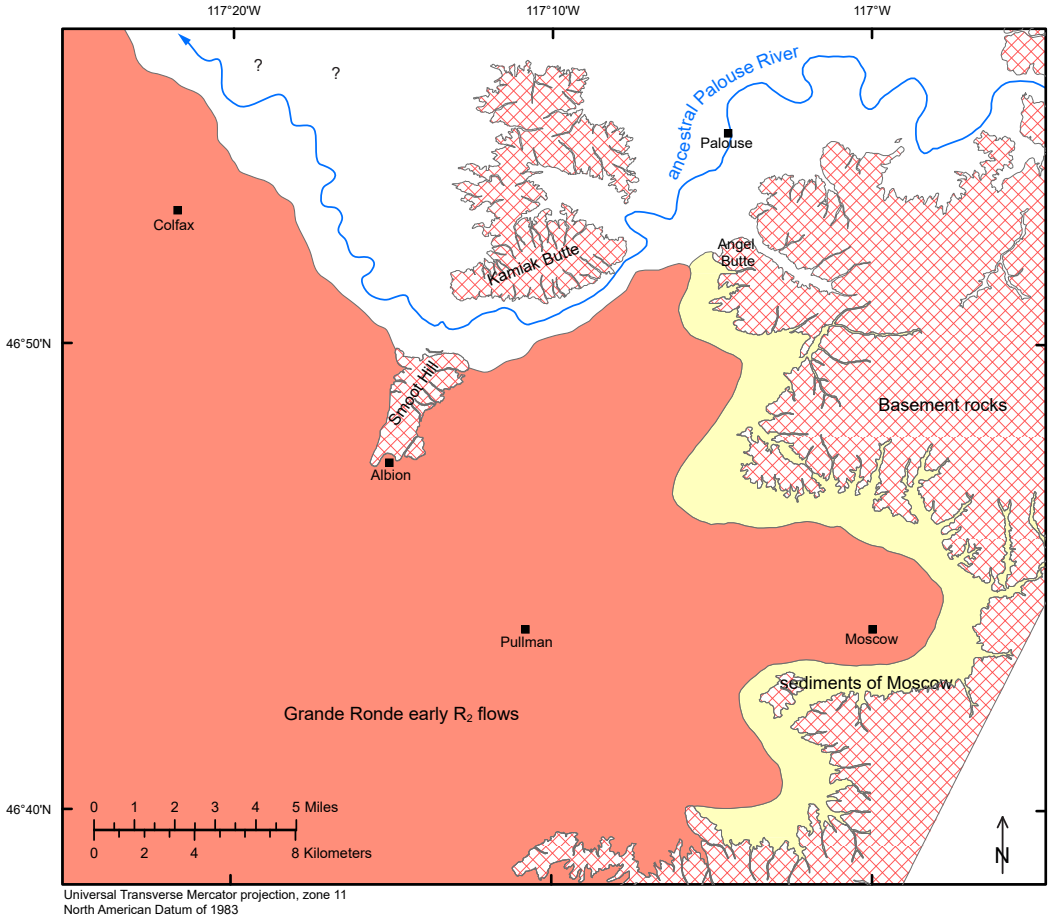

Figure 12. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the early R_2 flows of the Grande Ronde Basalt.

was reactivated at this time. Early Vantage sediments of sand, silt and clay accumulated in the area between the edge of the basalt plateau and the basement rocks. This setting continued into the N_2 interval as illustrated in Figure 14.

On the northern edge of the basin, flows of the early(?) Meyer Ridge Member occur in the DOE Butte Gap well and Palouse city well 3. Conrey and others (2013) suggested the Meyer Ridge Member occurs in the DOE Butte Gap well as a channel filler. Bush and others (2016) believed that flows of the Meyer Ridge Member crossed the gap between Angel and Kamiak Buttes and extended into the Palouse city area.

GRANDE RONDE BASALT N_2 INTERVAL

Most of the N_2 flows in the MPB (Conrey and Wolff, 2010) belong to the Sentinel Bluffs Member. It is the youngest of eight members of the N_2 (Reidel and Tolan, 2013a) and has been subdivided into six compositional types (Reidel, 2005). However, only the basalts of McCoy Canyon and Spokane Falls have been identified within the MPB. Of these two compositional types the basalt of Spokane Falls is the most dominant (Appendix A). In Pullman the Sentinel Bluffs Member (180 ft [55 m] in thickness) thins to 72 ft (22 m) at the PTO well, and N_2 flows probably do not occur beneath Moscow. Conrey and Wolff (2010) correctly noted that Bush (2006) misidentified Meyer Ridge basalt as N_2 (instead of R_2) in IDWR well 4 and that the N_2 is absent in the DOE Butte Gap well and Palouse city well 3 where the Vantage overlies the Meyer Ridge Member. Bush and others (2016) noted the presence of at least 100 ft (30 m) of N_2 basalt in a domestic well in the gap between Kamiak Butte and Smoot Hill where it is overlain by a

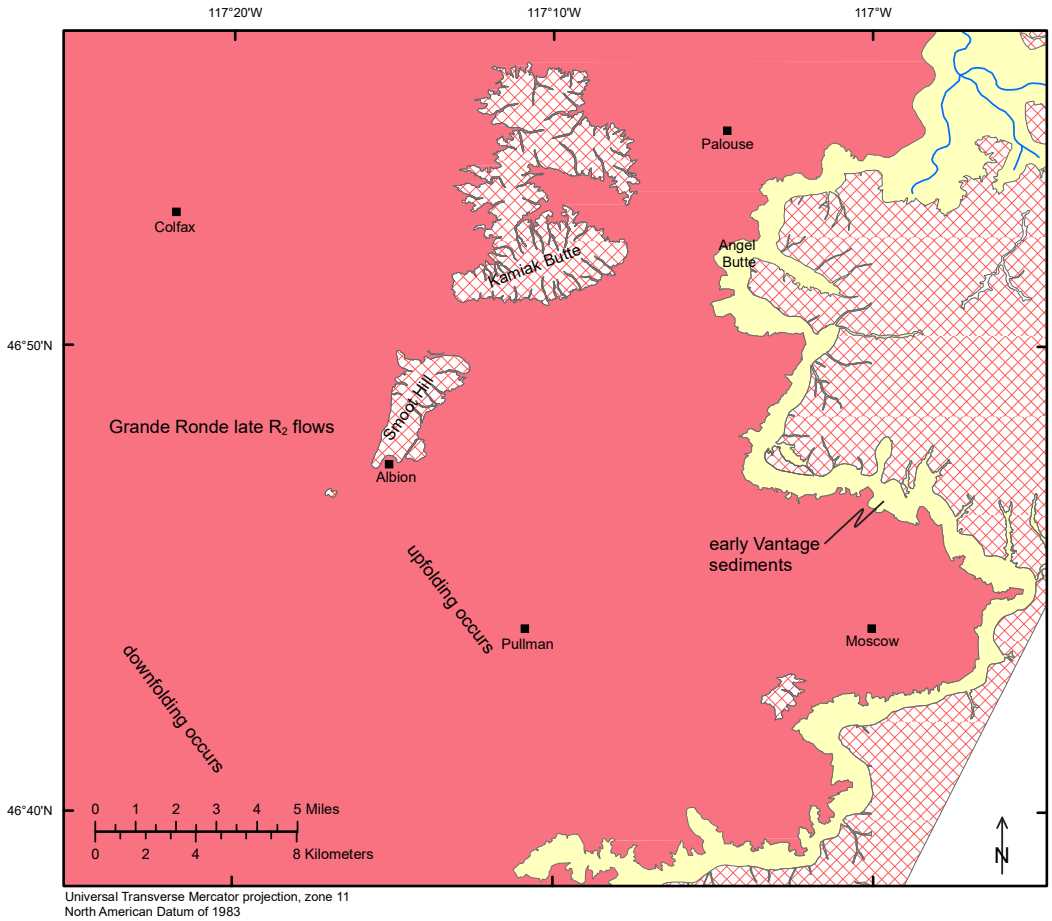

Figure 13. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the late R_2 flows of the Grande Ronde Basalt.

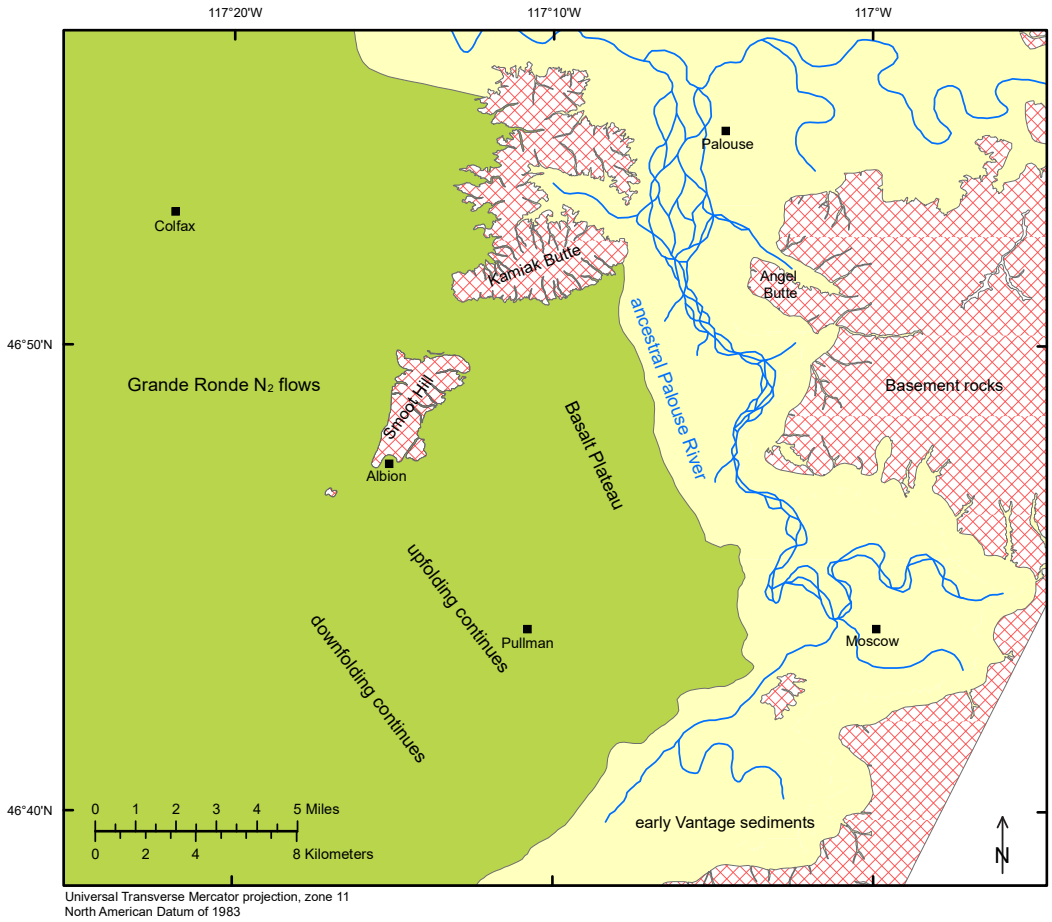

Figure 14. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the N_2 flows of the Grande Ronde Basalt; modified from Bush and others (2016, Figure 11).

very thin Vantage and the Roza Member of the Wanapum Basalt. The extent of the Sentinel Bluffs Member is well defined in the Washington side of the MPB, because numerous domestic wells were completed in the underlying R_2 Meyer Ridge Member, and the contact between the two members can generally be traced from well to well. The emplacement of the Sentinel Bluffs flows added to the basalt plateau and deposition and reworking continued between the plateau and the very eastern edge of the basin.

A detailed study of the Sentinel Bluffs Member by Reidel (2005) can be used to understand a part of the paleogeographic history of the MPB during the N_2 interval. He showed that the flows of the Sentinel Bluffs Member originated from northerly trending dikes in eastern Washington and Oregon, mixed at the surface, flowed westward, and formed the Cohasset flow in the Pasco Basin of south-central Washington (Reidel, 2005). Spokane Falls dikes crop out along the north side of the Snake River 9 mi (14 km) southwest of Pullman (Reidel, 2005).

A regional study of the uppermost Grande Ronde Basalt from Almota (about 14 mi west of Pullman) northward to Rock Lake (about 24 mi northwest of Colfax) in Whitman County, Washington, shows that mixing occurred during emplacement of the N_2 basalt flows west of the MPB. Eleven samples (see Appendix B for location information) were analyzed from N_2 Grande Ronde flows (Table 2). These samples were from the very uppermost flows; four different compositional types including Spokane Falls were identified. The basalt of Spokane Falls is the youngest of these

compositional types (Reidel, 2005). Pullman must have been at a higher elevation during the earliest eruptions of the Sentinel Bluffs Member due to subsidence of the Columbia Basin and formation of the anticline near Pullman which restricted eastward movement. However, as the volume increased, the younger Spokane Falls flows crested the anticline into the western part of the MPB. The only exit for any major drainage out of the basin at the end of the N_2 interval was between Kamiak and Angel Buttes where the Vantage Member overlies the Meyer Ridge Member (Figure 14). Both the anticline and the emplacement of the basalt of Spokane Falls prohibited westward stream development.

VANTAGE AND WANAPUM INTERVAL

There was a regional decrease in volume and an apparent slowing of volcanic events at the end of the Grande Ronde emplacement. This change is expressed in the western part of the Columbia River flood basalt province by the presence of extensive Vantage sediments that separate the Wanapum Basalt from the Grande Ronde Basalt at most localities (Beeson and others, 1989). Subsidence exceeded volcanism as the early Wanapum flows were primarily confined to the central part of the basin (Reidel and Tolan, 2013b). The source areas for these flows moved westward and northward from the Chief Joseph dike swarm to areas in the northwestern Blue Mountains and into the central part of the Columbia Basin. Upward in the section flows of the Wanapum Basalt onlapped earlier flows toward Pullman until a flow of the Roza Member reached the edge of the MPB. During this time weathering, deposition, and reworking occurred throughout the MPB.

The Vantage Member in the MPB rests on different Grande Ronde Basalt flows and is not a chronostratigraphic unit. Comparisons of lithologies and thicknesses show that there were several different depositional settings within the Moscow-Pullman area. From these comparisons composite reconstructions are possible although time lines have not been determined within the sediments themselves.

On the buried plateau between Moscow and Pullman (Figure 15) the Vantage consists primarily of clay and generally does not exceed 25 ft (8 m) in thickness. Descriptions of these clays from domestic drillers' reports are inconsistent, but dark brown colors dominate. It is believed that these clays are due primarily to soil development on the uppermost Grande Ronde flow. Development of saprolites on uppermost Grande Ronde flows along the eastern margins of the

Table 2. Major-element oxides and trace elements for surface samples of the Sentinel Bluffs Member, Grande Ronde Basalt. Location information provided in Appendix B. [All samples analyzed by Peter Hooper GeoAnalytical Laboratory, WSU, Pullman, Wash.; *, total Fe expressed as FeO]

Sample ID	SR17- ALM-1	SR17- ALM-2	SR17- ALM-3	SR17- CN-1	SR17- CN-2	SR17- DI-1	SR17- EL-1	SR17- MA-1	SR17- PC-1	SR17- PC-2	SR17- TH-1
Elevation (ft)	1520	1430	1420	1990	2090	1900	2195	2240	1840	2000	1770
Flow	basalt of Spokane Falls	basalt of McCoy Canyon	basalt of McCoy Canyon	basalt of Spokane Falls	basalt of Airway Heights– basalt of California Creek	basalt of Spokane Falls	basalt of Spokane Falls– basalt of Stember Creek	basalt of Spokane Falls	basalt of Airway Heights– basalt of California Creek	basalt of Spokane Falls	basalt of California Creek
Major oxides (weight percent)											
SiO_2	54.17	56.55	53.35	53.75	54.39	54.05	53.75	54.22	54.25	54.23	54.80
TiO_2	1.88	2.05	2.54	1.82	1.92	1.83	1.80	1.87	1.91	1.85	2.33
Al_2O_3	14.09	13.94	13.81	14.33	14.42	14.36	14.28	14.61	13.95	14.39	14.12
FeO*	11.85	12.29	14.19	11.61	11.05	11.18	11.59	11.15	11.98	11.21	10.83
MnO	0.21	0.17	0.23	0.20	0.21	0.20	0.20	0.19	0.21	0.20	0.23
MgO	4.57	3.05	3.52	4.97	4.75	4.97	5.09	4.63	4.59	4.71	4.34
CaO	8.52	6.54	7.30	8.97	8.71	8.92	9.04	9.04	8.34	8.90	8.39
Na_2O	2.96	3.41	3.31	2.89	2.94	2.92	2.92	2.84	3.16	2.95	3.04
K_2O	1.36	1.64	1.33	1.18	1.24	1.27	1.06	1.16	1.22	1.26	1.42
P_2O_5	0.38	0.35	0.43	0.29	0.36	0.31	0.27	0.29	0.39	0.29	0.51
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Trace elements (parts per million, ppm)											
Ni	13	6	6	19	15	17	18	18	13	20	12
Cr	32	1	0	41	34	42	44	40	31	41	24
Sc	34	30	34	36	37	37	36	38	36	35	36
V	291	296	366	315	301	317	324	332	291	326	278
Ba	530	722	741	471	558	476	462	493	542	488	836
Rb	31	34	28	28	29	30	26	28	30	30	32
Sr	317	332	339	313	323	314	311	322	310	316	331
Zr	164	188	186	150	162	152	147	154	167	153	176
Y	37	40	40	33	36	34	32	34	36	33	46
Nb	11.5	12.8	13.8	10.4	11.3	10.9	10.2	11.0	11.5	10.8	13.0
Ga	21	21	22	21	21	20	21	21	20	21	20
Cu	31	15	10	37	26	32	34	34	31	36	25
Zn	123	124	139	114	122	112	111	116	121	115	147
Pb	7	11	9	6	6	5	6	6	6	7	7
La	24	25	24	20	22	19	19	23	17	20	25
Ce	49	56	52	38	43	42	39	46	47	43	51
Th	4	6	7	4	4	4	3	4	3	4	5
Nd	25	30	29	23	25	24	23	24	27	22	29
U	2	1	2	2	1	2	3	1	2	0	2

Columbia River flood basalt province is prominent and pervasive (Swanson and others, 1979; Camp, 1981; Reidel and others, 1989a; Tolan and others, 2009). The general lack of coarse sediment between the uppermost Grande Ronde and overlying Wanapum indicates that permanent east-west drainages across the plateau did not exist or were rare at this time.

In Moscow the N_2 of the Grande Ronde and all early Wanapum flows are absent. The Vantage separates the lower part of the Meyer Ridge Member from the overlying Lolo flow, and the duration of deposition may be significant (Bush and others, 2016). These deposits are the thickest of anywhere in the MPB and were reworked numerous times. Sand lenses and layers are common in the clay-silt dominated sequence, and the lack of well-sorted, coarse-grained sediments attests to the lack of consistent stream energy. Bush and others (2016) suggested that the Vantage in Moscow was deposited by anastomosing low-gradient meandering streams. An alternate interpretation is that depositional environments also consisted of coalescing clay- and silt-rich alluvial fans. The sands and occasional gravels encountered in the Vantage in the Moscow area are believed to be channel lag deposits. Wood fragments occur throughout but are most common at the top of the Vantage.

Samples of the clays are difficult to obtain, because the Vantage beneath Moscow is saturated and tends to cave in, requiring rapid drilling. A brown clay typically overlies the Grande Ronde Basalt and is interpreted as a possible saprolite. Overlying coarse sands suggest fluvial processes were active enough to create floodplains with ponds and shallow lakes. The small subbasin at Moscow, surrounded on three sides

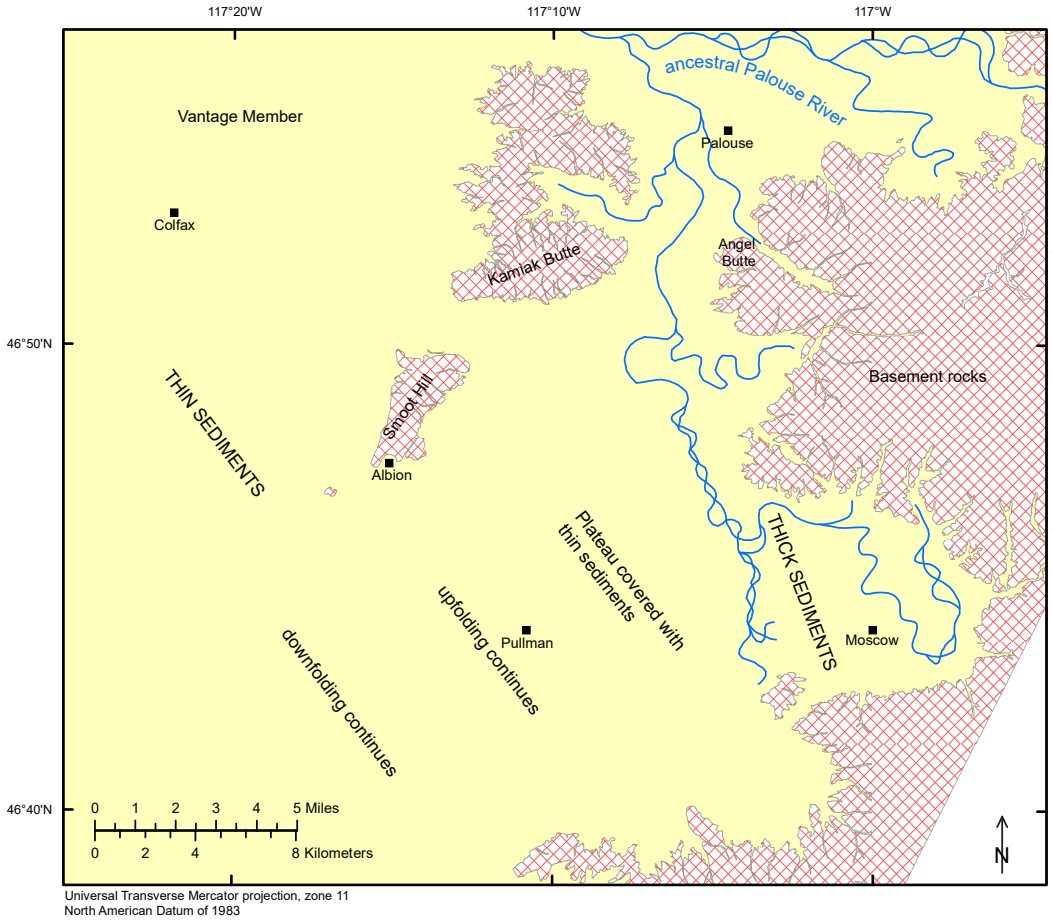

Figure 15. Possible paleogeographic setting for the Moscow-Pullman Basin during deposition of the Vantage Member of the Latah Formation.

by steep mountain fronts, may have been a catch basin that produced a continued water supply to prohibit thick saprolite development.

In Pullman, the Vantage ranges up to 44 ft (13 m) in thickness and consists mostly of clay interbedded with lesser sand and silt on top of N_2 Grande Ronde Basalt. The Vantage exposure along the South Fork Palouse River on the west side of Pullman consists, from base upward, of 4 ft (1.2 m) weathered Grande Ronde Basalt (saprolite), 3 ft (0.9 m) light-gray, silty, fine sand, 4 ft (1.2 m) micaceous, light-gray silt, and 4 ft (1.2 m) light-yellow to gray, silty sand. The coarse sediments follow, in part, the path of the present-day South Fork Palouse River from basement rocks on the south into Pullman along the eastern edge of the anticline. North and northeast of Pullman the composition of the Vantage is variable, but the presence of sands east of the anticline in a few wells suggests that a small stream may have flowed north to northeast to join the drainage from Moscow at the Kamiak-Angel Butte gap area (Figure 15). The anticline was a high area during at least the early part of Vantage deposition as shown by the Roza flow thinning and ending against its western edge (Figure 16). However, thin, sand-bearing Vantage sediments can be traced in the subsurface over the anticline suggesting it may have been crossed a few times by west- or north-flowing streams.

Vantage sediments along the edges and west of the MPB were overlain by a flow of the Roza Member in late Wanapum time. These sediments are generally thin, consist of clay and silt, and rest on the N_2 flows of the Sentinel Bluffs Member. Locally, small pillow lavas at

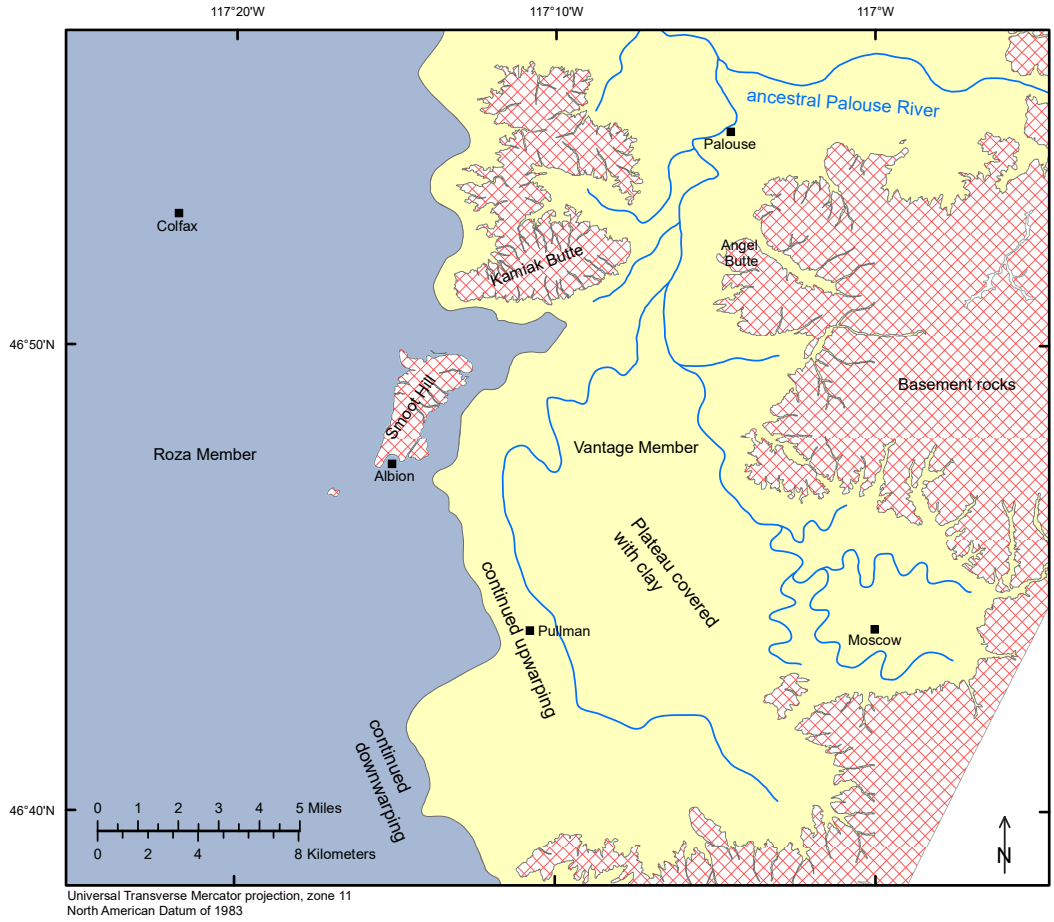

Figure 16. Possible paleogeographic setting for the Moscow-Pullman Basin after the emplacement of the Roza Member of the Wanapum Basalt; modified from Bush and others (2016, Figure 13).

the base of the Roza are present, and muscovite grains are common in the silts. A possible interpretation is that there was minor stream development from the east or edges and inside the MPB. This flow, sourced from linear vents on the Palouse Slope (Swanson and others, 1975; Martin, 1989), covered the Vantage west of the anticline near Pullman (Moxley, 2012) and in the Colfax area northwest of Pullman (Figure 16). The same flow did not reach the Palouse city area, but it must have blocked and pushed the Palouse River further northwest. Pillow lavas in the Roza are very common east of Rock Lake 20 mi (32 km) northwest of Colfax where the Palouse River may have been trying to go around the edges of the lava flow. Within the MPB the interpretation is that the Roza and the anticline continued to block western drainages, and the only exit out of the basin was via the gap between Kamiak and Angel Buttes (Figure 16).

The Lolo flow of the Priest Rapids Member of the Wanapum Basalt was the last of the laterally extensive flows of the CRBG. Vents for the Priest Rapids Member were generally situated along the eastern edges of the Columbia River flood basalt province, and the Lolo flow may have entered the MPB from the north, from within it, as well as from the west. In any case, the Lolo flow completely overwhelmed all drainages of the Palouse River, overran the anticline at Pullman, buried the old channel between Kamiak and Angel Buttes, and flowed to the far eastern edges of the basin (Figure 17). Contacts show that the pre-existing topography was very flat consisting of Vantage sediments and the Roza Member. The plateau between the two cities was probably not a major topographic feature, because the

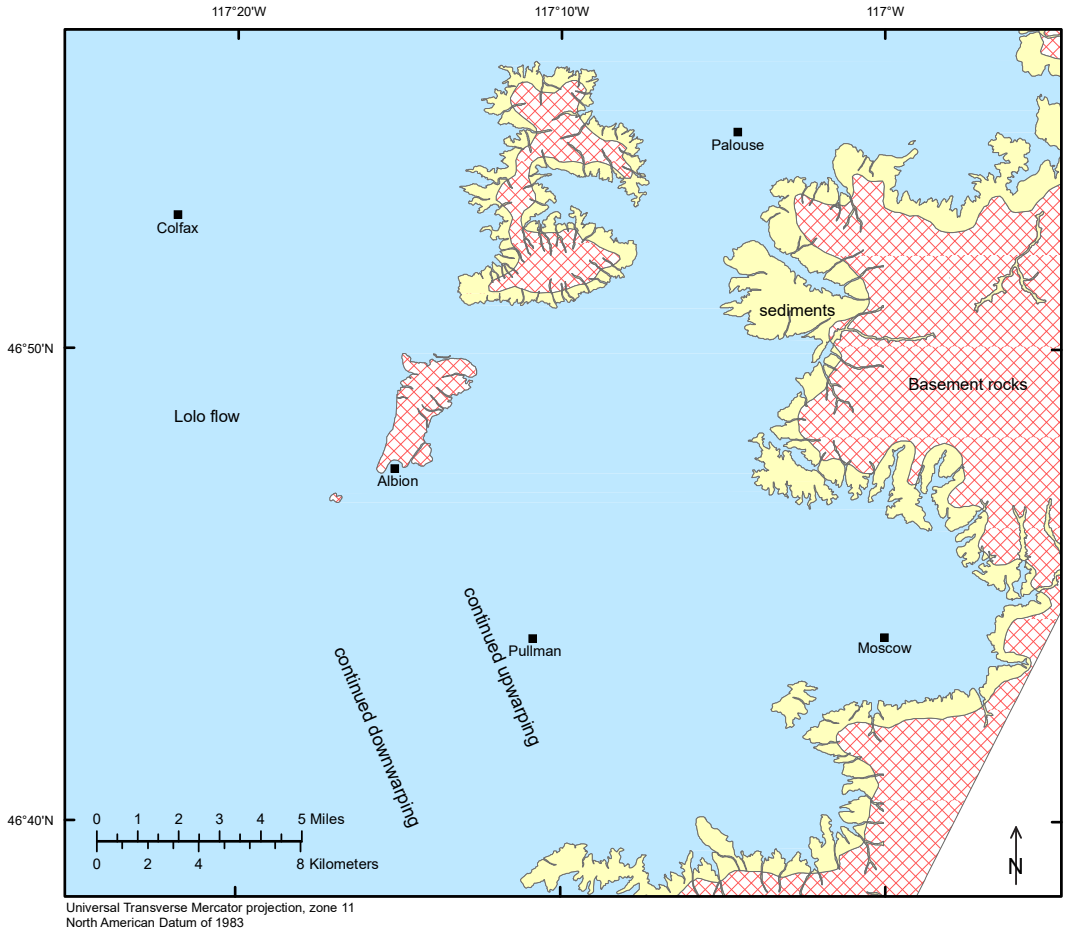

Figure 17. Possible paleogeographic setting for the Moscow-Pullman Basin after the emplacement of the basalt of Lolo of Priest Rapids Member of the Wanapum Basalt.

Vantage filled in the low along the eastern edge, and the Roza filled in the low west of Pullman. Once the Lolo flow had been emplaced, a total of at least 2,250 ft (686 m) of basalt and sediment had been emplaced into the MPB in less than a million years. The lack of any westward drainage and another sudden rise in base level caused deposition of the sediments of Bovill to prograde from weathered mountain fronts over the Lolo toward Pullman (Figure 18) completely covering most of the basin in early Saddle Mountains time.

SADDLE MOUNTAINS TIME

The sediments of Bovill are believed to have been deposited in clay-rich, alluvial fan-meandering stream complexes that extended out from the surrounding mountains (Bush and others, 2016). The primary channels occurred where the present-day headwaters of the Missouri Flat, Paradise, and South Fork Palouse River drainages suddenly change gradient along mountain fronts. Overall, in early Saddle Mountains time, the sediments were choked with clay, erosion was impaired, and coarse-grained sediments occurred only in channels near mountain sources. Later reworking produced coarse-grained sands and granules of quartz in channel areas away from the mountain fronts with kaolinite-rich clays deposited as overbank sediments. Westward from the mountain fronts toward the Idaho-Washington state line, fine sediments dominated and channel development was rare. Resistant quartzites along the northern and western edges contributed some sand, but most of the sediments were derived from high-elevation, weathered granitic rocks from the eastern and southern edges of the basin.

The Asotin and Weissenfels Ridge Members of the

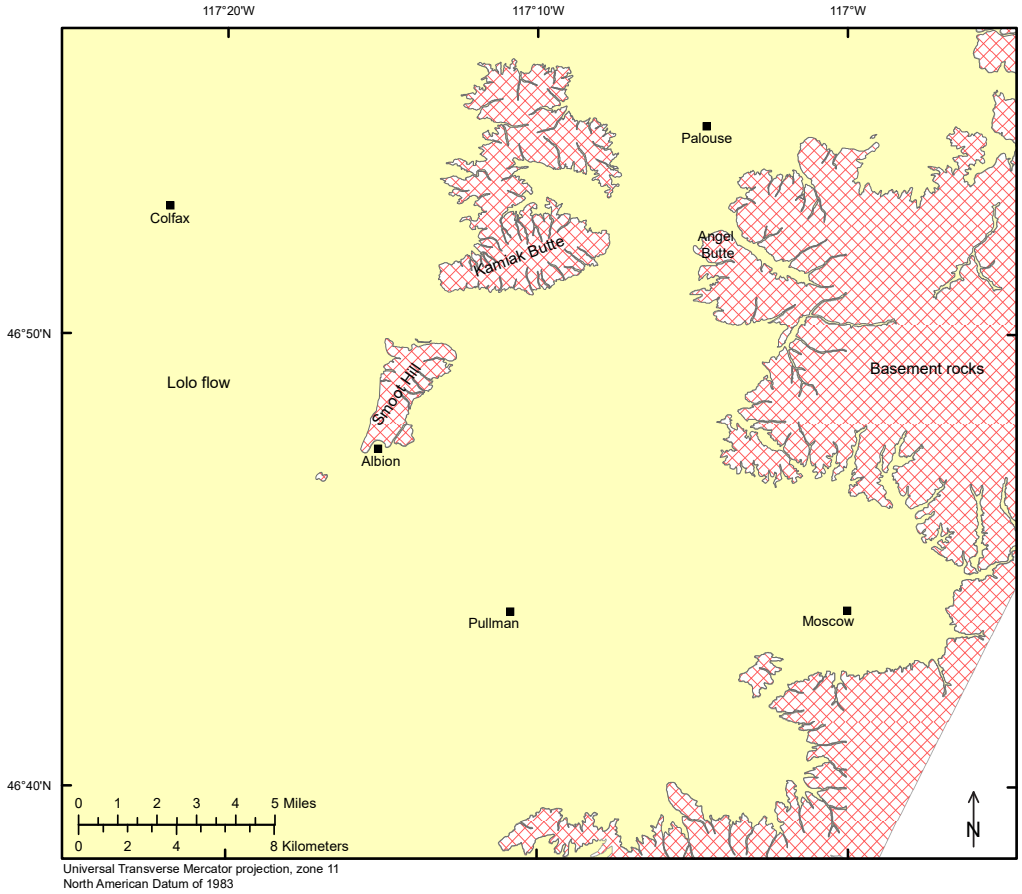

Figure 18. Possible paleogeographic setting for the Moscow-Pullman Basin during the early phases of deposition of the sediments of Bovill.

Saddle Mountains Basalt have been identified in the Moscow-Pullman area (Swanson and others, 1980; Hooper and Webster, 1982; Bush and Provant, 1998; Conrey and Wolff, 2010; Conrey and others, 2013; Bush and others, 2016). In the Lewiston Basin south of Moscow, the Asotin Member is overlain by the Weissenfels Ridge Member (Hooper and others, 1985). The Asotin basalt flowed down a paleochannel of the ancestral Salmon-Clearwater River which turned northwestward along the western edge of the MPB as it exited Idaho. The drainage followed a northwest-plunging syncline and was prohibited from entering the MPB by the anticline at Pullman. South of Colfax the drainage, now filled with Asotin Member basalt, turned westward to join the Columbia River in central Washington (Swanson and others, 1980; Reidel and Tolan, 2013b). These relationships document that subsidence continued west of Pullman after the emplacement of the Lolo flow, as demonstrated in Figure 19.

The Asotin Member was followed by local flows of the Weissenfels Ridge Member that trended northwest in both Pullman and Moscow. These flows, the basalts of Lewiston Orchards and Tenmile Creek, are interbedded with the sediments of Bovill and disrupted local drainage development. Conrey and Wolf (2010) also noted northwest-trending dikes of the basalt of Tenmile Creek in Pullman (Figure 19).

At some point in middle to late Saddle Mountains time a drainage of the South Fork Palouse River eroded a channel across the anticline at Pullman and (or) was captured by a northwest-flowing drainage toward Colfax. Isolated occurrences of sediments of Bovill

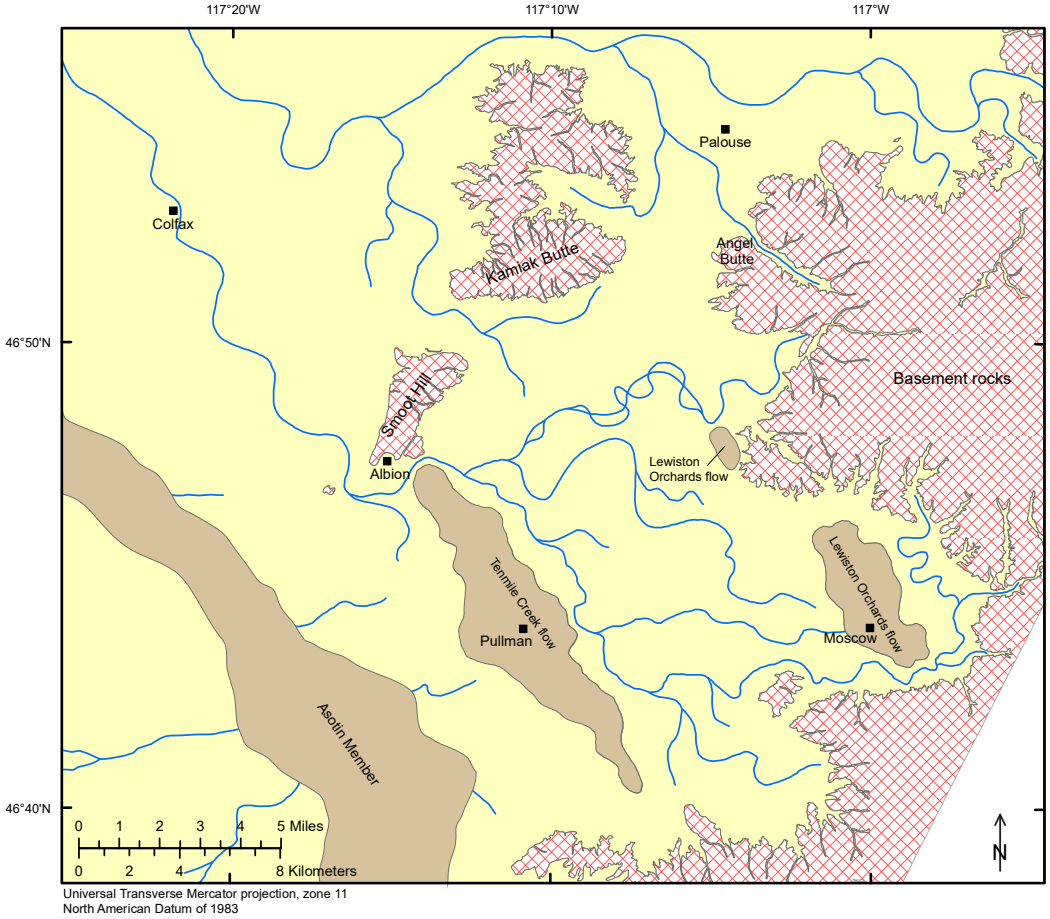

Figure 19. Possible paleogeographic setting for the Moscow-Pullman Basin after emplacement of the Saddle Mountains Basalt (brown).

and basalt flows of the Weissenfels Ridge Member in the Pullman area suggest that the South Fork Palouse River may have been superimposed onto the anticline as the sediments of Bovill were being eroded. Erosion and reworking lasted for over 10 My (Bush and others, 2016) so it is difficult to ascertain when this drainage joined the Palouse River at Colfax. In Moscow the slopes along mountain fronts are present-day, eroded remnants of alluvial fans. Modern streams still have not adjusted to the tremendous volume of sediment and lava emplaced into the MPB in a relatively short period of time.

SUMMARY AND CONCLUSIONS

Several methods were used to determine subsurface stratigraphic relationships within the CRBG and to generate best-fit paleogeographic reconstructions of the evolution of the MPB in the Miocene. They included synthesis of rock-chip chemistry, outcrop determinations, analysis of domestic water-well reports, and correlations of the regional stratigraphy. Our main conclusions are as follows:

1) The MPB, on the eastern edge of the Columbia River flood basalt province, is filled in with basaltic lava of the CRBG and related sediments. The MPB was a relatively stable area during eruption of the CRBG while the Columbia Basin continued to subside in central Washington.

2) Most of the CRBG lava flows entered the basin from the west and blocked primary drainages out of the MPB many times near what is now Pullman, Washington. Exceptions to eastward encroachment of these drainages may include the Lolo flow which erupted east of the MPB and may have, in part, flowed into the basin from the north, as well as the flows of Weissenfels Ridge Member, which were locally sourced.

3) The ancient Palouse River was pushed northwest in early Grande Ronde time; it attempted to reestablish itself at the end of the N_1 interval but eventually reversed direction and flowed north out of the basin toward the city of Palouse in late Grande Ronde time.

4) Sedimentation occurred along lava flow edges and steep mountain fronts, and at times prograded across newly formed basalt plains. Most sediments in the basin are clay rich, and the coarse-grained portions show little evidence of mature stream development. Vantage Member sediments were deposited over a long period of time, do not represent a chronostratigraphic unit, and differ in lithologic content and thicknesses.

5) At the end of Grande Ronde time, a basalt plateau built by westward-offlapping lava flows existed between Moscow and Pullman. A saprolite of clay developed on the plateau which was part of a regional surface along the eastern edge of the Columbia River flood basalt province. At the same time, thick sediments of the Vantage accumulated primarily in fluvial and pluvial environments along mountain fronts in the Moscow area.

6) The development of a northwest-trending growth anticline across the western edge of the basin was established at least as early as the R_2 interval of the Grande Ronde Basalt. This anticline played a role in controlling lava access to the basin and in the overall lack of stream development.

7) There were two major events that occurred in late Wanapum time. First, a Roza Member flow reached the western edge of the MPB, and second, the last laterally extensive flow (basalt of Lolo of the Priest Rapids Member) obliterated all remaining drainages as it overran a nearly flat terrain of basalt and sediment.

8) Folding continued after emplacement of the Lolo flow, and an early flow of the Saddle Mountains Basalt (Asotin Member) followed a shallow, ancestral Salmon-Clearwater drainage that had developed in a northwest-plunging syncline west of Pullman.

9) The sediments of Bovill unit is considered to have been deposited as clay-rich, westward-prograding alluvial fans that filled the basin up to depths of at least 500 ft (152 m) and covered the anticline at Pullman. Local flows of the Weissenfels Ridge Member were contemporaneously interbedded within the sediments.

10) The MPB has not recovered from the massive emplacement of the CRBG flows and associated sediments. The present-day Palouse River resides outside the basin, and the anticline at Pullman continues to impair the development of any major western drainage out of the basin.

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APPENDIX A: Geochemical Identification of Flow Units in the Columbia River Basalt Group

INTRODUCTION

Subdivision of the Columbia River Basalt Group (CRBG) into formations, members and individual flow units in the Moscow-Pullman basin was achieved primarily by geochemical analysis of rock chip samples collected from water and test wells drilled in the area. The stratigraphic sequence of units, as determined from our analysis, is consistent from well to well with minor overlap of interpretations at flow or member boundaries. The chemical signature of some CRBG units is so distinctive that they can be identified without additional comparative studies. Other CRBG flows require examination of comparative plots of major and minor elements to regional data sets. This appendix illustrates plots utilized to help identify and subdivide parts of the sequence into recognized stratigraphic members and flows.

OLDEST FLOWS OF THE COLUMBIA RIVER BASALT GROUP

The oldest basalt flow (328 ft [100 m] in thickness) encountered at depth in the Moscow-Pullman basin was penetrated in Washington State University (WSU) well 7 where it was originally interpreted as Imnaha Basalt (Bush and Hayden, 1987) based upon the presence of plagioclase phenocrysts in a coarse-grained matrix. This interpretation held in subsequent studies (Bush and Garwood, 2005; Conrey and Wolff, 2010). In this study, we reexamined the analyses to either verify or correct this interpretation. The overlying Grande Ronde Basalt is typically fine grained. However, the oldest member of the Grande Ronde Basalt, the Buckhorn Springs Member, is also relatively coarse grained and can have plagioclase phenocrysts (Reidel, 1983; Reidel and Tolan, 2013, Table 2), so it is possible to confuse the two based on well cuttings.Chemical composition is a more reliable means for identification.

Hooper and others (1984) stated that the Imnaha Basalt can be distinguished from the Grande Ronde Basalt by its lower K_2O and SiO_2 contents. In addition, Al_2O_3 is typically higher in the Imnaha Basalt than in the Grande Ronde Basalt. Hooper and Hawkesworth (1993) used Ce/Nb vs. Ce/Zr and Ba/Nb vs. Nb/Y plots to also separate the Imnaha Basalt from the Grande Ronde Basalt.

In Figure A1 we have plotted the analyses on four variation diagrams: (A) K_2O vs.Al_2O_3, (B) K_2O vs. SiO_2, (C) Nb vs. P_2O_5, and (D) Nb vs. Zr. These diagrams use a more current, larger database of Imnaha Basalt and Buckhorn Springs Member sample analyses (Stephen P. Reidel, 2017, unpub. data) than was available to Hooper and others (1984) and Hooper and Hawkesworth (1993). An overlap between the Imnaha Basalt and Buckhorn Springs Member is clearly visible in the K_2O vs. Al_2O_3 and K_2O vs. SiO_2 variation diagrams. Using the larger database, these oxides do not appearto be very useful in separating the oldest flow in WSU well 7 as either Imnaha Basalt or the Buckhorn Springs Member.

In Figure A1-C and D, the samples from the oldest flow in WSU well 7 are plotted using Nb, Zr, and P_2O_5. Hooper and Hawkesworth (1993) were able to distinguish Imnaha Basalt from the Grande Ronde Basalt using these elements and oxide.These two diagrams clearly show that the oldest flow in WSU well 7 is part of the Buckhorn Springs Member of the Grande Ronde Basalt and not Imnaha Basalt.

GRANDE RONDE BASALT MEMBERS AND FLOWS

Individual flows of the Grande Ronde Basalt are difficult to distinguish in well cuttings and outcrops because of the typically aphyric nature of the flows. Reidel and others (1989) proposed nomenclature based on the Grande Ronde stratigraphy of Reidel (1983). This nomenclature has since been updated (Reidel and Tolan, 2013) and forms the basis for flow identification used here. Figures A2 and A3 are variation diagrams from Reidel and Tolan (2013, Figure 7) which are used to identify the Grande Ronde Basalt members present in the Moscow-Pullman basin.

These diagrams show that the R_1 magnetostratigraphic unit (MSU) in the Moscow-Pullman basin, from the base upward, consists of the Buckhorn Springs Member, the basalt of Joseph Creek, Teepee Butte Member, and an overlying sequence of undifferentiated Downey Gulch, Brady Gulch, and Kendrick Grade members (Figures A1, A2-A). These units are similar in composition and

best differentiated by paleomagnetic polarity. The N_1 MSU consists of the Frye Point member (Figure A2-B) and the Cold Spring Ridge Member (Figure A3-A). The R_2 MSU consists of the Mount Horrible, Wapshilla Ridge, Meyer Ridge, and Grouse Creek members (Figure A3-B, C). The N_2 MSU consists of the Winter Water and Sentinel Bluffs members (Figure A3-D).

The Meyer Ridge Member and the basalt of Stember Creek, Sentinel Bluffs Member, are similar, and it can be difficult to distinguish them from one another. Reidel and Tolan (2013, Table 3) show the main discriminating elements are Ni and Cr, with the Meyer Ridge Member having higher concentrations. In the Moscow-Pullman basin, the Winter Water Member is present in WSU well 7 and lies between the Meyer Ridge and Sentinel Bluffs members, thus confirming that the Meyer Ridge Member is present and the basalt of Stember Creek absent at that location.

In Figure A4 we have plotted the Sentinel Bluffs compositions from the Moscow-Pullman basin in Figure 3 of Reidel (2005). Figure A4 shows that the flows of the Sentinel Bluffs Member mainly consist of the basalt of Spokane Falls. There are also compositions of the basalt of McCoy Canyon present near the base of the Sentinel Bluffs in WSU well 7 and at the top of the basalt of Spokane Falls in Pullman city wells 5 and 7.This is not unexpected as the basalt of McCoy Canyon was erupted nearby and at the same time which allowed several of the flows to mix or comingle. WSU well 7 and Pullman city wells 5 and 7 are near each other on the west side of the basin; this suggests that the first Sentinel Bluffs flow to enter the basin was of the McCoy Canyon composition and that the basalt of Spokane Falls either invaded it or mixed with it to produce a single flow.

WANAPUM BASALT

The fields of the main Wanapum Basalt members from our database (Reidel, 2017, unpub. data) are plotted in color in Figure A5. Superimposed on this diagram are samples, in black, from the Priest Rapids and Roza members in the Moscow-Pullman basin. This figure shows that the basalt of Lolo is the main flow of the Priest Rapids Member in this area and is easily distinguished from the Roza Member. The Roza Member is typically easy to identify in well cuttings due to abundant plagioclase phenocrysts that characterize the unit.

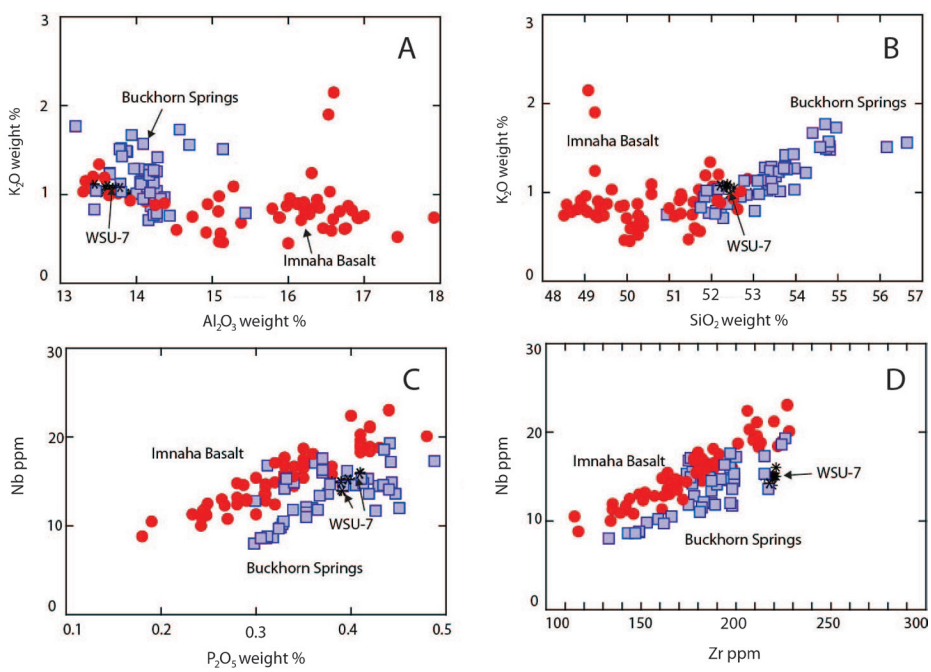

Figure A1. Variation diagrams of selected elements and oxides for Imnaha Basalt, Buckhorn Springs Member of the Grande Ronde Basalt, and samples from the oldest three flows in WSU well 7. Symbols in color are for Imnaha Basalt and Buckhorn Springs Member samples from our current database of Columbia River Basalt Group analyses (Stephen P. Reidel, 2017, unpub. data). Black asterisk (*), WSU well 7 (WSU-7); blue square, Buckhorn Springs Member; red circle, Imnaha Basalt.

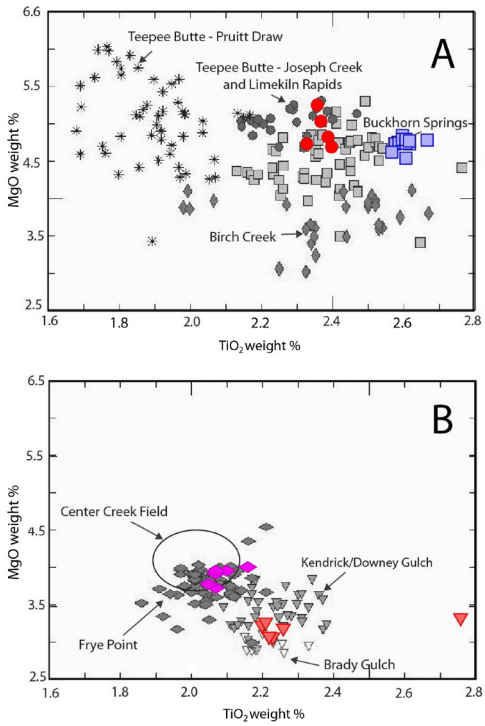

Figure A2. Variation diagrams of MgOvs. TiO_2 for Grande Ronde Basalt members in the R_1 and lower N_1 magnetostratigraphic units. Symbols in black are from our current database of Columbia River Basalt Group analyses (Reidel and Tolan, 2013, Figure 7; Stephen P. Reidel, 2017, unpub. data); symbols in color are for samples in the Moscow-Pullman basin. (A) blue square, Buckhorn Springs Member; red circle, basalt of Joseph Creek, Teepee Butte Member; (B) violet diamond, Frye Point member; red triangle, Downey Gulch-Bradley Gulch-Kendrick Grade members.

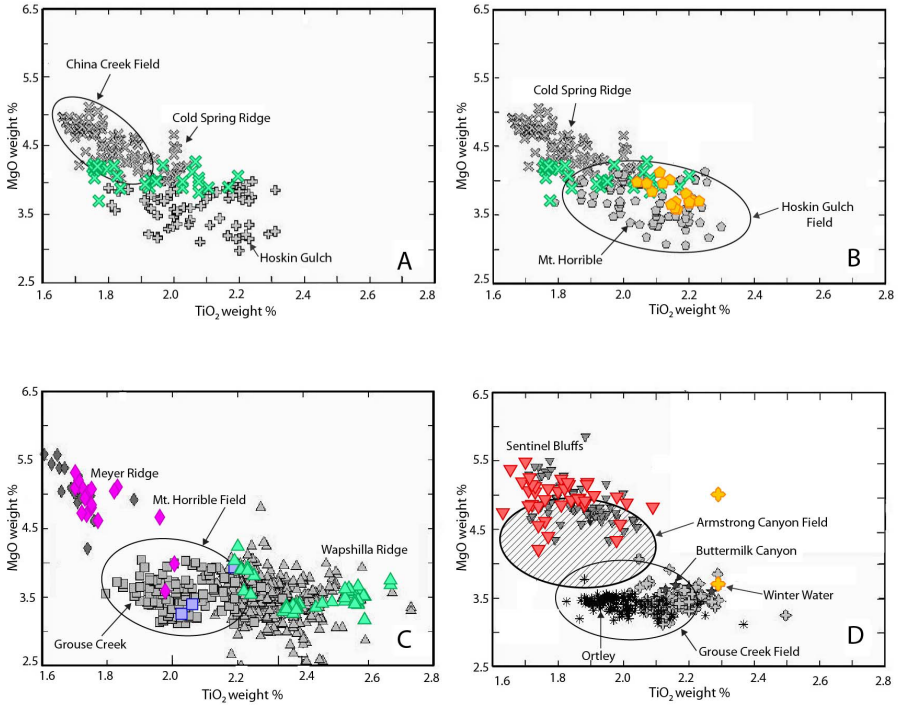

Figure A3. Variation diagrams of MgO vs. TiO_2 for Grande Ronde Basalt members in the upper N_1, R_2, and N_2 magnetostratigraphic units. Symbols in shades of black are from our current database of Columbia River Basalt Group analyses (Reidel and Tolan, 2013, Figure 7; Stephen P. Reidel, 2017, unpub. data). Corresponding symbols in color are for samples in the Moscow-Pullman basin: (A) green "x", Cold Spring Ridge Member; (B) green "x", Cold Spring Ridge Member; yellow pentagon, Mount Horrible member; (C) green triangle, Wapshilla Ridge Member; purple square, Grouse Creek member; dark pink diamond, Meyer Ridge Member; (D) yellow "plus" sign, Winter Water Member; red inverted triangle, Sentinel Bluffs Member.

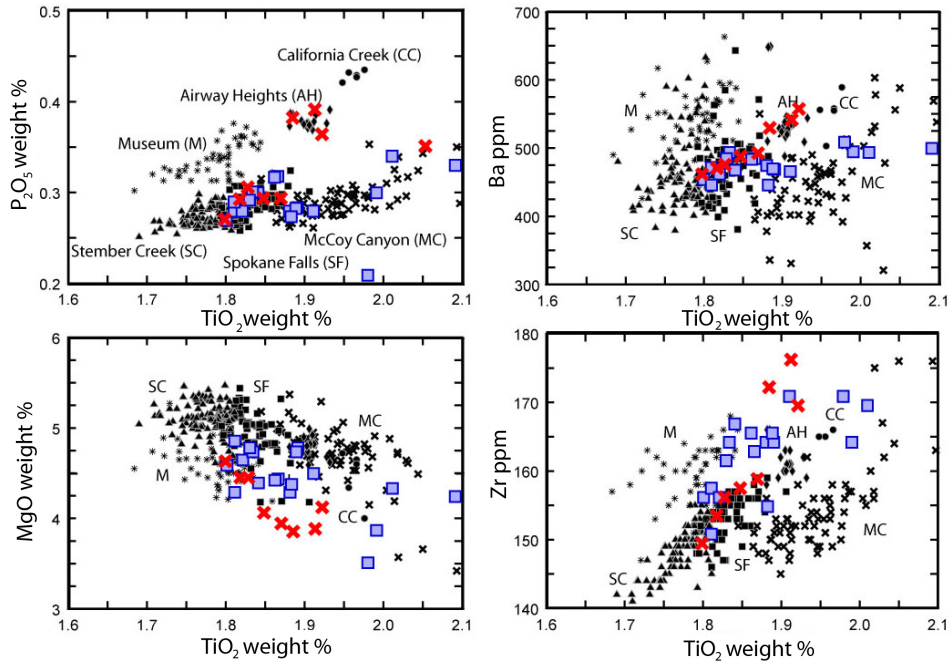

Figure A4. Variation diagrams showing the fields for four compositional types of the Sentinel Bluffs Member, Grande Ronde Basalt (from Reidel, 2005, Figure 3), as black symbols: asterisk (*), basalt of Museum (M); rectangle, basalt of Spokane Falls (SF); triangle, basalt of Stember Creek (SC); x, basalt of McCoy Canyon (MC). Symbols in color are from the Moscow-Pullman basin: blue square, basalt of Spokane Falls.

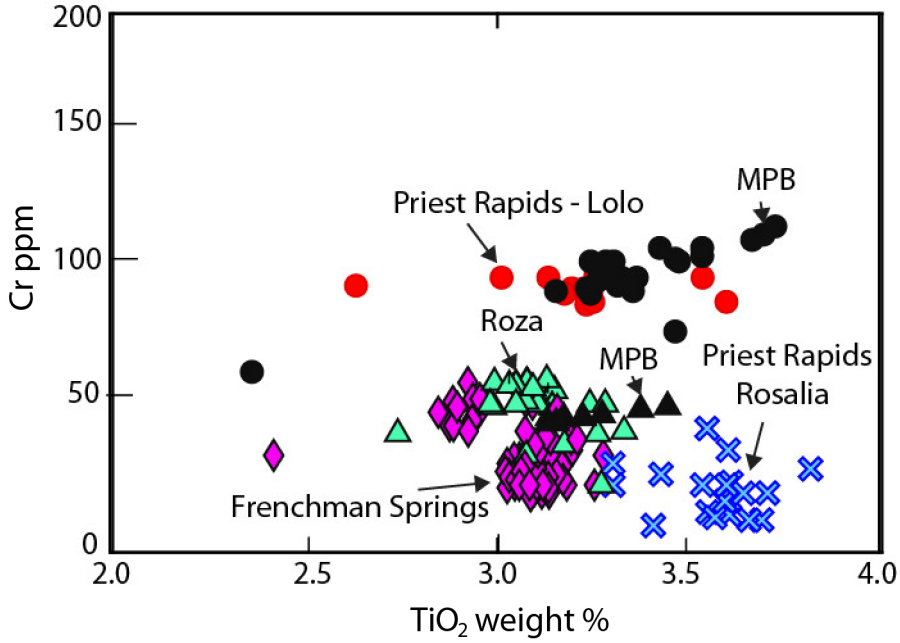

Figure A5. Variation diagram of Cr vs. TiO_2 for samples from the Wanapum Basalt. Symbols in color are for samples from our current database of Columbia River Basalt Group analyses (Stephen P. Reidel, 2017, unpub. data): blue "x", basalt of Rosalia, Priest Rapids Member; green triangle, Rosa Member; red circle, basalt of Lolo, Priest Rapids Member; violet diamond, Frenchman Springs Member. Symbols in black are for samples from the Moscow-Pullman basin (MPB): black circle, basalt of Lolo, Priest Rapids Member; black triangle, Roza Member.

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APPENDIX B: Regional Rock Samples

Locations for the eleven rock samples collected from the uppermost Grande Ronde Basalt flows that crop out southwest, west and northwest of the Moscow-Pullman basin are provided in Table B1.

Table B1. Sample location information.

Sample Identifier	Latitude (degrees)	Longitude (degrees)	Elevation (ft)	7.5-Minute Quadrangle	Comments
SR17-ALM-1	46.72123	-117.48391	1520	Almota	Almota grade, east side of Almota Road, below Roza Member; lots of thin (5–10 ft [1.5–3 m]) units.
SR17-ALM-2	46.71713	-117.48139	1430	Almota	Almota grade, east side of Almota Road; thin units, black glassy, pseudo flow banding, weathers with gray rind.
SR17-ALM-3	46.71631	-117.48186	1420	Almota	Almota grade, east side of Almota Road; thin vesicular units.
SR17-CN-1	46.89070	-117.36468	1990	Colfax North	North side of WA-26 at junction with US-195, downtown Colfax.
SR17-CN-2	46.93081	-117.28483	2090	Colfax North	East side of Glenwood Road, opposite junction with N. Palouse River Road at north end of Glenwood bridge.
SR17-DI-1	46.93956	-117.43000	1900	Diamond	North side of Manning Road, north side of Palouse River; large outcrop.
SR17-EL-1	46.98309	-117.22224	2195	Elberton	Southeast side of Elberton Road, under north abutment of bridge over Palouse River.
SR17-MA-1	47.23272	-117.37526	2240	Malden	Small quarry, west side of Rosalia, west of railroad tracks, east of John Wayne Trail and west of Betty Bruce Road (dead end road, south off W 7th St).
SR17-PC-1	47.23813	-117.59599	1840	Pine City	East side of Hole-In-The-Ground Road/Belsby Road, northeast of Rock Lake, southeast of Rock Creek, first bench up from creek.
SR17-PC-2	47.24313	-117.59681	2000	Pine City	North side of Hole-In-The-Ground Road/Belsby Road, northeast of Rock Lake, northwest of Rock Creek, second bench up from creek; lots of vesicles, spiracles.
SR17-TH-1	46.95306	-117.50441	1770	Thera	Southwest side of Shields Road, northwest bank of Palouse River at Torrence Bridge abutment.