The Geological Society of America
Field Guide 15
2009

An introduction to the stratigraphy, structural geology, and hydrogeology of the Columbia River Flood-Basalt Province: A primer for the GSA Columbia River Basalt Group field trips

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ABSTRACT

The Miocene Columbia River Basalt Group (CRBG) covers a large part of Oregon, Washington, and Idaho and is one of the youngest and perhaps the best studied flood-basalt province on Earth. Decades of study have established a regional stratigraphic framework for the CRBG, have demonstrated the CBRG flows can be correlated with dikes and vents, have documented a wide variety of physical features within the CRBG flows, and have demonstrated that many characteristics of the CRBG are recognizable throughout its extent. Detailed studies of individual flows and their feeder dikes have allowed the development of models for the emplacement of voluminous basaltic lava flows. The interplay between the regional structure, contemporaneous deformation, preexisting topography, and paleodrainage systems helped to control the emplacement of individual CRBG flows. These features have also affected the nature of late Neogene sedimentation in the region covered by basalt flows. Finally, the distribution of sediments within the CRBG and the character of the intraflow and interflow structures have played a significant role in the development of aquifers within the CRBG. In this paper we present an overview of the regional aspects of the stratigraphy, structural geology, tectonics, and hydrogeology of the CRBG.

Tolan, T.L., Martin, B.S., Reidel, S.P., Anderson, J.L., Lindsey, K.A., and Burt, W., 2009, An introduction to the stratigraphy, structural geology, and hydrogeology of the Columbia River Flood-Basalt Province: A primer for the GSA Columbia River Basalt Group field trips, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 599–643, doi: 10.1130/2009.fld015(28). For permission to copy, contact editing@geosociety.org.

INTRODUCTION

Four field trip guides in this volume examine the geology, tectonics, and hydrogeology of the Miocene Columbia River Basalt Group (CRBG), a flood-basalt province covering a large part of Oregon, Washington, and Idaho (Tolan et al., this volume; Wells et al., this volume; Lindsey et al., this volume; Burt et al., this volume). Decades of study have established a regional stratigraphy and nomenclature for the CRBG and have demonstrated that many characteristics of the CRBG are recognizable throughout its extent. The purpose of this paper is to present an overview of the common regional aspects of the stratigraphy, structural geology, and hydrogeology of the CRBG and to provide a basic stratigraphic framework for all of the field trips in the region.

The Columbia River Basalt Group is an example of a continental flood-basalt province, a type of large igneous province erupted onto largely continental crust and dominated by great thicknesses of basaltic lava flows (Jerram and Widdowson, 2005). The CRBG erupted between 17 and 6 Ma and inundated more than 200,000 km^2 of Washington, Oregon, and Idaho (Fig. 1). It is one of the youngest and best preserved continental flood-basalt provinces on Earth. Although the province includes the Steens Basalt and related flows of southeast Oregon as part of the CRBG (Camp et al., 2003; Camp and Ross, 2004), our focus in this paper is on the area covered by the field trips on the Columbia Plateau and in western Oregon and Washington.

The CRBG also hosts an important regional aquifer system that is the primary water supply for numerous communities and a multibillion-dollar agricultural economy. Understanding the basic geology and structural geology of the CRBG has played an important role in interpreting and defining the characteristics and behavior of the CRBG aquifer system across this province. The following sections will provide an introduction to (1) the regional setting and stratigraphic framework of the CRBG, (2) physical characteristics of CRBG flows, (3) eruptive history and mode of emplacement of CRBG flows, (4) structural geology, and (5) hydrogeology of the CRBG.

REGIONAL SETTING

The CRBG was erupted in a backarc setting from a series of dike swarms close to the boundary between the Precambrian craton and largely Mesozoic accreted terranes to the west (Fig. 1). The flood basalts inundated the intermontane basin in the backarc, flowing eastward to the Rocky Mountains and westward through the Cascade arc, Willamette Valley and Coast Range, and finally into the Miocene forearc basins offshore (Fig. 1). The basalt-filled intermontane basin (between the Cascade volcanic arc and the Rocky Mountains) is commonly called the Columbia Plateau, where the basalts are more than 3 km thick in its central and west-central portions (Reidel et al., 1989b).

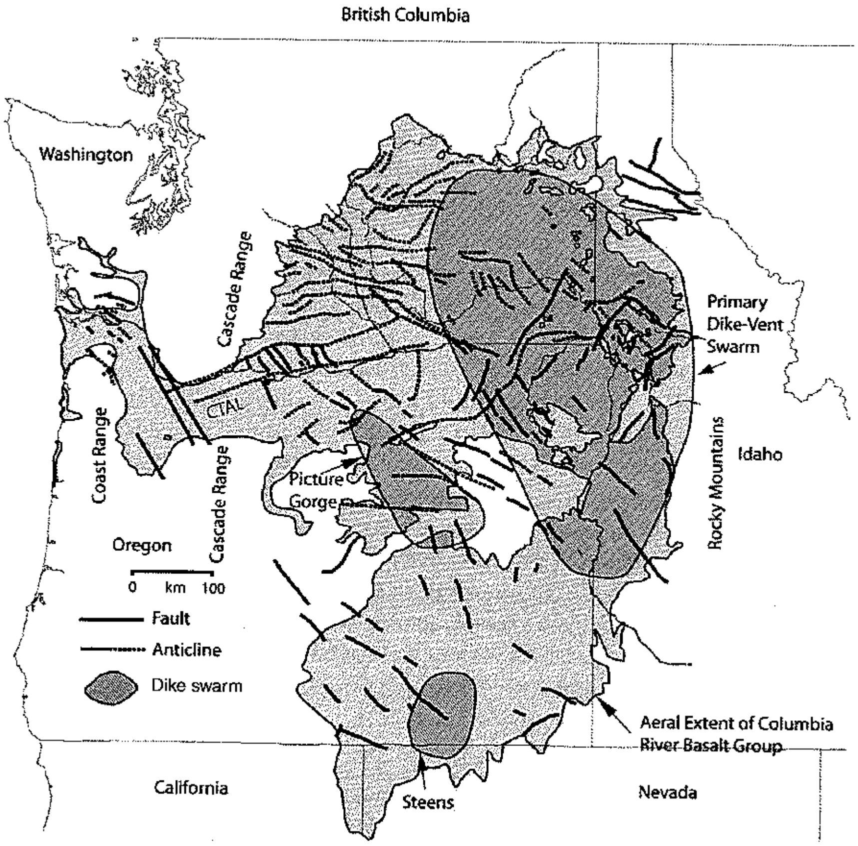


Figure 1. Map showing the extent of the Columbia River Flood-Basalt Province. CTAL—Columbia Trans-Arc Lowland.

Rocks older than the CRBG are exposed around the margins of the flood-basalt province and in deep boreholes. To the northeast, the CRBG laps onto a cratonic assemblage of Proterozoic metasediments of the Windermere and Belt Supergroups, miogeosynclinal lower Paleozoic shallow marine rocks, rocks associated with the Kootenay Arc, and granitic rocks of the Idaho Batholith and other Jurassic and Cretaceous intrusions (Stoffel et al., 1991). The structural grain of these rocks is north to northeast. To the southeast, the CRBG overlies lower to middle Tertiary volcanic rocks and related volcaniclastic rocks mostly assigned to the Clarno and John Day Formations, which themselves overlie northeast-trending belts of Cretaceous to Permian accreted terranes of intra-arc and volcanic arc origin (Walker, 1979; Walker and MacLeod, 1991).

The Cascade volcanic arc forms a broad, south-plunging arch along the western margin of the Columbia Plateau. The CRBG is uplifted 300 to >600 m on the flanks of the arch, and fault bounded pre-Tertiary terranes and Eocene and Oligocene sediment-filled rift basins of the North Cascades plunge to the southeast beneath the basalt (Tabor et al., 1984; Campbell, 1989).

Where the arch plunges to the south, the flood-basalt flows of the CRBG crossed the Miocene Cascade volcanic arc into the forearc via a 60-km-wide, east-northeast–trending lowland gap (Columbia Trans-Arc Lowland; Beeson et al., 1989a; Fig. 1). Cascade arc volcanism continued after emplacement of the flood basalt, and arc volcanic rocks overlie the CRBG in northern Oregon and southern Washington. Advancing westward, the flood basalts covered much of the northern Willamette Valley region and crossed the Coast Range (Fig. 1). Eventually the CRBG flows reached the Pacific Ocean (Fig. 1) and advanced out onto the continental shelf (Niem and Niem, 1985). In the forearc, the CRBG typically unconformably overlies marine strata, forearc related volcanics, and accreted oceanic terranes (Armentrout et al., 1983; Niem and Niem, 1985; Yeats et al., 1991; Wells, 2006).

STRATIGRAPHIC FRAMEWORK OF THE COLUMBIA RIVER BASALT GROUP

Historical Perspective

The pioneering studies of Waters (1961), Mackin (1955, 1961), and Grolier and Bingham (1971, 1978) developed a basic Columbia River basalt stratigraphic framework that could be correlated and mapped over geographically large areas. Subsequent studies of the Columbia River basalt employing traditional mapping methods along with geochemical and paleomagnetic fingerprinting, demonstrated that mappable units of regional extent (Fig. 2) could be uniquely defined (Swanson et al., 1979a, 1979b, 1980, 1981; Beeson and Moran, 1979).

Most of the research efforts in the CRBG from the late 1970s to 1988 were funded by the U.S. Department of Energy's (USDOE) Basalt Waste Isolation Project (BWIP), which examined the suitability of constructing a deep repository in the CRBG for the final disposal of high-level nuclear waste beneath Hanford in south-central Washington State.

A tremendous amount of data and information on CRBG geology and hydrogeology was produced by BWIP and its cooperative research partners. Results from BWIP's investigations are summarized in the first three volumes of the Site Characterization Plan (U.S. Department of Energy [USDOE], 1988). Geological Society of America Special Paper 239 (Reidel and Hooper, eds., 1989) presents a comprehensive summary of the results of this period of cooperative research into the regional stratigraphic framework and tectonics of the Columbia River Flood-Basalt Province. In the post-BWIP era, much of the effort in CRBG research has been directed into investigating the emplacement process and history of these huge flood-basalt flows (e.g., Reidel and Tolan, 1992; Reidel et al., 1994b; Ho and Cashman, 1997; Self et al., 1996, 1997; Reidel, 1998), refining the stratigraphy of the CRBG, especially the monotonous Grande Ronde Basalt, and understanding the hydrogeology of the CRBG (Oberlander and Miller, 1981; Livesay, 1986; Drost and Whiteman, 1986; Lite and Grondin, 1988; Davies-Smith et al., 1988; USDOE, 1988; Burt, 1989; Johnson et al., 1993; Hansen et al., 1994; Spane and Webber, 1995; Wozniak, 1995; Steinkampf and Hearn, 1996; Packard et al., 1996; Sabol and Downey, 1997; Tolan et al., 2000b; Ground Water Management Area [GWMA], 2007a, 2007b). The following sections describe our current understanding of the physical characteristics and emplacement mechanism of CRBG flows.

General

The CRBG (Fig. 2) consists of a thick sequence of more than 300 continental tholeiitic flood-basalt flows that were erupted over an 11 million year period from ca. 17 to 6 Ma (Swanson et al., 1979b; Tolan et al., 1989). These flood-basalt flows cover an area over 200,000 km^2 in Washington, Oregon, and western Idaho (Fig. 1) and have a total estimated volume of more than 224,000 km^3 (Camp et al., 2003). These volumetric figures include the Steens Basalt and correlative units in southeast Oregon, which are now considered to be part of the CRBG. The source for most of the flows was a series of north-northwest–trending linear fissure systems located in eastern Washington, eastern Oregon, and western Idaho (Fig. 1).

Although the eruptive activity associated with the CRBG spans an 11 million year period, more than 96% of the volume of the CRBG was erupted over a period of ~2.5 million years, from 17 to 14.5 Ma (Swanson et al., 1979b; Fig. 3). New radiometric ages (Barry et al., 2008) indicate that the entire Grande Ronde Basalt may have erupted in only 250,000 yr. During this peak period of activity, many of the flows that were erupted were of extraordinary size, exceeding 1000 km^3 in volume with some as much as 5000 km^3, and traveled many hundreds of kilometers from their vent system (Tolan et al., 1989; Reidel et al., 1989a; Reidel, 1998, 2005). These gigantic CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history. Figure 4 presents a same-scale comparison between a CRBG flow, the Laki (Skaftar Fires) flow field (largest basalt eruption in recorded human history; Thordarson and Self, 1993) and the ongoing Pu'u O'o eruption on the Big Island of Hawaii. CRBG flows represent the largest individual lava flows known on Earth (Tolan et al., 1989).

The flow of lava away from the vent systems was directed by major tectonic features of the Palouse Slope, Columbia Basin, and Columbia Trans-Arc Lowland (Fig. 1) and continued regional subsidence (Reidel et al., 1994a; Beeson et al., 1989a; Reidel and Tolan, 1992). They combined to produce a regional gradient to the west for the flows.

Stratigraphic Subdivisions of the CRBG and Their Identification

Detailed study and mapping of the Columbia River flood-basalts has allowed for the establishment of stratigraphic units that can be reliably identified and correlated on a regional basis (e.g., Swanson et al., 1979a, 1979b; Beeson et al., 1985; Reidel et al., 1989b; Wells et al., 1989; Reidel, 2005). The CRBG has been divided into five formal formations (Swanson et al., 1979b)—the Imnaha, Grande Ronde, Picture Gorge, Wanapum, and Saddle Mountains Basalts (Fig. 2). Figure 5 presents a series of maps

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

Figure 2. Chart showing stratigraphy and nomenclature for the Columbia River Basalt Group (CRBG). From Reidel et al. (2002).

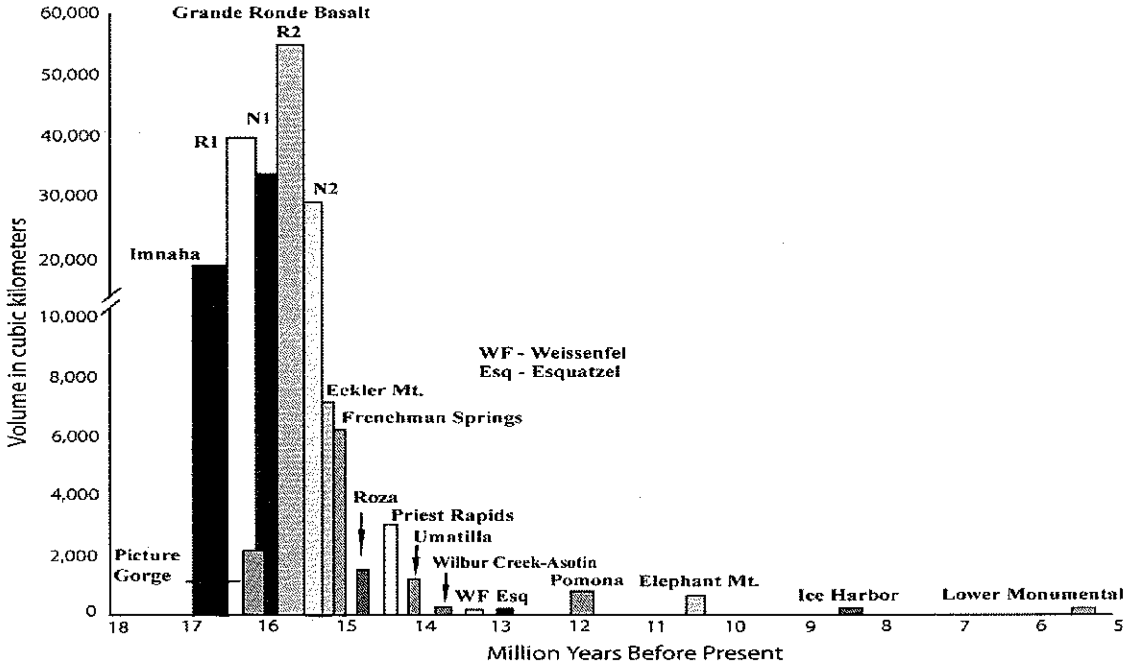


Figure 3. Plot showing the emplacement history for the Columbia River Basalt Group (CRBG) units based on volume estimates from Tolan et al. (1989). Note the change in scale for volume.

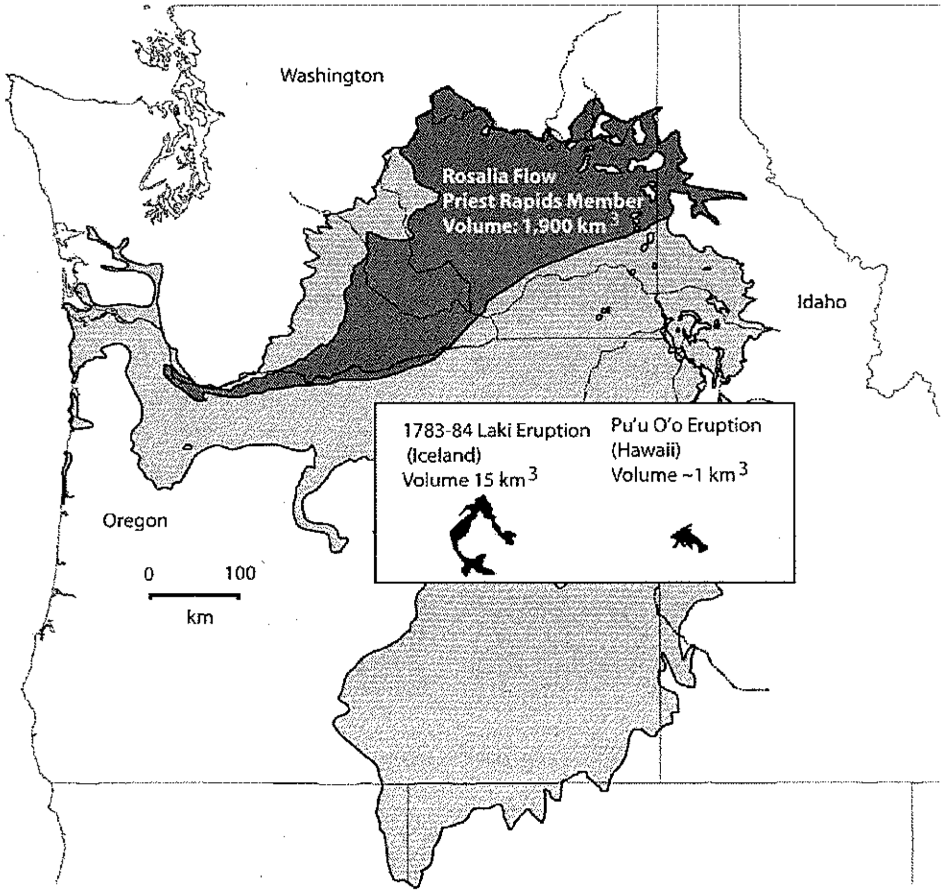


Figure 4. Comparison of the size of the Rosalia (Priest Rapids Member, Wanapum Basalt) flow to largest historical basalt flows (1783–1784 Laki eruption, Iceland, and 1983–present Pu'u O'o, Kilauea Volcano, Hawaii).

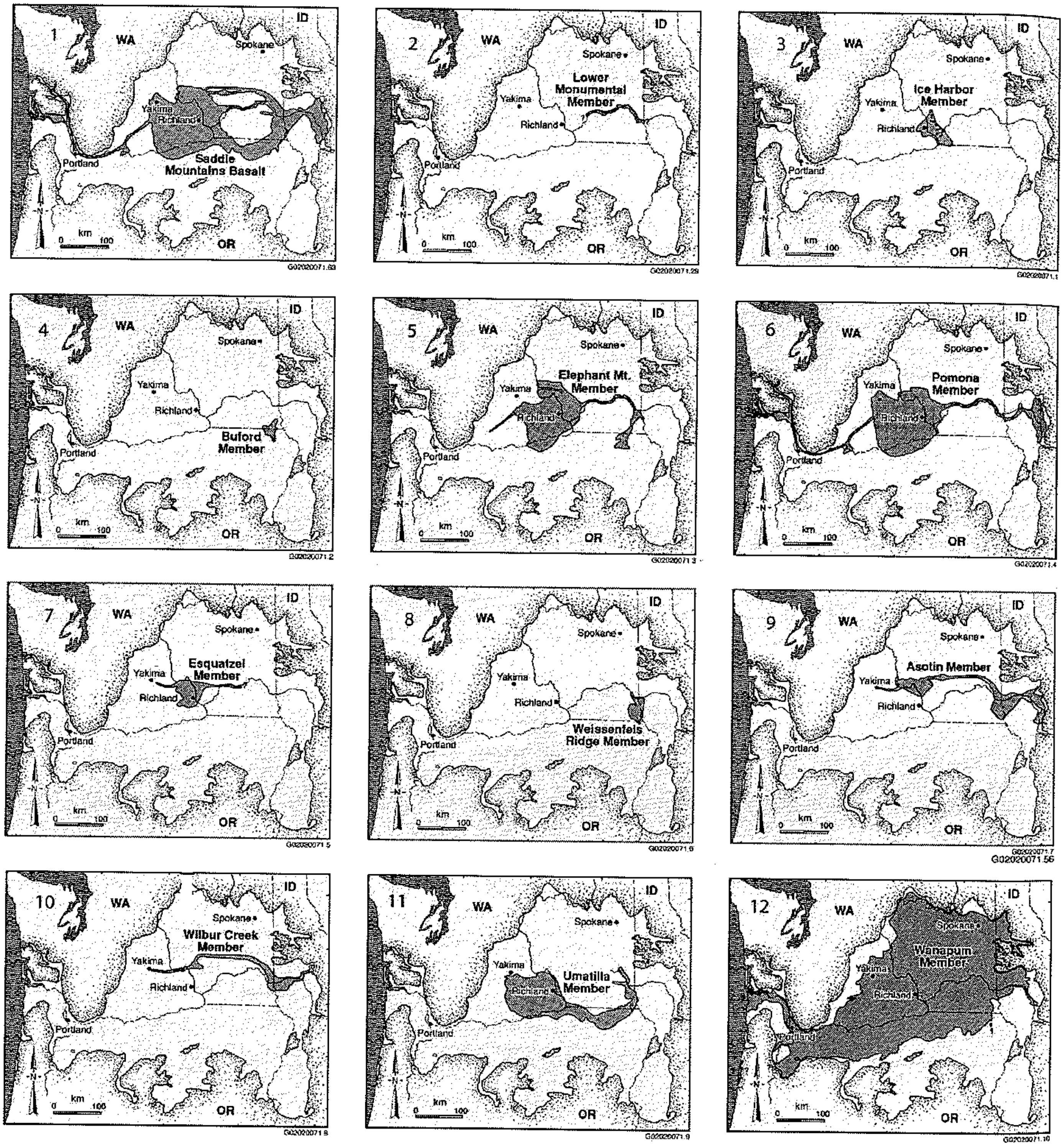
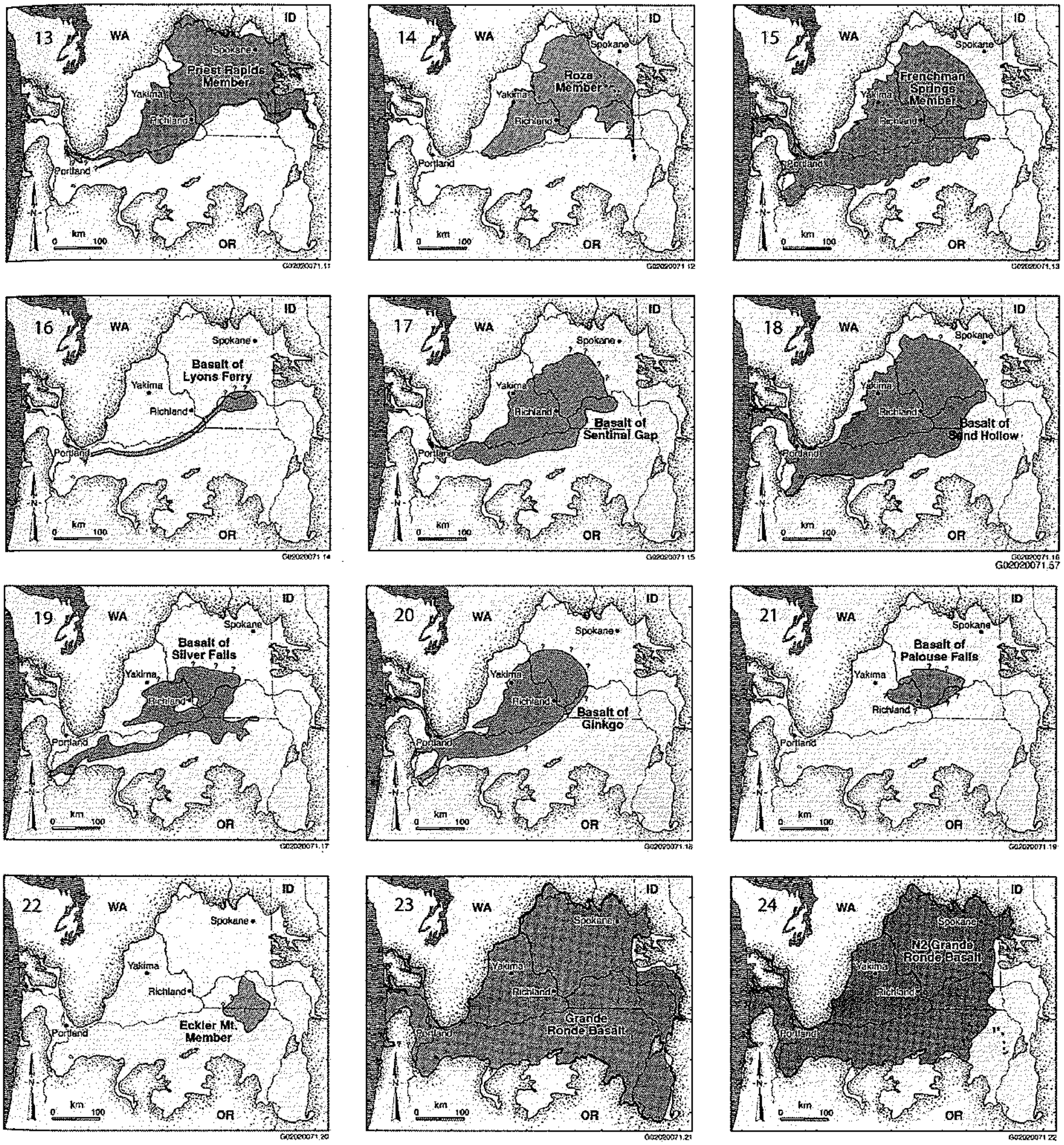


Figure 5 (*on this and following three pages*). Distribution maps for the Columbia River Basalt Group (CRBG). From Tolan et al. (1989) and Reidel et al. (1989b).



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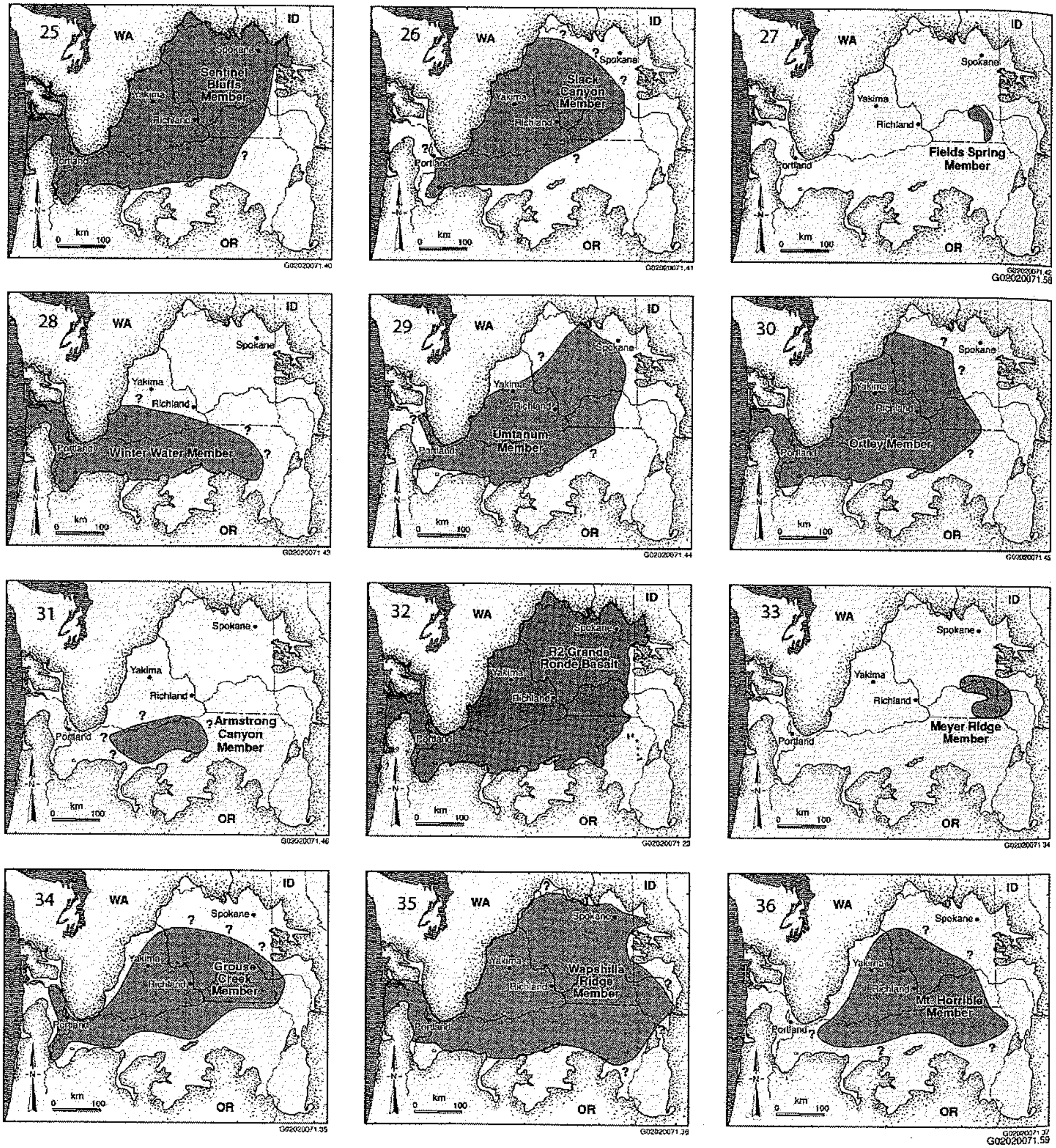

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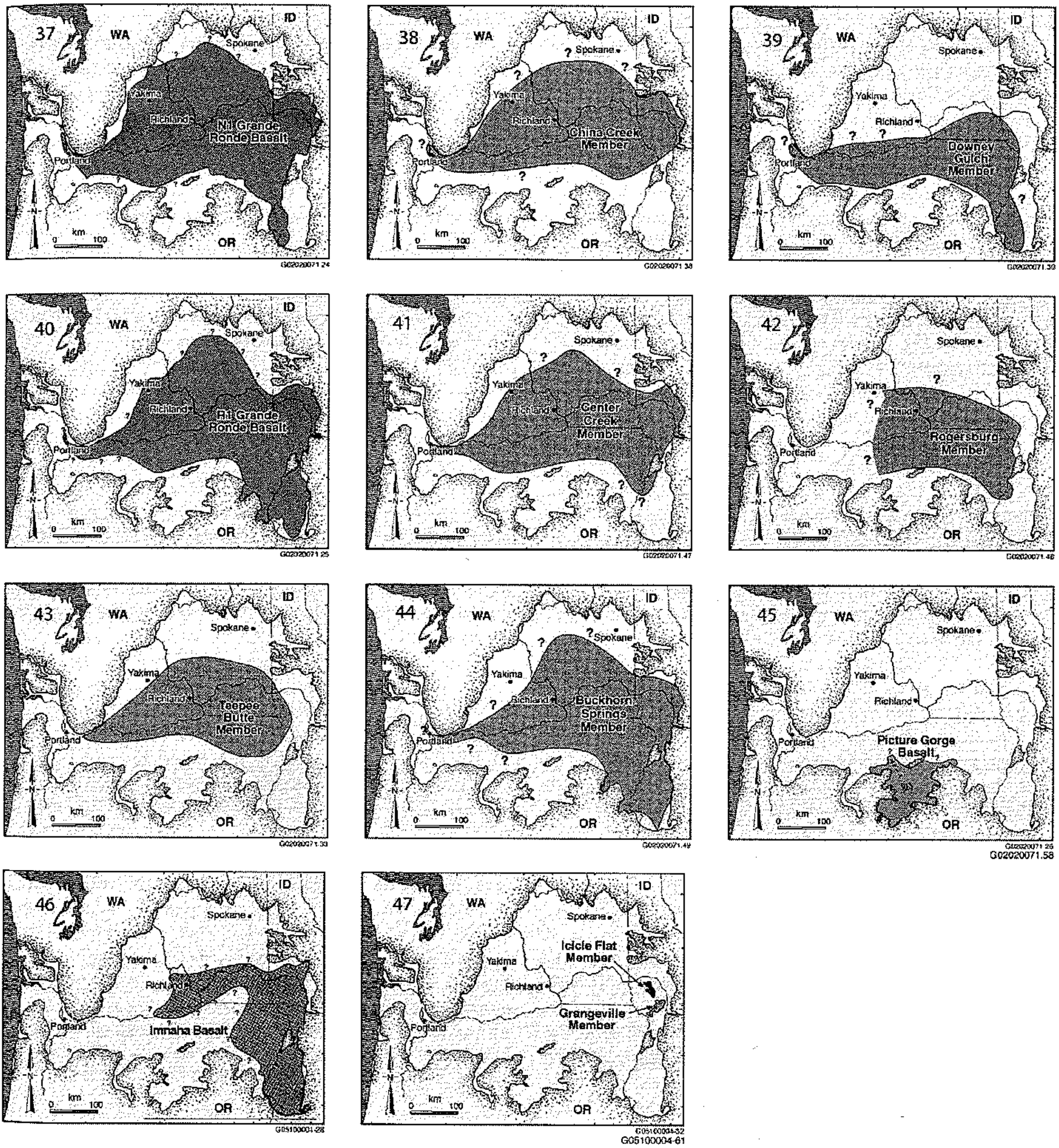

Figure 5 (*continued*).

showing the distribution of currently defined CRBG units. The field trips will examine mainly units belonging to the Grande Ronde, Wanapum, and Saddle Mountains Basalts.

CRBG units are identified using a combination of lithology, paleomagnetic properties, and geochemical composition with regard to superposition (Swanson et al., 1979b; Beeson et al., 1985, 1989a; Reidel et al., 1989b; Wells et al., 1989; Reidel, 1998, 2005). Lithology, paleomagnetic polarity, and superposition can be used to identify and map CRBG units in the field. The most important aspect of the lithology of CRBG units is the presence or absence of plagioclase phenocrysts (e.g., see Swanson et al., 1979b; Beeson et al., 1985; Reidel et al., 1989b). Variations in the relative abundance, sizes, and habits of the plagioclase phenocryst are often the best field diagnostic criterion for certain CRBG units. Some CRBG units (e.g., Frenchman Springs Member flows; Fig. 2) have several distinct size populations of plagioclase phenocryst. If the plagioclase phenocrysts are very small in size (0.1–0.5 cm), they are often referred to a "microphenocrysts" ("microphyric") to distinguish them from larger (0.5 to >3 cm) plagioclase phenocrysts or clots of plagioclase phenocrysts ("glomerocrysts"). Macroscopic olivine and augite phenocrysts are rare but do occur in a few CRBG units (e.g., Pomona Member, Saddle Mountains Basalt; Meyer Ridge Member, Grande Ronde Basalt) and serve as a distinguishing characteristic in the field.

Determination of the paleomagnetic polarity of CRBG flows (using a portable fluxgate magnetometer in the field) has proved to be an important criterion in the identification and mapping of CRBG units. Paleomagnetic laboratory analysis of oriented, small-diameter cores from CRBG flows have established that certain CRBG flows possess distinctive paleomagnetic directions (e.g., Rietman, 1966; Kienle, 1971; Coe et al., 1978; Choiniere and Swanson, 1979; Van Alstine and Gillette, 1981; Magill et al., 1982; Reidel et al., 1984; Beeson et al., 1985; USDOE, 1988; Wells et al., 1989, this volume). Although field collection of oriented cores can require much effort and be challenging, paleomagnetic data from this work has proved to be extremely useful in helping to establish and correlate CRBG units.

Over the past 30 years the CRBG has been extensively analyzed for major oxides, minor oxides, and trace and rare earth elements, which, coupled with other field criteria, has been used to establish a regional-scale, mappable, stratigraphy (Wright et al., 1973, 1989; Swanson et al., 1979b; Beeson et al., 1985; Reidel et al., 1989b; Wells et al., 1989; Hooper, 2000; Reidel, 2005). A major reason that CRBG geochemical stratigraphy was possible on a regional scale was due to the remarkable "bulk" geochemical homogeneity of individual CRBG eruptions despite their huge volumes and distances traveled (Wright et al., 1973, 1989; Beeson et al., 1985; Reidel et al., 1989b; Hooper, 2000). Apparent geochemical heterogeneity within CRBG flows is often due to varying degrees of secondary weathering and alteration of the CRBG flow that may not always be obvious (Wells et al., this volume). Therefore care must be exercised to always obtain the freshest rock for analysis, especially when the data are used for Grande Ronde Basalt and Frenchman Springs Member (Wanapum Basalt) unit identification. There are a few documented examples of primary geochemical heterogeneity within CRBG flows (e.g., minor crystal settling—Reidel and Tolan, 1992; surface mixing of CRBG flows—Reidel and Fecht, 1987; Reidel, 1998, 2005), but these appear to be the exception rather than the rule.

Table 1[1] presents geochemical composition of selected CRBG units. Although this selection does not include every CRBG unit known, it provides geochemical compositions of many of the CRBG units that will be encountered during the field trips.

Generally the most diagnostic elements to consider are TiO_2, P_2O_5, Cr, MgO, Zr, and Ba.

Saddle Mountains Basalt units typically have a much wider and diverse range of geochemical composition than the other older CRBG formations (Figs. 6A and 6B; Wright et al., 1989; Hooper, 2000; Reidel et al., 2002). The geochemical composition of Wanapum Basalt units generally falls into two broad groupings, the first encompassing the Shumaker Creek, Priest Rapids, Roza, and Frenchman Springs Members, and the second consisting of the older Eckler Mountain Member units (Fig. 6B; Wright et al., 1989; Hooper, 2000). Flows of the Wanapum Basalt typically will have higher TiO_2 than the Grande Ronde Basalt. Grande Ronde Basalt members display a relatively narrow range of geochemical compositions that typically exhibit small, but significant, variations in TiO_2, P_2O_5, Cr, and MgO (Fig. 6B; Table 1 [see footnote 1]).

When collecting CRBG samples for analysis, care should always be taken to obtain the freshest samples possible. This is especially important when dealing with CRBG units (e.g., Grande Ronde Basalt members) where the diagnostic geochemical variations have a small range. Table 2 presents a series of analyses from samples, collected at different locations, from the center portion of the same Sentinel Bluffs Member flow (Grande Ronde Basalt) in the northern Willamette Valley, Oregon. Degree of weathering for the samples reported in Table 2 increases from none (fresh, dark-gray–black-appearing basalt—sample AU-2) to moderate (light-gray oxidized-appearing basalt—sample WE-850). As shown in Table 2, even slight to moderate weathering can significantly alter the geochemical "signature" of CRBG flows. This underscores the importance of using the multiple criteria approach for the identification of CRBG units and not relying on a single criterion, such as geochemistry, alone.

Intraflow Structures

Intraflow structures are primary, internal features or stratified portions of basalt flows exhibiting grossly uniform macroscopic

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[1] GSA Data Repository Item 2009244, Table 1, geochemical data on selected CRBG units, is available at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

characteristics. These features originate during the emplacement and solidification of each flow and result from variations in cooling rates, degassing, thermal contraction, and interaction with the paleoenvironment during emplacement. They are distinct from features formed by tectonic processes.

Intact CRBG flows have a flow top, a dense interior, and a flow bottom (Fig. 7). The contact between two individual basalt flows (i.e., a flow top and overlying basalt flow bottom) is referred to as an interflow zone.

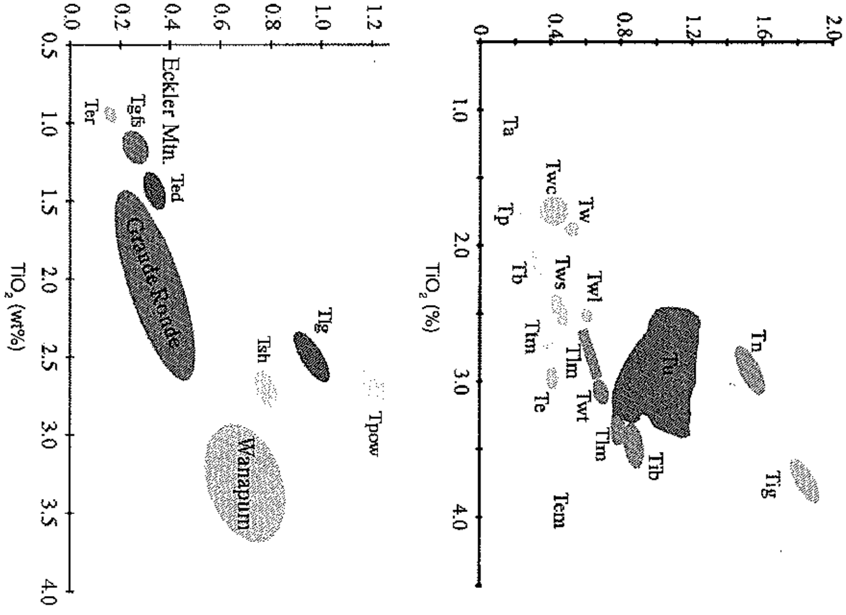

Figure 6. (A) TiO_2 versus P_2O_5 plot for all Saddle Mountains Basalt units. Abbreviations: Tlm—Lower Monumental Member; Ttm—Basalt of Tammany Creek; Tig—Basalt of Goose Island, Ice Harbor Member; Tim—Basalt of Martindale, Ice Harbor Member; Tib—Basalt of Basin City, Ice Harbor Member; Tb—Buford Member; Tem—Elephant Mountain Member; Tn—Basalt of Eden; Tp—Pomona Member; Te—Esquatzel Member; Tws—Basalt of Slippery Creek, Weissenfels Ridge Member; Twt—Basalt of Tenmile Creek, Weissenfels Ridge Member; Twl—Basalt of Lewiston Orchards, Weissenfels Ridge Member; Twc—Basalt of Cloverland, Weissenfels Ridge Member; Ta—Asotin Member; Tw—Wilbur Creek Member; and Tu—Umatilla Member. (B) TiO_2 versus P_2O_5 plot for Grande Ronde Basalt and Wanapum Basalt with selected members and flows of these formations shown separately. Abreviations: Tpow—Basalt of Powatka; Tsh—Shumaker Creek Member; Tlg—member of Lookingglass; Ted—Basalt of Dodge, Eckler Mountain Member; Ter—Basalt of Robinette Mountain, Eckler Mountain Member; and Tgfs—member of Fields Spring, Grande Ronde Basalt.

TABLE 2. THE EFFECTS OF WEATHERING ON THE COMPOSITION OF A SENTINEL BLUFFS MEMBER FLOW (GRANDE RONDE BASALT)

Sample ID	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	LOI (%)	TOTAL (%)			
AU-2	53.42	13.58	12.91	0.188	4.55	8.37	3.10	1.14	1.900	0.33	0.25	99.74			
WASH58005-130	53.43	13.69	13.06	0.173	4.36	8.15	2.89	1.06	1.915	0.33	0.77	99.82			
WASH58005-110	55.65	14.68	10.61	0.170	3.24	7.56	3.26	1.06	2.000	0.34	1.37	99.95			
DMW18A 28-29	53.77	14.47	10.67	0.154	3.95	8.20	2.91	1.11	1.997	0.34	1.79	99.36			
Canby 10	53.22	14.27	11.09	0.140	3.76	8.01	2.96	1.12	1.971	0.31	2.51	99.37			
WE-850	50.57	17.93	10.89	0.140	2.19	6.71	3.23	0.55	2.595	0.35	3.90	99.06			
Sample ID	Co (ppm)	Cr (ppm)	Cs (ppm)	Hf (ppm)	Sc (ppm)	Th (ppm)	U (ppm)	La (ppm)	Ce (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Tb (ppm)	Yb (ppm)	Lu (ppm)
AU-2	45	39	–0.5	4.0	40.3	3.5	1.5	22.1	49	28	6.7	2.0	0.8	3.6	0.54
WASH58005-130	35	29	–0.5	3.9	37.9	3.6	–0.5	19.7	39	19	6.0	1.7	0.8	3.2	0.45
WASH58005-110	50	35	1.9	4.1	38.2	3.8	–0.5	21.2	42	27	6.2	1.8	–0.5	3.3	0.48
DMW18A 28-29	28	38	1.0	4.1	37.0	3.5	1.1	20.9	41	20	5.9	2.0	0.9	3.2	0.52
Canby 10	29	39	1.9	3.3	41.0	3.2	0.9	29.5	37	27	7.4	2.0	0.9	3.3	0.51
WE-850	66	54	2.2	6.1	52.7	4.7	1.3	39.8	76	46	10.8	3.5	1.7	6.4	0.99
Sample ID	Ag ppm	Cd ppm	Cu (ppm)	Ni (ppm)	Pb (ppm)	Zn (ppm)	Bi (ppm)	S (ppm)	Ba (ppm)	Sr (ppm)	Y (ppm)	Zr (ppm)	Be (ppm)	V (ppm)	
AU-2	1.0	–0.3	25	14	6	112	3	0.046	497	312	34	152	1	319	
WASH58005-130	0.6	–0.3	20	14	15	123	–2	0.012	478	320	32	154	1	316	
WASH58005-110	0.6	–0.3	28	14	14	138	–2	0.005	577	343	33	160	1	310	
DMW18A 28-29	–0.3	0.7	31	12	–3	119	5	NR	611	335	34	161	1	317	
Canby 10	0.4	0.4	43	15	–3	112	14	0.030	563	338	37	147	2	313	
WE-850	1.1	–0.3	14	14	9	230	–2	0.007	685	377	69	191	2	379	

Note: Degree of weathering increases from none (sample AU-2) to moderate (sample WE-850). All samples collected from the northern Willamette Valley, Oregon. Analyses performed by ActLabs, Ancaster, Ontario, Canada. LOI—loss on ignition. NR—no reading.

Flow Top

The flow top is the chilled, glassy upper crust of the flow. It may consist of vesicular to scoriaceous basalt, displaying pahoehoe- or a'a-like textures, or it may be rubbly to brecciated (Waters, 1960; Diery, 1967; Swanson and Wright, 1981). Typically a CRBG flow top occupies ~10%–20% of the thickness of a flow, but in extreme cases, it can range from <1% to >90% of the entire flow thickness. The physical character of flow tops falls between two basic end-members, a simple vesicular flow top and a flow-top breccia (Figs. 7 and 8).

A simple vesicular flow top (Fig. 8A) commonly consists of glassy to fine-grained basalt that displays a rapid increase in the density of vesicles as you near the top of the flow (USDOE, 1988; McMillan et al., 1989). Vesicles may be isolated or interconnected (USDOE, 1988). CRBG simple vesicular flows commonly display features and textures indicative of pahoehoe flows (i.e., has a glassy, smooth, and billowy or undulating surface).

A flow-top breccia (Fig. 8B) consists of angular, scoriaceous to vesicular fragments of basaltic rubble that lies above a zone of nonfragmented, vesicular to vuggy basalt. Flow-top breccias can be very thick (over half the flow thickness—more than 30 m thick) and laterally extensive (USDOE, 1988). There are two models for the origin of CRBG flow-top breccias: (1) the scoria (breccia) was originally produced along the linear fissure system and subsequently rafted away on top of the flowing lava and (2) an autobrecciation process similar to that which creates a'a flows in Hawaii. In either case, laterally extensive flow-top breccias are relatively common flow-top feature within the CRBG.

Dense Interior

CRBG flow interiors typically consist of dense, nonvesicular, glassy to crystalline basalt that contains numerous contraction joints (termed "cooling joints"). These cooling joints formed in response to tensional stress created by the contraction of solidified portions of a flow as it cooled below the solidus (Spry, 1962). CRBG cooling joints most often form regular patterns or styles, with the two most common being entablature-colonnade and columnar-blocky jointing (Figs. 7 and 9). Columnar-blocky jointing typically consists of mostly vertically oriented, poorly to well-formed, polygonal columns (Figs. 9A and 9B) that can range from 0.5 m to greater than 3 m in diameter. The vertical columns are often cut by horizontal to subhorizontal cooling joints. Entablature-colonnade jointing (Fig. 9C) displays a more complex pattern that forms within a single flow. The entablature portion displays patterns varying from numerous, irregular jointed small columns to randomly oriented cooling joints that abruptly overlie a thinner zone displaying well-developed columnar jointing. The transition zone between the entablature and the basal colonnade may be very narrow, generally less than several centimeters in width. Typically the entablature is thicker than the basal colonnade, often comprising at least two-thirds of the total flow thickness. Another characteristic of entablatures is that

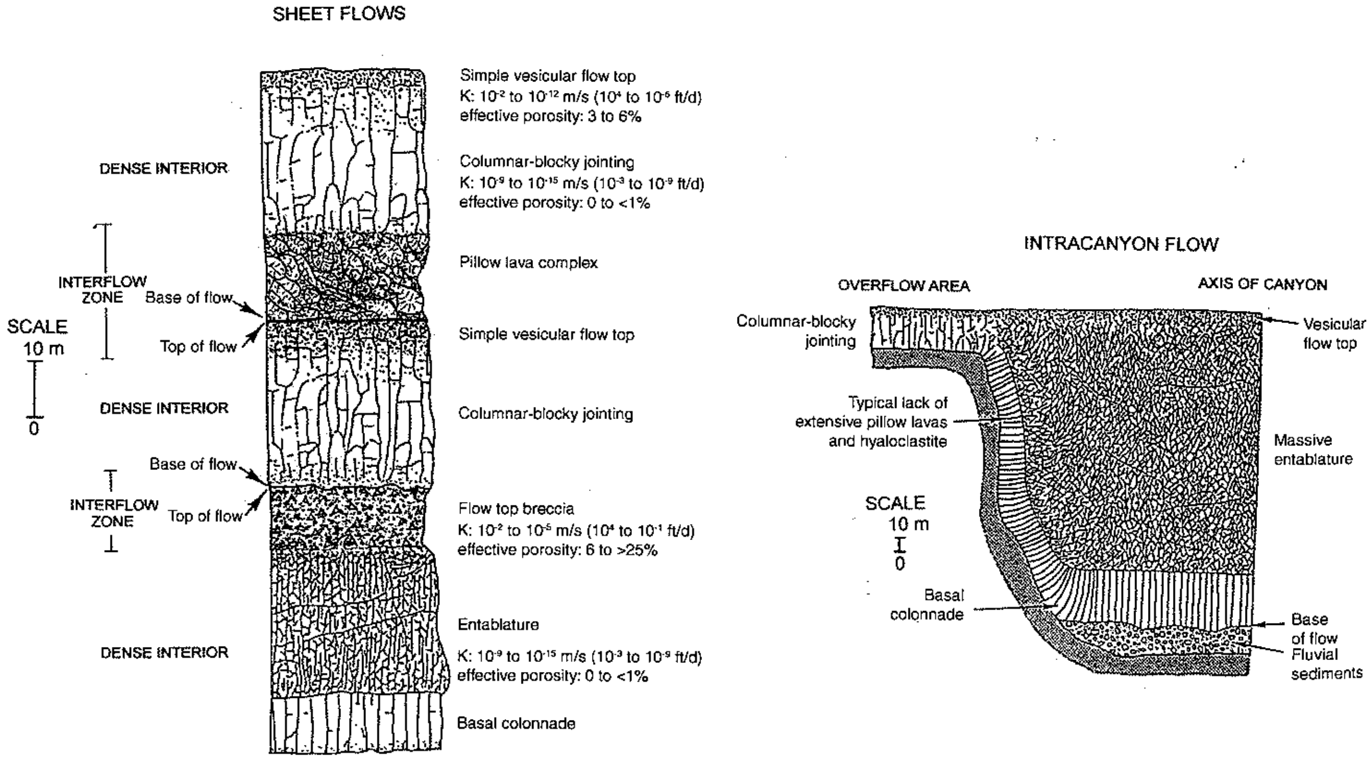

Figure 7. Diagram depicting Columbia River Basalt Group (CRBG) intraflow structures associated with sheet flows and intracanyon flows.

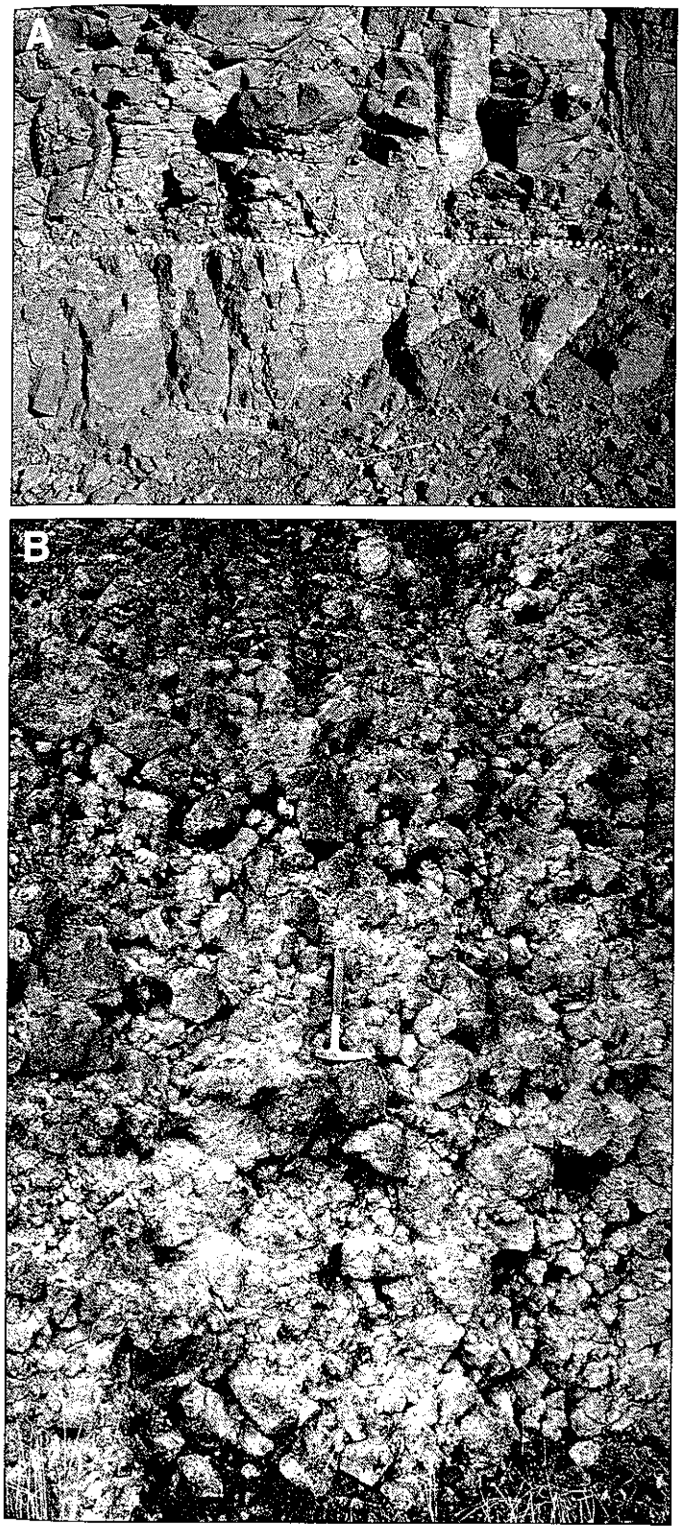

Figure 8. Columbia River Basalt Group (CRBG) flow tops. (A) Simple vesicular flow. White dots delineate the contact and rock hammer for scale. Note the "normal" flow bottom of the overlying flow. (B) Flow-top breccia.

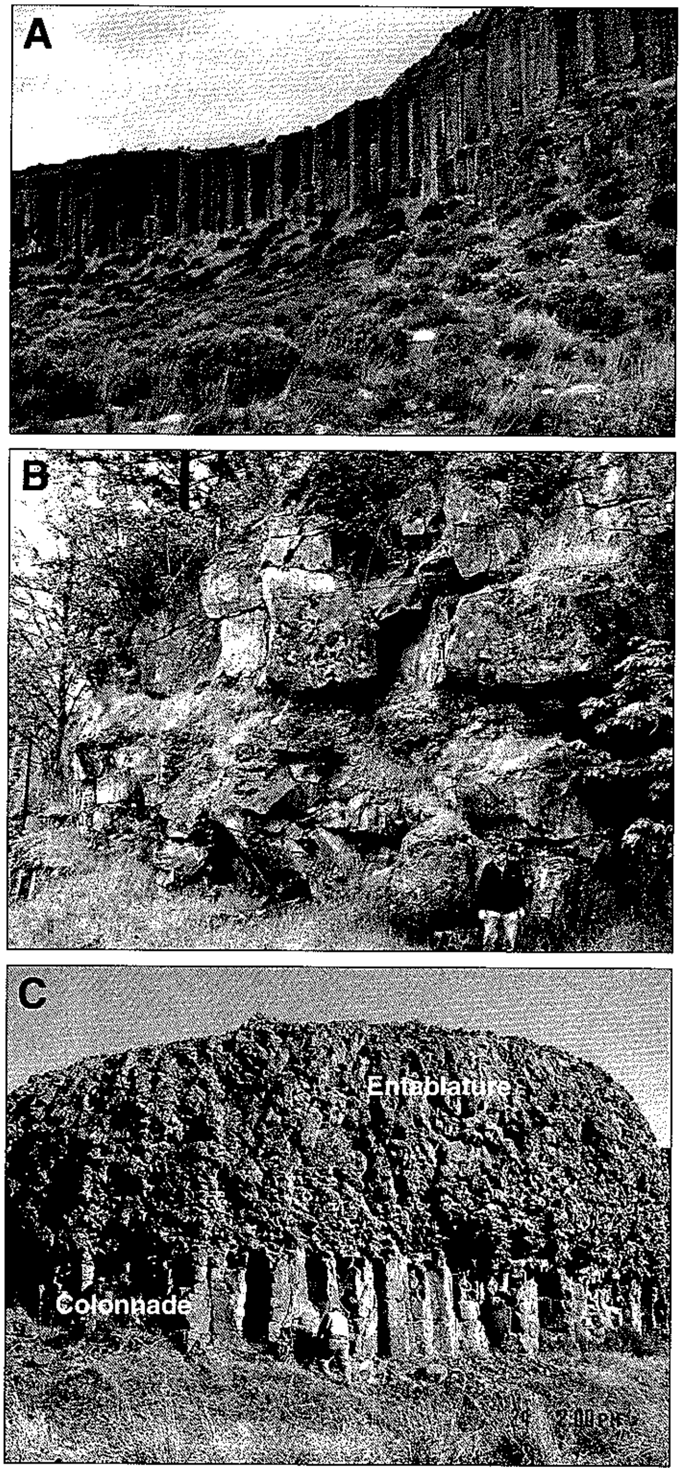

Figure 9. Cooling joint patterns (styles) for Columbia River Basalt Group (CRBG) dense interiors. (A) Prismatic columnar jointing with horizontal platy joints. (B) Blocky-columnar jointing. (C) Entablature and colonnade jointing.

the basalt comprising it contains a very high percentage of glass (50%–95%) in contrast to the colonnade (Long and Wood, 1986; USDOE, 1988). While entablature-colonnade jointing style is commonly observed in CRBG flows, it is actually a very uncommon jointing pattern for lava flows elsewhere in the world. The origin of entablature-colonnade jointing has been the subject of much speculation and conjecture (e.g., Long and Wood, 1986; Reidel et al., 1994b), but it has not been resolved.

Frequency and spacing of cooling joints measured in outcrops indicate that frequencies typically range from 1 to 37 joints per meter with entablatures showing a greater number of joints per meter than colonnades. The spacing of cooling joints (number of meters per fracture) appears to follow a log normal distribution for groups of cooling joints with similar attitudes. Meints (1986) found that the spacing of cooling joints was highly variable both between flows and within flows and could not be used to differentiate flows and intraflow structures.

Cooling joints are distinct from secondary tectonic fractures such as faults, shear zones, and joint sets. These secondary features are distinguishable by their appearance and occurrence. Tectonic fractures typically occur in sets of parallel to subparallel, closely spaced fractures. The presence of associated shatter breccias and gouge (often altered to clay) distinguishes them from cooling joints.

Flow Bottoms

The physical characteristics of CRBG flow bottoms (Fig. 10) are largely dependent on the environmental conditions the molten lava encountered as it was emplaced (Mackin, 1961; Swanson and Wright, 1978, 1981; USDOE, 1988; Beeson et al., 1989a; Reidel et al., 1994b; Beeson and Tolan, 1996). If the advancing CRBG lava encountered relatively dry ground, the flow bottom that results typically consists of a narrow (<1 m thick) zone of sparsely vesicular, glassy to very fine grained basalt (e.g., Fig. 9A). This type of flow bottom structure is very common within the CRBG.

If advancing CRBG lava encountered lakes, rivers, and/or areas of water-saturated, unconsolidated sediments, far more complex flow bottom structures formed (Mackin, 1961; Schmincke, 1967a, 1967b; Bentley, 1977; Byerly and Swanson, 1978; Grolier and Bingham, 1978; Swanson and Wright, 1978, 1981; Beeson et al., 1979, 1989a; Swanson et al., 1979b; Bentley et al., 1980; Camp, 1981; Stoffel, 1984; Tolan and Beeson, 1984; Pfaff and Beeson, 1989; Ross, 1989; Reidel et al., 1994b; Beeson and Tolan, 1996; Wells et al., this volume). Where advancing lava encountered a lake, a pillow lava complex (Fig. 10A) would be created as the lava flowed into the lake. A pillow complex consists of elongate to spherical lobes of basalt (pillows) set in a matrix of glassy basalt fragments (hyaloclastite). The pillows represent subaqueous pahoehoe flow lobes that advanced down the front of the pillow lava delta. Studies of the active formation of basaltic pillow lavas in Hawaii (e.g., Moore et al., 1973; Moore, 1975; Tribble, 1991) indicate that molten lava can smoothly flow into the ocean without thermal disruption (phreatic brecciation) as long as a thin film of highly insulating steam protects the lava. This process allows for the formation of subaqueous lava tubes (pahoehoe flow lobes that advance and grow in a manner similar to observed on land (Swanson, 1973; Moore, 1975; Hon et al., 1994). Disruption of this insulating steam barrier (e.g., wave action, currents, and gas explosions within the lava lobe) allows water to come into direct contact with molten lava resulting in the production of glassy debris (hyaloclastite) by phreatic brecciation. CRBG pillow lava complexes and hyaloclastites are not an uncommon feature, but their occurrence and distribution reflects the paleodrainage pattern that existed at the time of their emplacement (Tolan and Beeson, 1984; Fecht et al., 1987; Beeson et al., 1989a; Reidel et al., 1994b; Beeson and Tolan, 1996).

A rare type of flow bottom structure is a spiracle (Fig. 10B). Spiracles are inferred to have been created when flowing lava rapidly crossed wet sediments and the trapped water within the sediments is explosively converted to steam. This localized phreatic explosion chills the overlying lava creating an irregular, cylindrical feature that is partially filled with glassy, angular debris (hyaloclastite and breccia). Spiracles can range from 1 m to more than 15 m in diameter and can extend upward through CRBG flows for distance of 1 m to more than 30 m. Commonly, spiracles terminate within the flow, but in rare cases they can pass entirely through the flow. In general, pillows form where there is a higher ratio of water to lava and spiracles form where that ratio is much lower.

The last type of flow bottom structures involves lava and sediment interaction that created a wide range and scale of invasive features. Tongues and lobes of lava emanating from the base of advancing CRBG flows occasionally burrowed into poorly consolidated sediments due to inherent density differences. Where this invading lava encountered water-saturated sediments, phreatic brecciation sometimes occurred creating a basalt and sediment mixture called a "peperite" (Schmincke, 1967a; Fig. 10C). CRBG flows are known to not only invade sediments but were also capable of lifting and rafting sediment (Byerly and Swanson, 1978; Swanson and Wright, 1978; Beeson et al., 1979, 1989a; Stoffel, 1984; USDOE, 1988; Ross, 1989). Invasive flows (Fig. 10D) can be identified based on several different criteria:

(1) the flow top is abnormally thin and consists of glassy, sparsely vesicular to microvesicular basalt;

(2) sediment immediately overlying the thin glassy flow top exhibits evidence of exposure to very high temperatures (i.e., baking), which are normally only associated with flow bottoms;

(3) dikelets and/or lobes are present originating at and extending from the flow top into the overlying sediments;

(4) bedding structures within the sedimentary interbed are disrupted and deformed with no obvious tectonic cause (faulting and folding); and/or

(5) the sedimentary interbed is not in its expected stratigraphic position.

CRBG invasive flows are also common in the coastal regions of northwestern Oregon and southwest Washington. Originally these invasive flows were believed to be feeder dikes and sills for the Miocene coastal basalt; these dikes and sills were thought to have come from the same source (magma chamber) as the CRBG, but they were erupted in coastal Oregon and Washington contemporaneously with CRBG eruptions on the Columbia Plateau (Snavely et al., 1973). Subsequent investigations (Beeson et al., 1979; Niem and Niem, 1985; Pfaff and Beeson, 1989; Wells et al., 1989; Beeson and Tolan, 2002; Wells et al., this volume) have shown that these coastal basalts represent the distal ends of CRBG flows and are classic examples of invasive flows.

Other Internal Features

Other intraflow features observed within the interior of CRBG flows include:

(1) Vesicle pipes and cylinders: Vesicle pipes and cylinders are cylindrical zones of gas bubbles that form as gas evolves from that lava and rises toward the top of the flow. The difference between pipes and cylinders is size; cylinders are larger but there is no size break. Vesicle cylinders, pipes, and sheets usually occur

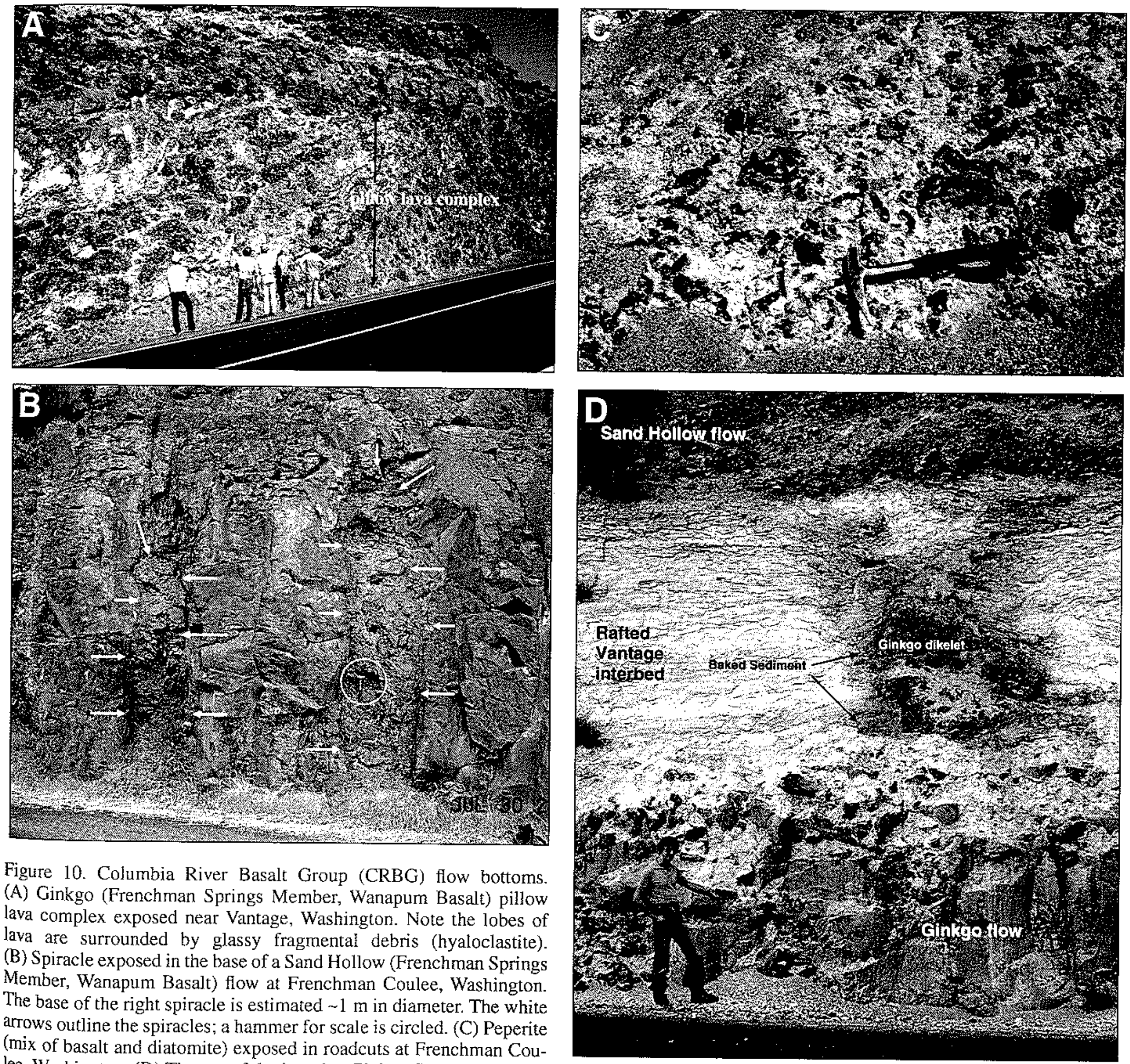

Figure 10. Columbia River Basalt Group (CRBG) flow bottoms. (A) Ginkgo (Frenchman Springs Member, Wanapum Basalt) pillow lava complex exposed near Vantage, Washington. Note the lobes of lava are surrounded by glassy fragmental debris (hyaloclastite). (B) Spiracle exposed in the base of a Sand Hollow (Frenchman Springs Member, Wanapum Basalt) flow at Frenchman Coulee, Washington. The base of the right spiracle is estimated ~1 m in diameter. The white arrows outline the spiracles; a hammer for scale is circled. (C) Peperite (mix of basalt and diatomite) exposed in roadcuts at Frenchman Coulee, Washington. (D) The top of the invasive Ginkgo flow (Frenchman Springs Member, Wanapum Basalt) and "rafted" Vantage interbed exposed in Rock Creek, west of Bickleton, Washington.

in relatively thin flows (5–30 m) that are composed of mainly colonnades and flow tops.

(2) Vesicle sheets: Vesicle sheets are horizontal to subhorizontal layers of vesicles. They typically are fed by vesicle cylinders and form below the solidification front. Vesicle zones within the interior of thicker flows can vary from centimeter to meters thick and can be laterally continuous, sometimes for kilometers.

(3) Vesicle zones: Vesicle zones are usually larger than vesicle sheets but probably form in much the same way. Vesicle zones can be up to several meters thick and are typically in the interior part of the lava flow.

(4) Laminae or dispersed diktytaxitic vesiculation: Diktytaxitic vesiculation or interstitial crystal-bounded vesicles can occur anywhere but is most prominent in thinner flows.

(5) Lava tubes: Lava tubes are rarely observed in CRBG flows except near their terminal margins. This is because CRBG flows were emplaced as sheet flows and were not tube fed as Hawaiian compound flows are.

(6) Sag flowouts: Sag flowouts are described as localized zones of complex tiering of colonnades and entablatures with some isolated flow-top material occurring below the top of the flow. A sag flowout is thought to have formed as the result of lava draining from a partly solidified flow leaving room for vesiculation to occur at the top of the remaining liquid.

Intraflow Structure Variation

Intraflow structures can be continuous for great distances, but the thickness and appearance of the intraflow structures are often highly variable. Lateral variations can occur gradually in some cases and very abruptly in other cases. The primary factor that appears to control changes is the environment where the feature formed. Studies in the central Columbia Basin (USDOE, 1988) showed that lateral changes in the Umtanum Member (Grande Ronde Basalt; Fig. 2), which has a rubbly to brecciated flow top, extremely thick entablature and very thin colonnade, occur over relatively short distances. However, studies on the McCoy Canyon flow (Sentinel Bluffs Member, Grande Ronde Basalt), which has a normal flow top with a thick entablature and thick colonnade, documented gradual changes with distance.

The composition of the paleo–ground surface, and whether it is wet or dry, appears to be a significant environmental consideration (Swanson and Wright, 1981). A dry basalt flow top has the least impact on the overlying flow, which probably is the situation for gradual changes in intraflow textures with distance. In contrast, wet sediment is the worst case and may be the cause of rapidly changing intraflow structure thickness. Wet sediments can rapidly reduce the temperature of the lava that increases its relative viscosity. The outward morphology of flows that advanced across wet sediments commonly resembles that of a compound flow, but the individual lobes are of much greater size (10 to >30 m thick); the larger lobes (>15 m thick) often display a complex internal jointing pattern, which is suggestive that lava was injected into the lobes (inflated) even after it came to rest.

Flow Geometries

Sheet versus Compound Flows

Rate and volume of lava erupted, lava composition and temperature (rheology), vent geometry, topography, and environmental conditions all play significant roles in flow rheology and emplacement dynamics, and overall geometry of individual basalt lava flows or flow fields (Shaw and Swanson, 1970; Beeson et al., 1989a; Martin, 1989, 1991; Reidel and Tolan, 1992; Reidel et al., 1994b; Hon et al., 1994; Self et al., 1996, 1997; Keszthelyi and Self, 1998; Reidel, 1998). There are two basic types of flow geometries—compound and sheet (Fig. 11).

A compound flow develops when the lava flow advances away from its vent in a series of distinct and separate lobes (flows) of flowing lava. Each lobe is subsequently covered by later lava lobes as the emplacement of lava continues. This results in the accumulation of elongated bodies of basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava. In comparison, a sheet flow results when lava is erupted at a high rate and is able to advance away from the vent as a single, uniform, moving sheet of lava. This type of flow consists of a relatively extensive, single layer or "sheet" of lava. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops and flow bottoms.

Individual, large-volume CRBG flows (especially Grande Ronde and Wanapum Basalts) display characteristics consistent with sheet flows (Swanson et al., 1979a; Beeson et al., 1985, 1989a; Tolan et al., 1989; Reidel et al., 1989b, 1994b; Beeson and Tolan, 1990, 1996; Reidel and Tolan, 1992; Reidel, 1998, 2005). CRBG flows typically only exhibit the complex features associated with compound flows at their flow margins or distal ends (Beeson et al., 1989a; Reidel and Tolan, 1992; Reidel et al., 1994b; Beeson and Tolan, 1996; Reidel, 1998). Such "atypical" flow morphologies are more commonly found along the margins of the CRBG (as expected) but can also be found in the basal (oldest present) CRBG units in the Willamette Valley region (Beeson et al., 1989a). Beeson et al. (1989a) attributed these atypical flow morphologies in the oldest CRBG flows to pre-emplacement environmental "ground" conditions. Specifically they were referring to ground conditions that resulted in the rapid heat extraction from the advancing CRBG lava flow, such as wet sediments or standing water (usually associated with topographic and structural lows), which caused the advancing flow to form relatively thick, energy-conserving flow lobe. Such flow lobes can be many tens of meters thick and formed constructional topography that subsequent CRBG sheet flows had to contend with. Excellent examples of such CRBG flow lobes are exposed in the Willamette Valley in the Turner, Oregon, area (Tolan et al., 2000a).

Intracanyon Flows

A much less common mode of emplacement for CRBG flows is as an intracanyon flow. In this case, an advancing CRBG sheet flow encounters a major river canyon that served to channel the lava into a ready-made conduit downslope. Such paleoriver canyons undoubtedly allowed some CRBG flows to travel significantly greater distances than they might have as sheet flows.

The development of major canyons by rivers within the ancestral Columbia River system during CRBG time was in large part governed by the length of time between large-volume CRBG flows. The emplacement of large-volume CRBG flows typically inundated existing low-lying areas which also resulted in the obliteration of the medial to distal reaches of the ancestral Columbia River system. While this portion of the drainage system was essentially destroyed, the upper reaches outside the flood-basalt province remained intact. This disarrangement of the drainage system often resulted in the formation of lakes along the margin of the newly emplaced flow, but inevitably (months to centuries later) the streams and rivers established new courses proximal to the margin of the CRBG flow.

Like CRBG flows, the ancestral Columbia River system was also directed by major tectonic features (i.e., Palouse Slope, Columbia Basin, Yakima Fold Belt, Columbia Trans-Arc Lowland) and continued regional subsidence to produce a westward, regional down-gradient flow. In the western Columbia Plateau and Columbia Trans-Arc Lowland, continuing subsidence of Yakima Fold Belt synclines during CRBG time was very important in that these synclines provided regional-scale pathways for the ancestral Columbia River.

During the peak period of CRBG eruptive activity (17–15.6 Ma), the duration of quiescent periods between emplacement of large-volume flows averaged ~13,000 yr (Reidel et al., 1989a, 1989b) and did not provide the time needed for the incision of major canyons. This changed during the waning phase of CRBG eruptive activity (15.6–6 Ma) when the length of quiescent periods between CRBG eruptions dramatically increased (commonly lasting 200,000 to >1,000,000 yr), and was accompanied by a general reduction in the size (volume) of CRBG flows (Tolan et al., 1989). These factors created opportunities for the ancestral Columbia River system to incise major canyons.

CRBG Dikes and the Chief Joseph Dike Swarm

Based on previous work as well as his own reconnaissance mapping, Waters (1961) identified three dike swarms as feeders to the CRBG—the Monument, Grande Ronde, and Cornucopia. Additional mapping by Taubeneck (1970) found no gap between the northerly Grande Ronde and southerly Cornucopia swarms and merged them into a single giant swarm that he named the Chief Joseph (Fig. 1). Beeson et al. (1985) and Reidel et al. (1989b) have extended the dike swam to the north-central and northeastern margin of the basalts based on a detailed study of units within the Wanapum and Grande Ronde Basalts. Chief Joseph dikes fed the main phase of CRBG volcanism that dominates the Columbia River Flood-Basalt Province, including huge-volume (>2500 km^3) flows of the Imnaha, Grande Ronde, and Wanapum Basalts. Dikes in the Monument swarm fed many of the Picture Gorge flows (Brown and Thayer, 1966; Wilcox and Fisher, 1966; Fruchter and Baldwin, 1975; Bailey, 1989).

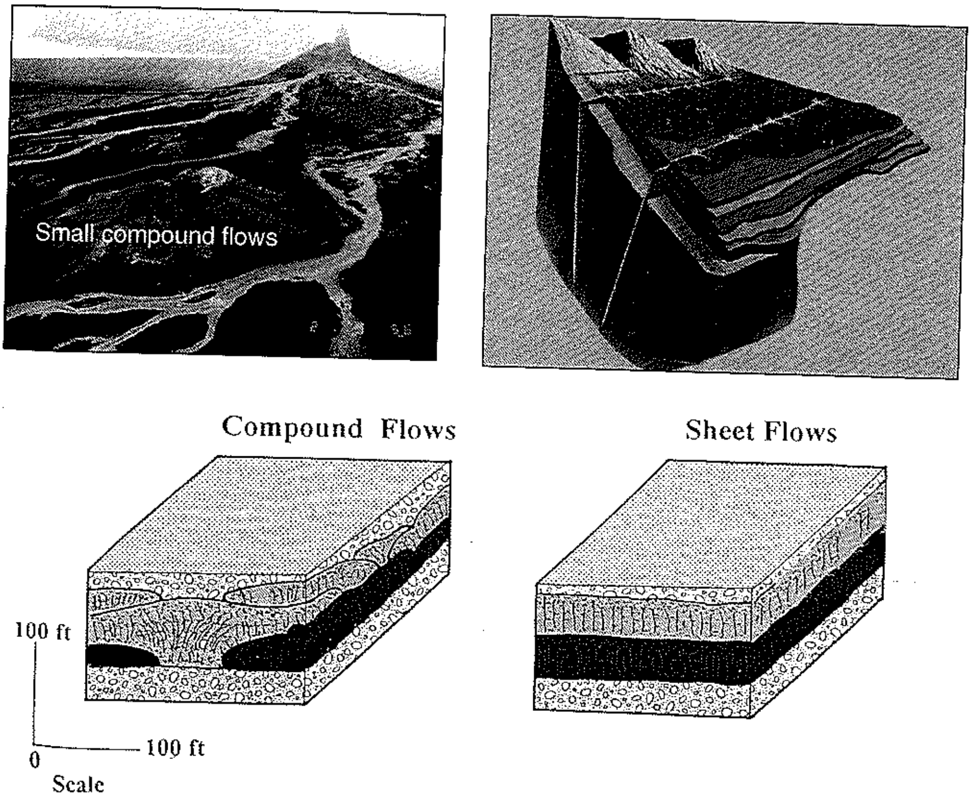

Figure 11. Comparison of compound versus sheet lava flow morphologies.

Taubeneck (1970) estimates that at least 21,000 dikes occur in the Chief Joseph swarm at the level of the regional unconformity below the CRBG. Overall, dikes are exposed at deeper stratigraphic levels southward through the swarm, due to uplift and erosion of the Wallowa and Blue Mountains. In the Columbia River Flood-Basalt Province, dikes are dominantly hosted by older CRBG units. In the Wallowa Mountains (Fig. 1) and southward, dikes are hosted in pre-Tertiary rocks, dominantly in granitoids with fewer in metasediments. Concentrations of dikes diminish rapidly at or within several kilometers of granitoid pluton margins, suggesting that dikes are preferentially hosted in these plutons, where local jointing controls their orientation (Taubeneck and Duncan, 1997; Taubeneck, 1998).

Dike Distribution and Geometry

In the past, it was assumed that dike density increased from north to south across the Chief Joseph dike swarm and hence correlated with increasing depth of erosion. In the Columbia River Flood-Basalt Province, dike concentration has been proposed to be less than three dikes per km^2 (Taubeneck, 1970). This concentration increases to around eight dikes per km^2 in the Wallowa Mountains (Taubeneck, 1970), and is as great as 10–12 dikes per km^2 south of the Wallowas (Taubeneck, 1989, 1990), probably due to exposure rather than actual dike density. The greatest number of flows, and hence dikes, occurs north of the Washington-Oregon border suggesting that more dikes occur in the northern part of the province. Dikes are rarely isolated but instead occur in closely spaced clusters of 7–12 dikes per km^2; presumably, each cluster or subswarm represents an eruptive axis for CRBG volcanism (Taubeneck and Duncan, 1997).

The overall trend of the Chief Joseph swarm is N10°W ± 10°, yet each subswarm has its own distinct orientation. The majority of dikes dip within 30° of vertical. Dikes hosted in pre-Tertiary rock in general are thicker than those hosted in CRBG flows, averaging 7.3 m and 5.8 m thick, respectively, but rarely exceeding 25 m thick (Taubeneck, 1970). Dike length ranges from a few hundred meters to 60 km, although many dikes occur in en echelon segments.

Dike-Wallrock Relationships

Dikes hosted in CRBG flows are chilled against their wallrock, commonly with centimeter-thick glassy margins. Dikes hosted in granitoids of the Wallowa and Blue Mountains, however, display more complex interactions with their wallrock (Taubeneck, 1970). These dikes have one or more of the following morphologies: dikes with chilled margins, dikes with quenched partially melted wallrock at their margins, dikes that have eroded their margins, and dikes containing whole to disaggregated crustal xenoliths that constitute locally as much as 30% of the dike (Grunder and Taubeneck, 1997). The majority of dikes hosted in granitoids have an aphyric chilled margin of basalt (a few cm thick) at the dike-wallrock contact. Rare dikes have caused partial melting in their wallrock; these partial melt zones (preserved as silicic glass plus mineral phases) are up to one-half the thickness of the dike and contain up to 50% quenched silicic melt. Dikes may also locally erode the chilled basalt at their margins, producing localized (cm-scale) zones of wallrock breakdown and a few percent melting. Only a handful of dikes contain granitoid or metasedimentary xenoliths that range from a few centimeters to 6 m in diameter (Taubeneck, 1970; Gorham and Martin, 2004). The majority of these xenoliths appear to be locally derived from stoping of wallrock.

Correlation of Dikes with Flows

Most Chief Joseph dikes have been identified to formation level, and some have been correlated with individual CRBG flows (Fig. 12). In general, dikes of Grande Ronde and Wanapum Basalts are located throughout the swarm, although exposures of Wanapum dikes and Grande Ronde flows indicate that they extend to the northern border of the province (Reidel et al., 1989b; Reidel, 2005). Saddle Mountains Basalt dikes occur in the northern half of the Chief Joseph swarm and are localized near the center of the Columbia Plateau (Fig. 1). Imnaha dikes are only exposed near the Oregon-Washington border and southward, but northern Imnaha dikes may be buried by younger flows. Within the northern half of the Chief Joseph swarm, the dikes and vents for Frenchman Springs Member tend to be nearer to the center of the Columbia Plateau; Priest Rapids dikes are nearer to the eastern margin of the Columbia Plateau along and east of the Washington-Idaho border; and the vents and dikes for the Roza Member form a 175-km-long system between the Frenchman Springs and Priest Rapids systems.

Many Wanapum and Saddle Mountains dikes have been correlated with individual flows based on direct observation of dike-flow connections. For example, the vent-fissure system for the Frenchman Springs flows, Ice Harbor flows, and the Roza flows are well known (Swanson et al., 1975; Martin, 1989, 1991). Direct connections between vents and flows have been observed for the Teepee Butte Member of the Grande Ronde Basalt (Reidel and Tolan, 1992) and the Umatilla Member of the Saddle Mountains Basalt (Reidel, 1998). In the absence of direct dike-flow connections, dikes have been successfully correlated with CRBG flows on the basis of compositional, petrographic, and paleomagnetic data (e.g., Price, 1977; Ross, 1983; Mangan et al., 1986; Reidel, 1998). The major and trace element composition of CRBG units is well established (e.g., Hooper, 2000) and provides a basis for compositional identification of dikes and dike-flow correlations.

Estimating CRBG Emplacement Rates from Dike-Wallrock Relationships

Emplacement rates and mechanisms of large-volume flood basalts have been a matter of some controversy. Early workers (Shaw and Swanson, 1970) suggested emplacement as turbulent flows racing across the landscape in weeks to months. However, in analogy to inflated pahoehoe flows observed in Hawaii (e.g., Hon et al., 1994; Self et al., 1996), it has been proposed that CRBG flows were emplaced as large, inflated flow fields. Flow inflation occurs as centimeter-scale lobes of lava develop a chilled, viscoelastic skin, and then expand with continued injection of fluid lava. Study of a CRBG flow (a Ginkgo flow, Frenchman Springs Member, Wanapum Basalt; Fig. 2) by Ho and Cashman (1997) concluded that less than 0.04 °C/km of heat loss had occurred along the 500-km-length of this flow suggesting emplacement under an insulating crust and/or rapid emplacement. Thordarson and Self (1998) have described lobes and other inflation structures in flows belonging to the Roza Member (Wanapum Basalt; Fig. 2). Inflation is also consistent with some compositional data; Reidel and Fecht (1987) and Reidel (1998) described compositionally zoned Saddle Mountains Basalt and Grande Ronde Basalt flows (Reidel, 2005) where progressively younger lava is preserved toward the center in a single cooling unit, which they interpret as the result of "surface mixing" of lava flows.

Whereas flow inflation is recognized as a critical mechanism for flood-basalt emplacement, controversy persists over eruption and emplacement rates. Slow emplacement over years to a few decades is advocated in the CRBG based on conductive cooling models in the Roza Member (Thordarson and Self, 1998), and is supported by thermal models (Keszthelyi and Self, 1998). Compositional data, however, are more consistent with eruption and emplacement over timescales of weeks to months (Reidel et al., 1994b). Reidel and Fecht (1987) and Reidel (1998, 2005) documented examples where two flows were preserved in individual dikes and vents, yet mixed together to form a single flow more than 200 km from the source, requiring rapid emplacement. Interestingly, recent thermal models by Keszthelyi et al. (2006) incorporate aspects of both "slow" and "rapid" emplacement.

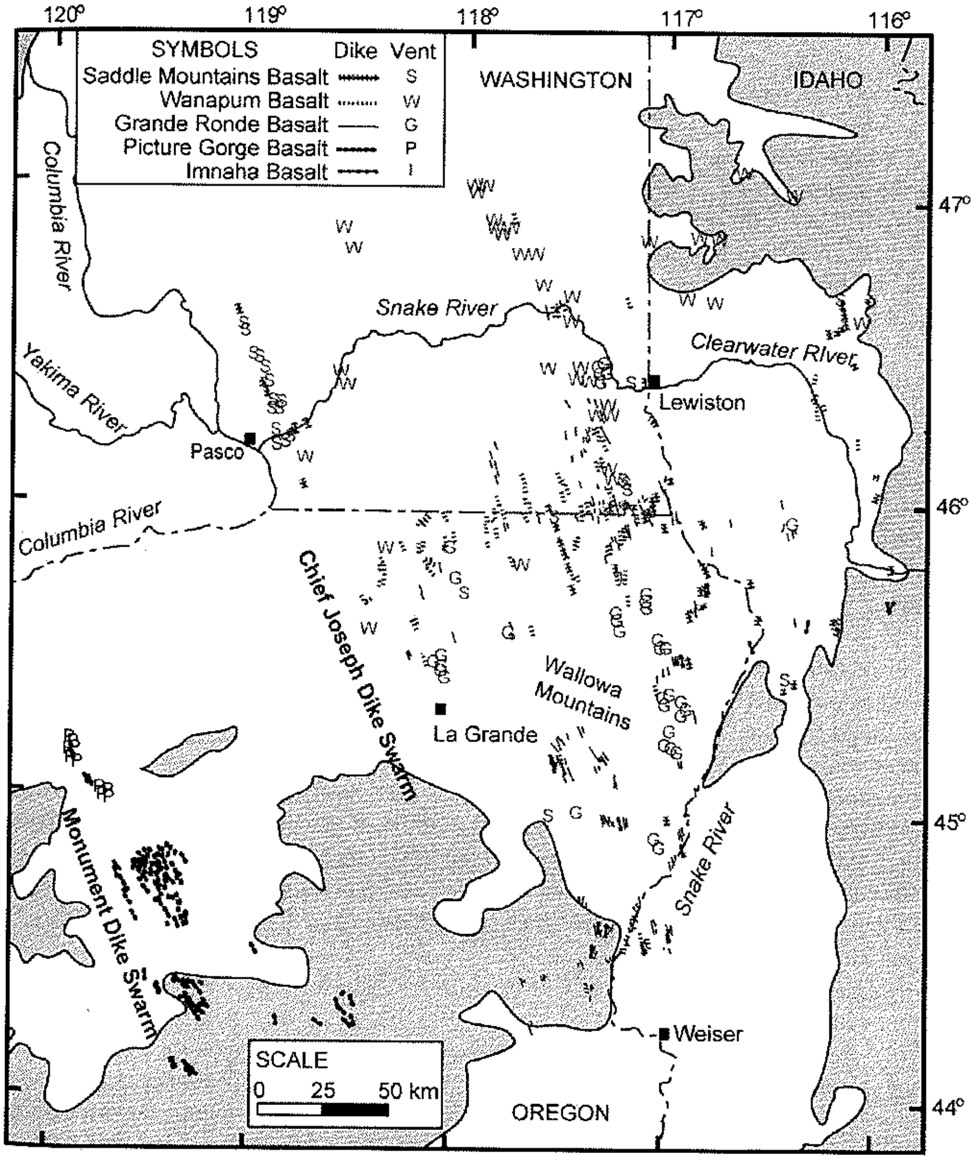

Figure 12. Map showing the locations of known Columbia River Basalt Group vents and dikes.

They envision a "typical" 1000 km^3 flood-basalt lava flow being emplaced as inflated sheet flows in under six years; however, they also propose that individual batches of lava traveling some 100–300 km beneath an insulating crust from the vent to the flow front in no more than ten days.

Petcovic and Grunder (2003) analyzed wallrock melting reactions in tonalite adjacent to the Maxwell Lake dike, a likely feeder to Wapshilla Ridge flows, the largest of all Grande Ronde Basalt members (Fig. 2), having an emplaced volume estimated at ~50,000 km^3 (Reidel et al., 1989b). Field work by the authors has shown that only one main dike is known for the Wapshilla Ridge Member.

Petcovic and Dufek (2005) used two types of models constrained by the field example of the Maxwell Lake dike in order to assess the rate of basalt eruption from development of wallrock melting due to basalt intrusion. Static conduction results suggested that sustained basalt flow for three to four years caused development of the melt zones observed in the dike. Advective transport simulations suggested that the initial basalt velocity in the dike center was ~10 m/s, but that basalt at the dike margin solidified, causing constriction and slowing of flow. After ~60 days, magma in the dike reached a sustained velocity of ~2 m/s for the duration of flow. Wallrock melting was initiated after approximately one year of flow, and the wallrock had dropped below its solidus temperature within approximately two years after flow ceased. The thickness, distribution, and fractions of wallrock melt zones produced by advective transport modeling closely approximate field observations of the Maxwell Lake dike (Petcovic and Dufek, 2005). Model results suggest that the dike was active for three to four years and likely represents a long-lived point source in flood-basalt eruptions. Furthermore, this suggests that >1000 km^3 of lava were erupted per month, consistent with estimates of eruptions rates made by Reidel et al. (1994a), Reidel and Tolan (1992), and Reidel (1998, 2005).

Implications for CRBG Flow Emplacement

Results of the simulations allow limits to be estimated for eruption rates of the Wapshilla Ridge flow. Assuming that the Maxwell Lake dike fed the entire Wapshilla Ridge Member of 50,000 km^3 over a period of three to four years yields an average eruption rate of 30–50 km^3/day. The eruption rate would have been lower, if flow in the dike were intermittent rather than continuous. Intermittent flow has been documented in historical basalt eruptions and during eruption of the Teepee Butte Member of the Grande Ronde Basalt (Reidel and Tolan, 1992). Some pauses during eruption cannot be ruled out, yet the lack of internal contacts as well as the regular textural progression across the dike and wallrock melt zones is more consistent with nearly continuous flow and a single cooling history.

The advective transport simulation provides a minimum estimate of basalt flux in the dike. Flow was assumed to be localized along the portions of the Maxwell Lake dike with partially melted wallrock margins, which yields an initial basalt flux of ~0.8 km^3/day waning rapidly to a sustained flux of ~0.1 km^3/day (Table 3). Waning discharge is commonly documented in basaltic eruptions (e.g., Wadge, 1981). However, cumulative magma discharge under this scenario produced a total flow volume of only 150 km^3 over four years. Clearly other fissure segments must have fed the same flow in order to produce a 2500–5000 km^3 cumulative volume typical of Grande Ronde flows. Based on the distribution of the Wapshilla Ridge unit, we estimate that the dike-fissure system was at least 100 km long. In historical basalt eruptions (e.g., Laki 1783 and Mauna Loa 1984), as well as has been proposed for the Roza Member fissure system (Martin, 1989, 1991; Self et al., 1997), eruptive activity migrated along the length of the dike-fissure system, with each fissure segment active for short periods (Table 3). The existence of additional dike segments feeding the Wapshilla Ridge unit has not been determined.

Volumetric eruption rates calculated on the basis of the thermal models for a typical Wapshilla Ridge flow are within the range reported for other CRBG eruptions (Table 1; see footnote 1). Minimum eruption rates are comparable to rates estimated from slow emplacement models for the Roza flow (Self et al., 1997; Thordarson and Self, 1998). Maximum eruption rates are an order of magnitude lower than rates calculated using rapid emplacement models (Swanson et al., 1975; Reidel and Tolan, 1992), yet they are an order of magnitude higher than slow emplacement estimates. Wapshilla Ridge eruption rates are similar to the maximum eruption rate of 0.2 km^3/day reported for the 1783 Laki (Skaftár Fires) eruption, the largest historical fissure eruption (Thordarson and Self, 1993). Although the maximum calculated volumetric eruption rate is consistent with models of rapid flow emplacement, the calculated minimum eruption rates and longevity of the Maxwell Lake dike (three to four years) support slower emplacement models (Petcovic and Dufek, 2005).

Model results suggest that the Maxwell Lake dike sustained high magma flux for at least several years. The transition from fissure eruption to localized vents during basaltic volcanism is often explained as a function of cooling in narrow portions of dikes coupled with enhanced flow in thicker portions, resulting in isolated, long-lived vents (e.g., Delaney and Pollard, 1982; Bruce and Huppert, 1990). This process may also explain the presence of wallrock melt zones only along two portions of the Maxwell Lake dike, which experienced higher mass and heat flux as surrounding portions of the dike solidified. Wallrock melt zones adjacent to the Maxwell Lake dike provide evidence for the existence of long-lived point sources playing an important role in flood-basalt eruptions.

General Conclusions for Emplacement of CRBG Flows

Data from studies of flows and dikes indicate a wide range of emplacement rates. The estimates range from rates as low as one to two months for emplacement of larger volume flows to as high as three to four years. This should not be surprising, and attempts

TABLE 3. ESTIMATES OF ERUPTION RATES FOR SELECTED CRBG FLOW UNITS

Flow field	Generic CRBG dike	Roza Member	Ice Harbor Member	Teepee Butte	Sentinel Bluffs Member	Umatilla Member	Roza Member	Wapshilla Ridge Member
Flow field volume (km^3)	Not given	1500	~7–8	5000	10,000	720	1300	~50,000
Flow field areal extent (km^2)	Not given	40,000	~700	52,000	82,461	15,110	40,300	~100,000
Individual flow volume (km^3)	"Typical" = 100 "Large" = 1000	700 per cooling unit	0.1 per cooling unit	Limekiln Rapids = 840 Joseph Creek = 1850 Pruitt Draw = 2350	Museum = 2349 Spokane Falls = 777 Stember Creek = 1192 California Creek–Airway Heights = 1543 McCoy Canyon = 4278	~310	Single eruption	~5000–10,000
Emplacement time	Days to weeks	7 days	10 days	Days-weeks, maybe months	Months	Months	0.4–4.2 years for individual flows. 6–14 years for flow field	3–4 years all flows
Volumetric eruption rate (km^3/day)	Typical = 14–50 Large = 140–500	1	0.01	10s to 100s	10s to 100s	10s to 100s	0.13–0.34	30–50 Petcovic and Dufek (2005) assumed the member was only 5000 km^3
Fissure system length (km)	Not given	~15 wide by ~120 long	~15 wide by ~90 long	70	100	>50	~5 wide by ~150 long	At least 100 long
Eruption rate (km^3/day/km of fissure)	14 (for fissures >3 m wide)	1	0.0002	>1	>1	>1	0.08 (assuming 4 km active at once)	Unknown
Method of eruption rate estimate	Numerical model based on rheology arguments. Requires turbulent flow.	Based on field observations suggesting rapid emplacement and Shaw and Swanson's (1970) model.	Based on field observations suggesting rapid emplacement and Shaw and Swanson's (1970) model.	Based on assumption of rapid emplacement consistent with field data.	Evaluation of field data, chemical composition implications with respect to cooling calculations.	Evaluation of field data, chemical composition implications with respect to cooling calculations.	Based on model calculating cooling times to form upper crust on flows.	Minimum flux (advective transport model). Assumes Maxwell Lake dike fed member for 3–4 years.
Reference(s)	Shaw and Swanson (1970)	Swanson et al. (1975)	Swanson et al. (1975)	Reidel and Tolan (1992)	Reidel (2005)	Reidel (1998)	Self et al. (1997); Thordarson and Self (1998)	Petcovic and Dufek (2005); Petcovic and Grunder (2003)

Note: CRBG—Columbia River Basalt Group.

to fit all flows into one model are probably unrealistic. We suggest that the interpretations are correct and that some flows are emplaced over long periods of time, such as the Maxwell Lake dike, while others are emplaced during very short intervals, such as that estimated for the Sentinel Bluffs Member of the Grande Ronde Basalt. In fact, it is probably more realistic to think in terms of a continuous spectrum of emplacement times rather than just the two extremes. The most important question that still remains unanswered is: what mechanism drives the rate at which these flood-basalt flows are erupted?

MIDDLE MIOCENE–PLIOCENE (LATE NEOGENE) AND QUATERNARY SEDIMENT GEOLOGY

No discussion of CRBG geology and stratigraphy is complete without at least a brief introduction to the late Neogene sedimentary units found interbedded with, and overlying, the CRBG and major Quaternary sedimentary units. While not the primary focus of any of the field trips, these sediments have provided important insights to the geologic evolution of this flood-basalt province, and they do play a role in the hydrogeology of the CRBG. A brief summary of these units is presented here.

Late Neogene sediments in the Columbia River Flood-Basalt Province have been studied and mapped for almost a century (e.g., Bretz, 1917; Buwalda and Moore, 1927; Piper, 1932; Hodge, 1938, 1942; Thayer, 1939; Warren, 1941; Lowry and Baldwin, 1952; Waters, 1955; Laval, 1956; Mackin, 1961; Trimble, 1963; Hogenson, 1964; Schmincke, 1964, 1967b; Newcomb, 1965, 1966, 1971; Hampton, 1972; Bentley, 1977; Kent, 1978; Rigby et al., 1979; Swanson et al., 1979a, 1979b, 1981; Bentley et al., 1980; Farooqui et al., 1981a, 1981b; Tolan and Beeson, 1984; Hagood, 1986; Dames and Moore, Inc., 1987; Fecht et al., 1987; Smith, 1988; Smith et al., 1989; Walker and MacLeod, 1991; Yeats et al., 1991; Swanson et al., 1993; Lindsey, 1996; Gannett and Caldwell, 1998). These studies found that these sediments are interfingered with, and overlie the CRBG. This stratigraphic relationship with the CRBG provided a natural, mappable subdivision between those sediments intercalated with the CRBG (interbeds) and those that overlie the CRBG (suprabasalt sediments). The composition and mode of deposition of these sediments allowed them to be further separated and locally differentiated (e.g., Buwalda and Moore, 1927; Piper, 1932; Hodge, 1938, 1942; Waters, 1955; Schmincke, 1964; Tolan and Beeson, 1984).

The major late Neogene sedimentary units associated with the CRBG include:

(1) Ellensburg Formation: interbeds within the CRBG throughout much of the Columbia Plateau, Cascade Range, and Willamette Valley regions and suprabasalt sediments in the western Columbia Plateau in Washington;

(2) Latah Formation: interbeds within the CRBG and local suprabasalt sediments along the northeastern and eastern fringe of the Columbia Plateau;

(3) Ringold Formation and Snipes Mountain Conglomerate: suprabasalt sediments in the Pasco Basin and lower Yakima Valley, respectively, of south-central Washington;

(4) Dalles Group (Chenoweth, McKay Creek, and Alkali Canyon Formations): suprabasalt sediments in the Umatilla-Dalles-Mosier basins of northern Oregon;

(5) Rhododendron Formation: volcaniclastic suprabasalt sediments (and related lava flows) within the Cascade arc;

(6) Troutdale Formation: suprabasalt sediments in the western Cascade Range, northern Willamette Valley, and southwestern Washington; and

(7) Scappoose Formation: fluvial and marine sediments interbedded with the CRBG in the Coast Range (Van Atta and Kelty (1982).

Subsidence within the Columbia Plateau (Columbia Basin) and Columbia Trans-Arc Lowland and local structural basins (e.g., Portland Basin, Walla Walla Basin, La Grande Basin, etc.) allowed for the accumulation of both CRBG flows and epiclastic and volcaniclastic sediments. The thickest accumulations of these Neogene sediments (100 to >300 m thick) usually occur within these structural basins and lowlands developed within the flood-basalt province.

Smith et al. (1989) provides a good comprehensive review of the Neogene suprabasalt sediments. Based on that report, and several other regional studies, including Piper (1932), Hodge (1938), Trimble (1963), Newcomb (1965, 1966, 1971), Farooqui et al. (1981a, 1981b), Tolan and Beeson (1984), Fecht et al. (1987), Lindsey et al. (1993), Lindsey (1996), and Lindsey and Tolan (1996), the types of facies comprising the epiclastic sediments overlying the CRBG include:

(a) mixed lithology conglomerate and felsic sand deposited within the ancestral Columbia River and major tributaries (e.g., ancestral Salmon-Clearwater, Snake, and/or Willamette Rivers);

(b) mixed lithology conglomerate with a basaltic sand matrix;

(c) muddy, basaltic conglomerate;

(d) weakly indurated, massively bedded, siltstone and claystone displaying characteristics indicative of paleosols;

(e) well-stratified, weakly indurated, siltstone and diatomite deposited in lake environments; and

(f) volcaniclastic sediments derived from Cascade Arc volcanism (mainly western Columbia Plateau, Cascade Range, and Willamette Valley regions).

The CRBG unit upon which these Miocene–Pliocene sediments were deposited is not always the same CRBG unit. Thus the age of the base of the suprabasalt sediments can vary from 6.5 Ma, where it overlies the youngest Saddle Mountain Basalt unit, to 15.6 Ma, where it overlies the Sentinel Bluffs Member of the Grande Ronde Basalt (Fig. 13).

The major Quaternary sediment units consist primarily of Pleistocene to Holocene loess of the Palouse Formation and Pleistocene cataclysmic flood (Missoula floods) deposits that consist of gravels and sands along the flood tracts and slackwater sediments where the flood waters ponded. The cataclysmic floods were also responsible for eroding deep channels and valleys ("coulees") into the CRBG in the northern, central, and western portions of the Columbia Plateau, Columbia River Gorge, and northern Willamette Valley.

Sedimentary Interbeds in the CRBG: Ellensburg Formation

The nature and composition of sediments found interbedded with the CRBG vary greatly, ranging from epiclastic to volcaniclastic in origin. Within the central and western Columbia Plateau region and the eastern portion of the Cascade Range, the sedimentary interbeds within the CRBG are assigned to the Ellensburg Formation (Swanson et al., 1979a; Fecht et al., 1987; USDOE, 1988; Smith et al., 1989). These sediments were deposited by ancient river and lake systems (both channel and overbank deposits associated with the ancestral Columbia River system) and as air-fall tephras and reworked tephras from Miocene volcanoes active in the Cascade Range and northern Basin and Range. Events controlling the deposition of Ellensburg interbeds (Fecht et al., 1987; Smith, 1988; Smith et al., 1989) include: (1) emplacement of CRBG flows and their impact on paleodrainage systems, (2) synvolcanic sedimentation from Cascadian sources, and (3) local and regional tectonism (uplift and subsidence).

Individual interbeds within the Ellensburg Formation range from <1 to >30 m thick and can be traced laterally over large areas (Mackin, 1961; Schmincke, 1964; Bentley, 1977; Grolier and Bingham, 1978; Swanson et al., 1979a; Fecht et al., 1987; Smith, 1988; USDOE, 1988; Smith et al., 1989). Variability in sedimentary interbed composition directly controls their impact on the hydraulic behavior of CRBG interflow zones (USDOE, 1988).

The Ellensburg Formation is subdivided into a number of formal and informal members as shown in Figure 13. These members (interbeds) are solely defined and recognized by the CRBG units which bracket them (Laval, 1956; Mackin, 1961; Schmincke, 1964, 1967b; Bentley, 1977; Grolier and Bingham, 1978; Swanson et al., 1979b; Fecht et al., 1987; Smith, 1988;

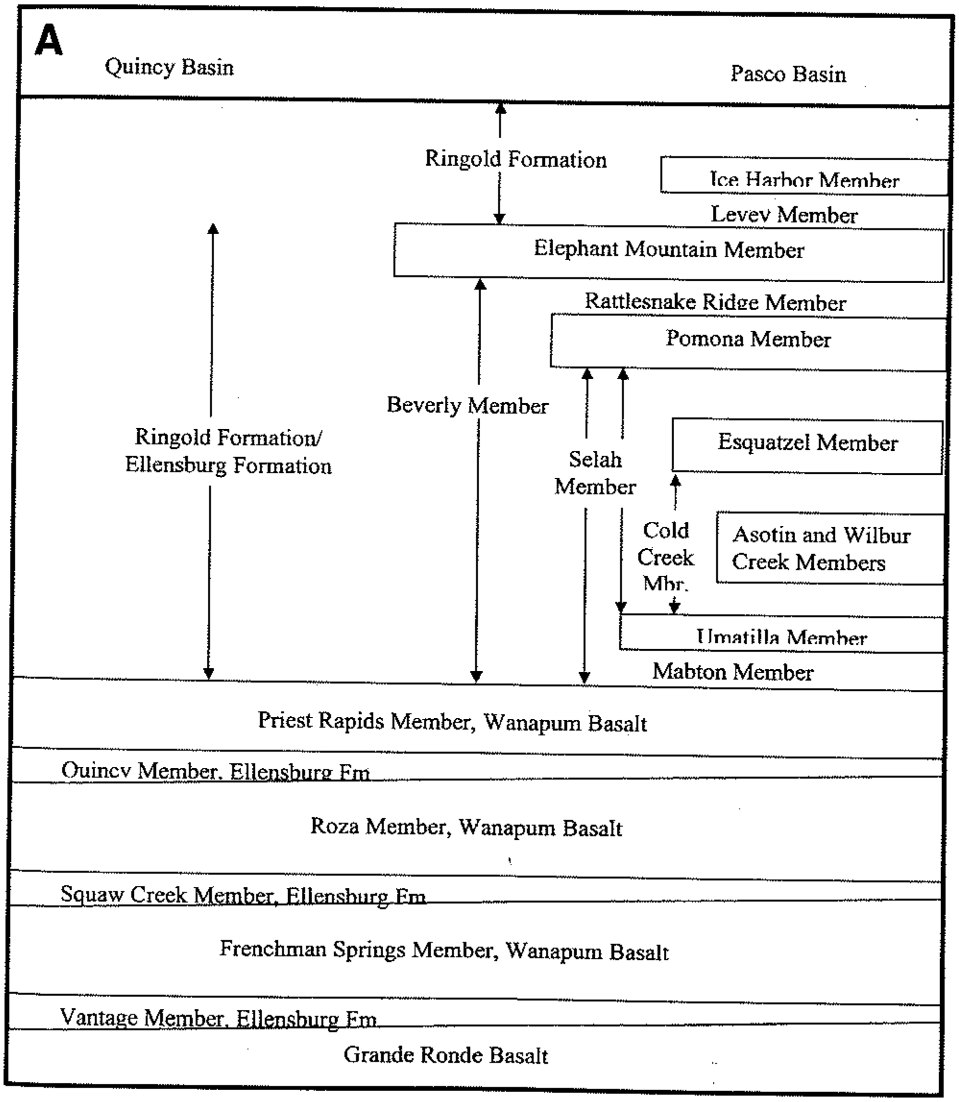

Figure 13 (*continued on following page*). Diagrams illustrating stratigraphic nomenclature and relationships between the Columbia River Basalt Group (CRBG), Ellensburg Formation, and suprabasalt sediments in the central and western Columbia Plateau. (A) Quincy-Pasco Basins area. WCM—Wilbur Creek Member; AM—Asotin Member; EM—Esquatzel Member; IHM—Ice Harbor Member. Modified from Fecht et al. (1987) and Smith et al. (1989). (B) Umatilla Basin area.

Smith et al., 1989). A number of problems arise because stratigraphic definitions of these units are based solely on the identity of the confining CRBG units and not independent sedimentological criteria. A fundamental problem with this scheme is that the defining CRBG units are not always present, and previously separate and named interbeds merge into one member or even become part of another formation (Fig. 13). This situation, as diagrammatically illustrated in Figure 13, can, and often does, create confusion when dealing with Ellensburg nomenclature. Also the Ellensburg interbed nomenclature has been informally extended into the western Oregon and Washington region (Beeson and Moran, 1979; Beeson et al., 1985, 1989a).

STRUCTURAL AND TECTONIC SETTING OF THE COLUMBIA RIVER FLOOD-BASALT PROVINCE

Brief Overview of the Tectonic Setting

The Columbia River Flood-Basalt Province spans a number of informally defined structural and/or physiographic subprovinces (Fig. 14), each with its own distinctive characteristics. Those structural subprovinces that will be visited during the field trips will be briefly described here.

The Columbia Plateau region can be general subdivided into the Yakima Fold Belt, Palouse Slope, Blue Mountains, and

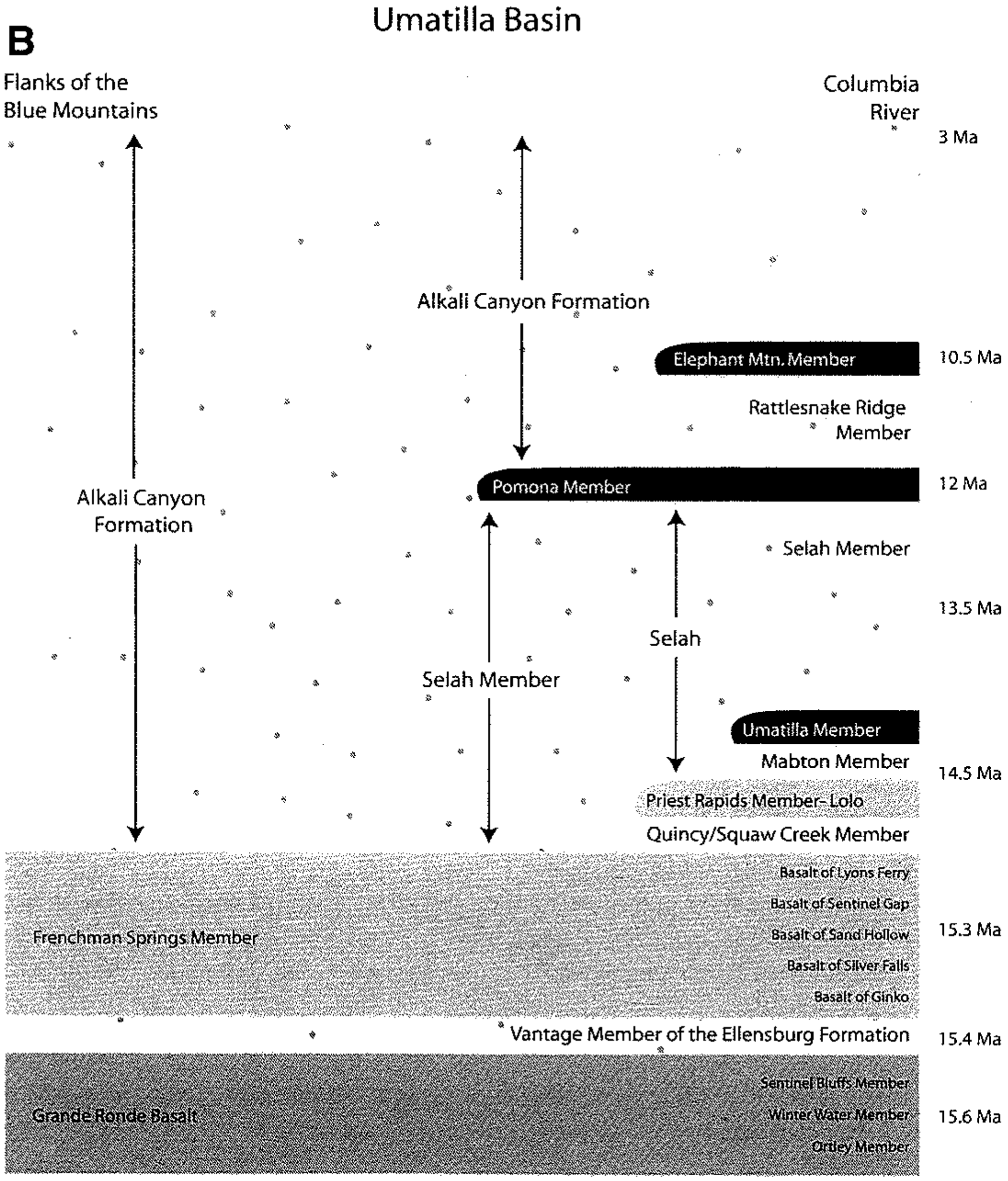

Figure 13 (*continued*).

Clearwater and Weiser Embayments subprovinces (Fig. 14). The Yakima Fold Belt includes the western and central parts of the Columbia Basin and is characterized by a series of major anticlinal ridges and synclinal valleys. The Yakima Fold Belt extends westward through the Cascade Range within a broad lowland gap (Columbia Trans-Arc Lowland) that existed during the middle Miocene and into western Oregon and Washington (Beeson et al., 1989a). The Palouse Slope subprovince comprises the eastern part of the Columbia Basin and is the least deformed subprovince, with only a few faults and low-amplitude, long-wavelength folds on an otherwise gently westward-dipping paleoslope (Swanson et al., 1980). The Yakima Fold Belt overlies rock west of the craton, while the Palouse Slope overlies the craton as well as accreted terranes. The Blue Mountains subprovince (Fig. 14) forms the southern boundary of the Columbia Basin. The Blue Mountains subprovince is a northeast-trending anticlinorium, and associated north-northeast–trending faults (e.g., Hite Fault), that extends 250 km from the Oregon Cascades to the eastern part of the Columbia Basin. The CRBG overlies the pre-Tertiary accreted terrane assemblages and Eocene and Oligocene volcaniclastic rocks. The Lewiston Basin (within the Clearwater Embayment) is a fault-bounded basin or graben lying northeast of the Blue Mountains subprovince (Fig. 14).

CRBG lavas occur in three additional subprovinces—the Cascade Range, Willamette Valley, and Coast Range subprovinces. The Cascade Range subprovince is mainly defined by the north-south–trending Cascade volcanic arc (Fig. 14). The Yakima Fold Belt subprovince extends into the Cascade Range subprovince along the Columbia Trans-Arc Lowland (Fig. 14). Uplift and intra-arc grabens are the main structural features directly associated with Cascade arc-volcanism (Swanson et al., 1981; Priest and Vogt, 1982).

The Willamette Valley subprovince is the lowland area that lies between the Cascade Range and Coast Range subprovinces (Fig. 14). The Willamette Valley subprovince is often depicted as a large north-south–trending trough that has been subsiding since at least Miocene time. However much of the subsidence within the Willamette Valley is directly associated with fault-bounded structural basins within this larger trough (e.g., Portland, Tualatin, Willamette, and Stayton Basins) that had begun to develop by at least CRBG time (Beeson et al., 1989a; Yeats et al., 1991).

The Coast Range subprovince is a broad structural arch cored by Tertiary volcanic and marine sedimentary strata that form the northern Oregon and southern Washington Coast Range. Uplift of the northern Oregon and southern Washington portion of the Coast Range began in middle Miocene time, and the CRBG flows crossed this subprovince through an ancestral Columbia River drainage roughly centered on the track of the present-day

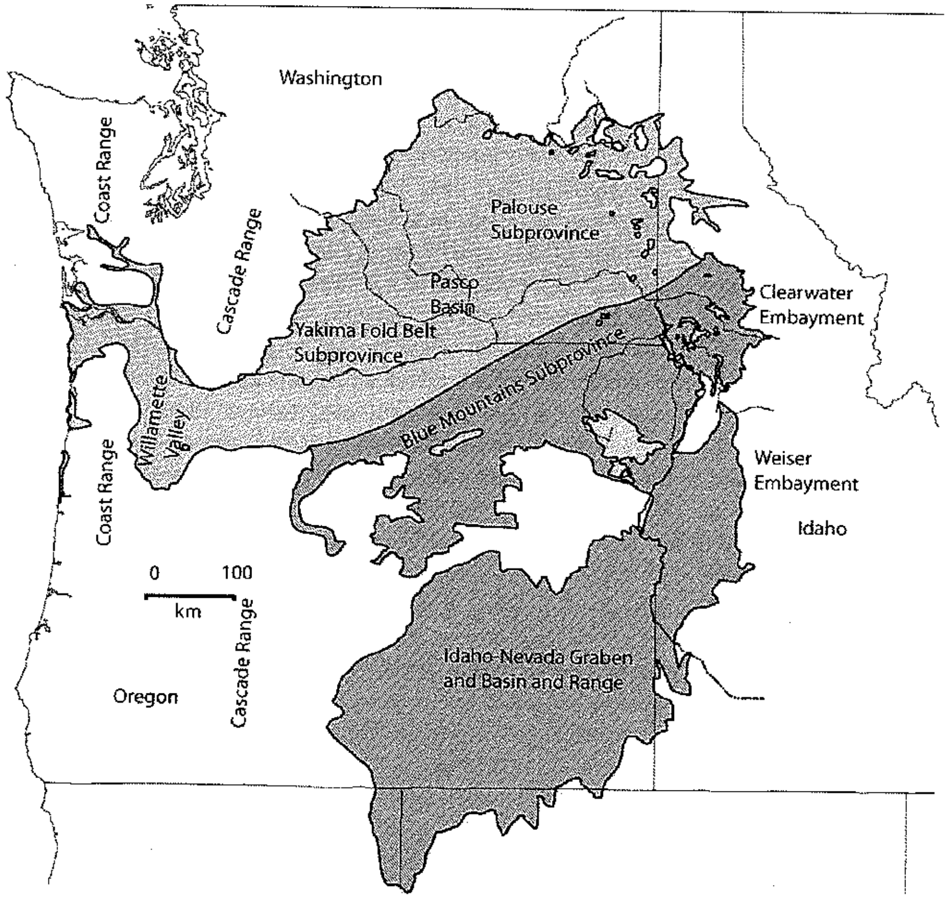

Figure 14. Map showing the structural subprovinces of the Columbia River Flood-Basalt Province.

Columbia River (Snavely et al., 1973; Choiniere and Swanson, 1979; Niem and Niem, 1985; Beeson et al., 1985; Wells et al., 1989, 1995, this volume).

Important Structures and Structural Trends

Olympic-Wallowa Lineament

The Olympic-Wallowa lineament (OWL) is a major northwest-trending topographic feature in Washington and Oregon (Fig. 14) that crosscuts the Columbia Basin (Raisz, 1945). This feature parallels pre-CRBG structural trends along the northwest margin of the Columbia Basin, but it has not been linked to any individual structure (Campbell, 1989; Reidel and Campbell, 1989). Within the Yakima Fold Belt, the OWL includes a zone of Miocene and post-Miocene deformation along Manastash Ridge and apparent bending of Umtanum Ridge, Yakima Ridge, Rattlesnake Ridge, and Horse Heaven Hills.

The portion of the OWL that crosses the central Washington is called the Cle Elum–Wallula deformed zone (CLEW; Kienle et al., 1977). It is a 10-km-wide, moderately diffuse zone of anticlines that have a N50°W orientation. As defined by Davis (1981), the CLEW consists of three structural parts: (1) a broad zone of deflected or anomalous fold and fault trends extending south from Cle Elum to Rattlesnake Mountain; (2) a narrow belt of topographically aligned domes and doubly plunging anticlines extending from Rattlesnake Mountain to Wallula Gap (RAW); and (3) the Wallula fault zone (Horse Heaven Hills), extending from Wallula Gap into the Blue Mountains.

Northwest of the CRBG margin, numerous northwest- and north-trending faults and shear zones lie subparallel to the OWL (Tabor et al., 1984). The 17–19.7 Ma Snoqualmie batholith intrudes these faults but is not cut by them, indicating that any possible movement along the OWL at the western margin of the Columbia Basin must pre-date the batholith, 17–19.7 Ma (Frizzell et al., 1984). The structural significance of the OWL has been called into question by two recent geophysical studies. Neither a seismic profiling survey by Jarchow (1991) nor a gravity survey by Saltus (1991) could find any obvious geophysical signature for the OWL below the CRBG.

On the other hand, recent global positioning system (GPS) results suggest that the OWL (in its broadest sense) is the locus of active, north-south crustal shortening driven by the clockwise rotation of Oregon about a pole in the backarc (McCaffrey et al., 2007). New, high-resolution aeromagnetic surveys of the OWL in the Cascades may also suggest a structural link between active folding and faulting in Puget Sound and in the western Yakima Fold Belt (Blakely et al., 2009).

Hog Ranch–Naneum Ridge Anticline

The Hog Ranch–Naneum Ridge (HR-NR) anticline is a broad north-south–trending anticline in the CRBG that crosses the Yakima Fold Belt at a high angle (Fig. 14). This anticlinal feature begins at the northern margin of the CRBG on Naneum Ridge, southwest of Wenatchee, Washington, and trends southeast for ~12 km, and then turns south toward Prosser, Washington, where it separates the Toppenish Basin from the Pasco Basin. This south-plunging structure passes through five Yakima Fold Belt anticlines and the OWL. A gravity gradient and a series of gravity highs delineate the HR-NR in the subsurface. The southern extension of the anticline appears to be a Bouguer gravity high near the Washington-Oregon border southeast of Prosser, Washington.

The HR-NR anticline was active in late to middle Miocene as demonstrated by thinning of CRBG flows across it (Reidel et al., 1989a), but the east-trending Yakima folds show no apparent offset produced by the HR-NR cross-structures (Kienle et al., 1977; Tabor et al., 1982; Campbell, 1989; Reidel et al., 1989a) nor is the HR-NR anticline offset where the OWL-CLEW crosses it. Growth of the HR-NR anticline continued from the Miocene to Recent and is now marked by the highest structural points along the Yakima Fold Belt anticlinal ridges that cross it.

White River–Naches River Fault Zone

The White River–Naches River Fault Zone (WR-NRFZ), a major fault zone (Fig. 14) that extends 90 km from Naches to Enumclaw, Washington, separates two domains of dissimilar structure, stratigraphy, and topography (Campbell, 1988, 1989). To the northeast of the zone, structures strike N60°W; to the southwest, structures in pre-Tertiary rocks trend N5°E to N20°W. The WR-NRFZ probably extends under the basalt at least as far as Konnowac Pass and either parallels or crosscuts the HR-NR anticline. The WR-NRFZ is the major structure trending into the Columbia Basin that can be demonstrated to be a fundamental structural boundary in rock below the CRBG.

Yakima Fold Belt

As mentioned above, the Yakima Fold Belt subprovince covers ~14,000 km^2 of the western and west-central Columbia Plateau (Fig. 14) and formed as CRBG flows and intercalated sediments were folded and faulted under north-south–directed compression. Most of the present structural relief in the western and central Columbia Plateau has developed since ca. 10.5 Ma when the last massive outpouring of lava, the Elephant Mountain Member (Saddle Mountains Basalt; Fig. 2), buried much of this area. The main deformation is concentrated in the Yakima Fold Belt; there is only minor deformation on the Palouse Slope. Almost all the present structural relief is post-CRBG.

The Yakima Fold Belt consists of narrow anticlinal ridges separated by broad synclinal valleys floored by relatively undeformed sediment. The anticlines and synclines are typically segmented and most have north vergence. However, south vergence occurs on some anticlines such as the Columbia Hills, Cleman Mountain, and a few segments of some other ridges. Fold length ranges from one kilometer to >200 km; fold wavelengths range from several kilometers to as much as 20 km. The folds are segmented by crosscutting faults and folds (Reidel, 1984, 1988; Anderson, 1987; Reidel et al., 1989a, 1994a). Structural relief is typically less than 600 m but varies along the length of the fold. The greatest structural relief along the Frenchman Hills, the Saddle Mountains, Umtanum Ridge, and Yakima Ridge occurs where they intersect the north-trending HR-NR anticline.

Anticlines in the southwest part of the Yakima Fold Belt, southwest of the CLEW, generally have N50°E trends (Swanson et al., 1979a; Reidel et al., 1989a, 1994a; Tolan and Reidel, 1989; Watters, 1989). Anticlines in the central part have east trends except along the CLEW where a N50°W trend predominates (Swanson et al., 1979a; Reidel et al., 1989a, 1994a; Tolan and Reidel, 1989; Watters, 1989). The Rattlesnake Hills, Saddle Mountains, and Frenchman Hills have overall east trends, but Yakima Ridge and Umtanum Ridge change eastward from east to N50°W in the CLEW (Swanson et al., 1979a; Reidel et al., 1989a, 1994a; Tolan and Reidel, 1989; Watters, 1989). The Horse Heaven Hills, the N50°W-trending Rattlesnake Hills, and the Columbia Hills abruptly terminate against the CLEW.

Although rarely exposed, nearly all the steep forelimbs of the asymmetrical anticlines are faulted. These frontal fault zones typically consist of imbricated thrusts (Bentley, 1977; Bentley in Swanson et al., 1979a; Goff, 1981; Reidel, 1984, 1988; Hagood, 1986; Anderson, 1987) that are emergent at ground surface. Near the ground surface the thrust faults merge into shallow-dipping surface of the basalt (Reidel, 1984). Where erosion provides deeper exposures, these frontal faults are shown to be steep reverse faults (e.g., 45° south in the Frenchman Hills at the Columbia River water gap (Grolier and Bingham, 1971) and 50°–70° north in the Columbia Hills at Rock Creek, Washington (Swanson et al., 1979a; Anderson, 1987).

Hydrocarbon exploration boreholes provide direct evidence for the dips of these Yakima Fold Belt frontal faults. Reidel et al. (1989a) have argued that the Saddle Mountains fault must dip more than 60° where the Shell-ARCO BN 1-9 borehole was drilled. Drilling of the Umtanum fault near Priest Rapids Dam (Puget Sound Power and Light Company [PSPL], 1982) suggests that this fault dips southward under the ridge with a dip of at least 30° to 40° (PSPL, 1982) but perhaps as high as 60° (Price, 1982; Price and Watkinson, 1989).

Although it is difficult to assess, total shortening increases from east to west across the Yakima Fold Belt. At ~120° longitude, it is estimated to be greater than 15 km but less than 25 km (Reidel et al., 1989a) or ~5%. Typically, shortening on an individual anticline due to folding is ~1–1.5 km. The amount of shortening on faults expressed at the surface is generally unknown. Estimates range from several hundreds of meters to as much as 3 km (Reidel et al., 1994a).

Synclines typically are structurally low areas formed between the gently dipping limb of one anticline and the steeply dipping limb of another where that limb was thrust up onto the gently dipping limb of the neighboring anticline. Few synclines were formed by synclinal folding of the CRBG.

Northwest-Trending Wrench Faults

Geologic mapping of the Columbia River Flood-Basalt Province (e.g., Newcomb, 1970; Anderson, 1979, 1987; Hammond, 1979; Swanson et al., 1979a, 1980, 1981; Barrash et al., 1980; Bentley et al., 1980; Kienle, 1980; Hammond et al. 1982; Niem and Niem, 1985; Dames and Moore, Inc., 1987; Walsh et al., 1987; Beeson et al., 1989b; Bentley, 1989; Walker and MacLeod, 1991; Blakely et al., 1995; Wells et al., 1995; Schuster et al., 1997; Tolan et al., 1999, 2000a) has found numerous northwest-trending, dextral (right-lateral), strike-slip faults in the western-half of the province. These northwest-trending faults range from relatively minor faults to features that can be traced for more than 50–100 km (e.g., Gales Creek–Mount Angel Structural Zone, Portland Hills–Clackamas River Structural Zone, Lacamas Lake–Sandy River Structural Zone, Maupin Trend, Luna Butte Trend, Arlington Trend; Fig. 14). The larger scale northwest-trending faults have been classified as wrench faults by most investigators (e.g., Bentley et al., 1980; Beeson et al., 1985, 1989a; Anderson and Tolan, 1986; Anderson, 1987; Dames and Moore, Inc., 1987; USDOE, 1988; Reidel et al., 1989a; Beeson and Tolan, 1990). This classification is based on distinctive characteristics that they typically display, including (1) conjugate en echelon faults, (2) genetically related en echelon folds, (3) reversal of apparent dip-slip displacement along strike, (4) lengths of tens to >80 km, and (5) seismicity with focal mechanism solutions indicating dextral strike-slip and/or oblique-slip movement.

Studies have found evidence that many of these northwest-trending faults developed contemporaneously with the Yakima Fold Belt structures and that deformation has apparently continued on these structures into the Holocene (Anderson and Tolan, 1986; Anderson, 1987; Dames and Moore, Inc., 1987). These northwest-trending wrench faults are also responsible for creating large-scale pull-apart basins (e.g., La Grande Basin, Portland Basin, Tualatin Basin, Willamette Basin, and Stayton Basin) within the flood-basalt province (Fig. 14).

In the western Columbia Plateau and Willamette Valley, minor earthquake activity (mainly small magnitude [<3.0] events) is associated with several of the northwest-trending wrench faults (USDOE, 1988; Yelin and Patton, 1991). However the 25 March 1993, M5.6, Scotts Mills earthquake (Willamette Valley) probably occurred on the Gales Creek–Mount Angel Structural Zone. This activity is direct evidence that some of these northwest-trending faults are still active today.

QUATERNARY DEFORMATION IN THE COLUMBIA RIVER FLOOD-BASALT PROVINCE

Columbia Plateau

Within the Columbia Plateau, probably all geologic structures developed much of their present relief prior to the Pleistocene. Although not common, evidence of Pleistocene faulting has been found at many locations across the Columbia Plateau. While age relations are generally poorly constrained, they suggest that faulting has continued since the last cataclysmic flood (ca. 13,000 yr B.P.).

Yakima Fold Belt

The following Yakima Fold Belt structures listed below have been identified as displaying evidence of Quaternary deformation.

(1) Toppenish Ridge. Campbell and Bentley (1980, 1981) describe a 0.5- to 2.2-km-wide zone of nearly 100 surface ruptures along a 32-km-long segment of the north flank of Toppenish Ridge. The scarps are subparallel to the ridge trend and range from 0.1 to 3 km in length. The lowest scarp (Mill Creek) is a thrust fault, but all other scarps are high-angle normal faults. Individual ruptures have displacements as great as 4 m; organic material in the ruptures yields C^{14} ages of 505 ± 160 yr and 620 ± 135 yr (Campbell and Bentley, 1981).

(2) Ahtanum Ridge. A Quaternary fault was exposed during highway construction near Union Gap, Washington, on Ahtanum Ridge. At this location, a high-angle reverse fault offsets Yakima River terrace gravels by at least 7 m, juxtaposing the basalt of Ginkgo, Frenchman Springs Member (Campbell, in Washington Public Power Supply System [WPPSS], 1981). A questionable U/Th caliche age of 30,000 yr was obtained for the terrace gravel (Campbell, 1983). The fault gouge appears to be capped by undeformed 13,000-yr-old slackwater sediments, but exposures of the fault 1 km to the east show faulted slackwater sediments (N.P. Campbell, 1992, personal commun.).

(3) Umtanum Ridge–Gable Mountain. Deposits 13,000 yr old are offset as much as 6.5 cm by the central Gable Mountain fault (PSPL, 1982) at the east end of Umtanum Ridge. The central Gable Mountain fault is a tear fault with a component of reverse movement and shows increasing offset in progressively older units suggesting a history of multiple rupture events.

(4) Other Localities. Undocumented and/or unpublished data for other suspected Quaternary faults within the Yakima Fold Belt include: Manastash Ridge (Geomatrix, 1988); Boylston Mountains (R.D. Bentley, 1983, oral commun.); Cleman Mountain (Geomatrix, 1988; N.P. Campbell, 1992, personal commun.); Yakima Ridge (R.D. Bentley, 1990, oral commun.); Medicine Valley (Geomatrix, 1988); Hog Ranch–Naneum Ridge anticline (Bentley, 1986, personal commun.); Tamarack Springs (Campbell, 1983); Frenchman Hills and Smyrna Bench, Saddle Mountains (Geomatrix, 1988; West and Shaffer, 1989; Shaffer and West, 1989); Wenas Valley (West, 1987); Kittitas Valley (Geomatrix, 1988); and Ahtanum Ridge (N.P. Campbell, 1992, personal commun.; Geomatrix, 1988).

There is no pattern of faulting in the Yakima Fold Belt that would suggest Quaternary faulting is more concentrated in one part than another. Rather, the broad distribution of contemporaneous deformation suggests that the entire fold belt has continued to develop through the Quaternary in a pattern similar to the Pliocene and Miocene.

Walla Walla Basin and Hite Fault

Quaternary deformation has been reported at 15 localities along the portion of the CLEW that defines the southern and western boundary of the Walla Walla Basin (WPPSS, 1981; Mann and Lewis, 1991). Suspected Quaternary faults, associated with the Hite Fault system along the eastern side of the Walla Walla Basin, have also been reported by Shannon and Wilson (1979, p. 28).

Northwest-Trending Wrench Faults

In the western Columbia Plateau, Anderson and Tolan (1986) report a potential Quaternary fault (cutting cataclysmic flood sediments) that is associated with the northwest-trending Luna Butte Trend.

Gehrels et al. (1979) report suspected Quaternary deformation associated with northwest-trending faults in the La Grande Basin.

In the Willamette Valley, Liberty et al. (1999) and Blakely et al. (2000) report suspected Quaternary offset along the northwest-trending Gales Creek–Mount Angel Structural Zone. Blakely et al. (2004) report Quaternary faulting related to the northwest-trending Portland Hills–Clackamas River Structural Zone.

CONTEMPORARY STRESS AND STRAIN

Regional Data

Contemporary horizontal strain for the central Columbia Plateau has been determined from geodetic surveys. Although local geodetic surveys (Prescott and Savage, 1984) across the Pasco Basin suggest north-south shortening at a rate of –0.27+ 0.22 microstrain/yr, analysis of robust continuous and campaign GPS data by McCaffrey et al. (2007) indicate 3.3 mm/yr north-south shortening across the Yakima Fold Belt. In their block model, the slip is partitioned onto the CLEW and the Entiat–Saddle Mountains fault systems, although it is likely to be more broadly distributed.

Earthquake focal mechanism solutions indicate that the maximum principal stress is generally north-south and the minimum principal stress is near-vertical (USDOE, 1988). Seismicity occurs in three stratigraphic zones—the CRBG, the sub-CRBG sediments, and the crystalline basement. Most of the seismicity is concentrated in the CRBG and the crystalline basement. Seismicity in the CRBG tends to be concentrated within the Yakima Fold Belt synclinal areas where surface deformation is minimal (USDOE, 1988). These data are consistent with geologic evidence (Reidel et al., 1989a) suggesting that the central Columbia Plateau has been under north-south compression since at least the Miocene and that the same stress pattern continues today.

Contemporary Stress in the Central Columbia Plateau

CRBG core disking and spalling are common in boreholes drilled in the Cold Creek syncline (Yakima Fold Belt–Pasco Basin, central Columbia Plateau) indicate relatively high in situ stress (USDOE, 1988). Core disking—when basalt drill core fractures into thin disks during drilling—is an indicator of high in situ stress, as well as remanent and residual stresses. Borehole spalling or breakouts indicate high horizontal deviatoric stress and suggest that in situ stress is not distributed lithostatically. Spalling occurs in the direction of least horizontal compression, and the consistent east-west orientation of borehole spalling also indicates that the maximum horizontal stress is oriented generally north-south.

Hydraulic fracturing tests were conducted in boreholes in the Cold Creek syncline at ~1 km depth in the upper part of the Grande Ronde Basalt (USDOE, 1988). The results indicated that the maximum horizontal stress ranges from 52.6 to 67.4 MPa (7630–9780 lbf/in^2), and the minimum horizontal stress ranges from 30.3 to 35.7 Mpa (4400–5180 lbf/in^2). The ratio of average horizontal stress $[(\sigma_H + \sigma_h)/2]$ to the vertical stress (σ_v) ranges from 1.41 to 2.14 with a mean value of 1.77 ± 0.20. This ratio is close to the higher end of known stress conditions at comparable depths at other locations. The mean orientation of induced fractures, and thus the direction of the maximum horizontal stress, is consistent with north-south compression (Paillet and Kim, 1987).

Given the high in situ stress conditions, Kim et al. (1986) suggested that movement is possible on an east-west–striking reverse fault that dips 60° to 65° and has an effective friction angle of 33° or less along the fault plane. A comparison of shear strength along potential faults (Byerlee, 1978) to test results on the properties of CRBG joint surfaces (USDOE, 1988) suggests that slip could occur on a preexisting fracture in the present stress field.

The pattern of regional Quaternary faulting indicates that the hypothesis of Kim et al. (1986) is correct, but the pattern of microseismicity is inconsistent with this. Microseismicity occurs in regional synclinal areas where the CRBG is typically fresh, unaltered, and competent. Microseismicity is apparently absent from frontal faults on anticlinal ridges.

Contemporary Stress in the Willamette Valley

In the Willamette Valley region, Werner (1990) analyzed borehole breakouts from 18 wells that were due to the spalling of the borehole wall caused by in situ stress. Werner found that the borehole breakouts generally indicated a north-northwest to north-northeast orientation of the maximum horizontal compression that coincided with the direction of maximum horizontal compression determined from local earthquake focal mechanisms.

Relationship between CRBG Emplacement Rates and Regional Subsidence

Overall, one of the most significant deformational processes to affect the Columbia River Flood-Basalt Province has been regional-scale subsidence beneath the Yakima Fold Belt and Columbia Trans-Arc Lowland (Beeson et al., 1989a; Reidel et al., 1989a, 1994a). Subsidence began prior to the eruption of the CRBG and continued until ca. 3 Ma (Beeson et al., 1989a; Reidel et al., 1989a; Beeson and Tolan, 1990; Fig. 15). The base of the CRBG section now lies nearly 4 km below the modern land surface in the Pasco Basin (Fig. 16). Basin subsidence kept pace with flood-basalt eruptions. Reidel et al. (1989a) showed that the rate of subsidence paralleled the rate of flood-basalt eruptions, with the greatest subsidence occurring during Grande Ronde time and subsequently declining through Wanapum and Saddle Mountains time. Assuming that the Grande Ronde Basalt was erupted over a 1 million year period, Reidel et al. (1989a) calculated the rate of subsidence to be ~2 cm/yr. However, the new age dates of Barry et al. (2008) indicate that the Grande Ronde Basalt was erupted over a period of 250,000 yr, thus increasing the rate of subsidence to as much as 8 cm/yr.

Origin of the Columbia River Flood-Basalt Province—The Plume Hypothesis

The existence of deep mantle plumes is currently one of the hot topics in CRBG research. It is beyond the scope of this paper to address the pros and cons of the plume debate. Discussion of the plume model and alternative hypotheses can be found in Hooper et al. (2007) and other papers in Foulger and Jurdy (2007). Some of the factors that need to be considered in this debate are:

(1) Models for the origin of the CRBG often call upon the presence of a mantle plume. Some of the important considerations are the size and compositional homogeneity of the flows and the short span of time for the peak of eruptions (e.g., 250,000 yr for the Grande Ronde Basalt (Barry et al., 2008)).

(2) Connections between a mantle plume and the age progressive volcanism of the Snake River Plain in southern Idaho to the Yellowstone Hotspot.

(3) Tectonic reconstructions place the Yellowstone Hotspot beneath the location where the modern states of Oregon, Idaho, and Nevada intersected ~17 million years ago.

(4) The problem of magma transport from the plume at the Oregon, Nevada, and Idaho borders to the Chief Joseph dike swarm ~400 km north of the plume center.

(5) The majority of the exposed portion of the Chief Joseph dike swarm lies in the Mesozoic accreted terranes of northeastern Oregon and southeastern Washington immediately west of the edge of the North American craton as defined by the

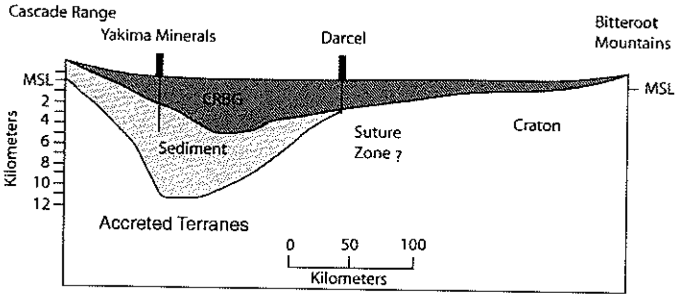

Figure 15. Diagrammatic, east-west cross section through the Columbia Basin showing the relative thickness of the Columbia River Basalt Group (CRBG) and pre-CRBG sediments.

0.706 $^{87}Sr/^{86}Sr$ line of Armstrong et al. (1977). Thus the plume magmas may have been transported to the north along zones of crustal weakness associated with the boundary between the thicker Precambrian crust of the North American craton and the thinner Mesozoic crust of the accreted terranes

(6) Discussion of geochemical patterns in the CRBG by Hooper et al. (2007) generated considerable debate. See the discussions and replies at the end of that paper.

COLUMBIA RIVER BASALT GROUP HYDROGEOLOGY

Introduction

Numerous studies of CRBG aquifers have been conducted within the Columbia Plateau region to better understand their hydraulic characteristics and to develop a model of how various factors (e.g., CRBG flow physical characteristics and properties, tectonic features and properties, erosional features, climate, etc.) interact to create and govern this confined groundwater system (e.g., Newcomb, 1961, 1969; Hogenson, 1964; Brown, 1978, 1979; Gephart et al., 1979; Oberlander and Miller, 1981; Drost and Whiteman, 1986; Livesay, 1986; Davies-Smith et al., 1988; Lite and Grondin, 1988; USDOE, 1988; Burt, 1989; Lum et al., 1990; Johnson et al., 1993; Hansen et al., 1994; Spane and Webber, 1995; Wozniak, 1995; Steinkampf and Hearn, 1996; Packard et al., 1996; Sabol and Downey, 1997). The general similarity of the hydrogeologic characteristics, properties, and behavior of the CRBG aquifers across the flood-basalt province is one of the most significant findings to emerge from these studies. Therefore much of the general knowledge that has been learned about the characteristics and behavior of the CRBG aquifers is readily applicable to CRBG aquifers in other areas. The purpose of this section is to present a review of the general hydraulic characteristics.

In the Columbia Plateau and western Oregon and Washington, groundwater in the CRBG generally occurs as a series of aquifers hosted by the upper three CRBG formations (Grande Ronde, Wanapum, and Saddle Mountains) and the interstratified Ellensburg Formation sediments. CRBG aquifers have been characterized as generally semiconfined to confined. The major water-bearing and transmitting zones (aquifers) within the CRBG are variously identified as occurring in sedimentary interbeds, between adjacent basalt flows (interflow zone), and in basalt flow tops (Gephart et al., 1979; Hansen et al., 1994; Packard et al., 1996; Sabol and Downey, 1997; USDOE, 1988). The following sections summarize basic hydrogeologic characteristics of CRBG intraflow structures, stratigraphic controls on groundwater flow within the CRBG, and secondary controls on CRBG hydrology.

Hydraulic Characteristics of CRBG Intraflow Structures

The physical characteristics and properties of individual CRBG flows affect their intrinsic hydraulic properties and influence potential distribution of groundwater within the CRBG. Fundamental to this discussion is the mode of CRBG flow

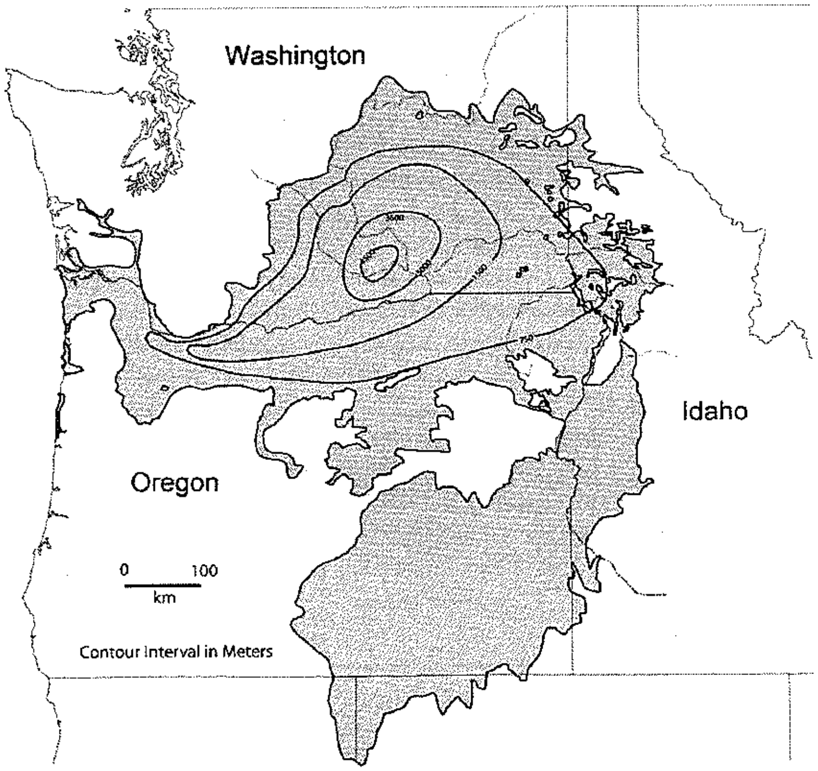

Figure 16. Isopach map of the Columbia River Basalt Group (CRBG) in the northern and western portions of the Columbia River Flood-Basalt Province. Thicknesses are constrained by field and borehole stratigraphic sections.

emplacement and types and extent of the intraflow structures associated with each flow. As reviewed earlier, there are three basic modes for lava flow emplacement—compound flow, sheet flow, and intracanyon flow. The internal arrangement of physical (intraflow) structures is far more irregular in compound flows than sheet flows. The presence of these structures in compound flows provides numerous potential pathways for both horizontal and vertical groundwater movement through the flow. Based on both surface and subsurface data and mapping, CRBG flows are most commonly classified as sheet flows (e.g., Beeson et al., 1985, 1989a; Beeson and Tolan, 1990, 1996; Reidel and Tolan, 1992; Reidel et al., 1994b; Reidel, 1998).

As described earlier, CRBG sheet flows exhibit a basic three-part internal arrangement of internal intraflow structures that originate during the emplacement and cooling of the lava flows. These features are referred to as the flow top, flow interior, and flow bottom (Fig. 7). The combination of a flow top of one flow and the flow bottom of the overlying flow is commonly referred to as the "interflow zone." The interflow zones, in comparison to the flow's dense interior, form the predominant water-transmitting zones (aquifers) within the CRBG (USDOE, 1988). In their original undisturbed state, individual interflow zones are as laterally extensive as the sheet flows between which they occur. Given the extent and thickness (geometry) of individual interflow zones, this creates a series of relatively tabular, stratiform layers that could potentially play host to aquifers within the CRBG.

It is widely agreed that within CRBG aquifers, given the typical distribution and physical characteristics of CRBG intraflow structures, groundwater primarily resides within the interflow zones (Newcomb, 1969; Oberlander and Miller, 1981; Lite and Grondin, 1988; Davies-Smith et al., 1988; USDOE, 1988; Wozniak, 1995; Tolan et al., 2000b; Tolan and Lite, 2008). The presence of interbedded sediments can either enhance (e.g., sandstone and conglomerate) or inhibit (e.g., mudstone and paleosols) groundwater storage and movement within this zone. Another critical aspect with respect to interflow zones, that is not commonly recognized, is their potential lateral variability. For example, thick flow-top breccias are known to abruptly end with a much thinner normal flow top taking its place. The same is true for flow-bottom features (e.g., pillow complexes) that can abruptly end or transition to a more simple flow bottom. These intraflow structure "facies changes" can result in radical changes of the hydraulic properties and behavior of an individual CRBG aquifer.

The physical properties of undisturbed, laterally extensive, dense interiors of CRBG flows make this portion of the flow essentially impermeable for all practical purposes (Newcomb, 1969; Oberlander and Miller, 1981; Davies-Smith et al., 1988; Lite and Grondin, 1988; USDOE, 1988; Lindberg, 1989; Wozniak, 1995). While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be typically 77% to >99% filled with secondary minerals (clay, silica, and zeolite), and void spaces that do occur are typically not interconnected (USDOE, 1988; Lindberg, 1989). The fact that CRBG dense flow interiors typically act as aquitards accounts for the confined behavior exhibited by most CRBG aquifers. Artesian (flowing) conditions have been encountered within many areas around the flood-basalt province.

Field data and inferences based on modeling studies suggest that the hydraulic properties of CRBG aquifers are areally and vertically complex (e.g., Drost and Whiteman, 1986; USDOE, 1988; Hansen et al., 1994; Whiteman et al., 1994). For example, vertical profiles of hydraulic head from Hanford Site test wells indicate that there is the potential for upward movement of groundwater from Grande Ronde and Wanapum aquifers and downward movement of groundwater from the overlying Saddle Mountains aquifer (USDOE, 1988; Johnson et al., 1993). On the other hand, the regional water-level contours for the Grande Ronde and Wanapum aquifers presented in Hansen et al. (1994) suggest that the direction of vertical flow between these two aquifers is variable over the region. However, the results of hydrologic tests in wells at the Hanford Site show that lateral groundwater flow in the CRBG interflow zones appears to greatly exceed vertical movement through dense flow interiors (USDOE, 1988).

A range of hydraulic conductivity values is reported for CRBG aquifers in USDOE (1988), Whiteman et al. (1994), and Sabol and Downey (1997), and these values are summarized in Table 4. The values of hydraulic conductivity reported in Whiteman et al. (1994) rely heavily on data reported on driller's well reports from many wells that are open to multiple CRBG aquifers. These lateral conductivities integrate values over the entire depth of penetrated CRBG and, therefore, reflect the contribution from interlayer vertical movement of groundwater past CRBG flow pinchouts, faulting, and other discontinuities in individual CRBG flow layers. The hydraulic conductivities of an individual interflow zone within the tested intervals may be substantially higher (or lower) than the reported value.

Values of storativity in the CRBG are commonly between 10^{-4} and 10^{-5}, reflecting the high degree of confinement of the interflows and incompressible aquifer matrix (McFarland and Morgan, 1996; Conlon et al., 2005). Higher values of storativity calculated from some aquifer tests may indicate less confinement in some parts of the CRBG system. Some may represent tests in the uppermost basalt interval that are hydraulically connected through surface fractures to the overlying sediments or land surface. Lateral facies changes in the interflow zones, wells open to multiple and often different interflow zones, and the presence of structural boundaries complicate estimation of aquifer parameters based on Theisien analysis of pumping test data, and may result in misleading parameter values.

The available data on hydraulic properties of the various CRBG aquifers, including permeability, porosity, and storativity, indicate that a large variability in local flow characteristics is expected. However, hydraulic data are generally sparse and cannot be extrapolated easily to other locations within the area. Finally, pumping and recharge can locally alter hydraulic gradients and flow directions during the year, especially in the vicinity of aquifer boundaries.

TABLE 4. REPORTED HYDRAULIC CONDUCTIVITY RANGES FOR CRBG AQUIFERS

Feature		Hydraulic conductivity ranges ft/day	Hydraulic conductivity ranges m/day (approx. conversion)	Reference	Comments
Flow tops	Kh	1×10^{-6} to 1000	3×10^{-7} to 3×10^{-2}	USDOE (1988)	Average = 0.1 ft/day
	Kv	3×10^{-9} to 3×10^{-3}	9×10^{-10} to 9×10^{-4}	USDOE (1988)	
	Kv	1×10^{-5} to 1×10^{-1}	3×10^{-6} to 3×10^{-2}	Sabol and Downey (1997)	Measured near Lind, Washington
Flow interiors	Kh	1×10^{-9} to 1×10^{-3}	3×10^{-10} to 3×10^{-4}	USDOE (1988)	Approximately five orders of magnitude less than flow tops
	Kv	3×10^{-9} to 3×10^{-3}	9×10^{-10} to 9×10^{-4}	USDOE (1988)	
	Kv	1×10^{-5} to 1×10^{-1}	3×10^{-6} to 3×10^{-2}	Sabol and Downey (1997)	Measured near Lind, Washington
Flow tops	Kh	7×10^{-3} to 1892	2×10^{-3} to 6×10^{2}	Whiteman et al. (1994)	Vertically averaged for Saddle Mountains Basalt
	Kh	7×10^{-3} to 5244	2×10^{-3} to 2×10^{3}		Vertically averaged for Wanapum Basalt
	Kh	5×10^{-3} to 2522	5×10^{-3} to 6×10^{2}		Vertically averaged for Grande Ronde Basalt
Ellensburg Formation interbeds	Kh	1×10^{-6} to 1	3×10^{-7} to 3×10^{-1}	USDOE (1988)	Average for various interbeds = 0.01 to 0.1 ft/day
	Kh	1×10^{-6} to 100	3×10^{-7} to 3×10^{-1}	Sabol and Downey (1997)	Measured for interbeds in Pasco Basin

Note: Abbreviations: CRBG—Columbia River Basalt Group; Kh— horizontal hydraulic conductivity; Kv—vertical hydraulic conductivity; USDOE—U.S. Department of Energy.

Secondary Controls on CRBG Hydraulic Characteristics

There are several processes that can modify the specific, and overall, hydraulic characteristics and behavior of CRBG aquifers and aquitards. These include tectonic fracturing forming faults and/or tectonic joints, folding, and secondary mineralization and/or alteration. The potential effect and impact of these various processes on CRBG groundwater systems can range from benign to profound. Understanding their impact on CRBG aquifers is critically important to accurately interpreting the behavior of CRBG aquifer systems.

Faults and Tectonic Joints

The presence of faults in the CRBG can potentially impact groundwater movement (e.g., Newcomb 1959, 1961, 1969; Lite and Grondin, 1988; USDOE, 1988; Johnson et al., 1993). Faulting in the CRBG tends to produce a roughly planar zone composed of coarsely shattered basalt that grades into very fine rock flour. Figure 17 presents a diagrammatic sketch of the typical physical features and terminology for a fault zone cutting CRBG flows. The width of the fault zone (shatter breccia and gouge) can be highly variable (<1 m to >150 m thick), and its thickness typically depends on: (1) magnitude of fault displacement, (2) type of fault (low-angle fault versus high-angle fault), and (3) type(s) of CRBG intraflow structures cut by the fault (Price, 1982; Reidel, 1984; Hagood, 1986; Anderson, 1987; USDOE, 1988). The dense interior portions of CRBG flows have a greater mechanical strength than either the flow top or flow bottom (interflow zone). This greater susceptibility is typically manifested by the widening of the fault zone, and associated effects, as it passes through these mechanically weaker portions of the flow (Price, 1982; USDOE, 1988). It has also been suggested that the presence of water within intraflow structures may decrease the relative strength of the rock and may be another factor contributing to deformational behavior in flow tops and flow bottoms (USDOE, 1988).

Fault zone shatter breccias often display significant degrees of alteration (clays) and/or secondary mineralization (silica, zeolite, calcite, and pyrite). These materials can cement shatter breccias and create a rock that is so massive and tough that CRBG fault breccias are commonly more resistant to erosion than unbrecciated CRBG (Myers and Price, 1981; Price, 1982; Anderson, 1987). The types of secondary minerals present within CRBG fault zones appear to be dependent on both environmental conditions (oxidizing versus reducing) and in situ conditions (e.g., water chemistry, thermal regime, and hydrologic regime; Myers and Price, 1981; Price, 1982; USDOE, 1988).

Faults have been found to impact the CRBG groundwater system in a number of ways. They can form barriers to the lateral and vertical movement of groundwater; a series of faults can create hydrologically isolated areas. Faults and joints can provide a vertical pathway (of varying length) for groundwater movement allowing otherwise confined CRBG aquifers to be in direct hydraulic communication. They can expose interflow zones creating local opportunities for aquifer recharge and/or discharge.

The ability of faults to affect CRBG groundwater systems in a variety of ways reflects the potential for both lateral and vertical heterogeneities in the physical characteristics of fault zones. For example, the degree of secondary alteration and mineralization along a fault zone may vary. Complete alteration and/or mineralization of fault shatter breccias and gouge zones would "heal" these features and produce rock of very low permeability. Variations in the completeness of this process would produce hydrologic heterogeneities along the trace of the fault. Even if a fault zone is completely healed by secondary alteration and mineralization, renewed movement (displacement) on the fault could produce new permeability within the healed shatter breccia (e.g., USDOE, 1988; Johnson et al., 1993).

Folding

A number of groundwater investigations in the Columbia Plateau area have noted that folds (primarily anticlinal and monoclinal folds) affect the occurrence and movement of groundwater through CRBG aquifers (e.g., Newcomb 1961, 1969; Gephart et al., 1979; Oberlander and Miller, 1981; Lite and Grondin, 1988; USDOE, 1988; Burt, 1989; Packard et al., 1996). In many cases, folds have been identified as groundwater barriers or impediments that either block or restrict lateral groundwater movement through the CRBG aquifer system (e.g., Newcomb, 1969; Oberlander and Miller, 1981; USDOE, 1988). Because most of the folds in this region have genetically related faults, one would initially suspect that the observed impacts of folds on the CRBG groundwater system are caused by related faults. However, the process of folding CRBG can affect the hydraulic characteristics of interflow zones.

During the process of folding, slippage parallel to the layers (CRBG flows) will occur, in part, to accommodate structural shortening. An analogy for this process is seen when a deck of playing cards is flexed and the individual cards slip past one another to accommodate the flexure. The tighter the flexure of the cards, the greater the "intercard" slippage. In folds, this type of flexural slip typically occurs within CRBG interflow zones (Newcomb, 1969; Price, 1982; Anderson, 1987) that are the mechanically weakest layers in the Columbia River basalt. The effects of this flexural slip on CRBG interflow zone range from minor shearing to nearly complete destruction (production of fault shatter breccia and gouge material) and are directly related to the intensity and magnitude of deformation (Price, 1982; Anderson, 1987). This process also impacts the original hydraulic characteristics of interflow zones, reducing or even destroying the permeability of these features (Newcomb, 1969).

Secondary Mineralization and Alteration

Secondary processes can change the physical characteristics of CRBG interflow zones and, consequently, affect the hydraulic properties of these features. The common aspect to all of these secondary processes is that they fundamentally change the original physical (and hydraulic) characteristics of CRBG flow tops and flow bottoms. The two most important of these processes are briefly described in the following sections.

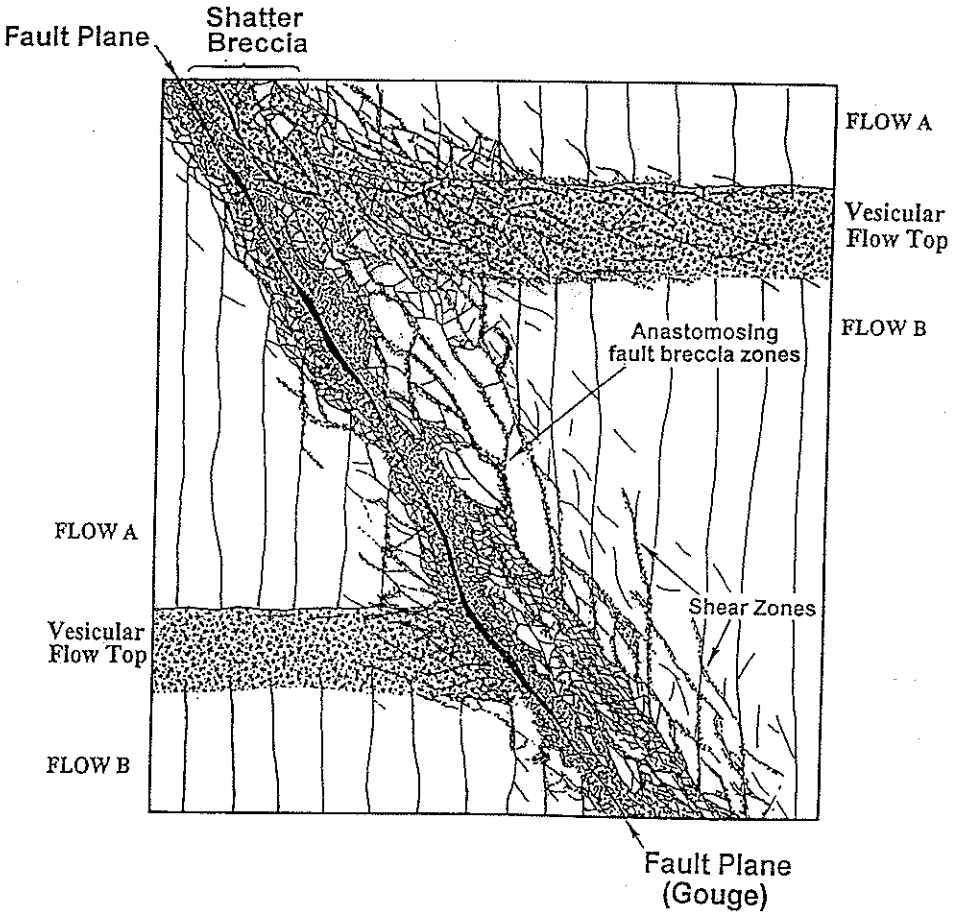

Figure 17. Diagram depicting common features found within fault zones that transect Columbia River Basalt Group flows.

Paleosol Development and Laterization

If a sufficiently long hiatus occurred between emplacement of CRBG flows, weathering and chemical breakdown of the glassy vesicular flow top will occur and lead to soil formation. This process would typically alter and destroy the original physical texture of a portion of the flow top as well as most of its original permeability. The extent of the flow top involved and degree to which these paleosols are developed vary tremendously. Factors controlling their development are thought to be duration of interval before the flow top is covered by the next CRBG flow, absence of sediment cover, and environmental conditions (e.g., climate, vegetation, paleogeography, etc.).

In the Willamette Valley and Coast Range regions, the degree of weathering and alteration of the CRBG is highly variable, ranging from little to total conversion to laterite (ferruginous bauxite). Notable occurrences of areally widespread laterization of the CRBG are found in the Salem–Eola Hills and Tualatin Mountains areas (Thayer, 1939; Libbey et al., 1945; Corcoran and Libbey, 1956; Trimble, 1963; Schlicker and Deacon, 1967). In these areas, it is typically the uppermost portion of the CRBG section that exhibits the most severe effects of weathering, with the interflow zones (flow tops and flow bottoms) being more susceptible to the weathering process, while the dense flow interiors are initially less susceptible (Fig. 18A). The depth of weathering (laterization) is highly variable, ranging from less than 5 m to greater than 60 m (Fig. 18B). Various studies on the origin of deep CRBG weathering in the Willamette Valley area (e.g., Libbey et al., 1945; Corcoran and Libbey, 1956; Trimble, 1963) have concluded that the CRBG section needs to be exposed for a long period of geologic time to conditions that will continuously leach and remove the more soluble constituents of Columbia River basalt.

Precipitation of Secondary Minerals

After the emplacement and burial of the CRBG flows, secondary minerals (e.g., silica, cryptocrystalline quartz, calcite, zeolite, pyrite, clay minerals, etc.) can partially to completely fill existing voids within interflow zones. Processes by which precipitation of these minerals occurs can be very complex and are dependent on a host of variables including groundwater chemistry, groundwater mobility and mixing rates, groundwater

Figure 18. (A) Partial laterization of a columnar jointed dense interior of a Sentinel Bluffs Member (Grande Ronde Basalt) flow. Note preserved outlines of the columnar jointing and relatively unweathered "corestones" in the center of the "blocks." (B) Nearly completely laterized portion of a two Grande Ronde Basalt flows exposed in roadcuts in the south Salem Hills. The roadcut is ~3 m in height.

residence time, and local geothermal regime (USDOE, 1988). The net effect of secondary mineralization on CRBG interflow zones is a reduction, ranging from slight to total, in the permeability of these zones. This process also is important in sealing cooling fractures in dense flow interiors.

Stratigraphic Controls on Groundwater Flow in CRBG Aquifers

Groundwater flow direction and rates within CRBG aquifers depend on the presence and extent of both intrinsic and external factors and features associated with the CRBG flows. Groundwater flow within CRBG aquifers appear to be generally separated from one another by very low permeability flow interiors. Some groundwater flow may occur locally around the flow pinchouts (Fig. 19), through vertically oriented fractures, and through faults. However, overall vertical groundwater flow rate through the basalt interiors between interflow zones is expected to be orders of magnitude lower than the horizontal flow through the interflow zones because of the very low permeability of flow interiors.

Incision into the CRBG intraflow zones, and consequent formation of "erosional windows" into deeper CRBG aquifers, can create recharge and discharge areas into and out of CRBG aquifers. Throughout the Columbia Plateau, erosional windows potentially connecting CRBG aquifers are known to occur in the Channeled Scablands region of the Columbia Plateau (Fig. 20) and can be inferred from geologic mapping (e.g., Stoffel et al., 1991; Reidel and Fecht, 1994a, 1994b; Schuster et al., 1997). Erosional windows into the CRBG and uplifted areas along the margin of the CRBG in the Willamette Valley also create such conditions.

From a hydrogeologic standpoint, understanding the distribution of CRBG units and interbedded Ellensburg sediments is a very important aspect of any analysis or model of CRBG aquifer system. First, where Ellensburg interbeds are composed of coarse-grained epiclastic sediments, they can potentially yield significant quantities of groundwater. However, where an Ellensburg unit consists of fine-grained sediments, it may form an aquitard. Second, as illustrated in Figure 21, the termination of CRBG flows may allow Ellensburg units to be in local hydrologic communication with each other, as well as post-CRBG (suprabasalt) sediments. This situation does not commonly occur within the Willamette Valley because interbeds are typically absent or very thin and fine grained.

Water Level Data—Evidence for a Layered Confined Aquifer System

Washington Department of Ecology (Ecology) has measured groundwater levels for up to 40 years in numerous wells distributed throughout the Columbia Plateau. As part of this effort, Ecology and the U.S. Geological Survey (USGS) constructed a number of multilevel observation well clusters in the central Columbia Plateau region in the 1970s and early 1980s to evaluate the state of the groundwater resource and the response of the CRBG aquifers to development away from the direct influence ("noise") of a pumping well.

Groundwater elevation measurements obtained during the same discrete time period can be used as an indicator of possible connection between groundwater and surface water and how well connected the basalt interflow zones are laterally and vertically.

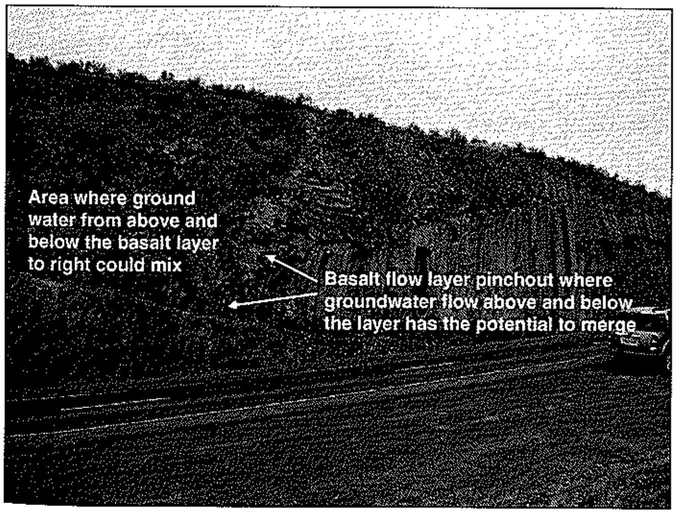

Figure 19. Termination ("pinchout") of a Sentinel Bluffs Member flow (Grande Ronde Basalt), west of Quincy, Washington. All Columbia River Basalt Group flows have flow margins (pinchouts) that mark the lateral termination of individual basalt flows. Where flows pinch out, the impermeable flow interior is absent and potentially water-bearing flow tops and bottoms are in direct hydrologic connection. Flow margins can create very limited (single flow) vertical connections.

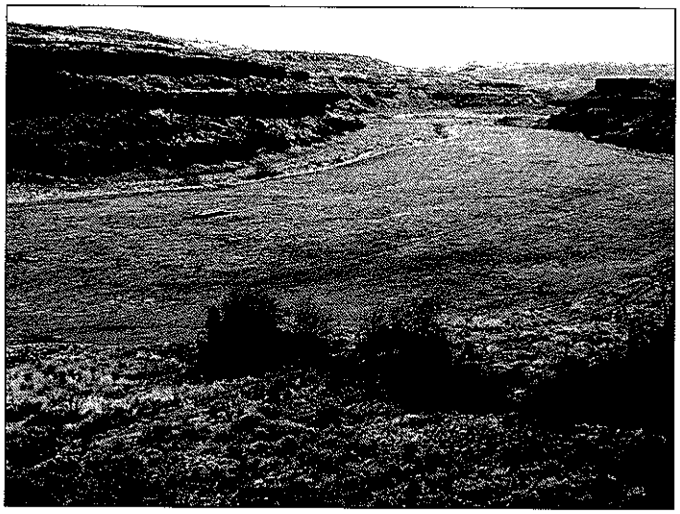

Figure 20. Wilson Creek Coulee in western Lincoln County, Washington. The coulee is eroded through the Wanapum Basalt (Roza and Frenchman Springs Members) into the Sentinel Bluffs Member of the Grande Ronde Basalt. This coulee is like dozens in the Columbia Plateau region that were incised into multiple Columbia River Basalt Group units, providing an opportunity to influence groundwater flow, recharge, and discharge.

Regular measurements taken over a number of years, particularly from non-pumping wells, provide a record of pumping and recharge to the interflow zones monitored by the well. The water level measured in each well represents the water pressure in the interflow zone(s) open to the well. Similarities and differences in the levels and the trends between each well of a multiwell cluster define the relationship with interflow zones monitored by each of the wells in the cluster. If good vertical connection exists between CRBG interflow zones, we would expect the water levels in different zones to be similar, and to react similarly over time. Conversely, differences in levels and/or trends indicate vertical separation between the monitored zones.

Review of historical groundwater levels from multilevel well clusters demonstrates that vertical flow pathways between the CRBG interflow zones are limited and of low permeability. As a consequence, the CRBG aquifers hosted by these zones commonly are hydraulically and geochemically separate and distinct. The water levels from multilevel well clusters located throughout the region corroborate this observation. Figure 22 shows a vertical profile of historical water-level trends in two different parts of the Columbia Plateau.

Figure 22, which displays water levels from a CRBG multiwell cluster west of Odessa, Washington, shows that each CRBG aquifer (interflow zone) has a distinctly different water level. While all three aquifers show declining water levels from the beginning of monitoring in 1973, each zone shows a different trend, and those differences are maintained over the entire record. The shallowest zone (M02) experiences the greatest declines between 1973 and 1990, whereas the deepest zone (M04) exhibits a lesser water-level decline over the same period, followed by a drastic increase in the rate of decline after 2000. This increase in the rate of decline in the deeper zone reflects the shift in pumping from shallower to deeper CRBG aquifers in the Odessa area. The relatively high water level in

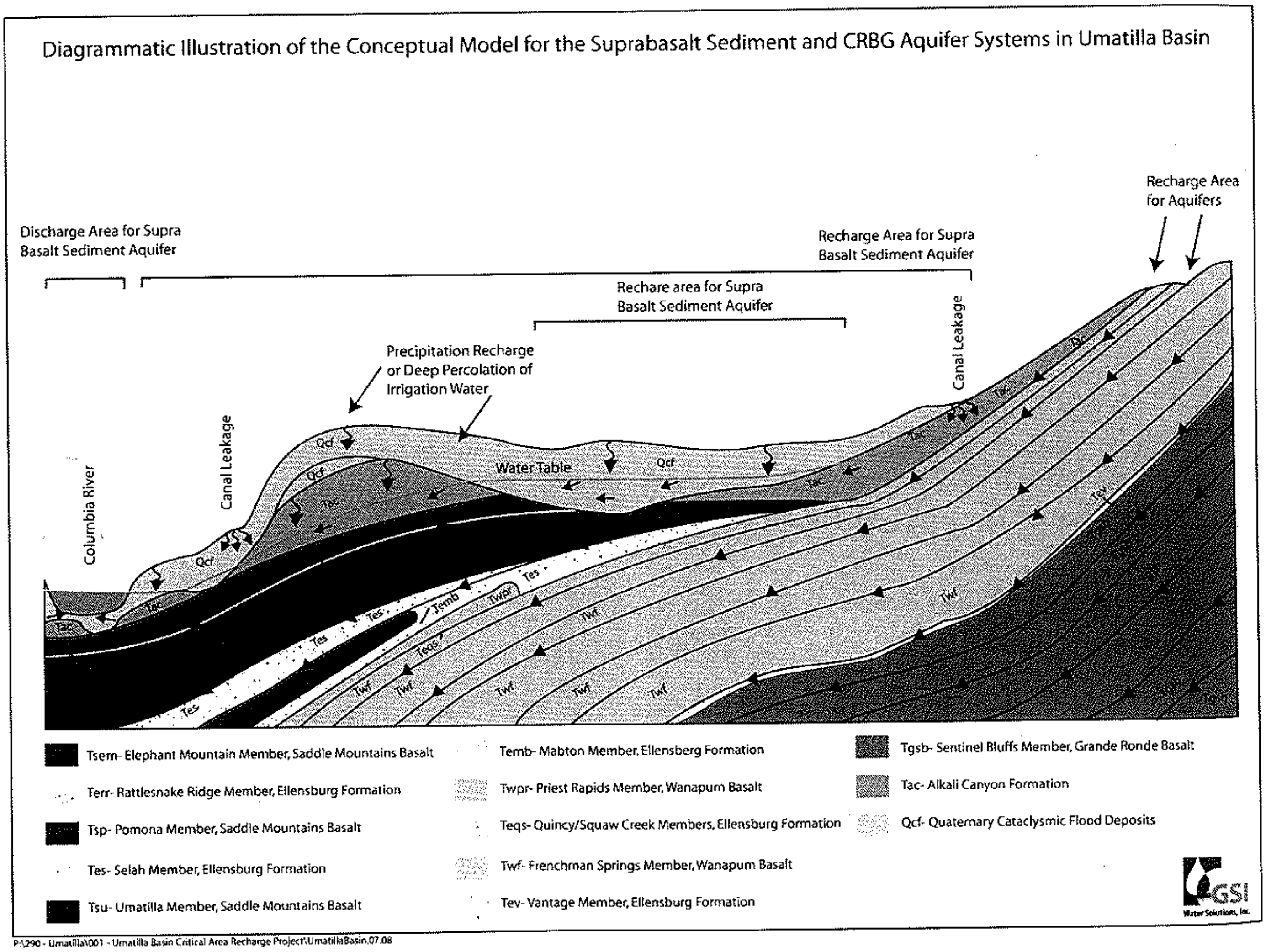

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Figure 21. Diagrammatic illustration of the conceptual hydrogeologic model for the suprabasalt sediment and Columbia River Basalt Group (CRBG) aquifer systems in the Umatilla Basin.

the deepest CRBG aquifer illustrates a high degree of confinement and isolation from the shallower CRBG aquifers. While the drilling into the deep CRBG aquifer would restore the water level in a well that was originally completed in one of the shallower aquifers, the sharp rate of decline also shows that the deepest CRBG aquifer is isolated from the others, and that the higher water level condition realized by tapping into this deeper aquifer is temporary.

The hydrographs from a CRBG multiwell cluster west of Odessa, Washington, also raises some interesting questions regarding traditional well construction practices in the CRBG. In the past the construction of water wells open to multiple CRBG

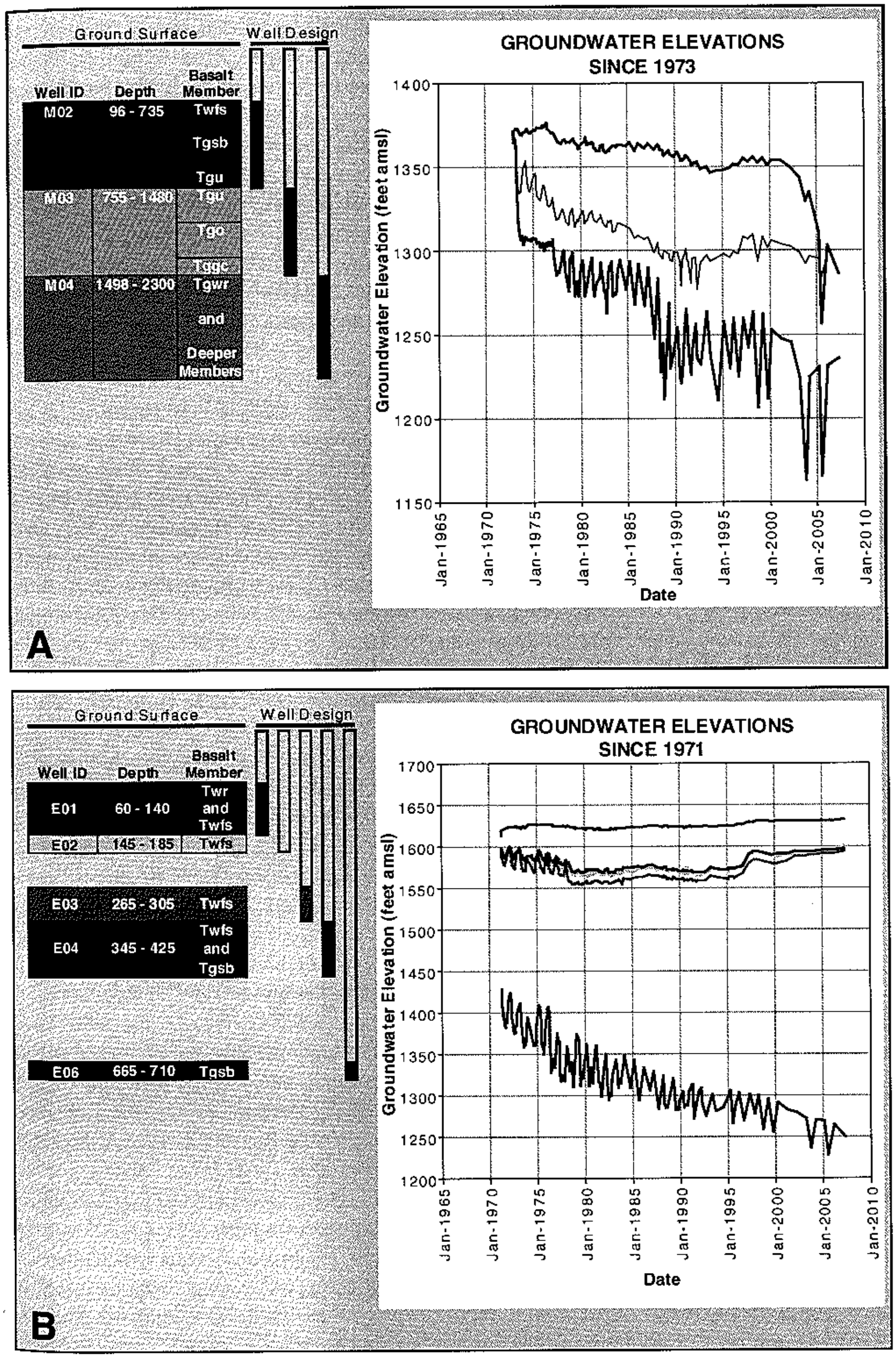

Figure 22. (A) Three hydrographs from a piezometer well in the north Columbia Plateau showing generally similar water level decline trends. Note, however, the deepest measured interval has the highest water level through much of this record. (B) Hydrographs for a piezometer well showing marked differences in water-level trends between the shallower zones and the deepest zone. Abbreviation: amsl—above mean sea level.

interflow zones (aquifers) has been the norm, rather than the exception. This is due to the fact that the CRBG has been generally treated as a single aquifer instead of a multiple confined aquifer system. Therefore construction of water wells that are open to more than one CRBG aquifer (interflow zone) creates manmade, vertical pathways which allow groundwater to migrate between CRBG aquifers having different hydraulic heads (USDOE, 1988; Lite and Grondin, 1988; Wozniak, 1995). Therefore in regions where groundwater within the CRBG is the primary source of water, the CRBG groundwater system can have a significant degree of vertical connectivity due to the large number of water wells open to multiple aquifers.

Potential Recharge and Discharge—CRBG Aquifers

Early researchers recognized that the unique nature of the CRBG aquifers provides limited opportunity for significant recharge (Newcomb, 1959, 1969; USDOE, 1988; Hansen et al., 1994). Recharge can occur by diffuse percolation through the CRBG flow interiors over large areas. The very low vertical permeability limits the rate of recharge by this process, but the large areal extent of the CRBG could potentially result in significant recharge on geologic timescales. Interflow zones for CRBG units that are not exposed to overlying sediments nor are present near the surface where they can receive direct recharge can only receive recharge through these processes. However, the development of secondary mineralization along vertical fractures (USDOE, 1988; Lindberg, 1989) reduces the vertical permeability and thus the rate of recharge via this pathway over time.

Infiltration vertically downward along faults, past the ends of CRBG flow pinchouts, where CRBG flows are breached by erosional windows, and on highlands within, and bordering the flood-basalt province also are postulated mechanisms for recharge of CRBG interflow zones. However the predominant mechanism for enhanced recharge, particularly at rates and on a timescale relevant to stresses imposed by withdrawals in most areas, is direct infiltration to CRBG interflow zones where they are present at, or near, the surface, and in direct hydrologic connection with surface water or exposed to percolating precipitation (Hart and Newcomb, 1956; Newcomb, 1959). Interflow zones of a given CRBG unit typically crop out, or are in connection with overlying sediment, over a limited area and thus may only have limited recharge potential by this mechanism. Climatic and other hydrologic changes over time may reduce (or increase) the water available for recharge at the locations where a given CRBG interflow zone is present to accept recharge, and thus the unit may receive significantly less (or more) recharge under present conditions than past.

On the Columbia Plateau, recharge of the deeper Wanapum and Grande Ronde aquifers is inferred to result from interbasin groundwater movement originating around the edge of the Columbia Plateau in areas where the Wanapum and Grande Ronde Basalts are exposed (Gephart et al., 1979; USDOE, 1988; Hansen et al., 1994) and from downward through overlying CRBG flows (Hansen et al., 1994), although the physical characteristics of CRBG flow interiors would limit the effectiveness of this recharge mechanism.

Geochemical tracers and age dating in the central Columbia Plateau region (Columbia Basin Groundwater Management Area) indicates that deep CRBG units cropping out in coulees in northern Lincoln County, Washington, received the bulk of recharge in the Pleistocene. Interflow zones of these units are not in connection with existing surface water sources, and precipitation amounts are very low relative to evapotranspiration. However, these areas were inundated in the past during the Pleistocene. Whichever mechanism recharges the aquifer system, the amount of recharge often is small relative to the amount of current withdrawals, rendering the CRBG aquifers vulnerable to overdraft.

Groundwater discharge from the shallow CRBG aquifer (Saddle Mountains Basalt) on the Columbia Plateau, is inferred to be to surface water bodies (e.g., Columbia, Snake, and Yakima Rivers) or to suprabasalt sediment aquifers (Newcomb, 1969; USDOE, 1988; Hansen et al., 1994). Where the stratigraphically older CRBG aquifers (i.e., Wanapum and Grande Ronde aquifers) are shallow, such as within Yakima Fold anticlines, water gaps, and/or scabland coulees, it is inferred that these aquifers discharge to the overlying suprabasalt sediment aquifer, surface waters (e.g., Crab Creek, Columbia, and Snake Rivers), and the shallower CRBG (Saddle Mountains Basalt) aquifer, if present (Hansen et al., 1994). Erosional windows through CRBG dense flow interiors at the top of the CRBG aquifers allow direct interconnection between the suprabasalt sediment and CRBG aquifers (Graham et al., 1984) and between CRBG aquifers.

Potential discharge areas for the deeper CRBG aquifers (i.e., Wanapum and Grande Ronde aquifers) in the Columbia Plateau region are inferred where folds and faults bring Wanapum and Grande Ronde flows closer to the surface. In contrast, Hansen et al. (1994) also suggested that discharge from deep CRBG aquifers may be directly upward through dense basalt flow interiors into the major rivers (e.g., Columbia and Snake Rivers). However, it is difficult to envision this potential discharge scenario given the physical properties of CRBG basalt flows in this stratiform aquifer system.

Groundwater Resource Limitations

CRBG aquifers present challenges to sustainable groundwater development throughout their extent (e.g., Newcomb, 1965; Sceva, 1966; Luzier et al., 1968; Bartholomew, 1975; Luzier and Skrivan, 1975; Oberlander and Miller, 1981; Norton and Bartholomew, 1984; Lite and Grondin, 1988; Zwart, 1990; Cline and Collins, 1992; Miller et al., 1994; Grondin et al., 1995; Conlon et al., 2005). The hydraulic properties inherent to CRBG aquifers have led to overdraft conditions in many areas. Low storativity values and relatively high horizontal conductivity of interflow zones combined with very low vertical conductivity of dense flow interiors result in a productive aquifer. With time, pumping produces rapidly moving and coalescing cones of depression with low annual recharge rates. High horizontal conductivity in interflow zones allows high well yields, but low vertical permeability and limited recharge pathways result in low annual recharge rates. Combined with low storativity and low bulk porosity, these factors commonly lead to overdraft of CRBG aquifers. The presence of low permeability boundaries such as faults or interflow "facies changes" can exacerbate seasonal drawdowns and limit opportunity for annual recovery of the hydraulic head. For example, all but two of the ~22 areas declared groundwater-limited or critical groundwater areas in Oregon are associated with overdraft conditions in CRBG aquifer systems, and 17 of these areas are located within the Willamette Valley.

Another ongoing challenge is well construction. Construction of water wells that are open to more than one CRBG interflow zone creates several challenges: (1) water level measurements, water flow rates, and water quality represent the properties of multiple interflow zones and make comparison between wells difficult; and (2) the open boreholes create manmade, vertical pathways that allow groundwater (and contaminants) to migrate between CRBG aquifers having different hydraulic heads (Lite and Grondin, 1988; USDOE, 1988; Grondin et al., 1995). In the past, construction of water wells open to multiple CRBG interflow zones (aquifers) was common because drillers sought to insure a productive well, and the CRBG has been generally treated as a single aquifer instead of a multiple aquifer system. The consequences of this "open-hole" type of well construction results in depressurizing, and ultimately dewatering, the aquifers. Rapid depressurizing of small, compartmentalized CRBG aquifers leads to water-level decline, increased pumping costs, and when declines fall below pumps, results in deepening of wells. The percentage of water-level declines that can be attributed to this mechanism is generally not known, but recent work in the Mosier, Oregon area (Erick Burns, 2009, written commun.) indicates that it can be a significant cause of decline.

Impacts on surface water resources from CRBG groundwater development is another challenge that, to date, has received very little attention. The connection between CRBG interflow zones and surface water drainages is often inferred (e.g., Miller et al., 1994), but the hydrologic relationship is seldom quantified aside from regional modeling studies. However, one of the best examples of where the impact has been directly measured is near Mosier, Oregon (Newcomb, 1969; Lite and Grondin, 1988). Mosier Creek changes from a gaining stream (Newcomb, 1969) to a losing stream where the stream flows across a contact between CRBG units (Lite and Grondin, 1988), and the change has been correlated with declining groundwater levels.

ACKNOWLEDGMENTS

We would like to thank Jim O'Connor for his comments and suggestions on an earlier version of this manuscript. We would also like to acknowledge the valuable contributions Russ Evarts, Ray Wells, and Terrence Conlon (U.S. Geological Survey) have made to our general understanding of the various aspects of the CRBG discussed in this manuscript. We consider them all as "coauthors," and their names would appear on this manuscript except for time-constraint problems pertaining to the internal U.S. Geological Survey review process. We would also like to acknowledge Heather Petcovic for her contribution to our understanding of the Maxwell Creek dike.

REFERENCES CITED

Anderson, J.L., 1979, The stratigraphy and structure of the Columbia River basalt in the Clackamas River drainage [M.S. thesis]: Portland, Oregon, Portland State University, 136 p.

Anderson, J.L., 1987, Structural geology and ages of deformation of a portion of the southwest Columbia Plateau [Ph.D. thesis]: Los Angeles, University of Southern California, 283 p.

Anderson, J.L., and Tolan, T.L., 1986, Ages of wrench faulting in interridge basins, southwest Columbia Plateau, Washington and Oregon: Geological Society of America Abstracts with Programs, v. 18, p. 82.

Armentrout, J.M., Hull, D.A., Beaulieu, J.D., and Rau, W.W., 1983, Correlation of Cenozoic stratigraphic units of western Oregon and Washington: Oregon Department of Geology and Mineral Industries Oil and Gas Investigations 7, 90 p.

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397–411, doi: 10.1130/0016-7606(1977)88<397:RAKGOM>2.0.CO;2.

Bailey, M.M., 1989, Revisions to stratigraphic nomenclature of the Picture Gorge Basalt Subgroup, Columbia River Basalt Group, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 67–84.

Barrash, W., Bond, J.G., Kaufmann, J.C., and Venkatakrishnan, R., 1980, Geology of the La Grande area, Oregon: Oregon Department of Geology and Mineral Industries Special Paper 6, scale 1:62,500, 5 plates, 47 p. text.

Barry, T.L., Self, S., Kelley, S.P., Hooper, P.R., and Widdowson, M., 2008, New age dates from Grande Ronde lavas, Columbia River basalts: Implications for periodicity of flood basalt eruptions and duration of major pulses: Eos (Transactions, American Geophysical Union), v. 89, no. 53, Fall Meeting Supplement, Abstract V53A-2127.

Bartholomew, W.S., 1975, Groundwater conditions and declining water levels in the Butter Creek area, Morrow and Umatilla Counties, Oregon: Oregon Water Resources Department Ground Water Report 24, 102 p.

Beeson, M.H., and Moran, M.R., 1979, Columbia River Basalt Group stratigraphy in western Oregon: Oregon Geology, v. 41, p. 11–14.

Beeson, M.H., and Tolan, T.L., 1990, The Columbia River Basalt Group in the Cascade Range—A middle Miocene reference datum for structural analysis: Journal of Geophysical Research, v. 95, p. 19,547–19,559, doi: 10.1029/JB095iB12p19547.

Beeson, M.H., and Tolan, T.L., 1996, Field trip guide to Columbia River Basalt intracanyon flows in western Oregon and Washington—Ginkgo, Rosalia, and Pomona flows: Portland, Oregon, Cordilleran Section meeting, Geological Society of America, 35 p.

Beeson, M.H., and Tolan, T.L., 2002, Basalt of Huntzinger, Asotin Member of the Saddle Mountains Basalt, Columbia River Basalt Group (CRBG) identified in western Washington: Geological Society of America Abstracts with Programs, v. 34, no. 5, p. 33.

Beeson, M.H., Perttu, R., and Perttu, J., 1979, The origin of the Miocene basalt of coastal Oregon and Washington: Oregon Geology, v. 41, p. 159–166.

Beeson, M.H., Fecht, K.R., Reidel, S.P., and Tolan, T.L., 1985, Correlations within the Frenchman Springs Member of the Columbia River Basalt Group: New insights into the middle Miocene tectonics of northwest Oregon: Oregon Geology, v. 47, p. 87–96.

Beeson, M.H., Tolan, T.L., and Anderson, J.L., 1989a, The Columbia River Basalt Group in western Oregon: Geologic structures and other factors that controlled flow emplacement patterns, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River Flood-

Basalt Province: Geological Society of America Special Paper 239, p. 223–246.

Beeson, M.H., Tolan, T.L., and Madin, I., 1989b, Geologic map of the Lake Oswego quadrangle, Oregon: Oregon Department of Geology and Mineral Industries Map GMS-59, scale 1:24,000, 1 sheet.

Bentley, R.D., 1977, Stratigraphy of the Yakima basalts and structural evolution of the Yakima ridges in the western Columbia Plateau, *in* Brown, E.H., and Ellis, R.C., eds., Geological Excursions in the Pacific Northwest: Bellingham, Western Washington University, p. 339–390.

Bentley, R.D., 1989, Geology and stratigraphy of the Columbia Hills area (Wood Gulch Report), *in* Pacific Groundwater Group, Hydrogeologic Characterization: Rabanco Regional Landfill, Klickitat County, Washington: Consultant Report prepared for the Rabanco Regional Landfill Company, Appendix F, 16 p.

Bentley, R.D., Anderson, J.L., Campbell, N.P., and Swanson, D.A., 1980, Stratigraphy and structure of the Yakima Indian Reservation, with emphasis on the Columbia River Basalt Group: U.S. Geological Survey Open-File Report 80-200, 86 p.

Blakely, R.J., Wells, R.E., Yelin, T.S., Madin, I.P., and Beeson, M.H., 1995, Tectonic setting of the Portland-Vancouver area, Oregon and Washington: Constraints from low-altitude aeromagnetic data: Geological Society of America Bulletin, v. 107, p. 1051–1062, doi: 10.1130/0016-7606(1995)107<1051:TSOTPV>2.3.CO;2.

Blakely, R.J., Wells, R.E., Tolan, T.L., Beeson, M.H., Trehu, A.M., and Liberty, L.M., 2000, New aeromagnetic data reveal large strike-slip (?) faults in the northern Willamette Valley, Oregon: Geological Society of America Bulletin, v. 112, p. 1225–1233, doi: 10.1130/0016-7606(2000)112<1225:NADRLS>2.3.CO;2.

Blakely, R.J., Wells, R.E., Cruikshank, K., Johnson, A., and Beeson, M., 2004, Gravity study through the Tualatin Mountains, Oregon: Understanding crustal structure and earthquake hazards in the Portland urban area: Bulletin of the Seismological Society of America, v. 94, p. 1402–1409, doi: 10.1785/012003045.

Blakely, R J, Sherrod, B.L., Weaver, C.S., and Wells, R.E., 2009, Connecting crustal faults and tectonics from Puget Sound across the Cascade Range to the Yakima Fold and Thrust Belt, Washington—Evidence from new high-resolution aeromagnetic data: Eos (Transactions, American Geophysical Union), v. 90, no. 22, Joint Assembly Supplement, Abstract GP23A-02.

Bretz, J.H., 1917, Satsop formation of Washington and Oregon: The Journal of Geology, v. 25, p. 446–458.

Brown, C.E., and Thayer, T.P., 1966, Geologic map of the Canyon City Quadrangle, northeastern Oregon: U.S. Geological Survey Miscellaneous Geological Investigations Map I-447, scale 1:250 000, 1 sheet.

Brown, J.C., 1978, Discussion of geology and groundwater hydrology of the Columbia Plateau with specific analysis of the Horse Heaven Hills, Sagebrush Flat, and Odessa-Lind areas, Washington: Washington State University, Pullman, Washington, College of Engineering Research Report 78/15-23, 51 p.

Brown, J.C., 1979, Investigation of stratigraphy and groundwater hydrology, Columbia River Basalt Group, Washington: Washington State University, College of Engineering Research Division Research Report 79/15-37, 60 p.

Bruce, P., and Huppert, H., 1990, Solidification and melting along dykes by laminar flow of basaltic magma, *in* Ryan, M., ed., Magma transport and storage: New York, John Wiley and Sons, p. 87–102.

Burt, W.C., 1989, The hydrogeology of structurally complex basalts in Black Rock and Dry Creek Valleys, Washington [M.S. thesis]: Moscow, Idaho, University of Idaho, 78 p.

Burt, W.C., Conlon, T., Tolan, T., Wells, R., and Melady, J., 2009, this volume, Hydrogeology of the Columbia River Basalt Group in the northern Willamette Valley, Oregon, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, doi: 10.1130/2009.fld015(31).

Buwalda, J.P., and Moore, B.N., 1927, Age of the "Satsop" and Dalles formations of Oregon and Washington: Science, v. 66, p. 236, doi: 10.1126/science.66.1706.236.

Byerlee, J., 1978, Friction of rocks: Pure and Applied Geophysics, v. 116, p. 615–626, doi: 10.1007/BF00876528.

Byerly, G.R., and Swanson, D.A., 1978, Invasive Columbia River Basalt Group flows along the northwest margin of the Columbia Plateau, north-central Washington: Geological Society of America Abstracts with Programs, v. 10, p. A98.

Camp, V.E., 1981, Geologic studies of the Columbia Plateau: Part II, Upper Miocene basalt distribution, reflecting source locations, tectonism, and drainage history in the Clearwater embayment, Idaho: Geological Society of America Bulletin, v. 92, p. 669–678, doi: 10.1130/0016-7606(1981)92<669:GSOTCP>2.0.CO;2.

Camp, V.E. and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in intermontane Pacific Northwest: Journal of Geophysical Research, v. 109, B08204, doi: 10.1029/2003JB002838.

Camp, V.E., Ross, M.E., and Hanson, W.E., 2003, Genesis of flood basalts and Basin and Range volcanic rocks from Steens Mountain to the Malheur River Gorge, Oregon: Geological Society of America Bulletin, v. 115, p. 105–128, doi: 10.1130/0016-7606(2003)115<0105:GOFBAB>2.0.CO;2.

Campbell, N.P., 1983, Correlation of late Cenozoic gravel deposits along the Yakima River drainage from Ellensburg to Richland, Washington: Northwest Science, v. 57, p. 179–193.

Campbell, N.P., 1988, Structural geology along the northwestern Columbia River basalt margin, Washington: Washington Division of Geology and Earth Resources Open-File Report 88-5, 108 p., 8 plates.

Campbell, N.P., 1989, Structural and stratigraphic interpretation of the rocks under the Yakima Fold Belt based on recent surface mapping and well data, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 209–222.

Campbell, N.P., and Bentley, R.D., 1980, Late Quaternary faulting, Toppenish Ridge, south-central Washington: Geological Society of America Abstracts with Programs, v. 12, no. 3, p. 101.

Campbell, N.P., and Bentley, R.D., 1981, Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington: Geology, v. 9, p. 519–524, doi: 10.1130/0091-7613(1981)9<519:LQDOTT>2.0.CO;2.

Choiniere, S.A., and Swanson, D.A., 1979, Magnetostratigraphy and correlation of Miocene basalts of the northern Oregon coast and Columbia Plateau, southeast Washington: American Journal of Science, v. 279, p. 755–777.

Cline, D.R., and Collins, C.A., 1992, Groundwater-water pumpage from the Columbia Plateau regional aquifer system, Washington and Oregon, for selected years during the period 1945–1984: U.S. Geological Survey Water-Resources Investigations Report 90-4085, 31 p.

Coe, R.S., Bogue, S., and Myers, C.W., 1978, Paleomagnetism of the Grande Ronde (Lower Yakima) Basalt exposed at Sentinel Gap—Potential use for stratigraphic correlations: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-ST-2, 24 p.

Conlon, T.D., Wozniak, K.C., Woodcock, D., Herrera, N.B., Fisher, B.J., Morgan, D.S., Lee, K.K., and Hinkle, S.R., 2005, Ground-water hydrology of the Willamette basin, Oregon: U.S. Geological Survey Scientific Investigations Report 2005-5168, 83 p. (http://pubs.usgs.gov/sir/2005/5168/).

Corcoran, R.E., and Libbey, F.W., 1956, Ferruginous bauxite deposits in the Salem Hills, Marion County, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 46, 53 p.

Dames and Moore, Inc., 1987, Geologic and hydrogeologic site characterization report, Chem-Security Systems, Inc., Arlington facility, Arlington, Oregon: Bellevue, Washington, Consultant report to Chem-Security Systems, Inc.

Davies-Smith, A., Bolke, E.L., and Collins, C.A., 1988, Geohydrology and digital simulation of the ground-water flow system in the Umatilla Plateau and Horse Heaven Hills area, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 87-4268, 72 p.

Davis, G.A., 1981, Late Cenozoic tectonics of the Pacific Northwest with special reference to the Columbia Plateau: Richland, Washington, Washington Public Power Supply System Final Safety Analysis Report for WNP-2, Appendix 2.5 N, 44 p.

Delaney, P.T., and Pollard, D.D., 1982, Solidification of basaltic magma during flow in a dike: American Journal of Science, v. 282, p. 856–885.

Diery, H.D., 1967, Stratigraphy and structure of the Yakima Canyon between Roza Gap and Kittitas Valley, Central Washington [Ph.D. thesis]: Seattle, University of Washington, 117 p.

Drost, B.W., and Whiteman, K.J., 1986, Surficial geology, structure, and thickness of selected geohydrologic units in the Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 86-4326.

Farooqui, S.M., Beaulieu, J.D., Bunker, R.C., Stensland, D.E., and Thoms, R.E., 1981a, Dalles Group: Neogene formations overlying the Columbia River Basalt Group in north-central Oregon: Oregon Geology, v. 43, p. 131–140.

Farooqui, S.M., Bunker, R.C., Thoms, R.E., and Clayton, D.C., 1981b, Post-Columbia River Basalt Group stratigraphy and map compilation of the Columbia Plateau, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report 81-10, scale 1:250,000, 6 plates, 79 p. text.

Fecht, K.R., Reidel, S.P., and Tallman, A.M., 1987, Paleodrainage of the Columbia River system on the Columbia Plateau of Washington State—A Summary, *in* Schuster, J.E., ed., Selected Papers on the Geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 219–248.

Foulger, G.R., and Jurdy, D.M., eds., 2007, Plates, plumes, and planetary processes: Geological Society of America Special Paper 430, 974 p.

Frizzell, V.A., Jr., Tabor, R.W., Booth, D.B., Ort, K.M., and Waitt, R.B., Jr., 1984. Preliminary geologic map of the Snoqualime Pass 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 84-693, scale 1:100,000, 1 sheet, 43 p. text.

Fruchter, J.S., and Baldwin, S.F., 1975, Correlations between dikes of the Monument swarm, central Oregon, and Picture Gorge Basalt flows: Geological Society of America Bulletin, v. 86, p. 514–516, doi:10.1130/0016-7606(1975)86<514:CBDOTM>2.0.CO;2.

Gannett, M.W., and Caldwell, R.R., 1998, Geologic framework of the Willamette Lowland Aquifer System, Oregon and Washington: U.S. Geological Survey Professional Paper 1424-A, 32 p.

Gehrels, G.E., White, R.R., and Davis, G.A., 1979, The La Grande pull-apart basin, northeast Oregon: Richland, Washington, Letter report for Washington Public Power Supply System.

Geomatrix, 1988, Seismotectonic evaluation, North Cascade geomorphic province: Geomatrix Consultants, Inc., Final Report to Bureau of Reclamation, Denver, Colorado, 154 p.

Gephart, R.E., Arnett, R.C., Baca, R.G., Leonhart, L.S., and Spane, F.A., Jr., 1979, Hydrologic studies within the Columbia Plateau, Washington—An integration of current knowledge: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-ST-5.

Goff, F.E., 1981, Preliminary geology of eastern Umtanum Ridge, south-central Washington: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-C-21, 100 p.

Gorham, S.J., and Martin, B.S., 2004, Xenolith-bearing dikes of the Grande Ronde Basalt, Columbia River Basalt Group, southeast Washington State: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 223.

Graham, M.J., Last, G.V., and Fecht, K.R., 1984, An assessment of aquifer intercommunication in the B Pond-Gable Mountain Area of the Hanford Site: Richland, Washington, Rockwell Hanford Operations, RHO-RE-ST-12P.

Grolier, M.J., and Bingham, J.W., 1971, Geologic map and sections of parts of Grant, Adams, and Franklin Counties, Washington: U.S. Geological Survey Miscellaneous Geologic Investigations Series Map I-589, scale 1:62,500, 6 sheets.

Grolier, M.J., and Bingham, J.W., 1978, Geology of parts of Grant, Adams, and Franklin Counties, east-central Washington: Washington Division of Geology and Earth Resources Bulletin 71, 91 p.

Grondin, G.H., Wozniak, K.C., Nelson, D.O., and Camacho, I., 1995, Hydrogeology, groundwater chemistry and land uses in the lower Umatilla basin groundwater management area: Northern Morrow and Umatilla counties Oregon (final review draft): Oregon Department of Environmental Quality, 966 p.

Grunder, A.L., and Taubeneck, W.H., 1997, Partial melting of tonalite at the margins of Columbia River Basalt Group dikes, Wallowa Mountains, Oregon: Geological Society of America Abstracts with Programs, v. 29, p. 18.

GWMA (Ground Water Management Area), 2007a, Geologic framework of selected suprabasalt sediment and Columbia River Basalt units in the Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington, Edition 2: Consultants report prepared for Columbia Basin GWMA by GSI Water Solutions, Inc. and Franklin Conservation District, August 2007.

GWMA, 2007b, Geologic framework of the suprabasalt sediment aquifer system, Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington: Consultants report prepared for Columbia Basin GWMA by GSI Water Solutions, Inc., and Franklin Conservation District, August 2007.

Hagood, M.C., 1986, Structure and evolution of the Horse Heaven Hills in south-central Washington: Richland, Washington, Rockwell Hanford Operations, RHO-BW-SA-344 P, 1 plate, 190 p. text.

Hammond, P.E., 1979, A tectonic model for the evolution of the Cascade Range, *in* Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., eds., Cenozoic Paleogeography of the Western United States: Anaheim, California, Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologist and Mineralogists, Pacific Section, p. 219–237.

Hammond, P.E., Geyer, K.M., and Anderson, J.L., 1982, Preliminary geologic map and cross sections of the upper Clackamas and North Santiam Rivers area, northern Oregon Cascade Range: Portland, Oregon, Publication of the Department of Earth Sciences, Portland State University, scale 1:62,500.

Hampton, E.R., 1972, Geology and ground water of the Molalla-Salem Slope area, northern Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 1997, 83 p.

Hansen, A.J., Jr., Vaccaro, J.J., and Bauer, H.H., 1994, Ground-water flow simulation of the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey, Water-Resources Investigations Report 91-4187, 81 p.

Hart, D.H., and Newcomb, R.C., 1956, Preliminary report on the ground-water resources of the Tualatin Valley, Oregon: U.S. Geological Survey Water Supply Paper 1697, 172 p.

Ho, A.M., and Cashman, K.V., 1997, Temperature constraints on the Ginkgo Flow of the Columbia River Basalt Group: Geology, v. 25, p. 403–406, doi: 10.1130/0091-7613(1997)025<0403:TCOTGF>2.3.CO;2.

Hodge, E.T., 1938, Geology of the lower Columbia River: Geological Society of America Bulletin, v. 49, p. 831–930.

Hodge, E.T., 1942, Geology of north central Oregon: Corvallis, Oregon, Oregon State University Monographs, Studies in Geology, no. 3, 76 p.

Hogenson, G., 1964, Geology and ground water of the Umatilla River basin, Oregon: U.S. Geological Survey Water-Supply Paper 1620, 162 p.

Hon, K., Kauahikaua, J., Denlinger, R., and MacKay, K., 1994, Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 106, p. 351–370, doi: 10.1130/0016-7606(1994)106<0351:EAIOPS>2.3.CO;2.

Hooper, P.R., 2000, Chemical discrimination of Columbia River basalt flows: Geochemistry Geophysics Geosystems, v. 1, paper no. 2000GC000040.

Hooper, P.R., Camp, V.E., Reidel, S.P., and Ross, M.E., 2007, The origin of the Columbia River Flood-Basalt province: Plume versus nonplume models, *in* Foulger, G.R., and Jurdy, D.M., eds., Plates, Plumes, and Planetary Processes: Geological Society of America Special Paper 430, p. 635–668.

Jarchow, C.M., 1991, Investigations of magmatic underplating beneath the northwestern Basin and Range Province, and seismic data acquisition and tectonic problems of the Columbia Plateau, Washington, and the nature of the Mohorovičić discontinuity worldwide [Ph.D. thesis]: Stanford, California, Stanford University, 271 p.

Jerram, D.A., and Widdowson, M., 2005, The anatomy of continental flood basalt provinces: Geological constraints on the processes and products of flood volcanism: Lithos, v. 79, p. 385–405, doi: 10.1016/j.lithos.2004.09.009.

Johnson, V.G., Graham, D.L., and Reidel, S.P., 1993, Methane in Columbia River basalt aquifers—Isotopic and geohydrologic evidence for a deep coal-bed gas source in the Columbia Basin, Washington: American Association of Petroleum Geologists Bulletin, v. 77, p. 1192–1207.

Kent, M.H., 1978, Stratigraphy and petrography of the Selah Member of the Ellensburg Formation in south-central Washington and north-central Oregon [M.S. Thesis]: Portland, Oregon, Portland State University, 118 p.

Keszthelyi, L., and Self, S., 1998, Some physical requirements for the emplacement of long basaltic lava flows: Journal of Geophysical Research, v. 103, p. 27,447–27,464, doi: 10.1029/98JB00606.

Keszthelyi, L., Self, S., and Thordarson, T., 2006, Flood lavas on Earth, Io, and Mars: Journal of the Geological Society [London], v. 163, p. 253–264, doi: 10.1144/0016-764904-503.

Kienle, C.F., 1971, The Yakima Basalt in western Oregon and Washington [Ph.D. thesis]: Santa Barbara, University of California, 171 p.

Kienle, C.F., 1980, Geologic reconnaissance of parts of the Walla Walla and Pullman, Washington and Pendleton, Oregon 1° × 2° AMS quadrangles: Seattle, Washington, U.S. Army Corps of Engineers, Seattle District, scale 1:250,000, 76 p. text.

Norton, M.A., and Bartholomew, W.S., 1984, Update of ground-water conditions and declining water levels in the Butter Creek area, Morrow and Umatilla Counties, Oregon: Oregon Water Resources Department Ground Water Report 30, 201 p.

Oberlander, P.L., and Miller, D.W., 1981, Hydrologic studies in the Umatilla structural basin—An integration of current knowledge: Oregon Department of Water Resources, unpublished preliminary report, 41 p.

Packard, F.A., Hansen, A.J., Jr., and Bauer, H.H., 1996, Hydrogeology and simulation of flow and the effects of development alternatives on the basalt aquifers of the Horse Heaven Hills, south-central Washington: U.S. Geological Survey Water-Resources Investigations Report 94-4068, 92 p.

Paillet, F.L., and Kim, K., 1987, Character and distribution of borehole breakouts and their relationships to in situ stresses in deep Columbia River basalts: Journal of Geophysical Research, v. 92, p. 6223–6234, doi: 10.1029/JB092iB07p06223.

Petcovic, H.L., and Dufek, J.D., 2005, Modeling magma flow and cooling in dikes: Implications for the emplacement of Columbia River flood basalts: Journal of Geophysical Research, v. 110, p. B10201, doi: 10.1029/2004JB003432.

Petcovic, H.L., and Grunder, A.L., 2003, Textural and thermal history of partial melting in tonalitic wallrock at the margin of a basalt dike, Wallowa Mountains, Oregon: Journal of Petrology, v. 44, p. 2287–2312, doi: 10.1093/petrology/egg078.

Pfaff, V.J., and Beeson, M.H., 1989, Miocene basalt near Astoria, Oregon; Geophysical evidence for Columbia Plateau origin, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 143–156.

Piper, A.M., 1932, Geology and ground-water resources of the Dalles Region, Oregon: U.S. Geological Survey Water-Supply Paper 659-B, 189 p.

Prescott, W.H., and Savage, J.C., 1984, Crustal deformation near Hanford, Washington: U.S. Geological Survey Open-File Report 84-797, 247 p.

Price, E.H., 1982, Structural geology, strain distribution, and tectonic evolution of Umtanum Ridge at Priest Rapids Dam, and a comparison with other selected localities within the Yakima fold belt structures, south-central Washington: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-SA-138, 197 p.

Price, E.H., and Watkinson, A.J., 1989, Structural geometry and strain distribution within east Umtanum Ridge, south-central Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 265–282.

Price, S.A.M., 1977, An evaluation of dike-flow correlations indicated by geochemistry, Chief Joseph swarm, Columbia River Basalt [Ph.D. thesis]: Moscow, University of Idaho, 343 p.

Priest, G.R., and Vogt, B.F., eds., 1982, Geology and geothermal resources of the Mount Hood area, Oregon: Oregon Department of Geology and Mineral Industries Special Paper 14, 100 p.

Puget Sound Power and Light Company (PSPL), 1982, Skagit/Hanford Nuclear Project; Preliminary safety analysis report: Bellevue, Washington, Puget Sound Power and Light Co., v. 4, Appendix 20, Amendment 23, 71 p.

Raisz, E., 1945, The Olympic-Wallowa-Lineament: American Journal of Science, v. 243-A, p. 479–485.

Reidel, S.P., 1984, The Saddle Mountains: The evolution of an anticline in the Yakima fold belt: American Journal of Science, v. 284, p. 942–978.

Reidel, S.P., 1988, Geological map of the Saddle Mountains, south-central Washington: Washington Division of Geology and Earth Resources Geologic Map GM-38, scale 1:48,000, 5 sheets, 28 p. text.

Reidel, S.P., 1998, Emplacement of Columbia River flood basalt: Journal of Geophysical Research, v. 103, p. 27,393–27,410, doi: 10.1029/97JB03671.

Reidel, S.P., 2005, A lava flow without a source: The Cohasset Flow and its compositional components, Sentinel Bluffs Member, Columbia River Basalt Group: The Journal of Geology, v. 113, p. 1–21, doi: 10.1086/425966.

Reidel, S.P., and Campbell, N.P., 1989, Structure of the Yakima Fold Belt, Central Washington, *in* Joseph, N.L., et al., eds., Geologic guidebook for Washington and adjacent areas: Washington Division of Geology and Earth Resources Information Circular 86, p 275–303.

Reidel, S.P., and Fecht, K.R., 1987, The Huntzinger flow: Evidence of surface mixing of the Columbia River Basalt and its petrogenetic implication: Geological Society of America Bulletin, v. 98, p. 664–677, doi: 10.1130/0016-7606(1987)98<664:THFEOS>2.0.CO;2.

Reidel, S.P., and Fecht, K.R., 1994a, Geologic Map of the Richland 1:100,000 Quadrangle, Washington: Washington State Department of Natural Resources, Division of Geology and Earth Resources Open-File Report 94-8, scale 1:100,000, 1 sheet, 21 p. text.

Reidel, S.P., and Fecht, K.R., 1994b, Geologic Map of the Priest Rapids 1:100,000 Quadrangle, Washington: Washington State Department of Natural Resources, Division of Geology and Earth Resources Open-File Report 94-13, scale 1:100,000, 1 sheet, 22 p. text.

Reidel, S.P., and Hooper, P.R., eds., 1989, Volcanism and tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, 386 p.

Reidel, S.P., and Tolan, T.L., 1992, Eruption and emplacement of flood basalt: An example from the large-volume Teepee Butte Member, Columbia River Basalt Group: Geological Society of America Bulletin, v. 104, p. 1650–1671, doi: 10.1130/0016-7606(1992)104<1650:EAEOFB>2.3.CO;2.

Reidel, S.P., Scott, G.R., Bazard, D.R., Cross, R.W., and Dick, B., 1984, Post-12 million year clockwise rotation in the central Columbia Plateau, Washington: Tectonics, v. 3, no. 2, p. 251–273, doi: 10.1029/TC003i002p00251.

Reidel, S.P., Fecht, K.R., Hagood, M.C., and Tolan, T.L., 1989a, The geologic evolution of the Central Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 247–264.

Reidel, S.P., Tolan, T.L., Hooper, P.R., Beeson, M.H., Fecht, K.R., Bentley, R.D., and Anderson, J.L., 1989b, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 21–53.

Reidel, S.P., Fecht, K.R., Lindsey, K.A., and Campbell, N.P., 1994a, Late Cenozoic structure and stratigraphy of south-central Washington, *in* Lasmanis, R., and Cheney, E.S., eds.: Washington Division of Geology and Earth Resources Bulletin 80, p. 159–180.

Reidel, S.P., Tolan, T.L., and Beeson, M.H., 1994b, Factors that influenced the eruptive and emplacement histories of flood-basalt flows: A field guide to selected vents and flows of the Columbia River Basalt Group, *in* Swanson, D.A., and Haugerud, R.A., eds., Geologic Field Trips in the Pacific Northwest: Geological Society of America Annual Meeting Field Guide, p. 1B-1–1B-18.

Reidel, S.P., Johnson, V.G., and Spane, F.A., 2002, Natural Gas Storage in Basalt Aquifers of the Columbia Basin, Pacific Northwest USA: A Guide to Site Characterization: Richland, Washington, Pacific Northwest Laboratory PNNL-13962.

Rietman, J.D., 1966, Remanent magnetization of the late Yakima Basalt, Washington State [Ph.D. thesis]: Stanford, California, Stanford University, 87 p.

Rigby, J.G., Othberg, K., Campbell, N.P., Hanson, L., Kiver, E., Stradling, D., and Webster, G., 1979, Reconnaissance surficial geologic mapping of the late Cenozoic sediments of the Columbia Basin, Washington: Washington Division of Geology and Earth Resources Open-File Report 79-3, 7 plates, 94 p. text.

Ross, M.E., 1983, Chemical and mineralogical variations within four dikes of the Columbia River Basalt Group, southeastern Columbia Plateau: Geological Society of America Bulletin, v. 94, p. 1117–1126, doi: 10.1130/0016-7606(1983)94<1117:CAMVWF>2.0.CO;2.

Ross, M.E., 1989, Stratigraphic relationships of subaerial, invasive, and intracanyon flows of Saddle Mountains Basalt in the Troy Basin, Oregon and Washington, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 131–142.

Sabol, M.A., and Downey, S.E., 1997, Support document for consideration of the eastern Columbia Plateau aquifer system as a sole-source aquifer: Seattle, Washington, U.S. Environmental Protection Agency, Document 910/R-97-002, 35 p.

Saltus, R.W., 1991, Gravity and heat flow constraints on Cenozoic tectonics of the western United States Cordillera [Ph.D. thesis]: Stanford, California, Stanford University, 244 p.

Sceva, J.E., 1966, A brief description of the ground-water conditions in the Ordinance area, Morrow and Umatilla Counties, Oregon: Oregon Water Resources Department Ground-Water Report 11, 43p.

Schlicker, H.G., and Deacon, R.J., 1967, Engineering geology of the Tualatin Valley region, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 60, no. 103, p. 423.

Schmincke, H.-U., 1964, Petrology, paleocurrents, and stratigraphy of the Ellensburg Formation and interbedded Yakima Basalt flows, south-central Washington [Ph.D. thesis]: Baltimore, Maryland, Johns Hopkins University, 407 p.

Schmincke, H.-U., 1967a, Fused tuff and pépérites in south-central Washington: Geological Society of America Bulletin, v. 78, p. 319–330, doi: 10.1130/0016-7606(1967)78[319:FTAPIS]2.0.CO;2.

Schmincke, H.-U., 1967b, Flow directions in Columbia River Basalt flows and paleocurrents of interbedded sedimentary rocks, south-central Washington: Geologische Rundschau, v. 56, p. 992–1020, doi: 10.1007/BF01848776.

Schuster, J.E., Gulick, C.W., Reidel, S.P., Fecht, K.R., and Zurenko, S., 1997, Geologic map of Washington-Southeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-45, scale 1:250,000, 2 sheets, 20 p. text.

Self, S., Thordarson, T., Keszthelyi, L., Walker, G.P.L., Hon, K., Murphy, M.T., Long, P., and Finnemore, S., 1996, A new model for the emplacement of Columbia River basalts as large, inflated pahoehoe lava flow fields: Geophysical Research Letters, v. 23, p. 2689–2692, doi: 10.1029/96GL02450.

Self, S., Thordarson, T., and Keszthelyi, L., 1997, Emplacement of continental flood basalt lava flows, *in* Mahoney, J.J., and Coffin, M.J., eds., Large igneous provinces: Continental, oceanic, and planetary flood volcanism: Washington, D.C., American Geophysical Union Geophysical Monograph 100, p. 381–410.

Shaffer, M.E., and West, D.O., 1989, Quaternary faulting in the Frenchman Hills anticline, Yakima fold belt, central Columbia Basin, Washington: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 142.

Shannon and Wilson, 1979, Geologic reconnaissance of Wallula Gap, Washington–Blue Mountains–La Grande, Oregon region: Richland, Washington, Shannon and Wilson, Inc., Consultant report for Washington Public Power Supply System, Richland, Washington.

Shaw, H.R., and Swanson, D.A., 1970, Eruption and flow rates of flood basalts, *in* Gilmour, E.H., and Stradling, D., eds., Proceedings of the second Columbia River basalt symposium: Cheney, Eastern Washington State College Press, p. 271–299.

Smith, G.A., 1988, Neogene synvolcanic and syntectonic sedimentation in central Washington: Geological Society of America Bulletin, v. 100, p. 1479–1492, doi: 10.1130/0016-7606(1988)100<1479:NSASSI>2.3.CO;2.

Smith, G.A., Bjornstad, B.N., and Fecht, K.R., 1989, Neogene terrestrial sedimentation on and adjacent to the Columbia Plateau: Washington, Oregon and Idaho, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 187–198.

Snavely, P.D., Macleod, N.S., and Wagner, H.C., 1973, Miocene tholeiitic basalt of coastal Oregon and Washington and its relation to coeval basalt of the Columbia Plateau: Geological Society of America Bulletin, v. 84, p. 387–424, doi: 10.1130/0016-7606(1973)84<387:MTBOCO>2.0.CO;2.

Spane, F.A., and Webber, W.D., 1995, Hydrochemistry and hydrogeologic conditions within the Hanford Site upper basalt confined aquifer system: Richland, Washington, Battelle Pacific Northwest Laboratory, Report PNL-10817, 40 p.

Spry, A., 1962, The origin of columnar jointing particularly in basalt flows: Geological Society of Australia Journal, v. 8, p. 191–216.

Steinkampf, W.C., and Hearn, P.P., Jr., 1996, Ground-water geochemistry of the Columbia Plateau aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey Open-File Report 95-467, 67 p.

Stoffel, K.L., 1984, Geology of the Grande Ronde lignite field, Asotin County, Washington: Washington Division of Geology and Earth Resources Report of Investigations 27, 79 p.

Stoffel, K.L., Joseph, N.L., Waggoner, S.Z., Gulick, C.W., Korosec, M.A., and Bunning, B.B., 1991, Geologic map of Washington-Northeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-39.

Swanson, D.A., 1973, Pahoehoe flows from the 1969–1971 Mauna Ulu eruption, Kilauea volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 615–626, doi: 10.1130/0016-7606(1973)84<615:PFFTMU>2.0.CO;2.

Swanson, D.A., and Wright, T.L., 1978, Bedrock geology of the northern Columbia Plateau and adjacent areas, *in* Baker, V.R., and Nummedal, D., eds., The Channeled Scabland: A Guide to the geomorphology of the Columbia Basin, Washington: Washington, D.C., Planetary Geology Program, Office of Space Science, National Aeronautics and Space Administration, p. 37–57.

Swanson, D.A., and Wright, T.L., 1981, Guide to geologic field trip between Lewiston, Idaho and Kimberly, Oregon, emphasizing the Columbia River Basalt Group, *in* Johnston D.A., and Donnelly-Nolan, J., eds., Guides to Some Volcanic Terranes in Washington, Idaho, Oregon, and Northern California: U.S. Geological Survey Circular 838, p. 1–28.

Swanson, D.A., Wright, T.L., and Helz, R.T., 1975, Linear vent systems and estimated rates of magma production and eruption of the Yakima Basalt on the Columbia Plateau: American Journal of Science, v. 275, p. 877–905.

Swanson, D.A., Anderson, J.L., Bentley, R.D., Byerly, G.R., Camp, V.E., Gardner, J.N., and Wright, T.L., 1979a, Reconnaissance geologic map of the Columbia River Basalt Group in parts of eastern Washington and northern Idaho: U.S. Geological Survey Open-File Report 79-1363, scale 1:250,000, 12 sheets.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979b, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S., Geological Survey Bulletin 1457-G, 59 p.

Swanson, D.A., Wright, T.L., Camp, V.E., Gardner, J.N., Helz, R.T., Price, S.M., Reidel, S.P., and Ross, M.E., 1980, Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla Walla Quadrangles, southeast Washington and adjacent Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-1139, scale 1:250,000, 2 sheets.

Swanson, D.A., and Anderson, J.L., Camp. V.E., Hooper, P.R., Taubeneck, W.H., and Wright, T.L., 1981, Reconnaissance geologic map of the Columbia River Basalt Group, northern Oregon and western Idaho: U.S. Geological Survey Open-File Report 81-797, scale 1:250,000, 6 sheets.

Swanson, R.D., McFarland, W.D., Gonthier, J.B., and Wilkinson, J.M., 1993, A description of hydrogeologic units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4196, 56 p. 10 sheets, scale 1:100 000.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.A., and Bentley, R.D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, scale 1:100,000, 1 sheet, 26 p. text.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of Lower and Middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington—Application to the tectonic history of the Straight Creek Fault: Geological Society of America Bulletin, v. 95, p. 26–44, doi: 10.1130/0016-7606(1984)95<26:AASOLA>2.0.CO;2.

Taubeneck, W.H., 1970, Dikes of Columbia River basalt in northeastern Oregon, western Idaho, and southeastern Washington, *in* Gilmour, E.H., and Stradling, D., eds., Proceedings of the Second Columbia River Basalt symposium: Cheney, Eastern Washington State College, p. 73–96.

Taubeneck, W.H., 1989, Recently defined axes of eruption in northeast Oregon in the southernmost part of the Chief Joseph dike swarm of Columbia River Basalt (CRB) Oregon, Idaho, and Washington: Geological Society of America Abstracts with Programs, v. 21, p. 151.

Taubeneck, W.H., 1990, Significant discoveries during 1989 involving dikes of Columbia River Basalt in pre-Tertiary rocks in eastern Oregon (OR) and western Idaho (ID): Geological Society of America Abstracts with Programs, v. 22, p. 88.

Taubeneck, W.H., 1998, Control of strike and dip of dikes of Columbia River Basalt Group (CRBG) by major joint sets in granitic rocks or Wallowa Batholith (WB), Northeast Oregon: Geological Society of America Abstracts with Programs, v. 30, p. 68.

Taubeneck, W.H., and Duncan, R.A., 1997, Preferential occurrence of eruptive axes of dikes of the Columbia River Basalt Group in unmetamorphosed Mesozoic granitic intrusives, with ^{40}Ar/^{39}Ar dates for four dikes and two of the earliest flows of basalt: Northeast Oregon and Western Idaho: Geological Society of America Abstracts with Programs, v. 29, no. 2, p. 48.

Thayer, T.P., 1939, Geology of the Salem Hills and the North Santiam River Basin, Oregon: Oregon Department of Geology and Mineral Industries Bulletin no. 15, 40 p., 2 plates.

Thordarson, T., and Self, S., 1993, The Laki (Skaftár Fires) and Grímsvötn eruptions in 1783–1785: Bulletin of Volcanology, v. 55, p. 233–263, doi: 10.1007/BF00624353.

Thordarson, T., and Self, S., 1998, The Roza Member, Columbia River Basalt Group: A gigantic pahoehoe lava flow field formed by endogenous processes?: Journal of Geophysical Research, v. 103, p. 27,411–27,445, doi: 10.1029/98JB01355.

Tolan, T.L., and Beeson, M.H., 1984, Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorge and their relationship to the Troutdale Formation: Geological Society of America Bulletin, v. 95, p. 463–477, doi: 10.1130/0016-7606(1984)95<463:IFOTCR>2.0.CO;2.

Tolan, T.L., and Lite, K., 2008, Geology and Hydrogeology of the Columbia River Basalt Group: A Field Trip Guide to Selected Localities in the Columbia River Gorge, Oregon: Prepared for the National Ground Water Association International Conference on Nonrenewable Ground Water Resources Field Trip, October 15, 2008.

Tolan, T.L., and Reidel, S.P., compilers, 1989, Structure map of a portion of the Columbia River Flood-Basalt Province, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, scale 1:576 000, 1 plate.

Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 1–20.

Tolan, T.L., Beeson, M.H., and Wheeler, K.L., 1999, Geologic map of the Scotts Mills, Silverton, and Stayton Northeast 7.5-minute quadrangles, northwest Oregon: A digital database: U.S. Geological Survey Open-File Report 99-141, scale 1:24,000.

Tolan, T.L., Beeson, M.H., and DuRoss, C.B., 2000a, Geologic map and database of the Salem East and Turner 7.5-minute quadrangles, Marion County, Oregon: A digital database: U.S. Geological Survey Open-File Report 00-351, scale 1:24,000.

Tolan, T.L., Campbell, N.P., and Lindsey, K.A., 2000b, Exploring the hydrogeology of the Columbia River Basalt Group—A field guide to selected localities in the Columbia Plateau, Washington: Tacoma, Washington, Third Washington State Hydrogeology Symposium, October 14–15, 2000, 66 p.

Tolan, T.L., Martin, B.S., Reidel, S.P., Kauffman, J.D., Garwood, D.L., and Anderson, J.L., 2009, this volume, Stratigraphy and tectonics of the central and eastern portions of the Columbia River Flood-Basalt Province: An overview of our current state of knowledge, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, doi: 10.1130/2009.fld015(29).

Tribble, G.W., 1991, Underwater observations of active lava flows from Kilauea volcano, Hawaii: Geology, v. 19, p. 633–636, doi: 10.1130/0091-7613(1991)019<0633:UOOALF>2.3.CO;2.

Trimble, D.E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p.

U.S. Department of Energy, 1988, Site characterization plan reference repository location, Hanford Site, Washington: Washington, D.C., U.S. Department of Energy, DOE/RW-0164, v. 1–2.

Van Alstine, D.R., and Gillette, S.L., 1981, Magnetostratigraphy of the Columbia River basalt, Pasco Basin and vicinity, Washington: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-C-110, 57 p.

Van Atta, R.O., and Kelty, K.B., 1982, Nonmarine lithofacies included in Scappoose Formation, Northwest Oregon: American Association of Petroleum Geologists Bulletin, v. 60, no. 10, p. 1702.

Wadge, G., 1981, The variation of magma discharge during basaltic eruptions: Journal of Volcanology and Geothermal Research, v. 11, p. 139–168, doi: 10.1016/0377-0273(81)90020-2.

Walker, G.W., 1979, Reconnaissance geologic map of the Oregon part of the Grangeville quadrangle, Baker, Union, Umatilla, and Wallowa Counties, Oregon: U.S. Geological Survey Miscellaneous Investigations Map I-1116, scale 1:250 000, 1 sheet.

Walker, G.W., and MacLeod, N.S., 1991, Geologic map of Oregon: U.S. Geological Survey, scale 1:500,000, 2 sheets.

Walsh, T.J., Korosec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987, Geologic map of Washington—Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, scale 1:250,000, 2 sheets, 28 p. text.

Warren, C.R., 1941, Course of the Columbia River in south-central Washington: American Journal of Science, v. 239, p. 106–127.

Waters, A.C., 1955, Geomorphology of south-central Washington as illustrated by the Yakima East quadrangle: Geological Society of America Bulletin, v. 66, p. 663–684, doi: 10.1130/0016-7606(1955)66[663:GOSWIB]2.0.CO;2.

Waters, A.C., 1960, Determining direction of flow in basalts: American Journal of Science, v. 258-A, p. 350–366.

Waters, A.C., 1961, Stratigraphic and lithologic variations in the Columbia River Basalt: American Journal of Science, v. 259, p. 583–611.

Watters, T.R., 1989, Periodically spaced anticlines of the Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 283–292.

Wells, R.E., 2006, Oregon geology—Parent of the soil, foundation for the vine: U.S. Geological Survey Open-File Report 2006-1069.

Wells, R.E., Simpson, R.W., Bentley, R.D., Beeson, M.H., Mangan, M.T., and Wright, T.L., 1989, Correlation of Miocene flows of the Columbia River Basalt Group from the central Columbia River Plateau to the coast of Oregon and Washington, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 113–130.

Wells, R.E., Snavely, P.D., Jr., MacLeod, N.S., Kelly, M.M., Parker, M.J., Fenton, J.S., and Felger, T.J., 1995, Geologic map of the Tillamook Highlands, northwest Oregon Coast Range: A digital database: U.S. Geological Survey Open-File Report 95-670.

Wells, R.E., Niem, A.R., Evarts, R.C., and Hagstrum, J.T., 2009, this volume, The Columbia River Basalt Group—From the gorge to the sea, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, doi: 10.1130/2009.fld015(32)

Werner, K.S., 1990, I. Direction of maximum horizontal compression in western Oregon determined from borehole breakouts; II. Structure and tectonics of the northern Willamette Valley, Oregon [M.S. thesis]: Corvallis, Oregon, Oregon State University, 159 p.

West, D.O., 1987, The Wenas Valley fault—Holocene normal faulting or gravitational sliding in the Yakima fold belt, Columbia Plateau?: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 463.

West, D.O., and Shaffer, M.E., 1989, Late Quaternary tectonic deformation in the Smyrna Bench and Saddle Gap segments, Saddle Mountains anticline, Yakima fold belt, central Columbia Basin, Washington: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 157–158.

Whiteman, K.J., Vaccaro, J.J., Gonthier, J.B., and Bauer, H.H., 1994, Hydrological framework and geochemistry of the Columbia Plateau aquifer system in parts of Washington, Oregon, and Idaho: U.S. Geological Survey Professional Paper 1413-B, 73 p.

Wilcox, R.E., and Fisher, R.V., 1966, Geologic map of the Monument Quadrangle, Grant County, Oregon: U.S. Geological Survey Map GQ-541, scale 1:62 500, 1 sheet.

Wozniak, K.C., 1995, Chapter 2—Hydrogeology, *in* Hydrogeology, Groundwater Chemistry, and Land Uses in the Lower Umatilla Basin Groundwater Management Area, Northern Morrow and Umatilla Counties, Oregon—Final Review Draft: Salem, Oregon, Oregon Department of Environmental Quality Report, p. 2.1–2.80.

WPPSS (Washington Public Power Supply System), 1981, Nuclear project No. 2—Final safety analysis report: Richland, Washington, v. 2, Amendment 18.

Wright, T.L., Grolier, M.J., and Swanson, D.A., 1973, Chemical variation related to stratigraphy of the Columbia River Basalt: Geological Society of America Bulletin, v. 84, p. 371–386, doi: 10.1130/0016-7606(1973)84<371:CVRTTS>2.0.CO;2.

Wright, T.L., Mangan, M.T., and Swanson, D.A., 1989, Chemical data for flows and feeder dikes of the Yakima Basalt Subgroup, Columbia River Basalt Group, Washington, Oregon, and Idaho, and their bearing on a petrogenetic model: U.S. Geological Survey Bulletin 1821, 71 p.

Yeats, R.S., Graven, E.P., Werner, K.S., Goldfinger, C., and Popowski, T.A., 1991, Tectonics of the Willamette Valley, Oregon: U.S. Geological Survey Open-File Report 91-441-P, 47 p.

Yelin, T.S., and Patton, H.J., 1991, Seismotectonics of the Portland, Oregon, region: Seismological Society of America Bulletin, v. 81, p. 109–130.

Zwart, M.J., 1990, Groundwater conditions in the Stage Gulch area, Umatilla County, Oregon: Oregon Water Resources Department Ground Water Report 35, 94 p.

Manuscript Accepted by the Society 12 July 2009

Printed in the USA