Northwest Geological Society
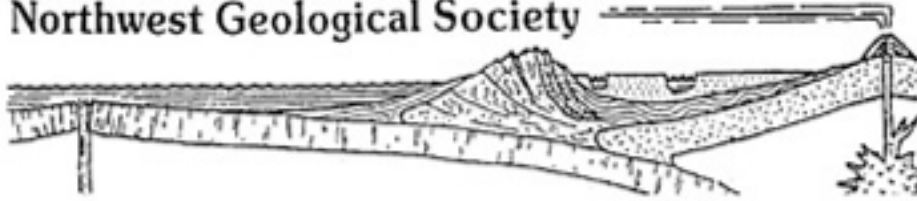## Society Field Trips in Pacific Northwest Geology

The Effects of Volcanism and Tectonism on the Evolution of the Columbia River System

A Field Guide to Selected Localities in the Southwestern Columbia Plateau and Columbia River Gorge of Washington and Oregon State.

September 28 -29 2002

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INTRODUCTION

Over the past 70 years, numerous geologic studies have been conducted in the Columbia Plateau and Columbia River Gorge. These investigations have revealed that this region was formed and modified by the dynamic interplay of a series of phenomenal geologic events and processes that took place during the last 17 million years.   One constant factor during this 17 million-year history was the presence of a drainage system through this region that was the forerunner of today's Columbia River system. Results from geologic studies (e.g., Piper, 1932; Hodge, 1938, 1942; Warren. 1941; Waters, 1955; Laval, 1956; Mackin, 1961; Schmincke, 1964;Newcomb 1966, 1971; Bentley, 1977; Grolierand Bingham, 1978; Ross, 1989; Kent, 1978; Farooqui and others, 198la, b; Swanson and Wright, 1978, 1981; Myers and Price, 1979; Swanson and others, 1979a,b, 1980, 1981; Camp, 1981; Webster and others, 1982; Campbell, 1983; Stoffel, 1984; Tolan and Beeson, 1984; Anderson and Vogt, 1987; Fecht and others, 1987; USDOE, 1988; Smith, 1988; Smith and others, 1989; Lindsey and others, 1993; Goodwin, 1993; Reidel and others, 1994; Lindsey, 1996; Beeson and Tolan, 1996; Lindsey and Tolan, 1996; Tolan and others, 1996; Beeson and Tolan, 2002) have found that the ancestral Columbia River has not always followed its present-day course. The path of the ancestral Columbia River across this region (as well as its major tributaries) has been repeatedly changed due to the effects of flood basalt volcanism, Cascade Arc volcanism, and regional-scale deformation. The present-day path and Gorge of the Columbia River are the end result of this dynamic geologic history.

The focus of this two-day field trip will be the paleodrainage history and evolution of the Columbia River system in the southwestern Columbia Plateau and Columbia River Gorge region. The trip will examine:
- Nature, emplacement histories, and stratigraphy of giant Miocene Columbia River flood-basalt flows and how they impacted and controlled the evolution of the Columbia River system;
- Nature, lithology, and depositional environments of Neogene sediments and what they tell us about the paleodrainage development and history of this region;
- The nature of regional-scale structures (Yakima Folds and northwest-trending, dextral wrench faults) that transect this region and their impact on the evolution of the Columbia River system;
- Nature and role of Cascade Arc volcanism on the evolution of the Columbia River system;
- Timing and impact of regional-scale uplift on the Columbia River system;
- Affects of the Pleistocene Cataclysmic Floods and their role in shaping the Columbia River Gorge.

Field localities to be visited are some of those that reveal important aspects and features that have helped us decipher and interpret the geologic evolution of the Columbia River system and this region.

Although this is a two-day trip, we will only have enough time to visit a handful of selected localities. For those that are interested in further exploring the geologic and paleodrainage history of this region, we refer you to field trip guides presented in Tolan and others (1984a,b); Reidel and others (1994), and Beeson and Tolan (1996).

STRATIGRAPHIC SETTING

GENERAL

Figure 1 presents a generalized stratigraphy and nomenclature for the western Columbia Plateau and Columbia River Gorge region. The oldest exposed units in this region are found in the western-half of the Gorge and represent Oligocene- to early Miocene-age Cascade volcanic arc deposits (Western Cascade Group of Hammond (1989)). These older Western Cascade Group rocks are estimated to have a thickness of more than 6,000 m (Wise, 1970). Although these units are important in understanding the geologic history of this region, they do not play a central role in the paleodrainage history of the ancestral Columbia River system that we will be examining and discussing on this trip. For those interested in more information about these units, see papers by Wise (1970), Hammond (1979, 1989), Swanson and others (1989), and Evarts and Swanson (1994).

The stratigraphic units that this trip will focus on are the Columbia River Basalt Group, sediments of the Ellensburg, Alkali Canyon, Chenoweth, and Troutdale Formations, and Cascade volcanics belonging to the Rhododendron Formation, Simcoe Volcanics, and High Cascade Group. These units are described in more detail in the following sections because of what they indicate about the paleodrainage history of the ancestral Columbia River system.

COLUMBIA RIVER BASALT GROUP (CRBG)

Historical Perspective

The pioneering studies that developed a basic Columbia River basalt stratigraphic framework that could be correlated and mapped over geographically large areas were conducted in the western and central Columbia Plateau region by Waters (1961), Mackin (1955, 1961), and Grolier and Bingham (1971, 1978). Ensuing studies of the Columbia River basalt, employing traditional mapping methods coupled with geochemistry and paleomagnetic polarity "tools", demonstrated that mappable units (Fig. 2) of regional extent (Fig. 3) could be uniquely defined (Swanson and others, 1979a,b, 1980, 1981; Beeson and Moran, 1979). The impetus (and funding for) for most Columbia River Basalt Group (CRBG) research

efforts from the late 1970's to 1988 was the U.S. Department of Energy's Basalt Waste Isolation Project (BWIP) which examined the suitability of constructing a deep, mined, repository for the final disposal of high-level nuclear waste in the CRBG beneath the Hanford Site.

A tremendous amount of data and information was produced by BWIP, and its cooperative research partners, on a diverse range of CRBG topics. Results from BWIP's investigations are summarized in the first three volumes of Site Characterization Plan (US-DOE. 1988). The 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 efforts 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 and others, 1994; Ho and Cashman/1997; Self and others, 1996, 1997; Reidel, 1998), refining the stratigraphy of the CRBG, and understanding the hydrogeology of the CRBG.

One of the most significant results that came from this period of regional CRBG study is the evolution of our "conceptual model" for the CRBG. There were several stages in this evolution reflecting modification of the existing "model" to accommodate new data and information being rapidly generated by then on-going field studies. This process gave rise to some strange non sequiturs concerning the estimated number of CRBG flows vs. average flow volume/extent.

CRBG Basics

The CRBG consists of a thick sequence of more than 300 continental tholeiitic flood basalt flows (Table 1) that cover an area of more than 164,000 km2 in Washington, Oregon, and western Oregon (Fig. 3; Tolan and others. 1989). The total estimated volume for the CRBG is greater than 174,000 km3 (Table 1; Tolan and others, 1989) with the maximum thickness of over 3.2 km occurring in the Pasco Basin area based on geophysical and deep hydrocarbon exploration well data (Reidel and others, 1982, 1989a. b). The CRBG can be divided into a host of regionally mappable units (Figs. 2 and 3) based on variations in physical, chemical, and paleomagnetic properties - in regard to stratigraphic position - that exist between flows and packets of flows (Swanson and others. 1979a: Beeson and others, 1985; Reidel and others, 1989b; Bailey, 1989).

CRBG flows were erupted during a period from about 17 to 6 Ma from long (10 to >50 km), north-northwest-trending linear fissure systems located in eastern Washington, northeastern Oregon, and western Idaho (Fig. 4). Although CRBG eruptive activity spanned an 11 million year period, most (>96 volume %) of the CRBG flows were emplaced over a 2.5 million year period from 17 to 14.5 Ma (Fig. 5; Swanson and others, 1979a; Tolan and others, 1989).

During this intense period of CRBG volcanism, most of the flows emplaced were of extraordinary size, commonly exceeding 500 to 1,000 km in volume (Table 1), traveled many hundreds of kilometers from their linear vent systems, and covered many thousands of square kilometers (Tolan and others, 1989; Reidel and others, 1989b). These gigantic CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history. Figure 6 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 know on the earth (Tolan and others. 1989).

The flowage of lava away from the vent systems was directed by major tectonic features (i.e., Palouse Slope, Columbia Basin, Columbia Trans-Arc Lowland) and continued regional subsidence (Reidel and others, 1994; Beeson and others, 1989; Reidel and Tolan. 1992) that combined to produce a westward, regional down-gradient pathway (Fig. 7). Of these features, it was the Columbia Trans-Arc Lowland (Fig. 7) that provided voluminous CRBG flows a lowland route across the Miocene Cascade Range in western Oregon and Washington (Beeson and others, 1989; Beeson and Tolan, 1990). Without the presence of the Columbia Trans-Arc Lowland, and the continued subsidence that maintained its viability as a pathway, CRBG flows would have ponded against the eastern slope of the Miocene Cascade Range and probably followed narrow river channels through the Cascade Range. Once in western Oregon and Washington, the paths of CRBG flows were strongly influenced by two major northwest-trending, dextral strike-slip fault zones (Fig. 7) and the apparent continuation of the Columbia Trans-Arc Lowland (Sherwood Trough - Beeson and others, 1989).

Mode of Emplacement

Sheet vs. Compound Flows.

Rate/volume of lava erupted, lava composition/temperature (rheology), vent geometry, topography, and environmental conditions all play significant roles in the eruption dynamics and overall geometry of individual basalt lava flows or flow fields (Shaw and Swanson, 1970; Reidel and Tolan. 1992; Reidel and others, 1994; Beeson and others. 1989; Hon and others. 1994; Keszthelyi and Self. 1996; Self and others, 1996, 1997: Reidel. 1998). There are two basic types of flow geometries - compound and sheet (Fig. 8).

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
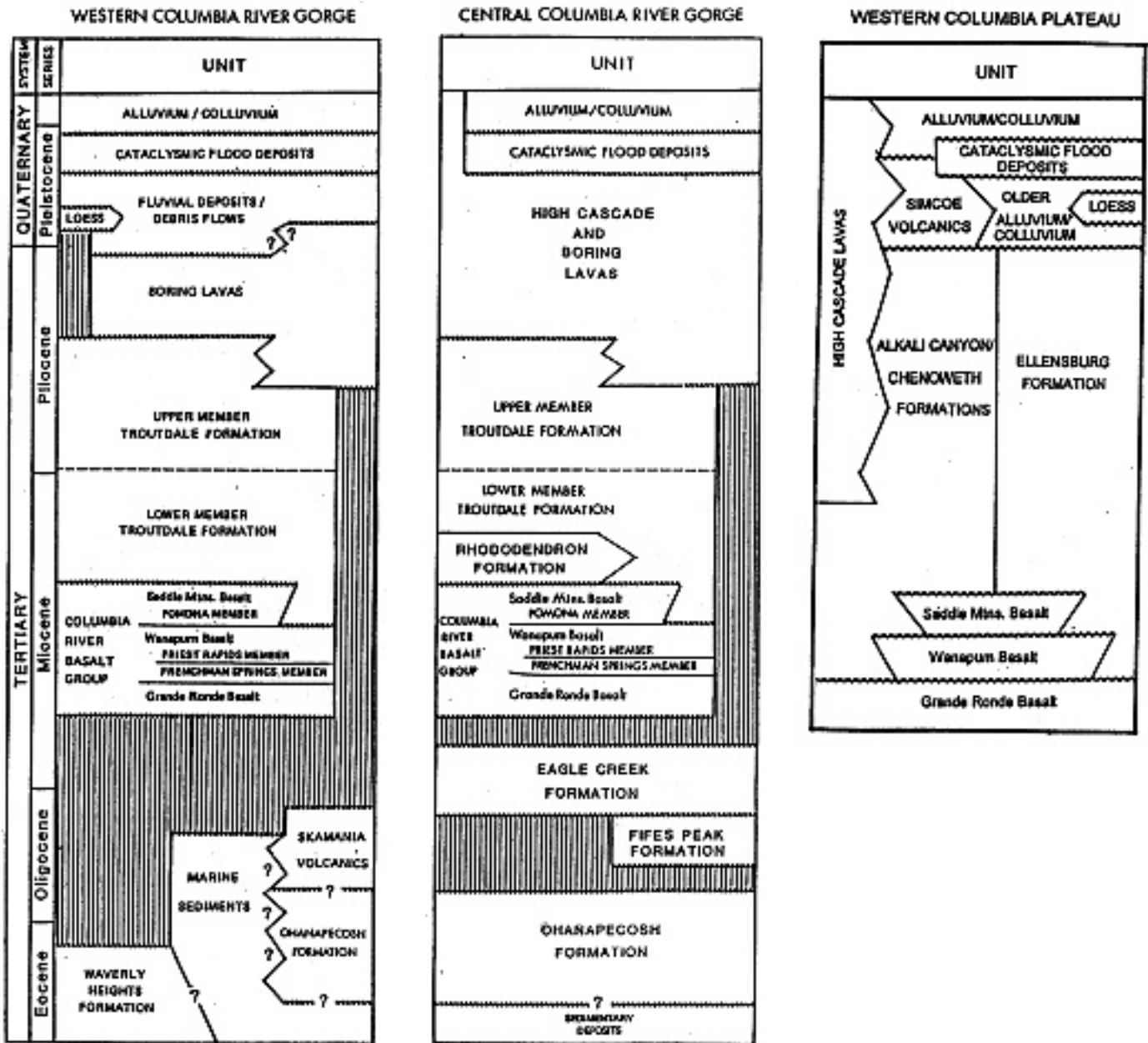
Figure 1: *Generalized stratigraphy of the area of the field trip*

Figure 2
Stratigraphic nomenclature of the CRBG.
Modified from Tolan and others (1989) and
Reidel and others (1989)

SERIES	GROUP	FORMATION	MEMBER	ISOTOPIC AGE (m.y.)	MAGNETIC POLARITY
MIOCENE / UPPER			LOWER MONUMENTAL MEMBER	8	N
			Erosional Unconformity		
			ICE HARBOR MEMBER	8.5	
			Basalt of Goose Island		N
			Basalt of Martindale		R
			Basalt of Basin City		N
			Erosional Unconformity		
			BUFORD MEMBER		R
			ELEPHANT MOUNTAIN MEMBER	10.5	R T
			Erosional Unconformity		
			POMONA MEMBER	12	R
			Erosional Unconformity		
		SADDLE MOUNTAIN BASALT	ESQUATZEL MEMBER		N
			Erosional Unconformity		
			WEISSENFELS RIDGE MEMBER		
			Basalt of Slippery Creek		N
			Basalt of Tenmile Creek		N
			Basalt of Lewiston Orchards		N
			Basalt of Cloverland		N
			ASOTIN MEMBER	13	
			Basalt of Huntzinger		N
			WILBUR CREEK MEMBER		
			Basalt of Lapwai		N
			Basalt of Wahluke		N
			Local Erosional Unconformity		
MIDDLE			UMATILLA MEMBER	13.5	
			Basalt of Sillusi		N
			Basalt of Umatilla		N
			Local Erosional Unconformity		
			PRIEST RAPIDS MEMBER		
			Basalt of Lolo	14.5	R
			Basalt of Rosalia		R
			Local Erosional Unconformity		
			ROZA MEMBER		T,R
			SHUMAKER CREEK MEMBER		N
		WANAPUM BASALT	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		E
			Basalt of Palouse Falls		E
			ECKLER MOUNTAIN MEMBER		
			Basalt of Dodge		N
			Basalt of Robinette Mountain		N
			Local Erosional Unconformity		
			SENTINEL BLUFFS MEMBER	15.6	
			SLACK CANYON MEMBER		
			FIELD SPRINGS MEMBER		
			WINTER WATER MEMBER		N_2
			UNTANUM MEMBER		
			ORTLEY MEMBER		
		GRANDE RONDE BASALT	ARMSTRONG CANYON MEMBER		
		(PRINEVILLE BASALT)	MEYER RIDGE MEMBER		
		(PICTURE GORGE BASALT)	GROUSE CREEK MEMBER		
LOWER			WAPSHILLA RIDGE MEMBER		R_2
			MOUNT HORRIBLE MEMBER		
			CHINA CREEK MEMBER		
			DOWNEY GULCH MEMBER		N_1
			CENTER CREEK MEMBER		
			ROGERSBURG MEMBER		
			TEEPEE BUTTE MEMBER		R_1
			BUCKHORN SPRINGS MEMBER	16.5	
		IMNAHA BASALT		17.5	

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Figure 3 *Distribution maps for the Columbia River Basalt Group (From Tolan and others 1989) See page 8 for unit identificatns (Map numbers)*

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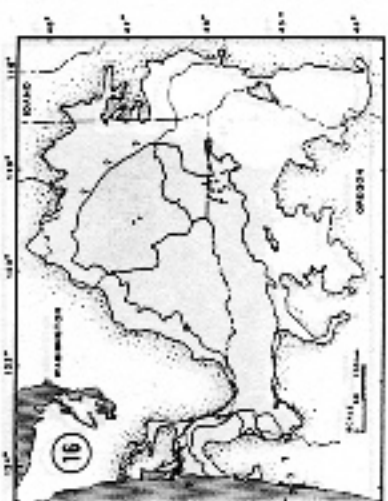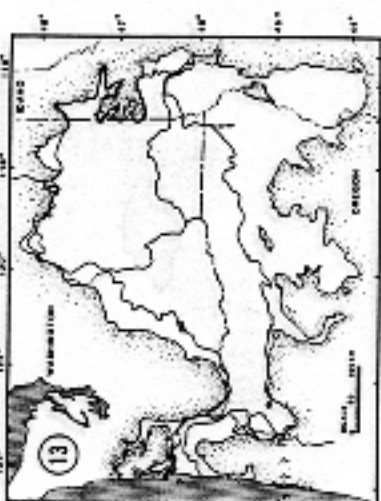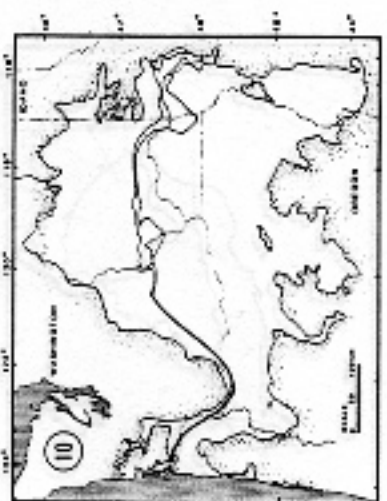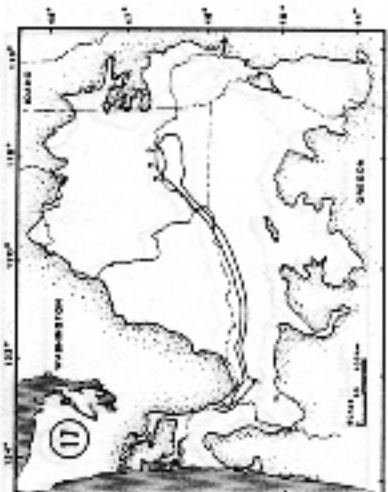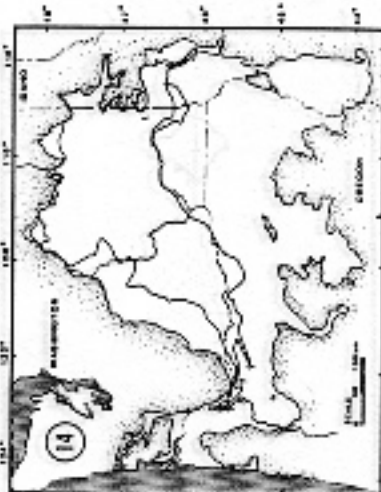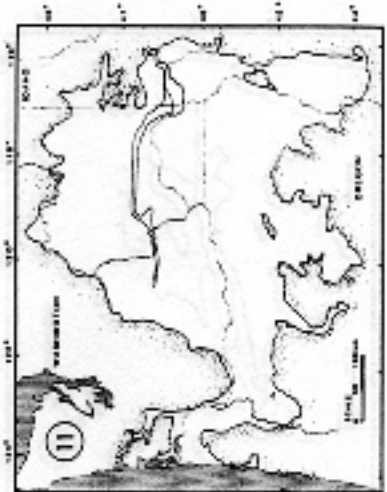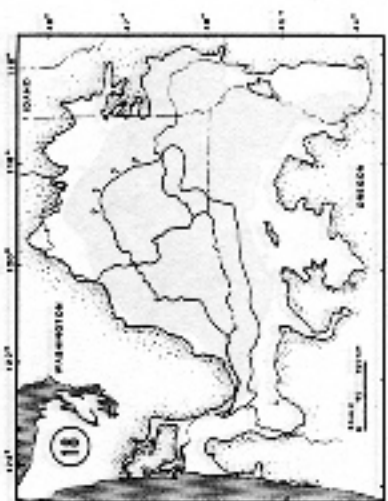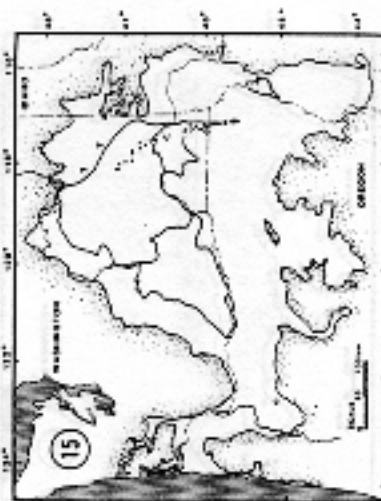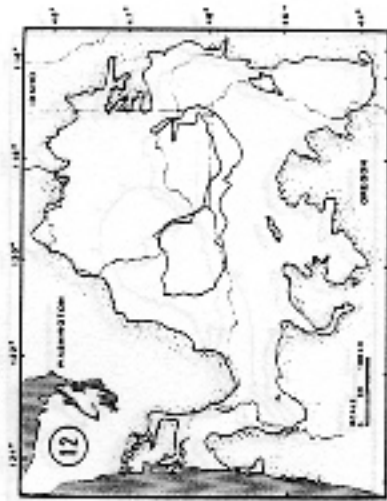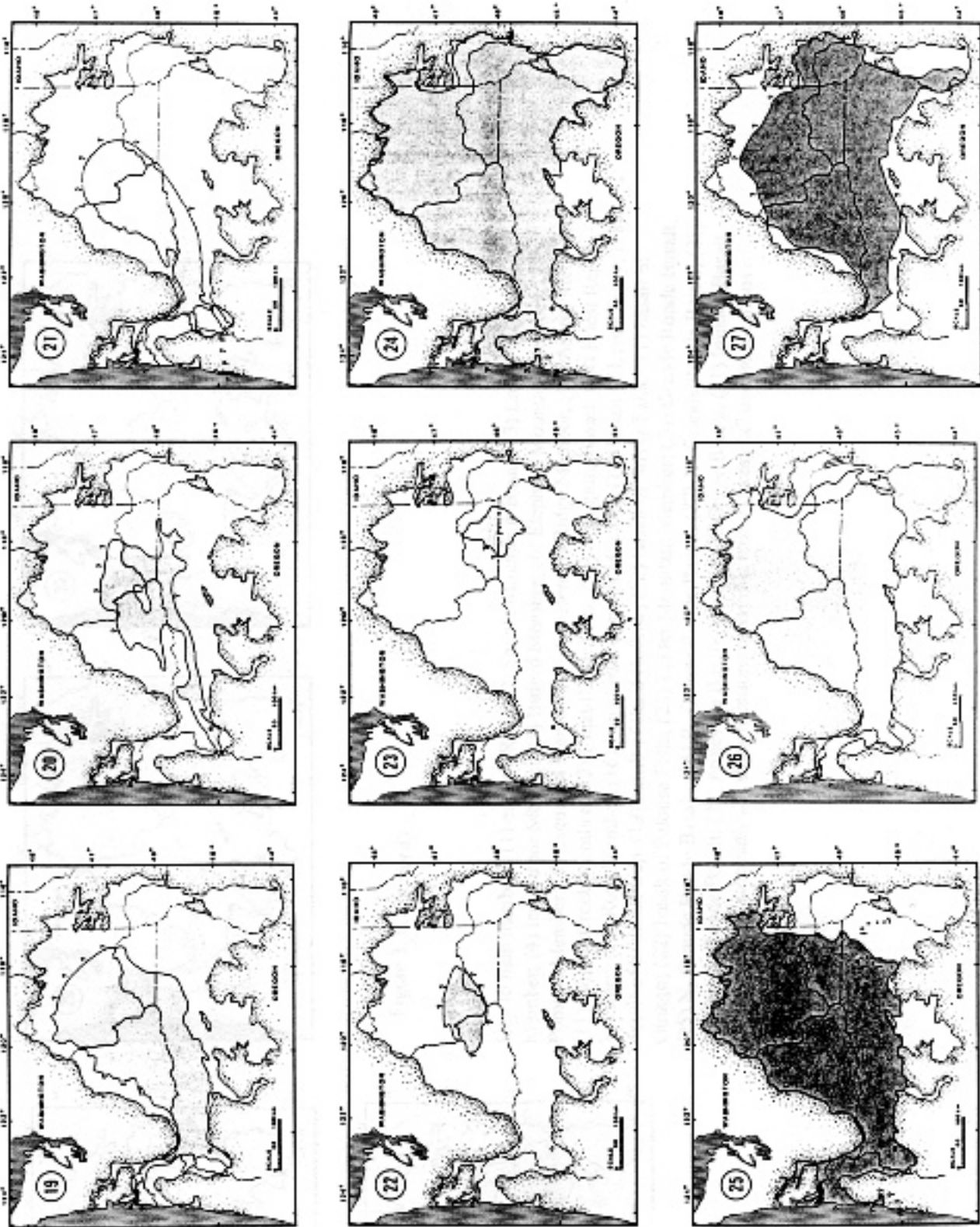
Figure 3 *(Continued)*
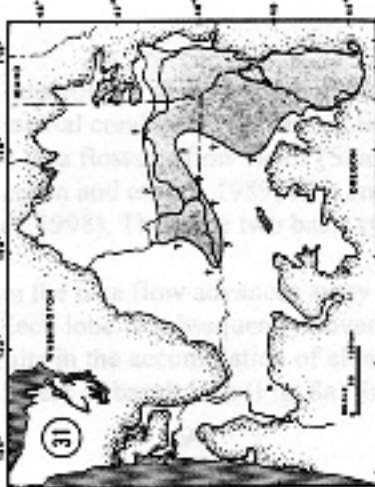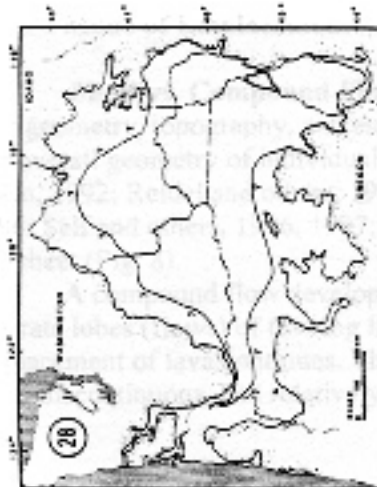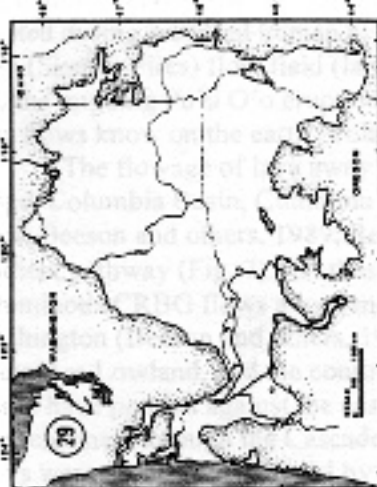
Key to map numbers: (1) entire CRBG; (2) Saddle Mountains Basalt; (3) Lower Monumental Member; (4) Ice Harbor Member; (5) Buford Member; (6) Elephant Mountain Member; (7) Pomona Member; (8) Esquatzel Member; (9) Weissenfels Ridge Member; (10) Asotin Member; (11) Wilbur Creek Member; (12) Umatilla Member; (13) Wanapum Basalt; (14) Priest Rapids Member; (15) Roza Member; (16) Frenchman Springs Member; (17) basalt of Lyons Ferry; (18) basalt of Sentinel Gap; (19) basalt of Sand Hollow; (20) basalt of Silver Falls; (21) basalt of Ginkgo; (22) basalt of Palouse Falls; (23) Eckler Mountain Member; (24) Grande Ronde Basalt; (25) N2 Grande Ronde Basalt; (26) R2 Grande Ronde Basalt; (27) N, Grande Ronde Basalt; (28) R, Grande Ronde Basalt; (29) Prineville Basalt; (30) Picture Gorge Basalt; (31) Imnaha Basalt. Thin solid lines schematically show locations of known feeder dikes; "x" denote locations of known vents.

basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava (Fig. 8a). 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 (Fig. 8b).

Individual, large volume CRBG flows (especially Grande Ronde and Wanapum Basalts) display characteristics consistent with sheet flows (Swanson and others. 1979a; Tolan and others, 1989; Reidel and others, 1989b, 1994; Reidel and Tolan, 1992; Beeson and others, 1985, 1989; Beeson and Tolan, 1990, 1996; Reidel, 1998). CRBG flows typically only exhibit the complex features associated with compound flows found at their flow margins (Beeson and others, 1989; Reidel and Tolan, 1992; Reidel and others, 1994; Beeson and Tolan, 1996; Reidel, 1998).

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 which served to channel the lava into a ready-made conduit to the west. 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) 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 pathways. In the western Columbia Plateau and Columbia Trans-Arc Lowland (Fig. 7), 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.

Creation of canyon(s) would begin by the relatively slow process of headward erosion. In many cases, it appears that it required periods of >100,000 years to create major canyons that extended for distances of >150 km. However during the peak period of CRBG eruptive activity (17 to 15.6 Ma), the duration of quiescent periods between emplacement of large-volume flows averaged about 13,000 years (Reidel and others, 1989) 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 to 6 Ma) when the length of quiescent periods between CRBG eruptions dramatically increased (commonly lasting 200,000 to >1,000,000 years) accompanied by a general reduction in the size (volume) of CRBG flows (Tolan and others, 1989). These factors created opportunities for the ancestral Columbia River system to incise major canyons.

Rate of Emplacement.

Two end-member models exist for the emplacement of huge-volume CRBG flows: rapid emplacement - on the order of weeks to months per flow (Shaw and Swanson, 1970; Swanson and others, 1975; Wright and others, 1989; Reidel and Tolan, 1992; Reidel and others, 1994; Beeson and Tolan, 1996; Reidel, 1998) vs. slow emplacement - on the order of many years to centuries per flow (Self and others, 1991, 1993, 1996; Long and others, 1991; Finneamore and others, 1993; Murphy and others, 1997). Field and laboratory evidence to date (Swanson and others, 1975; Mangan and others. 1986; Wright and others, 1989; Reidel and Tolan. 1992; Reidel and others, 1994; Beeson and Tolan, 1996; Ho and Cashman. 1997; Reidel, 1998; Ho, 1999) appears to favor a rapid, laminar flow model. Evidence supporting the rapid emplacement model includes:

•   The internal structure of CRBG flows (discussed in the next section) is relatively simple. The slow emplacement model requires low lava discharge that would produce very distinctive flow features such as lava tubes and lava inflation structures that would result in relatively complex internal arrangement of flow structures (Chitwood, 1994: Hon and others, 1994; Self and others, 1996). These complex flow features are rarely found within a CRBG flow except at the flow's margin. The pervasive presence of simple internal flow structures in CRBG flows supports a rapid emplacement model (Reidel and Tolan, 1992; Reidel and others, 1994; Beeson and Tolan, 1996; Reidel, 1998).

Table 1 (Right)
Estimates of the physical dimensions of CRBG units.

CRBG UNIT	AREAL EXTENT (km²)	VOLUME (km³)	VOLUME PERCENT	EST. NUMBER OF FLOWS	AVERAGE VOLUME PER FLOW (km³)	ISOTOPIC AGE (Ma)
SADDLE MTNS. BASALT						
Lower Monumental Member	430	15	0.01	1	15	6
Ice Harbor Member	2,150	75	0.04	4	19	
Buford Member	580	20	0.01	1	20	
Elephant Mountain Member	13,450	440	0.25	2	220	10.5
Pomona Member	20,550	760	0.44	1	760	12
Esquatzel Member	2,710	70	0.04	1	70	
Weissenfels Ridge Member	1,210	20	0.01	4	5	
Asotin Member	6,440	220	0.13	1	220	
Wilbur Creek Member	3,090	70	0.04	2	35	
Umatilla Member	15,110	720	0.41	2	360	
COMPOSITE SADDLE MTNS.	30,570	2,410	1.38	19	127	
WANAPUM BASALT						
Priest Rapids Member	57,300	2,800	1.61	3	933	14.5
Roza Member	40,350	1,300	0.74	4	325	
Frenchman Springs Member						
basalt of Lyons Ferry	5,900	90	0.05	1	90	
basalt of Sentinel Gap	38,760	1,190	0.68	4	297	
basalt of Sand Hollow	67,110	2,660	1.52	7	380	15.3
basalt of Silver Falls	28,840	710	0.41	4	177	
basalt of Ginkgo	37,170	1,570	0.90	4	392	
basalt of Palouse Falls	8,890	190	0.11	1	190	
Composite Frenchman Springs	69,740	6,410	3.67	21	305	
Eckler Mountain Member	6,090	170	0.10	8	21	
COMPOSITE WANAPUM	95,950	10,680	6.12	35	305	
GRANDE RONDE BASALT						
N_2 Grande Ronde Basalt	114,460	27,900	16.00	33	845	15.6
R_2 Grande Ronde Basalt	117,730	53,100	30.46	45	1,180	
N_1 Grande Ronde Basalt	102,340	31,400	18.01	15	2,093	
R_1 Grande Ronde Basalt	96,650	36,200	20.76	27	1,340	16.5
COMPOSITE GRANDE RONDE	149,000	148,600	85.23	120	1,238	
PRINEVILLE BASALT	11,440	590	0.34	8	74	
PICTURE GORGE BASALT	10,680	2,400	1.38	61	39	
IMNAHA BASALT	50,200	9,500	5.45	26	365	17–16.5
Craigmont member	280	6	0.003	1	6	
Swamp Creek member	140	3	0.002	1	3	
Grangeville member	520	11	0.006	1	11	
Icicle Flat member	350	7	0.004	1	7	
basalt of Feary Creek	60	1	0.001	3	0.33	
Onaway member	370	7	0.004	2	3.5	
basalt of Cuddy Mountain	70	1	0.001	4	0.25	
Weiser basalt	2,130	140	0.080	28	5	
CRBG – TOTALS	163,700	174,356	100	310	562	17–6
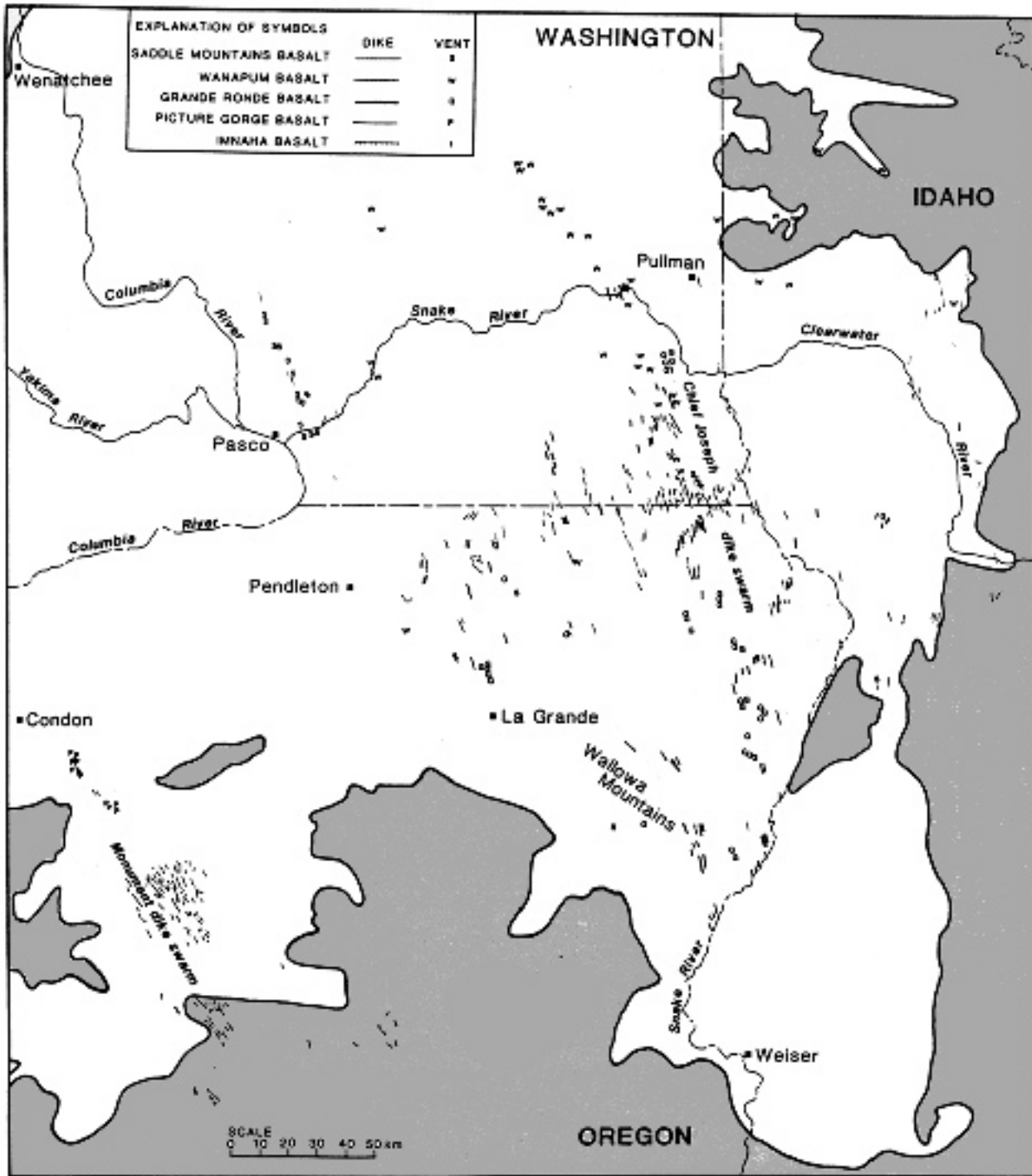
Figure 4 *Map showing the location of known CRBG feeder dikes and vents Modified from Tolan and others (1989)*
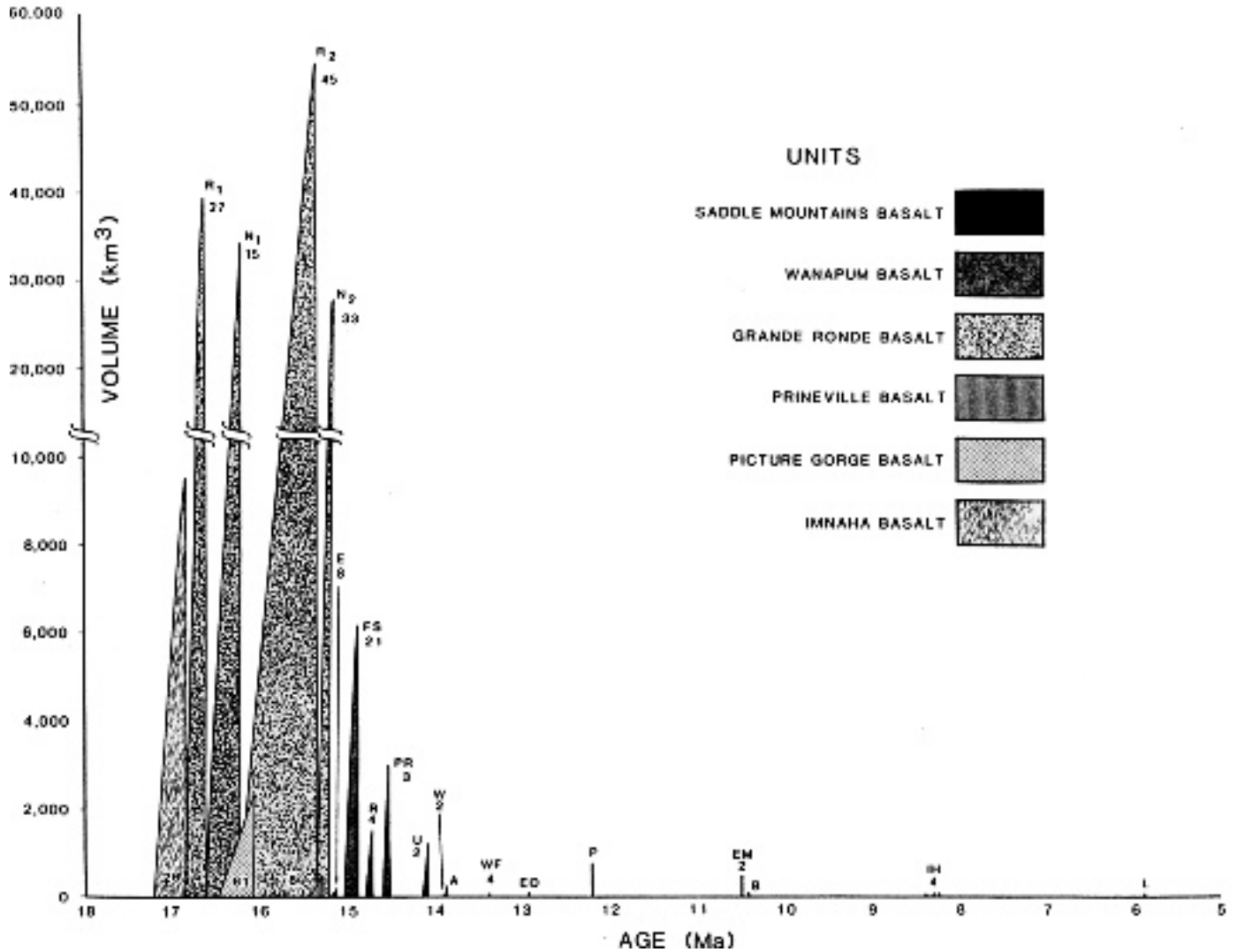
Figure 5. *Plot showing the emplacement history for CRI3G units based on volume estimates from Tolan and others (1989). Emplacement history of units composed of multiple flows (e.g., Frenchman Springs Member of the Wanapum Basalt) depicted by triangle whose apex represents total erupted volume Base of triangle represents duration of eruptive activity estimated from available isotopic dates. Note change in scale for volume. Members consisting of a single flow (e.g., Pomona Member) are represented by a single line. Lelter(s) designate following units: E, Eckler Mtn. Member; FS, Frenchman Springs Member; R, ROM Member; PR, Priest Rapids Member; U, Umatilla Member, W, Wilbur Creek Member; A, Asotin Member; Wl . Wcissenfels Ridge Member; EQ, Esqual/el Member; P, Pomona Member; EM, Elephant Mtn. Member, B, Buford Member; III. Ice Harbor Member; 1,. Lower Monumental Member. Number next to unit denotes number of Hows; absence of number indicates unit has only one flow. Individual How ages, and duration of eruptive activity for units containing multiple flows, attempt to reconcile isotopic dates and How paleomagnelic polarity to Miocene geomagnetic polarity lime scale.*
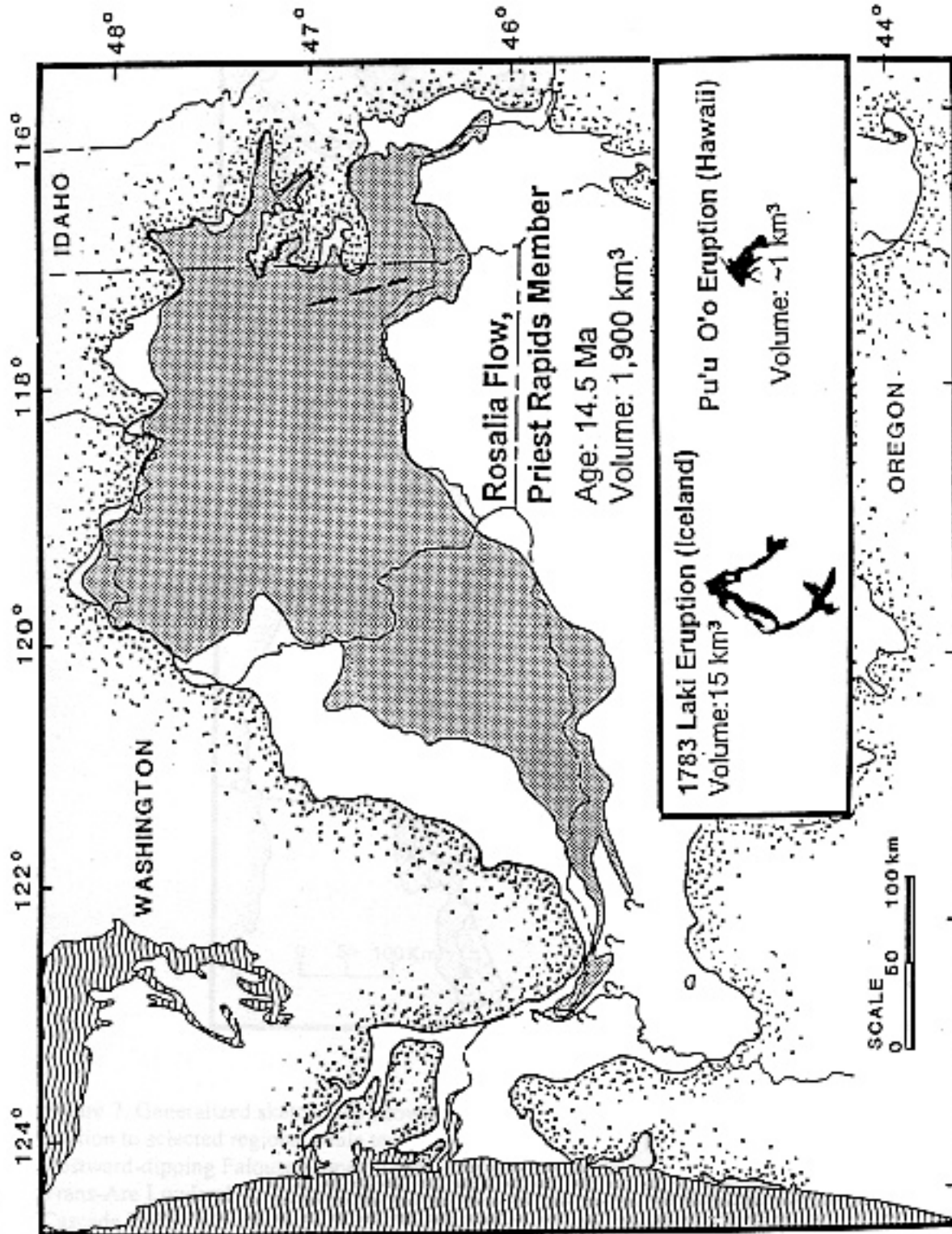
Figure 6 Map showing the areal extent of the Rosalia flow of the Priest Rapids Member (Wanapum Basalt) and a same scale comparison with the areal extent of two historic basalt flow fields. TheLaki eruption represents the largest basaltic eruption in recorded human history.
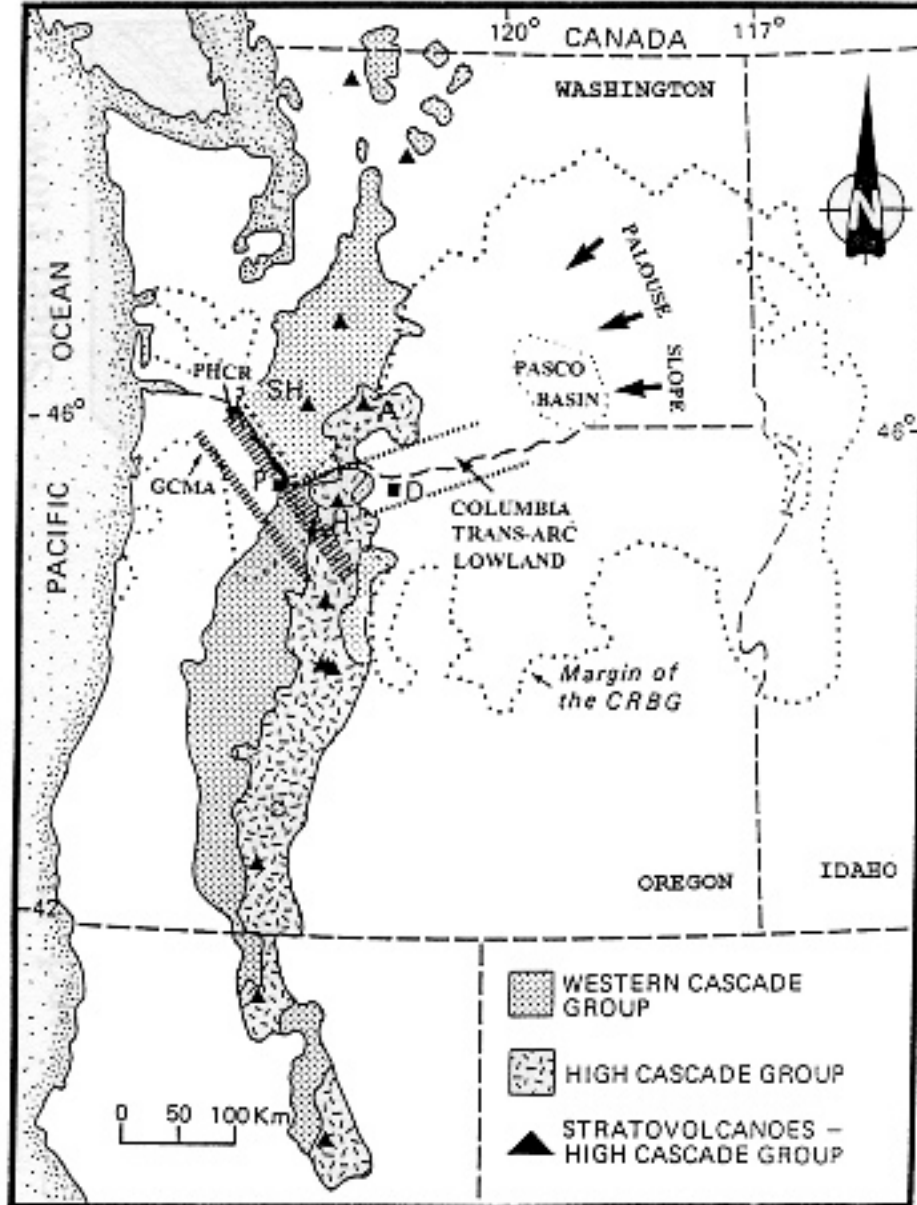
Figure 7. *Generalized sketch map showing the distribution of the Cascade volcanic arc and CRBG in relation to selected regional-scale tectonic elements (modified from Beeson and Tolan, 1990). The westward-dipping Palouse Slope directed erupting CRBG lava towards the Pasco Basin and Columbia Trans-Arc Lowland. The Columbia Trans-Arc Lowland was a low that transected the mid to late Miocene Cascade Range and allowed CRBG flows to enter western Oregon and Washington. In western Oregon, CRBG flows encountered two major northwest-trending dextral wrench fault systems, the Portland Hills-Clackamas River structural zone (PHCR) and the Gales Creek-Mount Angel structural zone (GCMA). P = Portland; D = The Dalles; H = Mount Hood; A = Mount Adams; SH = Mount Saint Helens.*

Compound Flows

Sheet Flows

100 ft

100 ft

0

Scale
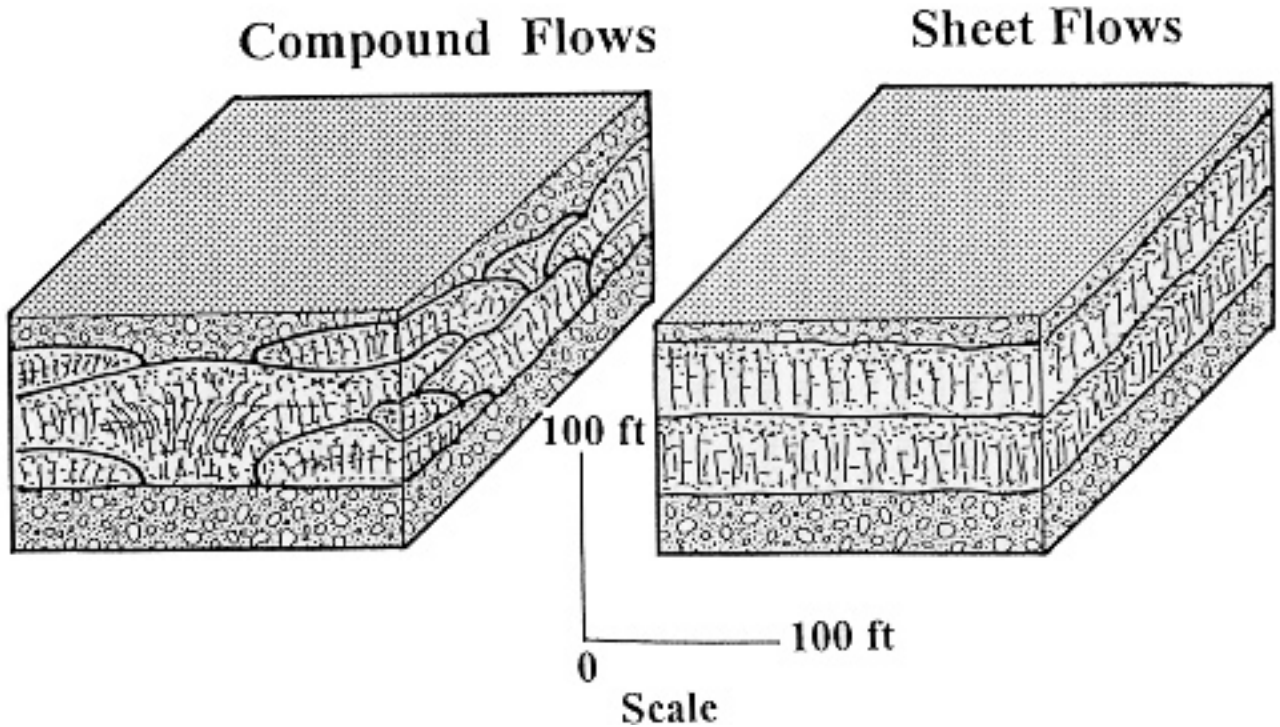
Figure 8. Diagram depicting the differences in the internal arrangement of intraflow structures between compound and sheets flows. Because of differences in the emplacement process, a compound flow displays a well developed lobe-like structure where as a sheet flow typically displays a far more simple arrangement of intraflow structures.

• Petrographic examination of quenched CRBG lava (e.g., rinds from pillow lava) from medial to distal parts of the flow has shown that the crystallinity is no greater than that of the glassy selvage zone of the feeder dike. This indicates that little or no crystal nucleation and growth occurred from the time the lava was erupted to when it reached it most distal point - distances ranging from 200 to >500 km (Shaw and Swanson, 1970; Swanson and others, 1975; Mangan and others, 1986; Wright and others, 1989; Ho and Cashman. 1997; Ho. 1999). These observations would not be consistent with a very long duration (slow) emplacement model.

• A basalt glass composition-based geothermometry study has been conducted for the Ginkgo flow (Frenchman Springs Member, Wanapum Basalt) along its 500 km length to provide a quantitative estimate of heat loss (Ho and Cashman, 1997; Ho, 1999). Results suggest cooling rates of 0.02 to 0.04 °C/km for the Ginkgo flow which are substantially lower than cooling rates observed in active and historic basalt flows (Ho and Cashman, 1997). This data would favor a rapid emplacement model over a slow emplacement model that would require extreme thermal efficiencies to produce these cooling rates (Ho and Cashman. 1997, p. 405).

• The lack of extensive pillow/hyaloclastite complexes

along the length of CRBG intracanyon flows favors a rapid emplacement model (Reidel and others, 1994; Beeson and Tolan, 1996). If CRBG intracanyon flows were emplaced over very long periods (years to centuries), dammed-off river(s) would have in a period of a few months over-topped the lava dam and reestablished their presence within their canyon(s) years before the flow reached its most distal point. This situation would result in the river encountering the advancing flow front and consequently the continuous creation of large quantities of hyaloclastic debris and pillow lava. Features consistent with this aspect of a slow emplacement model are not found along the length of CRBG intracanyon flows.

Intraflow Structures

Examination of vertical exposures through CRBG flows reveal that they all generally exhibit the same basic three-part internal arrangement of intraflow structures (Fig. 9). These features originated either during the emplacement of the flow or during the cooling and solidification of the lava after it ceased flowing. These features can be generally divided into flow top, flow interior, and flow bottom (Fig. 9). The combination of a flow top of one flow and the flow bottom of the overlying flow is commonly referred to as an

"interflow zone" (Fig. 9).

The flow top is the crust that formed on the top of a molten lava flow. Flow tops commonly consist of glassy to very fine-grained basalt that is riddled with countless spherical and elongate vesicles. Vesicles represent gas bubbles that were trapped (frozen) as the flow solidified. These gasses were originally dissolved within the magma, but reduction in pressure (and subsequent decrease in temperature) as the magma reached the surface allowed these gasses to come out of solution. CRBG flow tops can display a wide range of variation in both their physical character and thickness (USDOE, 1988). The physical character of flow tops falls between two basic end-members, a simple vesicular flow top and a flow top breccia (Fig. 9).

A simple vesicular flow top (Fig 9) 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; McMillian and others, 1989). Vesicles may be isolated or interconnected, resulting respectively in lower and higher permeability and effective porosity (USDOE, 1988). Tensional cooling joints, related to flow top formation/flow emplacement, can augment the overall permeability of this feature.

A flow top breccia (Fig. 9) consists of angular, scoriaceous to vesicular fragments of basaltic rubble that lies above a zone of non-fragmented, 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 aa flows in Hawaii. In either case, laterally extensive flow top breccias are relatively common features within the CRBG.
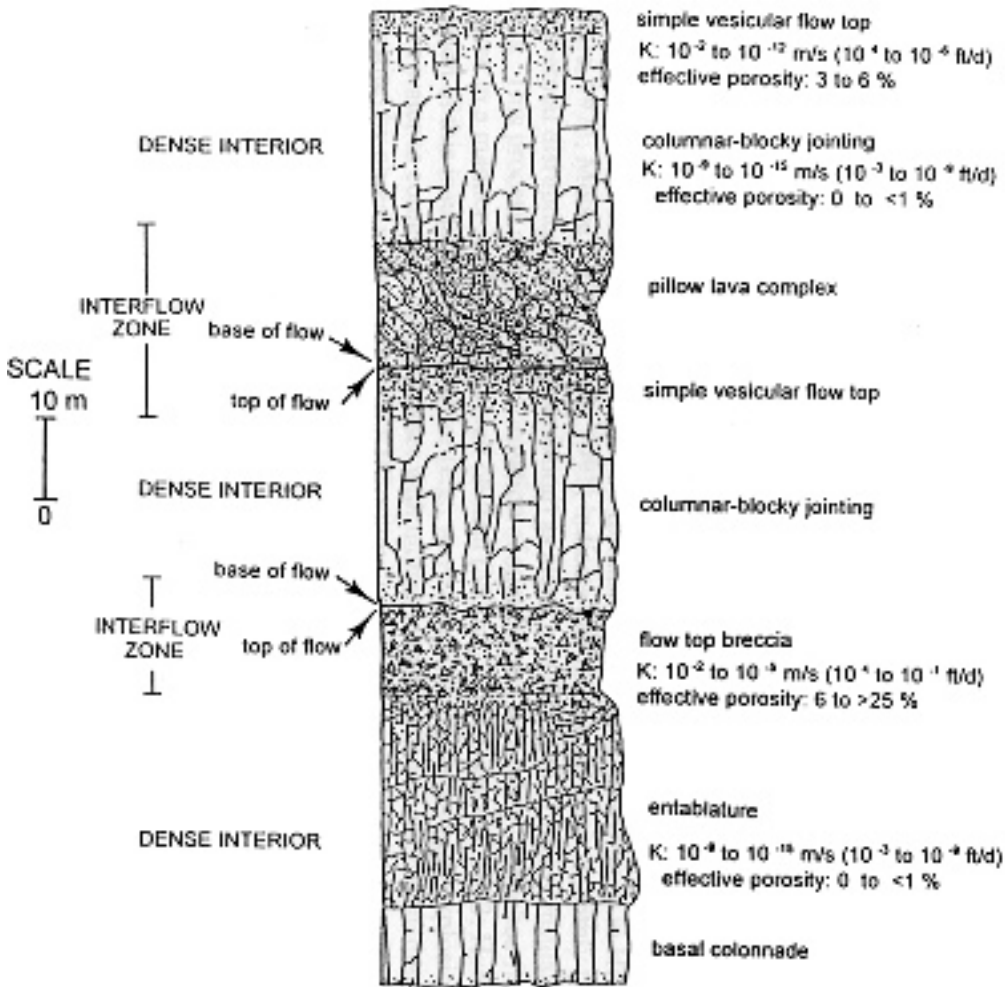
CRBG flow interiors typically consist of dense, non-vesicular, glassy to crystalline basalt that contains numerous contraction joints (termed "cooling joints") that formed when the lava solidified. CRBG cooling joints most often form regular patterns or styles, with the two most common being entablature-colonnade and columnar-blocky jointing (Fig. 9). Columnar-blocky jointing (Fig. 9) is usually associated with thinner (more fluid) flows and typically displays a mostly vertical-oriented, poorly to well-formed, polygonal columns that can range from 0.5 m to >3 m in diameter. The vertical columns are often cut by horizontal to subhorizontal cooling joints. Entablature-colonnade jointing (Fig. 9) is usually observed in thicker (more viscous) flows and displays a more complex pattern that forms within a single flow. The entablature portion displays a pattern of 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

a centimeter in width. Typically the entablature is thicker than the basal colonnade, often comprising at least two-thirds of the total flow thickness. The entablature is assumed to form due to cooling from the top of the flow downward and the colonnade forms due to cooling from the bottom upward. Another characteristic of entablatures is that the basalt comprising it contains a very high percentage of glass (50 to 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 and others, 1994), but has not been resolved.

The physical characteristics of CRBG flow bottoms (Fig. 9) 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 and others, 1989; Reidel and others, 1994; Beeson and Tolan, 1996). If the advancing CRBG lava encountered relatively dry ground conditions, the flow bottom that results typically consists of a narrow (<1 m-thick) zone of sparsely vesicular, glassy to very fine-grained basalt (Fig. 9). This type of flow bottom structure is very common within the CRBG.

If advancing lava encountered lakes, rivers, and/or areas of water-saturated, unconsolidated sediments, far more complex flow bottom structures formed (Mackin, 1961; Schmincke, 1967; Bentley, 1977; Grolier and Bingham, 1978; Byerly and Swanson, 1978; Swanson and others, 1979a; Swanson and Wright, 1978, 1981; Bentley and others. 1980; Camp, 1981; Beeson and others, 1979, 1989; Stoffel, 1984; Tolan and Beeson, 1984; Ross, 1989; Pfaff and Beeson, 1989; Reidel and others, 1994; Beeson and Tolan, 1996). Where advancing lava encountered a lake, a pillow lava complex (Fig. 9) 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 and others, 1973; Moore, 1975; Tribble, 1991) indicate that molten lava can smoothly flow into the ocean without thermal disruption (phreatic brecciation) as along 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 (Moore, 1975; Swanson, 1973; Hon and others, 1994)). Disruption of this insulating steam barrier (e.g., wave action, currents, and gas explosions within the lava lobe)

SHEET FLOWS

simple vesicular flow top
K: 10^{-2} to 10^{-12} m/s (10^{4} to 10^{-6} ft/d)
effective porosity: 3 to 6 %

DENSE INTERIOR

columnar-blocky jointing
K: 10^{-9} to 10^{-15} m/s (10^{-3} to 10^{-9} ft/d)
effective porosity: 0 to <1 %

pillow lava complex

base of flow

top of flow

simple vesicular flow top

INTERFLOW ZONE

SCALE
10 m

0

DENSE INTERIOR

columnar-blocky jointing

base of flow

top of flow

INTERFLOW ZONE

flow top breccia
K: 10^{-2} to 10^{-3} m/s (10^{4} to 10^{-1} ft/d)
effective porosity: 6 to >25 %

DENSE INTERIOR

entablature
K: 10^{-9} to 10^{-15} m/s (10^{-3} to 10^{-9} ft/d)
effective porosity: 0 to <1 %

basal colonnade

INTRACANYON FLOW

OVERFLOW AREA

AXIS OF CANYON

columnar-blocky jointing

vesicular flow top

canyon wall

typical lack of extensive pillow lavas & hyaloclastite

massive entablature

SCALE
10 m

0

basal colonnade
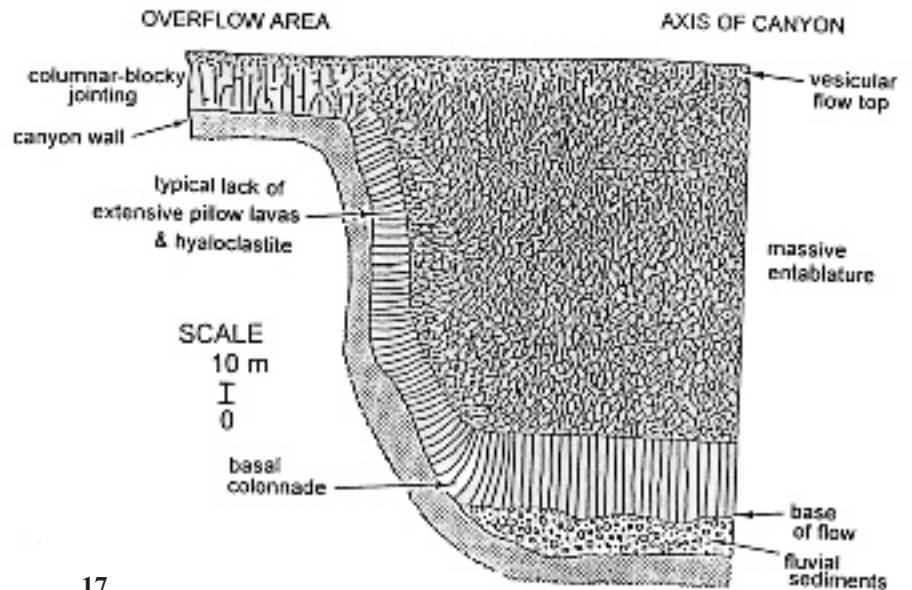
base of flow

fluvial sediments

Figure 9

Diagrammatic representation of common CRBG intraflow structures and terminology

allows water to come into direct contact with molten lava resulting in the production or 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 (Fecht and others, 1987; Tolan and Beeson. 1984; Beeson and others, 1989: Reidel and others, 1994; Beeson and Tolan, 1996).

A much more rare type of flow bottom structure is a spiracle. 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/breccia). Spiracles can range from <1 to >15 m in diameter and can extend upward through CRBG flows for distance of 1 to >30 m. Commonly spiracles terminate within the flow, but in rare cases they can pass entirely through the flow. In general, pillow form where there 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/sediment interaction which 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/sediment mixture called a peperite (Fig. 13d). CRBG flows are known to not only invade sediments, but were capable lifting and rafting sediment (Byerly and Swanson, 1978; Swanson and Wright, 1978; Beeson and others, 1979, 1989; Stoffel, 1984; USDOE, 1988; Ross, 1989). Invasive flows can be identified based on several different criteria:

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

- sediment immediately overlying the thin glassy flow top exhibit evidence of exposure to very high temperatures (i.e., baking) which is normally only as sociated with flow bottoms;

- dikelets/lobes are present that originate and extend from the flow top into the overlying sediments;

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

- sedimentary interbed is not in its expected stratigraphic position.

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

Neogene Sediments

General

The thick deposits of late Neogene sediments in the western Columbia Plateau and Columbia Trans-Arc Lowland have been studied and mapped for almost a century (e.g., Bretz, 1917; Buwalda and Moore, 1927; Piper, 1932; Hodge, 1938, 1942; Warren, 1941; Lowry and Baldwin, 1952; Waters, 1955; Laval, 1956; Mackin, 1961; Trimble, 1963; Schmincke. 1964, 1967; Hodgenson, 1964; Newcomb, 1966; 1971; Bentley, 1977; Kent, 1978; Rigby and others, 1979; Swanson and others, 1979a,b, 1981; Bentley and others, 1980; Farooqui and others, 1981a,b; Tolan and Beeson, 1984; Dames and Moore, 1987; Hagood, 1986; Fecht and others, 1987; Smith, 1988; Smith and others, 1989; Lindsey, 1996). These studies have found that these sediments are inter-fmgered 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; pyroclastic/volcaniclastic sediments derived from the adjacent Cascade volcanic arc were easily separated from more normal appearing epiclastic fluvial/lacustrine sediments (e.g., Buwalda and Moore, 1927; Piper, 1932; Waters, 1955; Hodge, 1938. 1942; Schmincke, 1964).

Knowledge of the lithologic composition of these fluvial sediments can be used to determine their provenance. In the field the easiest component to examine is the gravels. For example, a conglomerate composed entirely of Columbia River basalt clasts would indicate that the headwaters of the stream or river

that deposited these clasts lay wholly within the extent of the CRBG. Conversely, the presence of exotic (non-CRBG) clast lithologies would indicate that the river's headwaters lay beyond the margin of the CRBG.

Most studies (e.g., Bretz. 1917; Buwalda and Moore. 1927; Piper, 1932; Allen. 1932; Warren, 1941; Hodge, 1938, 1942; Lowery and Baldwin, 1952; Waters. 1955; Laval. 1956; Trimble, 1963; Schmincke, 1964) have found that the late Neogene sediments in the western Columbia Plateau and Gorge contain conglomerates that have varying abundance of exotic clasts. Particularly easy to recognize were bright-colored quartzite clasts which standout out from other dark-colored clasts.

The presence of quartzite clasts was interpreted as compelling evidence that the conglomerate was deposited by the ancestral Columbia River (Allen, 1932; Hodge, 1938; Warren, 1941; Lowery and Baldwin, 1952; Waters, 1955; Laval, 1956; Trimble, 1963; Schmincke, 1964). Despite the presence of such distinctive exotic clast lithologies, exotic clast-bearing conglomerates could not, by themselves, be utilized to define broad-scale, mappable units in the late Neogene sediments.

The primary problem was that exotic clasts (especially quartzite) appeared to the present throughout the entire late Neogene sedimentary record (Hodge. 1938; Waters, 1955, 1973: Laval, 1956: Schmincke, 1964). This coupled with complex lateral facies and lithologic changes within the deposits and difficulties in physically tracing horizons within the deposits largely thwarted the development of a detailed, mappable, stratigraphy based on traditional sedimentologic criteria.

The Neogene Sedimentary Nomenclature Quagmire

Despite the apparent complexity of the Neogene sedimentary deposits there is one excellent marker horizon - the Columbia River basalt. This allowed for the division of the Neogene sediments overlying the CRBG (suprabasalt sediments) into a number of formations in different geographic areas. These formations are:

• Ellensburg Formation: western Columbia Plateau in Washington;
• Ringold Formation: Pasco Basin of south-central Washington;
• Dalles Formation: Umatilla-Dalles basins of northern Oregon:
• Troutdale Formation: western Columbia River Gorge-northern Willamette Valley-southwestern Washington.

As CRBG stratigraphy was developed in the south-central

Columbia Plateau, the presence of identifiable and mappable CRBG flows interbedded with the Ellensburg Formation was utilized as a means for defining members within the Ellensburg Formation (Fig. 10). Studies demonstrated that many of the defining, interbedded CRBG flows could be reliably identified using a combination of physical, lithologic, geochemical, and paleomagnetic criteria (Waters, 1955; Laval, 1956; Mackin, 1961; Schmincke, 1964, 1967; Wright and others, 1973; Bentley, 1977; Swanson and others, 1979a,b, 1980, 1981; Beeson and others, 1985, 1989; Reidel and others, 1989b). This, coupled with the fact that many of these basalt flows have large areal extents (Swanson and others. 1979a), appeared to make them ideal marker horizons. A "side-effect" of the regional mapping of the CRBG was that Ellensburg nomenclature (e.g., Vantage, Selah Members) was also informally extended into northern and northwest Oregon (Laval, 1956; Mackin, 1961; Schmincke, 1964, 1967; Newcomb, 1969, 1971; Kent, 1978; Swanson and others, 1979a, 1981; Farooqui and others, 1981a,b; Smith and others, 1989; Beeson and others, 1985, 1989).

While existing Ellensburg nomenclature is widely used and accepted throughout the central and western Plateau region, it does have several inherent problems that can create confusion. The first problem is that the defining CRBG flow(s) are not always present. Beyond the terminus of the interbedded CRBG flows, the Ellensburg "members" can no longer be identified and the sedimentary section simply becomes part of another Ellensburg member or the suprabasalt sediment section (i.e., upper Ellensburg Formation; Fig. 10). In the case of the Umatilla Basin in northern Oregon, Ellensburg members beyond the bounding CRBG flow margins become part of the suprabasalt sediment Alkali Canyon Formation (formerly the Dalles Formation) of Farooqui and others (1981a,b).

Another potentially confusing aspect of Ellensburg stratigraphy is that the time-interval represented by an Ellensburg member at one locality may not be the same as at a different locality. For example in the Umatilla Basin, the Selah Member (Fig. 10) is simply defined by the presence of the Pomona flow (12 Ma) and whatever CRBG unit immediately underlies it (Schmincke, 1964, Newcomb, 1971, Kent, 1978; Smith and others, 1989). The underlying CRBG flow could belong to the Umatilla Member (13.5 Ma), the Priest Rapids Member (14.5 Ma), or the Frenchman Springs Member (15.3 Ma). So the span of time represented by the "Selah Member" within this basin could range from 1.5 to 3.3 million years.

A similar problem also occurs with the suprabasalt sediments. The Neogene suprabasalt sediment formations are simply defined as Neogene sediments that overlie the CRBG. However, the CRBG unit upon which these sediments lie is not always

the same. This is clearly illustrated in the Umatilla Basin by the Alkali Canyon Formation (Fig. 10). As you travel south from the Columbia River into Oregon, the Alkali Canyon Formation progressively lies atop older and older CRBG units (Fig. 10). So the age of the base of the "Alkali Canyon Formation" can vary from 10.5 Ma to 15.3 Ma.

As noted above, the suprabasalt sediments in the Umatilla and Dalles Basins have been historically mapped as the Dalles Formation (Piper. 1932; Hodge, 1938; Warren, 1941; Newcomb, 1969, 1971). However based on their regional reconnaissance mapping of late Neogene sediments in north-central Oregon, Farooqui and others (1981a,b) proposed a major revision to the stratigraphic nomenclature for these sedimentary deposits. They proposed that the late Neogene suprabasalt sediments, north of the axis of the Blue Mountains anticlinorium in Oregon, that had been historically referred to as the "Dalles Formation" could be subdivided into five unique, mappable formations that occupy geographically discrete and separate basins (Farooqui and others, 1981b, p. 132-133). These five new formations would comprise the redefined "Dalles Group". The Dalles Formation ofNewcomb (1966, 1969, and 1971) would be subdivided into the Chenoweth Formation (Dalles Basin) and the Alkali Canyon Formation (Umatilla Basin).

Early studies of the suprabasalt sediments in the Dalles-Umatilla Basins (e.g., Buwalda and Moore, 1927; Piper, 1932; Warren, 1941; Hodge. 1938, 1942) had noted the occasional presence of exotic clast lithologies (e.g., quartzite) within the fluvial conglomerate beds. Subsequent work by Newcomb (1966; 1969, 1971) and Farooqui and others (1981a.b) concluded that the Neogene fluvial conglomerate deposited within the Umatilla-Dalles Basins (i.e.. Alkali Canyon and Chenoweth Formations) were derived from "local" sources (Blue Mountains uplift/Cascade Range) and do not contain clast-Iithologies (e.g., quartzite, high-grade metamorphic. plutonic) that would indicate an distal provenance beyond the boundaries of the Columbia River flood-basalt province.

However re-examination of these late Neogene fluvial conglomerates in the Umatilla- Dalles Basins (Lindsey and others, 1993; Lindsey and Tolan, 1996; Tolan and others, 1996) has found that some units contain a significant percentage of exotic clasts (e.g.. metavolcanic and metasedimentary lithologies -including quartzite) implying a distal provenance (Fig. 11). This work supports and vindicates the observations made by Hodge (1938), Piper (1932), and Warren (1941) that exotic clast-lithologies are indeed present in late Neogene conglomerates within the Umatilla-Dalles Basins.

Cataclysmic Floods

Cataclysmic Floods ("Missoula" or "Spokane" floods) were generated by episodic, cataclysmic releases of huge volumes of water from glacial Lake Missoula that spilled across the Columbia Pla-

teau and through the Umatilla Basin on their way to the Pacific Ocean. These cataclysmic floods occurred many times during the Pleistocene between approximately 1,000,000 to 13,000 years ago (Bretz and others, 1956; Baker and Nummedal. 1978; Waitt, 1980, 1985; USDOE, 1988; Kiver and others. 1989; Baker and others, 1991; Waitt and others. 1994). These flood waters scoured and stripped the existing land surfaces creating the "Channeled Scablands" within the Columbia Plateau (Bretz and others, 1956). These same flood waters also deposited extensive tracts of boulders, gravels, and sands.

The only exit point for these flood waters from the Columbia Plateau was Walulla Gap (Fig. 12). This constriction caused the flood waters to hydraulically pond behind Walulla Gap and created a temporary lake that was more than 300 m-deep. This temporary lake inundated the Pasco Basin, Yakima Valley and Walla Valley (Fig. 12). The slackwater conditions created within this temporary lake allowed suspended sediments to settle out producing stratified silt and fine sand deposits (termed "Touchet Beds"). Constrictions along the Columbia River valley downstream of Walulla Gap also caused temporary lakes to form that inundated the Umatilla Basin, Dalles Basin, and the Willamette Valley (Bretz and others, 1956; Waitt and others, 1994).

As discussed in the next section, the Columbia River Gorge was cut by the Columbia River in response to regional uplift. Some popular accounts have wrongly attributed the Gorge's origin to Cataclysmic Flood processes. The Cataclysmic Floods did have a significant impact on the Columbia River Gorge, but it was restricted to scouring and reshaping an existing gorge.

STRUCTURAL GEOLOGY

General

The western Columbia Plateau region lies within the Columbia Basin and the eastern portion of the Columbia Trans-Arc Lowland (Fig. 7). Both the Columbia Basin and Columbia Trans-Arc Lowland have experienced considerable regional-scale subsidence, with the Columbia Basin experiencing 1.500 to +3,000 m of subsidence since the onset of CRBG volcanism approximately 17 million years ago (Myers and Price, 1979; Reidel and others. 1982. 1989b; USDOE, 1988; Watters, 1989). Although this region is commonly called the Columbia Plateau or Columbia Plain (Baker and others. 1987; USDOE, 1988), from a structural geology standpoint this entire region is more properly a "basin" due to the regional-scale subsidence that this area has experienced (Campbell, 1989).
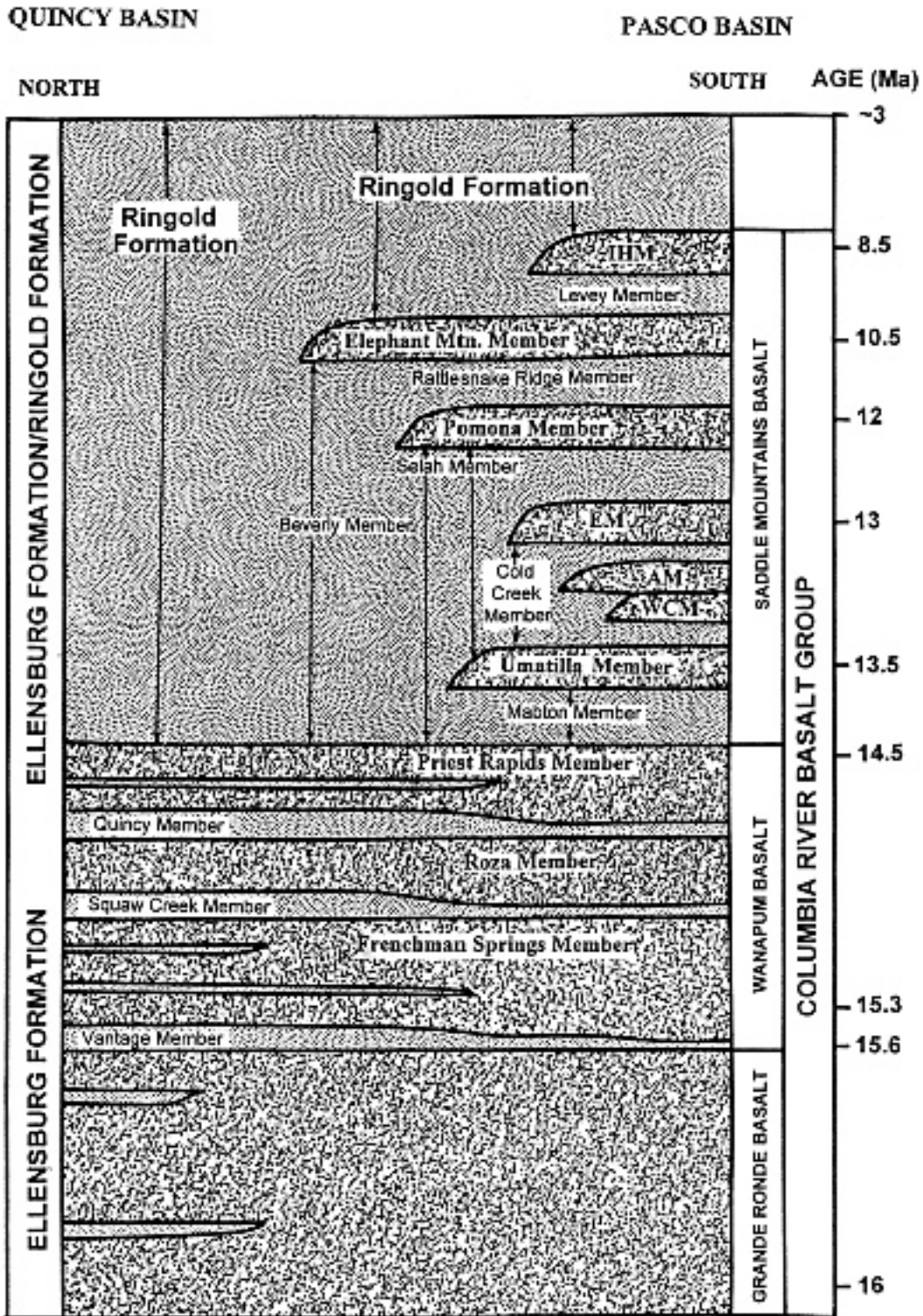
***Figure 10**. Diagrams illustrating stratigraphic nomenclature and relationships between CRBG, Ellensburg Formation interbeds, and suprabasalt sediments in the Quincy, Pasco, and Umatilla Basins. A. Quincy-Pasco Basins diagram. WCM = Wilbur Creek Member; AM = Asotin Member; EM = Esquatzel Member; IHM = Ice Harbor Member. Modified from Fecht and others (1987) and Smith and others (1989). B. Umatilla Basin diagram.*

Umatilla Basin

South

North

5 Ma

ALKALI CANYON
FORMATION

ALKALI CANYON FORMATION

Elephant Mtn. Member — 10.5 Ma

RATTLESNAKE RIDGE
MEMBER

ALKALI
CANYON
FORMATION

Pomona Member — 12 Ma

Ash

SELAH MEMBER

"SELAH MEMBER"

Umatilla Member — 13.5 Ma

MABTON MEMBER

"SELAH MEMBER"

Priest Rapids Member - Lolo — 14.5 Ma

BYRON MEMBER

"SELAH MEMBER"

Priest Rapids Member - Rosalia

QUINCY MEMBER

Roza Member

SQUAW CREEK MEMBER

basalt of Lyons Ferry

basalt of Sentinel Gap

Frenchman Springs Member

basalt of Sand Hollow

15.3 Ma

basalt of Silver Falls

basalt of Ginkgo — 15.4 Ma

VANTAGE MEMBER — 15.6 Ma

Sentinel Bluffs member

Winter Water member

GRANDE RONDE BASALT

Ortley member

LINDSEY & TOLAN 1996

B

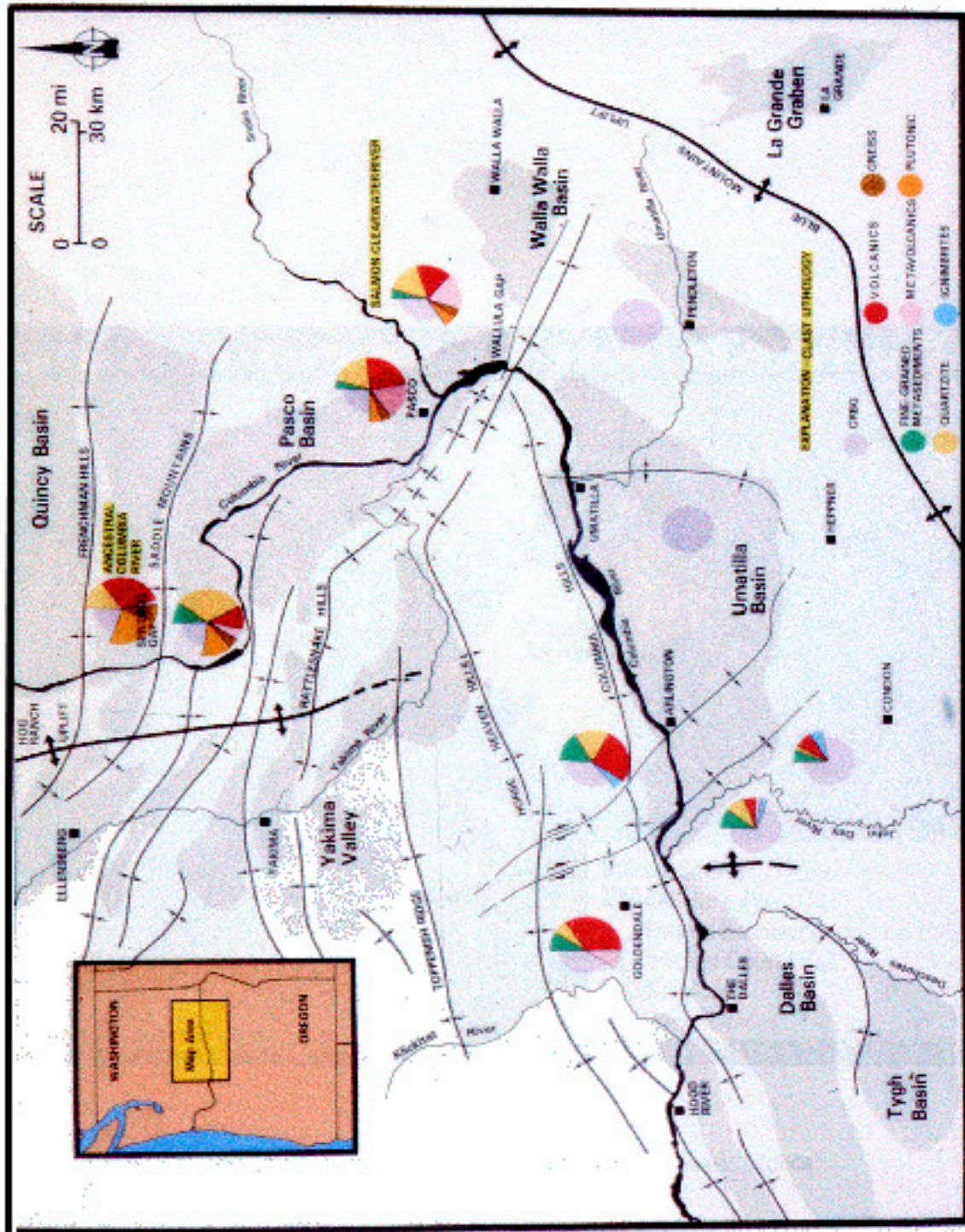***Figure 11***. *Relative abundance of exotic clast-lithologies within the Pasco Basin, Umatilla Basin, and Klickitat Valley.*

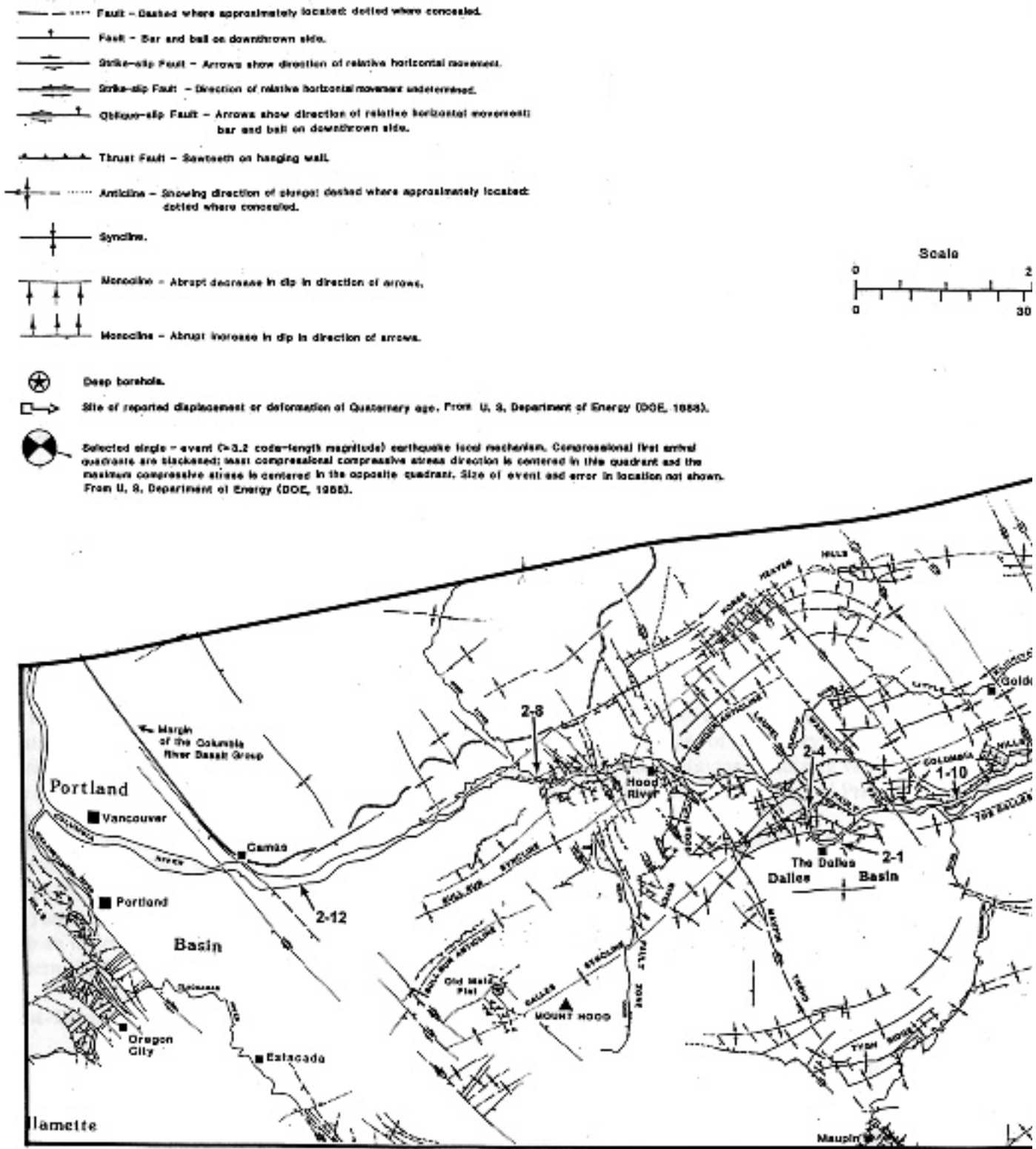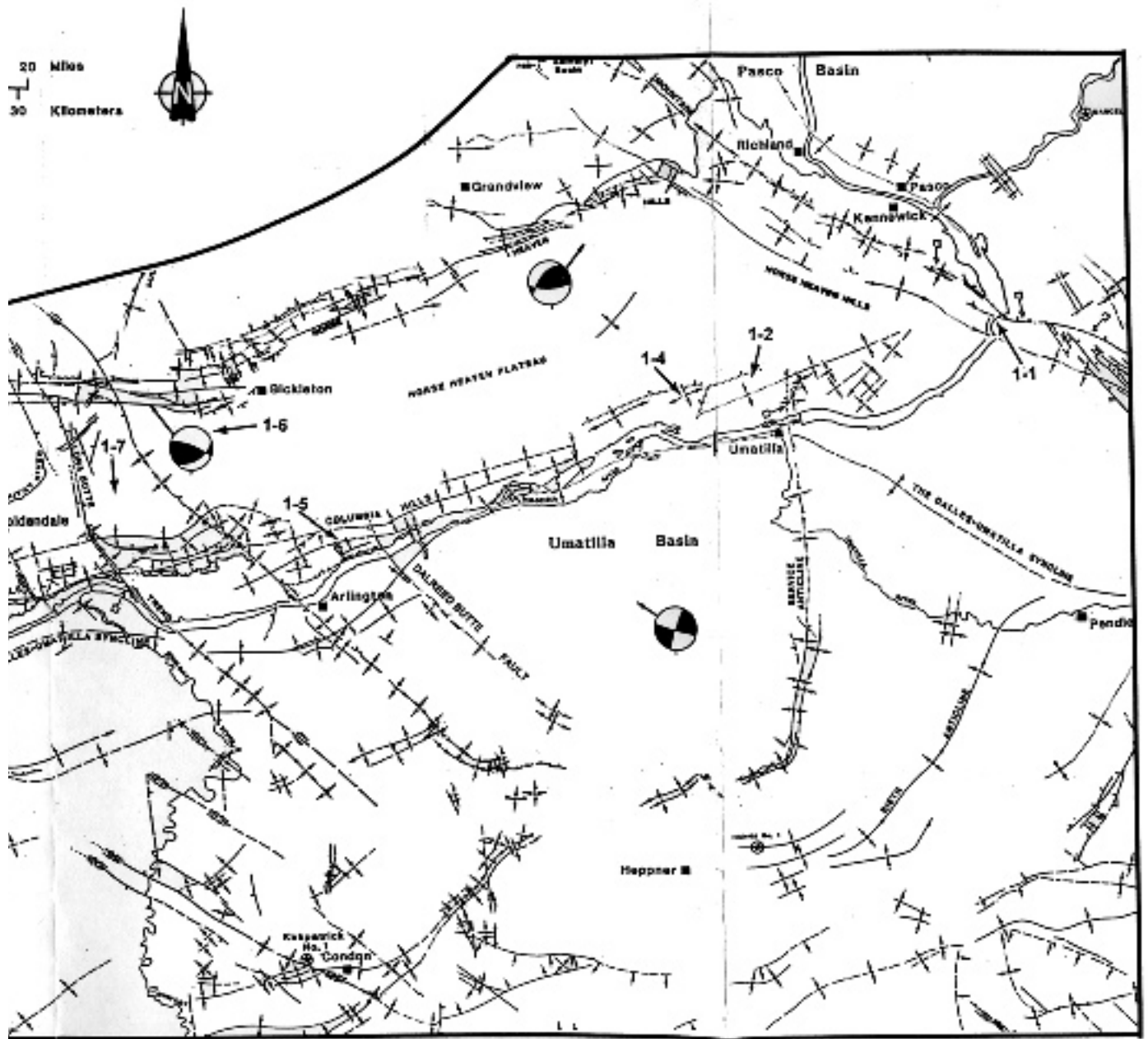***Figure 12*** *Map showing the path and extent of the Cataclysmic Floods*

Figure 13 *Structural geology map for the field trip area. Selected field trip stops are shown on map and are denoted by dashed numbers (e.g. 1-1) with arrow. Structural geology map modified from Tolan and Reidel (1989)*

In addition to regional subsidence, this region has been under a general north-south compression/east-west extension stress regime from the beginning of CRBG time (Davis, 1981; Myers and Price, 1979, 1981; Reidel and others, 1982^ 1989a; USDOE, 1988; Watters, 1989) to the present-day (USDOE, 1988; Geomatrix, 1988, 1990). This stress regime has led to the formation of folds and faults in the Columbia Basin and Columbia Trans-Arc Lowland. Within the Cascade Range, deformation associated with the Cascade volcanic arc (e.g., intra-arc grabens) also occurs and "overprints" these regional structures. Differences in the styles of folding and faulting allow this region to be subdivided into four distinct structural subprovinces - the Yakima Fold Belt, Blue Mountains. Palouse Slope, and Cleanvater Embayment (Myers and Price, 1979; WPPSS. 1981; USDOE, 1988; Reidel and others, 1989a). The route of this field trip is entirely in southern portion of the Yakima Fold Belt subprovince.

Yakima Fold Structures

For much of the trip we will be along the Columbia Hills and the adjacent Dalles-Mount Hood Syncline (Fig. 13), both major, regional-scale. Yakima Fold Belt structures. The Yakima Fold Belt is characterized by a series of northeast-trending, continuous, narrow (0.8 to 5 kilometer-wide), faulted anticlinal ridges that are separated by broad (16 to +50 kilometer-wide) synclinal valleys (Swanson and others, 1979b, 1981; Anderson, 1987: Watters, 1989; USDOE, 1988; Reidel and others, 1989a; Tolan and Reidel, 1989). Abrupt changes in fold geometry also commonly occur along the length of Yakima Folds (Swanson and others. 1979b, 1981; Bentley and others, 1980; Reidel, 1984; Anderson, 1987; Reidel and others, 1989a). These changes in fold geometry delineate ridge "segments" (Reidel, 1984; Anderson, 1987; USDOE. 1988; Reidel and others. 1989a). The length of individual ridge segments is quite variable, ranging from several kilometers to many tens of kilometers in length (Reidel. 1984; Anderson, 1987; USDOE, 1988: Reidel and others, 1989a, Tolan and Reidel. 1989). Segment boundaries are commonly marked by cross-faults and folds (Reidel, 1984; Anderson, 1987; Reidel and others. 1989a).

The cross-sectional geometry of the Columbia Hills anticline varies along its 250+ km length. For much of its length, this anticlinal ridge typically displays a non-cylindrical, asymmetric geometry with a steep or overturned, faulted northern limb (Swanson and others, 1981; Anderson, 1987; Beeson and others, 1989; Reidel and others, 1989a). The Columbia Hills fold geometry changes east of Paterson, Washington (Fig.13), where the anticlinal ridge begins to lose structural amplitude and has a more symmetrical, open geometry (Swanson ad others, 1981; Reidel and others, 1989a). This change in anticlinal fold style is typical where Yakima folds begin to lose ampli-

tude and die out (Reidel, 1984; Reidel and others, 1989a).

The base of the Columbia Hills anticline's asymmetrical limb is bounded by an emergent fault (Fig. 13) termed a "frontal fault" (Anderson, 1987; Reidel and others, 1989a). Where erosion has provided exposures into the core of the Columbia Hills anticline (e.g.. Rock Creek water gap - see Day Two trip log), the emergent frontal fault is observed to be a thrust fault (fault plane dipping 2° to 20° to the south) that rapidly steepens and becomes a high-angle reverse fault (>80° dip) within the core of the fold (Anderson, 1987). This same fault geometry is observed for frontal faults elsewhere in the Yakima Fold Belt (e.g., Frenchman Hills -Reidel and others, 1989a; USDOE, 1988). This change in fault plane geometry has also been confirmed by some of the deep wildcat exploration wells drilled on various Yakima Fold Belt ridges (e.g.. Saddle Mountains; Reidel and others, 1989a). The amount of stratigraphic offset on these frontal fault zones is dependant on the amplitude of the anticlinal fold, and therefore can vary from < 45 m to >800 m (Reidel, 1984; Anderson. 1987; USDOE. 1988; Reidel and others. 1989a). Other classes of faults, besides frontal faults and segment-defining cross-faults that are associated with Yakima fold structures include back thrust faults and out-of-syncline thrust faults (Fig. 14; Anderson, 1987).

Faulting in the CRBG tends to produce a roughly planer zone composed of coarsely shattered basalt that grades into very fine rock flour. Figure 15 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 vs. 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 is largely due to the nature of these features which allows the tops and bottom portions of CRBG flows to be more susceptible and sensitive to deformation. 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 structure may decrease the relative strength of the rock and may be another factor that contributes to deformational behavior of 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. 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 dependant on both environmental conditions (oxidizing vs. reducing) and in situ conditions (e.g., water chemistry, thermal regime, hydrologic regime; Myers and Price, 1981; Price, 1982; USDOE, 1988).

Based on the results of numerous studies (Myers and Price, 1979, 1981; Bentley and others, 1980; WPPSS, 1981; Price, 1982; Reidel and others, 1982, 1989a, 1994; Reidel, 1984; Hagood, 1986; Anderson, 1987; USDOE, 1988), Yakima folds began to develop during Grande Ronde time (approximately 16 million years ago) and have continued their growth through the present-day.   During CRBG time these developing folds were an important factor that influenced location of paleodrainage pathways for the ancestral Columbia River system (Fecht and others, 1987: Beeson and others, 1989; Beeson and Tolan, 1996).

Northwest-Trending Wrench Faults

Geologic mapping of the western Columbia Plateau (Newcomb, 1969, 1970; Swanson and others, 1979b, 1981; Bentley and others, 1980; Anderson, 1987; Dames & Moore, 1987: Bentley, 1989) has found a number of northwest-trending, dextral (right-lateral) strike-slip faults (Fig. 13). These faults have been classified as wrench faults by most investigators (e.g., Bentley and others, 1980; Anderson and Tolan, 1986; Anderson. 1987; Dames and Moore, 1987: USDOE. 1988; Reidel and others, 1989a). This classification is based on their distinctive characteristics, including (1) conjugate en echelon faults (2) genetically related en echelon folds (3) Reversal of apparent dip-slip displacement along strike (4) lengths of 10's to >80 kilometers 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 folds and that deformation has apparently continued on these structures into the Holocene (Anderson and Tolan. 1986; Anderson, 1987; Dames and Moore, Inc., 1987). Minor earthquake activity (mainly small magnitude (< 3.0) events) is associated with several of the northwest-trending wrench faults in the western Umatilla Basin and Klickitat Valley areas (USDOE, 1988). This activity is direct evidence that some of these northwest-trending faults are still active. Like the Yakima Folds, but to a much lesser degree, these faults did influence both CRBG flow distribution and paleodrainage pathways for the ancestral Columbia River system (Anderson and Tolan, 1986; Anderson, 1987; Beeson and others, 1989; Beeson and Tolan, 1996).

Regional Uplift

It has long been recognized that the western Columbia Plateau, northern Oregon-southern Washington Cascade Range, and western Oregon/Washington have experienced broad, regional-scale uplift during the late Neogene (e.g., Hodge, 1938; Lowry and Baldwin. 1952; Waters, 1961; Toian and Beeson, 1984; Fecht and others, 1987; USDOE, 1988; Hammond. 1989). The amount of apparent vertical uplift increases towards the axis of the Cascade Range (excluding the central Hood River graben) from on the order of 60 to > 120 m in the western Columbia Plateau and northwest Oregon, to more than 1200 m in the northern Oregon Cascades.

Field evidence suggests that the onset of this regional-scale uplift began approximately 3 to 2 million years ago (Tolan and Beeson, 1984; Fecht an others. 1987; USDOE, 1988; Beeson and Tolan, 1990). It was the onset of this uplift that marked the end of wide-spread sediment deposition within the region's basin (e.g., Troutdale. Ellensburg, and Ringold Formations) and the beginning of stream and river entrenchment and the creation of the Columbia River Gorge.

PALEODRAINAGE SYNOPSIS

General

Numerous studies over of the years have provided much data and insight into the Neogene evolution of the Columbia River system (e.g., Bretz, 1917; Buwalda and Moore, 1927; Piper, 1932; Hodge, 1938; Warren, 1941; Lowery and Baldwin, 1952; Waters, 1955; Laval. 1956: Mackin. 1961; Bond, 1963; Trimble, 1963; Schmincke, 1964; Hodgenson, 1964; Newcomb, 1966, 1969, 1971; Newcomb and others, 1972; Griggs. 1976; Bentley, 1977; Kent, 1978; Grolier and Bingham, 1978; Rigby and Othberg, 1979; Swanson and others, 1979a,b, 1981; Bentley and others, 1980; Camp, 1981; Farooqui and others, 1981a,b: Webster and others. 1982; Tolan and Beeson, 1984; Hagood. 1986; Fecht and others, 1987; Anderson and Vogt, 1987; Smith, 1988; USDOE, 1988; Smith and others. 1989; Lindsey and others, 1993; Goodwin, 1993; Reidel and others, 1994; Lindsey, 1996; Beeson and Tolan, 1996: Lindsey and Tolan, 1996; Tolan and others, 1996; Beeson and Tolan, 2002).   Previous summaries of late Neogene sediment stratigraphy and paleodrainage history of the ancestral Columbia River system have been published by Fecht and others (1987) and Smith and others (1989). The following synopsis builds upon these previous paleodrainage summaries by incorporating new data and information.
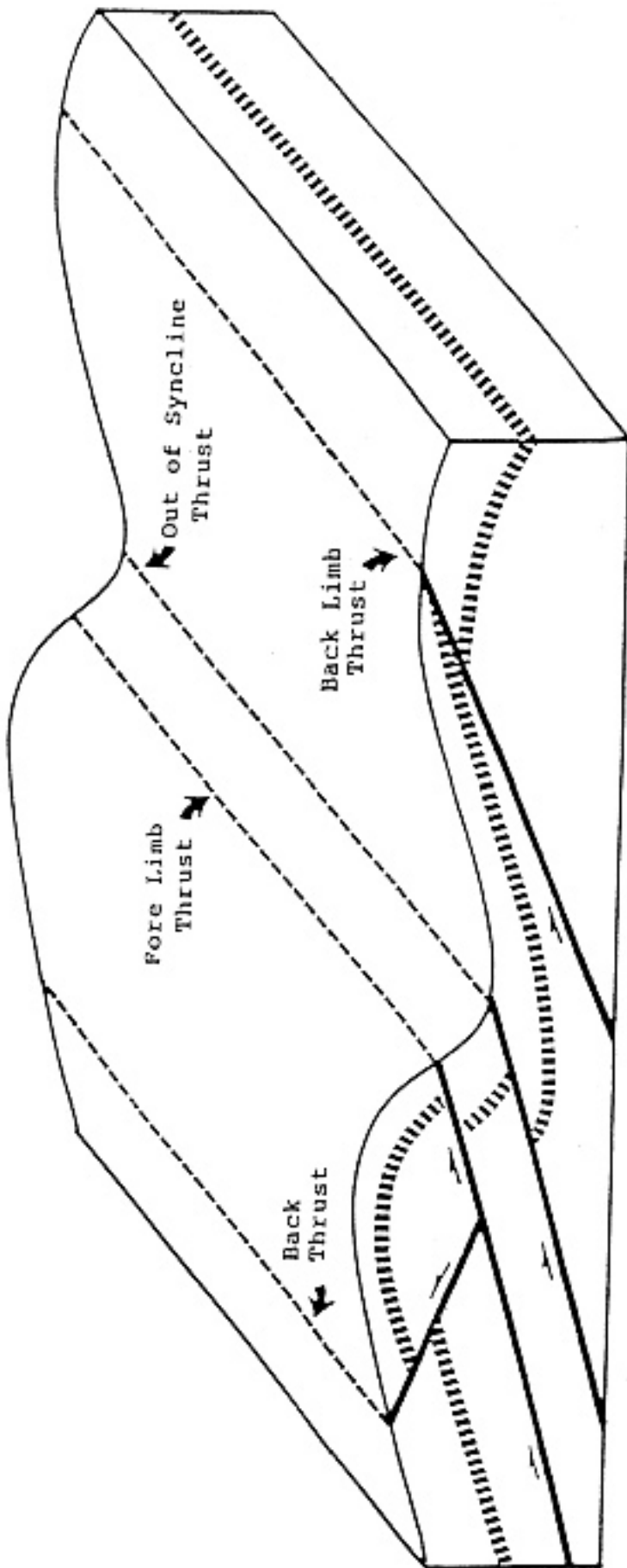
Recognition of Paleodrainage Courses

A combination of criteria is used to identify and trace ancestral river pathways within the western Columbia Plateau and Columbia River Gorge region. These criteria include:

- Distribution, texture, and lithologic composition of clastic fluvial sediment sequences;
- Nature and extent of intraflow structures and related deposits (e.g., pillow complexes; hyaloclastite);
- Erosional features and intracanyon lava flows.

As discussed above, the lithologic composition of the sediment is used to determine its general provenance (within vs. beyond the boundaries of flood-basalt province). Further refinement of the provenance and identification of specific streams can sometimes be made by careful determination of the types of "exotic" (non-CRBG) clasts present within gravel deposits (Fecht and others, 1987; Smith, 1988; Smith and others, 1989; Lindsey and others, 1993; Goodwin, 1993; Lindsey and Tolan, 1996; Tolan and others, 1996).

This, coupled with criteria listed above, has proven to be a powerful tool in deciphering the evolution of the ancestral Columbia River system. During this field trip we will have several opportunities to examine lithologically distinctive conglomerates deposited by different tributaries to the ancestral Columbia River.

Factors that Influenced Paleodrainage Courses.

A number of different geologic features and processes influence the courses of the rivers belonging to the ancestral Columbia River system. Generally it was a combination of these factors that shaped the courses of streams and rivers during the Neogene. These features and processes include:

- Broad-scale, regional structural features (e.g., Palouse Slope, Columbia Basin, and Columbia Trans-Arc Lowland) shaped the overall regional-scale geomorphology of this region.

Figure 14 (Left) Diagram showing different relationships beween folds and thrust faults. Terminology from Anderson (1987)
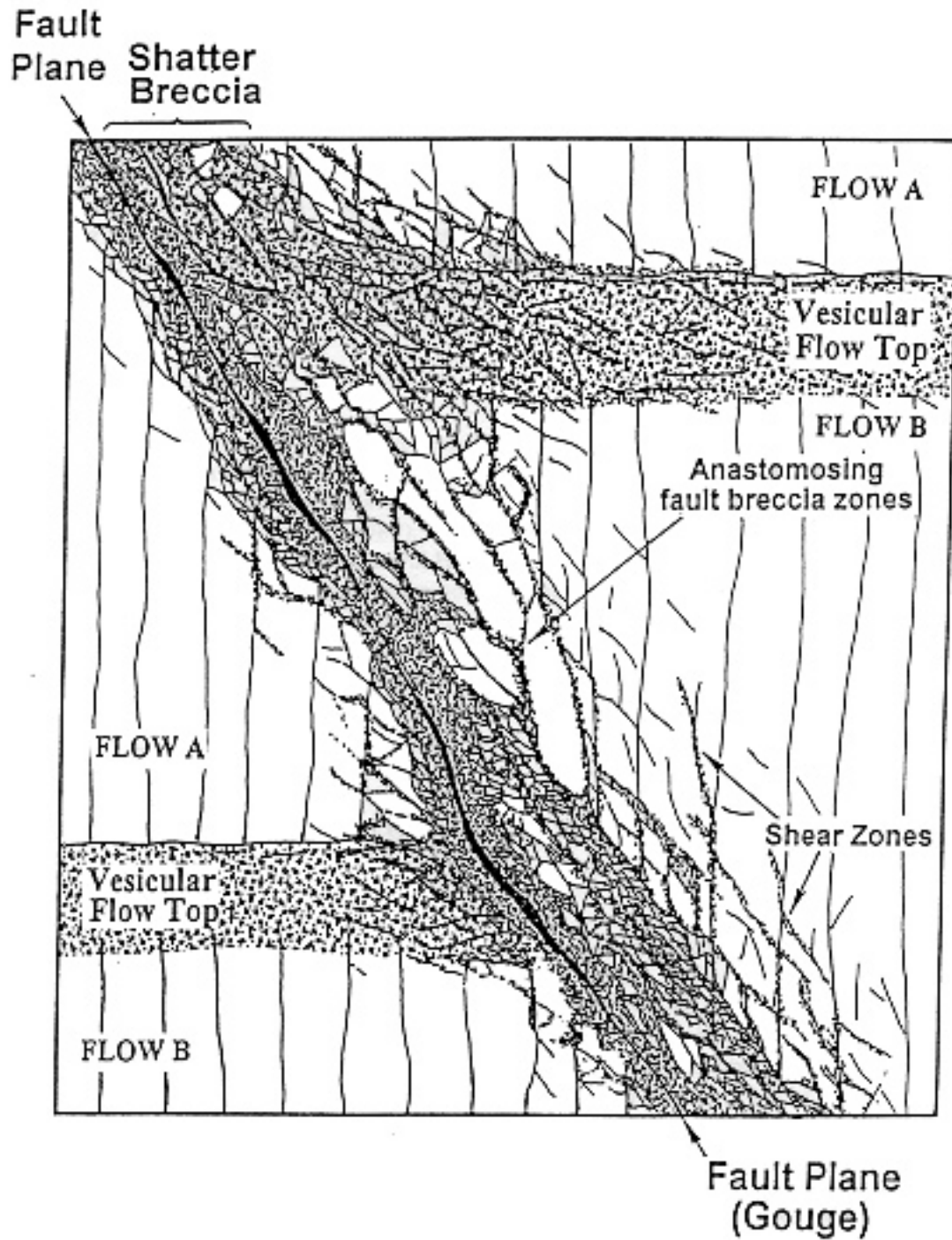
Figure 15 *Diagram depicting common features found within fault zones that transect CRBG flows*

-Volume and timing of CRBG volcanism. The
emplacement of vast CRBG sheet and
intracanyon flows which in many cases destroyed the
existing paleodrainage network and forced rivers and
streams to initially re-establish courses at the
margin   of these flood-basalt flows.

-Broad-scale, regional subsidence within the Columbia
Basin and Columbia Trans-Arc Lowland during the
Neogene.

-Development of Yakima Fold anticlines and synclines.
This generally resulted in either (1) the migration
of stream courses off of developing structural ridges
and into adjacent synclines or (2) the entrenchment of
streams into the anticlinal ridges.

-The presence and absence of Cascade Arc volcanism within,
and adjacent to, the Columbia Trans-Arc Lowland.

Evolution of the Ancestral Columbia River System

Figure 16 presents a series of diagrammatic sketch maps por-
traying the development and evolution of the ancestral Colum-
bia River system. These maps cover a period from about 15.5
to 3 Ma. A brief discussion of each of these maps is present in
the following sections.

Approximately 15.5 Ma - Vantage time (Figure 16a). This first
map depicts the course of the ancestral Columbia River during
the hiatus between Grande Ronde and Wanapum volcanism.
The duration of this hiatus is thought to be between 100,000
to 300,000 years. It was during this period that sediments of
the Vantage Member of the Ellensburg Formation (Fig. 10)
were deposited. The course of the ancestral Columbia River in
the western Columbia Plateau has been inferred based on the
distribution of micaceous, arkosic sandstone within the Van-
tage Member (Anderson, 1987; Fecht and others, 1987) which
represents main channel facies. Within the Columbia Trans-
Arc Lowland and Willamette Valley, the river course has been
traced using the Ginkgo (Frenchman Springs Member; Fig.
2) intracanyon flow which filled and destroyed this canyon of
the ancestral Columbia River (Beeson and others, 1985, 1989;
Beeson and Tolan, 1996).

Prior to 15.5 Ma. the repeated emplacement of large volume
Grande Ronde sheet flows had forced the ancestral Columbia
River to the northern and northwestern margin of the province
(Fecht and others, 1987; Smith. 1988). With the cessation of
Grande Ronde volcanism and continued regional subsidence,
the ancestral Columbia River began to shift towards the center
of the Columbia Basin and Columbia Trans-Arc Lowland.
During this period, there is no evidence that any significant
Cascade Arc volcanism within, or immediately adjacent to, the

Columbia Trans-Arc Lowland. Within the Columbia Trans-
Arc Lowland, the ancestral Columbia River developed a
channel along the Dalles Syncline and then southwest along,
and near, the margin of the Grande Ronde Basalt. It is in-
ferred that the ancestral Columbia River crossed the Oregon
Coast range and reached the Miocene Oregon coast in the
Cape Foulweather/Lincoln City area. As indicated on Figure
16a, the ancestral Columbia River at this time had been able
to incise a canyon (by headward erosion) to near the present-
day city of The Dalles.

Near the town of Marion, Oregon, in the Willamette Valley,
a vast hyaloclastite/pillow complex is found in the Ginkgo
flow (Beeson and Tolan, 1996). Relationships at this locality
indicate that these deposits were created when the Ginkgo
intracanyon flow backfilled a major tributary (ancestral Wil-
lamette River) to the ancestral Columbia River.

Approximately 14.5 Ma - pre-Rosalia time (Figure 16b).
This map depicts the paleodrainage pattern of the ances-
tral Columbia River system prior to the emplacement of
the Rosalia flow of the Priest Rapids Member (Wanapum
Basalt; Fig. 2). As the result of the emplacement of French-
man Springs and Roza Members and continuing warping in
the Yakima fold belt, the ancestral Columbia drainage in the
central and western Columbia Plateau consisted of a series of
shallow, interconnected lakes. These lakes provided an excel-
lent environment for diatoms - as reflected by the extensive
diatomite deposits that occur at this stratigraphic horizon
(Quincy Member of the Ellensburg Formation; Fig. 10). Dur-
ing this same time within the Columbia Trans-Arc Lowland,
the ancestral Columbia River had established a course within
the next Yakima Fold syncline to the north (the Bull Run-
Mosier Syncline).

The course of the river through this area has been traced us-
ing the Rosalia (Priest Rapids Member; Fig. 2) intracanyon
flow which filled and destroyed this canyon of the ances-
tral Columbia River (Waters, 1973; Vogt, 1981; Tolan and
Beeson. 1984; Anderson and Vogt, 1987; Timm, 1979). As
indicated on Figure 16b, the ancestral Columbia River at this
time had been able to incise a canyon (by headward erosion)
to the present-day city of Mosier, Oregon (Tolan and Beeson,
1984). During this period, there is no evidence that any
significant Cascade Arc volcanism within, or immediately
adjacent to, the Columbia Trans-Arc Lowland. The position
and paths of the various major tributaries of the ancestral
Columbia River are poorly constrained for this period. The
major problem is the lack of any time-stratigraphic marker
beyond the margins of the Priest Rapids flows. Beyond the
margins of the Priest Rapids Member, these sediments (if
present) simply become part of the suprabasalt sediment unit
(e.g., Alkali Canyon or upper Ellensburg Formations.

Figure 16. Maps depicting Neogene paleodrainage pattern on the western portion of the Columbia River flood-basalt province. Solid lines represent approximate location of river courses. Dashed and queried lines indicate location of river course uncertain. A. Vantage time (-15.5 Ma). Brackets indicate the eastern-most limit of canyon incised by ancestral Columbia River. B. Pre-Rosalia (Priest Rapids Member, Wanapum Basalt) time (-14.5 Ma). Brackets indicate the eastern-most limit of canyon incised by ancestral Columbia River. C. Pre-Huntzinger (Asotin Member, Saddle Mountains Basalt) **(Continued next page)**
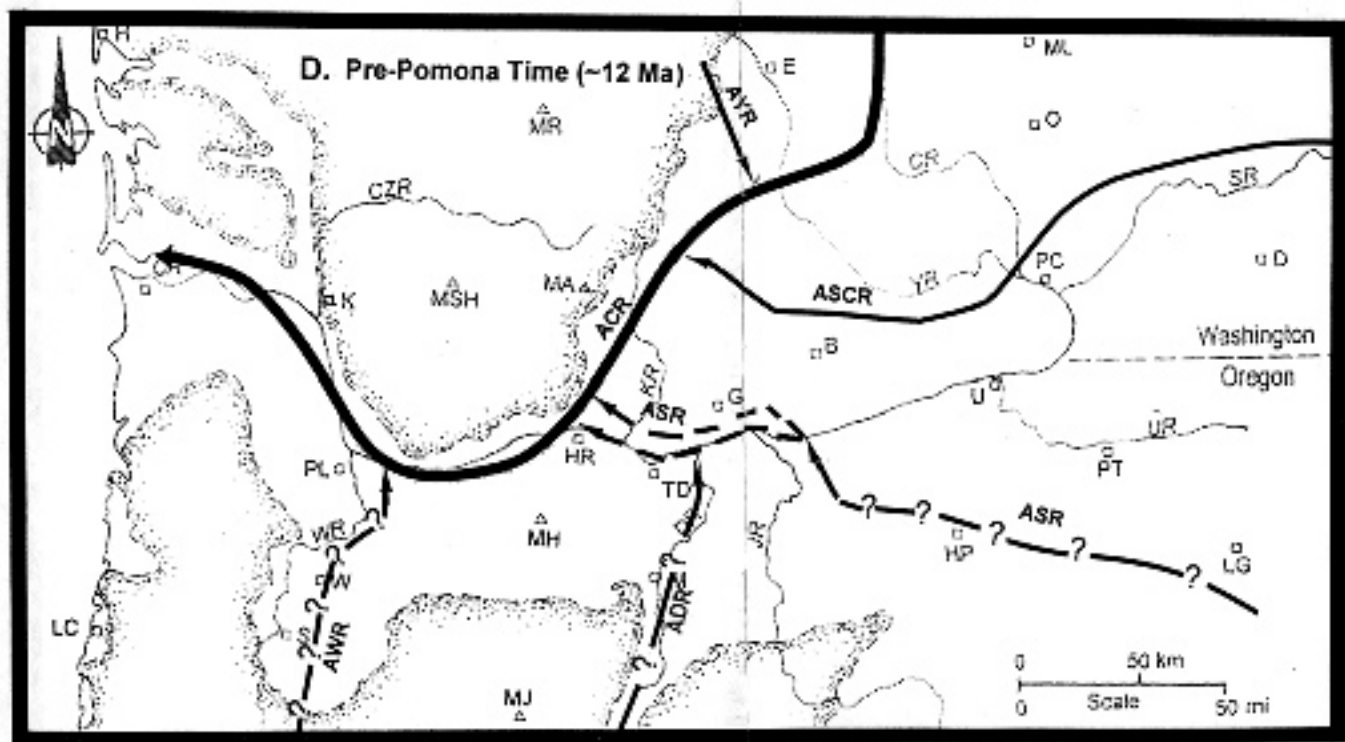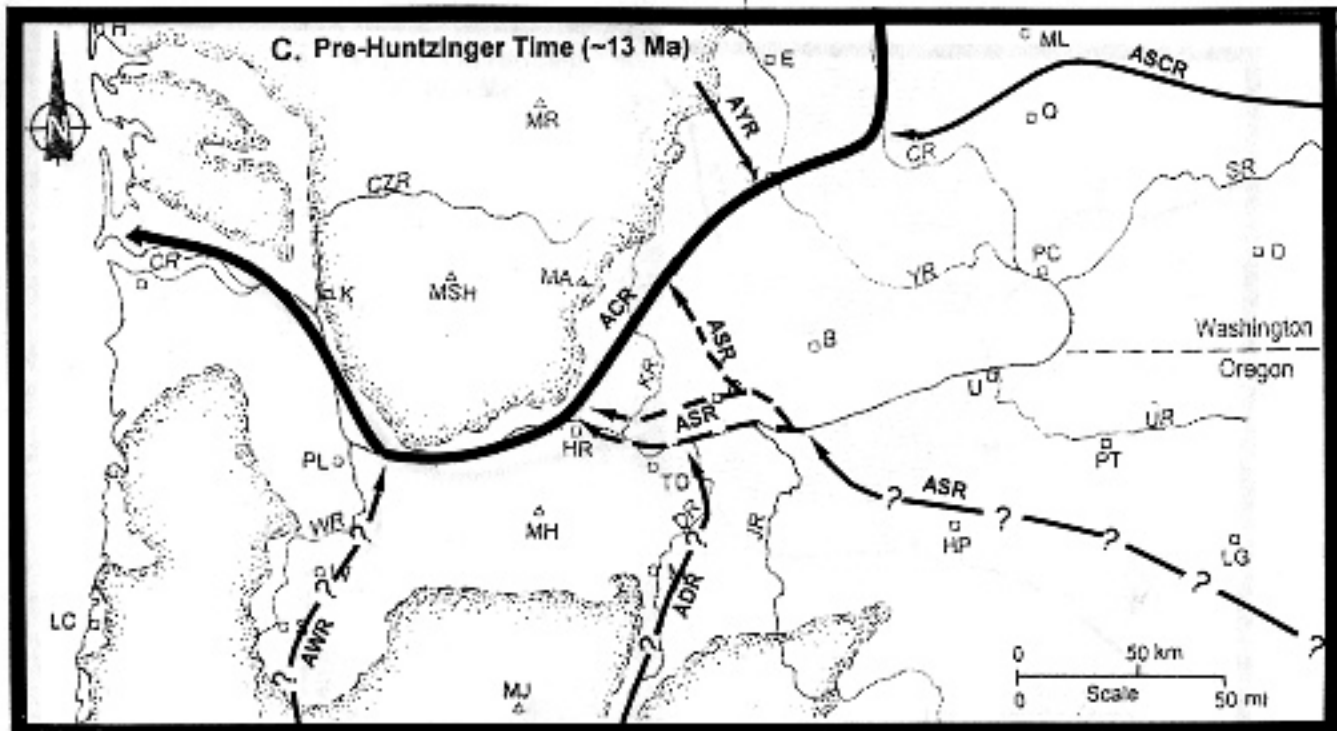
time (~13 Ma). D. Pre-Pomona (Saddle Mountains Basalt) time (-12 Ma). Paleorivers: ACR = ancestral Columbia River; AWR = ancestral Willamette River; ADR = ancestral Deschutes River; ASR = ancestral Snake River; ASCR = ancestral Salmon-Clear-watcr River; AYR = ancestral Yakima River. Present-day rivers: CR = Columbia River; CZR = Cowlitz River; WR = Willamette River; KR = Klickitat River; DR = Deschutes River; JR = John Day River; UR = Umatilla River; YR = Yakima River; SR = Snake River. Cities: LC = Lincoln City; H = Hoquiam; S = Salem; W = Woodburn; PL = Portland; K = Kelso; HR = Hood River; TD = The Dalles; HP = Heppner; G = Goldendaie; B = Blickleton; Y = Yakima; E = Ellensburg; ML = Moses Lake; O = Othello; PC = Pasco; D = Dayton; U = Umatilla; PT = Pendleton; LG = La Grande. Cascade Peaks: MJ = Mount Jefferson; MH = Mount Hood; MSH = Mount Saint Helens; MA = Mount Adams; MR = Mount Rainier.
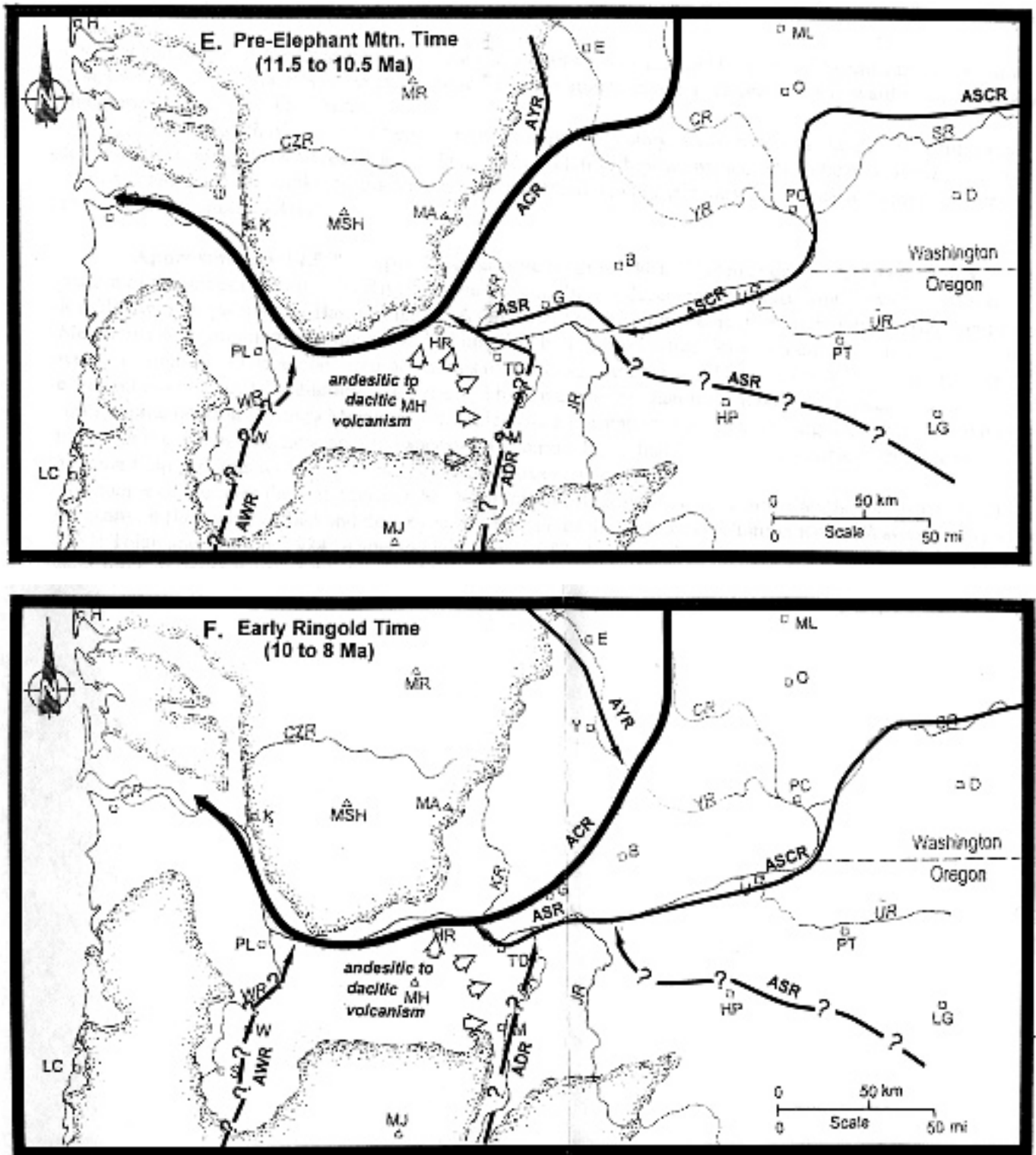
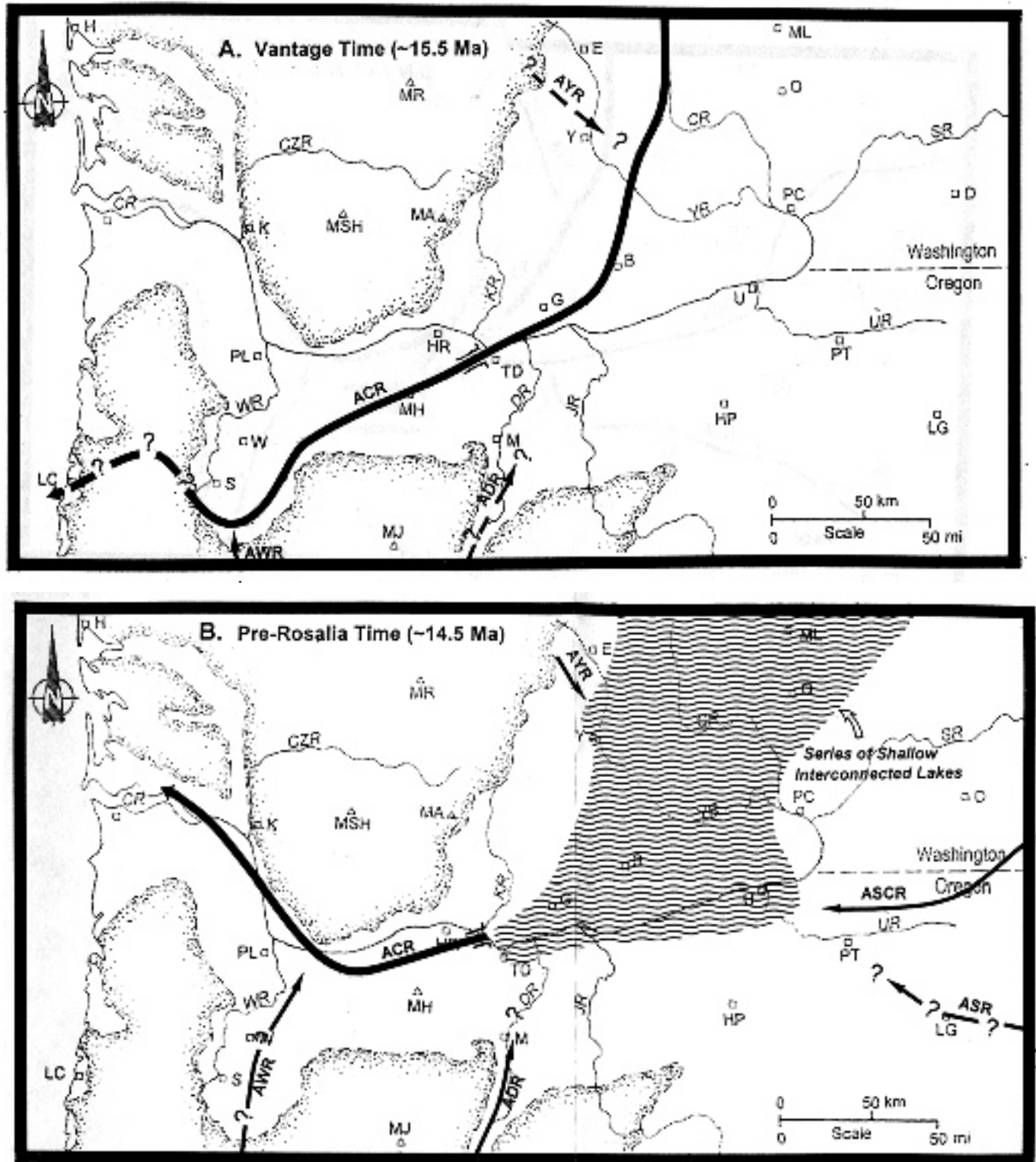***Figure 16 (Continued).*** *Maps depicting paleodrainage pattern on the western portion of the Columbia River flood-basalt province. Solid lines represent approximate location of river courses. Dashed and queried lines indicate location of river course uncertain. E. Pre- Elephant Mountain (Saddle Mountains Basalt) time (11.5 to 10.5 Ma). F. Early Ringold time (10 to 8 Ma). G. Early to mid Ringold time (8 to 5 Ma). H. Late Ringold time (5 to 2 Ma). Paleorivers: ACR = ancestral Columbia River; AWR = ancestral Willamette River; ADR = ancestral Deschutes River; ASR = ancestral Snake River; ASCR = ancestral Salmon-Clear-water River; AYR = ancestral Yakima River. Present-day rivers: CR = Columbia River; CZR = Cowlitz River; WR = Willamette River; K.R = Klickitat River; DR = Deschutes River; JR = John Day River; UR = Umatilla River* ***(Continued next page);***

G. Early to Mid Ringold Time (8 to 5 Ma)

H. Late Ringold Time (5 to 2 Ma)

YR = Yakima River; SR = Snake River. Cities: LC = Lincoln City; H = Hoquiam; S = Salem; W = Woodburn; PL = Portland; K = Kelso; HR = Hood River; TD = The Dalles; HP = Heppner; G = Goldendale; B = Blickleton; Y = Yakima; E = Ellensburg; ML = Moses Lake; O = Othello; PC = Pasco; D = Dayton; U = Umatilla; PT = Pendleton; LG = La Grande. Cascade Peaks: MJ = Mount Jefferson; MH = Mount Hood; MSH = Mount Saint Helens; MA = Mount Adams; MR = Mount Rainier.
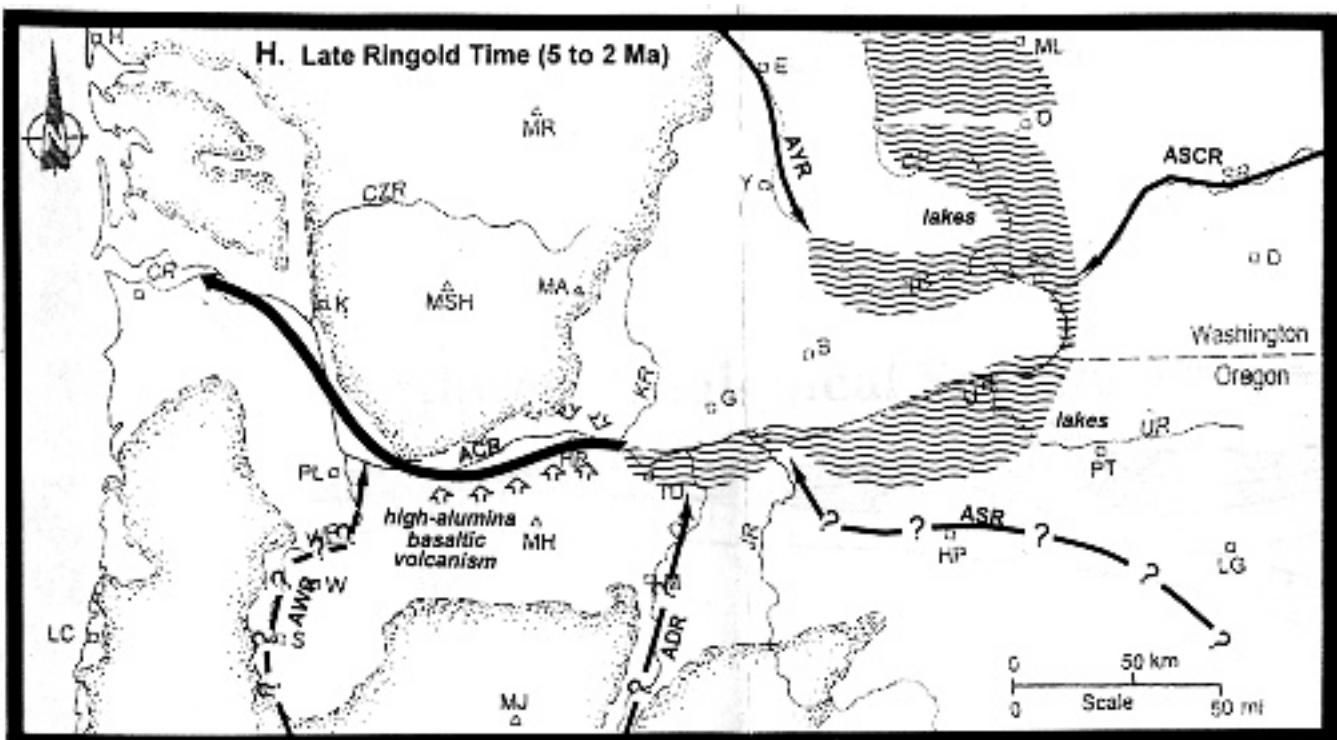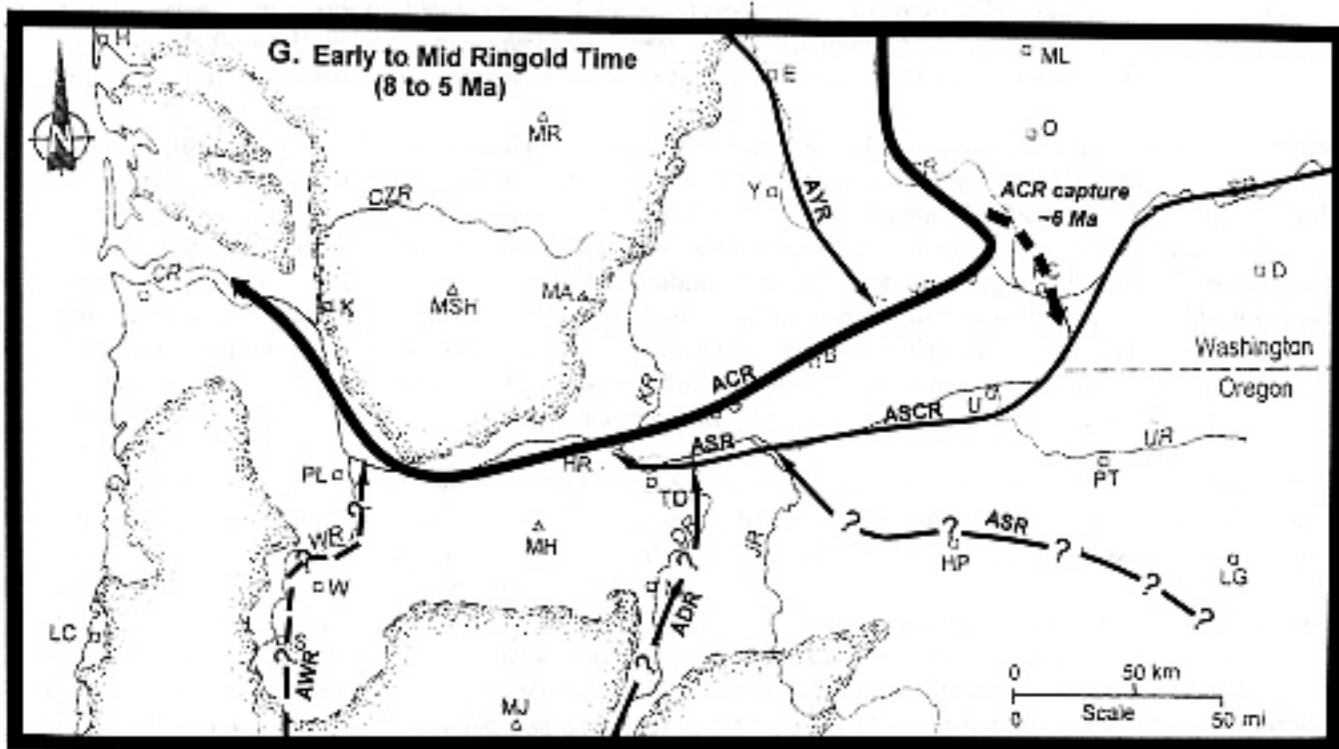
Approximately 13 Ma - pre-Huntzinger time (Fig. 16c). This map depicts the paleodrainage pattern of the ancestral Columbia River system in early Saddle Mountains Basalt time - post emplacement of the Umatilla Member and prior to the emplacement of the Wilbur Creek/Asotin Members (Fig. 2). With the end of Wanapum volcanism, the ancestral Columbia River established a path across the western Plateau and the Columbia Trans-Arc Lowland. The ancestral Columbia River had a period of approximately 1.5 million years from the end of Wanapum volcanism until the first Saddle Mountains flows reached its channel. During this period the Columbia River was able to incise a canyon across the Columbia Trans-Arc Lowland and the Columbia Plateau (Fecht and others, 1987). Within the Columbia Trans-Arc Lowland this channel of the Columbia River was established in the next Yakima Fold syncline to the north of the Bull Run-Mosier Syncline.

The locations of the ancestral Columbia and Salmon-CIearwater Rivers are defined on the basis of both intracanyon CRBG flows and sediment (gravel clast) lithologies (Fecht and others, 1987). Differences in the assemblages of "exotic"clast lithologies associated with the Columbia and its various tributaries allow for these different river tracts to be identified.

You will note that the ancestral Salmon-CIearwater River tract is separate from what we have defined as the "ancestral Snake River" which we depict as entering the Umatilla Basin during this time. Up until late Pliocene time the Snake and Salmon-CIearwater Rivers had separate drainage basins. Work by Wheeler and Cook (1954), Kimmel (1982), and Webster and others (1982) suggest that a tributary stream to the ancestral Salmon-CIearwater River captured the Snake River (Lake Idaho) around 2 million years ago. Field work in the Umatilla-Dalles Basins and the Klickitat Valley (Lindsey and others, 1993; Lindsey and Tolan. 1996; Tolan and others, 1996) has identified the presence of exotic clast-bearing conglomerates deposited by a large river. A southwestern Idaho/southeastern Oregon provenance is suggested for these exotic clasts and is interpreted to likely represent the "ancestral Snake River system" (Lindsey and others, 1993; Lindsey and Tolan. 1996; Tolan and others, 1996). Conglomerates from an ancestral Snake River have been found not only within the Dalles-Umatilla Basins, but also within the Klickitat Valley (Fig. 16c). It appears that the ancestral Snake River entered the Klickitat Valley via the Rock Creek Water Gap through the Columbia Hills (Lindsey and others, 1993; Tolan and Lindsey, 1996). Gravel tracts within the Klickitat Valley indicate that the ancestral Snake River may have taken different pathways at different time. One tract suggests it may have created the Satus Pass wind gap (Waters, 1955) before joining with the ancestral Columbia River. A second path is along the Swale Creek-Mosier Syncline. A third path is along the Dalles-Umatilla Syncline (present-day Columbia River course) where it joined with the ancestral Deschutes River (Fig. 16c).

The ancestral Columbia River canyon in the western Columbia Plateau/Columbia Trans-Arc Lowland served a conduit for Saddle Mountain Basalt flows and enabled some of them enter western Washington and Oregon. The first known Saddle Mountains flow to reach western Oregon and Washington via the ancestral Columbia River canyon was the Huntzinger flow (Asotin Member) approximately 13 Ma (Beeson and Tolan, 2002).

Approximately 12 Ma - pre-Pomona time (Fig. 16d). This map depicts the paleodrainage pattern of the ancestral Columbia River system just prior to the emplacement of the Pomona Member of the Saddle Mountains Basalt (Fig. 2). The overall drainage pattern is very similar to the previous map (Fig. 16c), except for the southern shift in the location of the ancestral Salmon-Clearwater River. The shift in the Salmon-Clearwater course was due to the impact of the emplacement of the Asotin (Huntzinger flow) and Esquatzel Members of the Saddle Mountains Basalt (Fig.2). The source area for these Saddle Mountains flows was the Clearwater Embayment (western Idaho) and these flows used the ancestral Salmon-Clearwater River as a conduit to the west (Camp, 1981; Fecht and others. 1987). Upon reaching the Pasco Basin, these flows overtopped the confines of the ancestral Salmon-Clearwater River canyon and were emplaced as sheet flows. This caused the destruction of the Salmon-Clearwater channel and forced the river to re-establish a new channel south of its former position (Reidel and Fecht, 1987; Fecht and others, 1987).

Approximately 11.5 to 10.5 Ma - pre-Elephant Mountain time (Fig. 16e). This map depicts the paleodrainage pattern of the ancestral Columbia River system during the period following the emplacement of the Pomona Member and prior to the emplacement of the Elephant Mountain Member (Fig. 2). The emplacement of the Pomona flow at approximately 12 Ma forced the ancestral Salmon-Clearwater River south into the Umatilla-Dalles Basins (Fecht and others. 1987). At this juncture, the ancestral Salmon-Clearwater. Snake, and Deschutes join prior to meeting the ancestral Columbia River just northeast of the present-day city of Hood River, Oregon. The Pomona flow was not voluminous enough to fill the ancestral Columbia River canyon west of the Pasco Basin, so the river re-occupied this same canyon in post-Pomona time.   At approximately 10.5 Ma the Elephant Mountain flow entered the ancestral Columbia River canyon flow and flowed west to the vicinity of the present-day Klickitat River (Anderson and Vogt, 1987) but apparently did not reach western Oregon and Washington.

It is during this period that Cascade Arc volcanism began within the Columbia Trans-Arc Lowland. The onset of dacitic-andesitic volcanism created pyroclastic and volcaniclastic deposits of the Rhododendron Formation (Fig. 1). Debris flows and lahars reached The Dalles/Mosier area and also entered the ancestral Columbia River canyon. We think that this volcanism. and resulting increased input of Cascadian volcaniclastic sediment load, may have caused temporary damming of this tributary system.

Approximately 10 to 8 Ma - early Ringold time (Fig. 16f). This map depicts the paleodrainage pattern of the ancestral Columbia River system during the period following the emplacement of the Elephant Mountain Member (10.5 Ma) to about 8 Ma. It is during this period that the course of the ancestral Columbia River began to shift southeast across the Yakima Valley-Klickitat Valley towards the Pasco Basin. Ancestral Columbia River channel deposits in the Yakima Valley of this age have been mapped as the Snipes Mountain Conglomerate (Fig. 10). Correlative deposits in the Pasco Basin, mapped as the Ringold Formation, record the later phases of this shift in river position. Lowermost Ringold deposits are interpreted to have been deposited in the Pasco Basin approximately 8 Ma by an ancestral Columbia River that: (1) entered the Basin from the northwest, (2) followed a southeast-trending course across the Basin until it encountered the constructional topography created by the flow margin of the Ice Harbor Member (Saddle Mountains Basalt; Fig. 2), and (3) the course of the river was deflected to the southwest and west (by the constructional topography - Ice Harbor flow margin) into the lower Yakima Valley and across the area now occupied by the Horse Heaven Hills (Fecht and others, 1987; Lindsey, 1996).

The reason for the eastward shift of the ancestral Columbia River towards the Pasco Basin is the subject of some debate. Ideas advanced include deformation associated with the Horse Heaven Hills (Warren, 1941), shedding of volcaniclastic sediments from the Cascade Volcanic Arc (Waters, 1955), and Simcoe Volcanism (associated uplift) coupled with subsidence of the Pasco Basin (Fecht and others, 1987). Dacitic to andesitic Cascade Arc volcanism continued during this period within the Columbia Trans-Arc Lowland. Debris flows and lahars continued to reach The Dalles/Mosier area and impact the tributary rivers.

Approximately 8 to 5 Ma - early/middle Ringold time (Fig. 16g). During this period the course of the ancestral Columbia River continued to shift east into the Pasco Basin where it was eventually captured by the ancestral Salmon-Clearwater River before approximately 6 Ma. A series of fluvial gravel units and correlative paleosols found in the Ringold Formation throughout most of the Pasco Basin are interpreted to record the establishment of the ancestral Columbia River in the Basin along a course similar to the one the modern river occupies

today (Lindsey, 1996). This is interpreted to have occurred approximately 6 Ma, by which time the ancestral Columbia River had been captured by the ancestral Salmon-Clearwater River in the Wallula Gap area. Throughout much of early to middle Ringold time (8 Ma to approximately 5.5 Ma) fluvial deposition in the ancestral river systems was dominated by aggradation of pebble to cobble gravel. However, at approximately 5.5 Ma this shifted very rapidly to sand-dominated deposition (Lindsey, 1996). The cause in this shift in deposition is unknown, but inferred to be related to some combination of uplift of Yakima fold structures and renewed Cascadian volcanism which resulted in the aggradation of the ancestral Columbia River canyon west of Hood River, Oregon. These events and processes would have reduced the river's gradient and drastically reduced the river's ability to transport coarser clastic sediment. West of the present-day city of Hood River, Oregon, the ancestral Columbia River still remained in the same canyon. Dacitic to andesitic Cascade Arc volcanism within the Columbia Trans-Arc Lowland end approximately 7 to 6 Ma (Gray and others, 1996).

Approximately 5 to 2 Ma - late Ringold time (Fig. 16h). During this period Cascadian high-alumina basaltic volcanism began in the Columbia Trans-Arc Lowland. Within the vicinity of the ancestral Columbia River canyon, this volcanic activity produced numerous basalt flows that flowed into this canyon. Phreatic brecciation of the high-alumina basaltic lava flowing into the ancestral Columbia River created vast amounts of hyaloclastic debris from approximately 5 to 2 Ma (Tolan and Beeson, 1984). The repeated influx of hyaloclastic debris resulted in the rapid aggradation of the ancestral Columbia River canyon west of the vicinity of present-day Hood River, Oregon (Tolan and Beeson, 1984). This aggradation of the canyon eventually allowed the ancestral Columbia River to escape the confines of this canyon and high-alumina basalt flows finally capped this former course. In the processes of destroying this course of the Columbia River, the high-alumina basalt flows forced the river to shift northward to its present-day location. The incision of the Columbia River Gorge was the result of regional uplift which began approximately 2 Ma (Tolan and Beeson, 1984).

Fecht and others (1987) speculated that the rapid aggradation of the ancestral Columbia River canyon caused by the creation of Cascadian hyaloclastic debris might have been a major contributing factor that lead to lakes forming within the Pasco Basin during late Ringold time.

Lacustrine deposits of probable middle to late Pliocene age (approximately 5 to 3 Ma) do occur in much of the Umatilla Basin, Yakima Valley, Pasco Basin, and north of the Pasco Basin (Lindsey, 1996; Lindsey and Tolan, 1996). The region-wide occurrence of these generally contemporaneous lacus-

trine deposits east and north of The Dalles, Oregon, suggests that, as Fecht and others (1987) speculated, aggradation of the ancestral Columbia River canyon by Cascadian high-alumina basalt and hyaloclastic debris decrease the river's gradient to the point that a lake system formed. The most complete vertical sequence of these lacustrine deposits found to date are in the Pasco Basin (Lindsey, 1996). In the Pasco Basin these strata are interpreted to record the formation and aggradation of 3 separate lakes during the period between approximately 5 and 3 Ma. This suggests the events that lead to the formation of these lakes was to some degree episodic. Beginning approximately 3 Ma east of the Cascade Range, widespread sediment deposition along the ancestral Columbia River system diminished. The most widespread deposits of this time appear to be pedogenic calcretes that cap the Ringold, Alkali Canyon, and Ellensburg Formations and the "upland" basalt surfaces.

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Road Log and Field Stop Descriptions

Day One - Saturday September 28, 2002

Travel directions between field trip stops will be indicated by italic text. Figure 17 shows the route we will follow for today's field trip.

Mileage and directions begin at the Highway 12/Highway 730 junction near Wallula Gap.

Miles **Comments**

0.0   Highways 12/730 Junction. Turn right (west-bound) onto Highway 730.

1.8   Twin Sisters - eroded remnant of an entablature/colonnade-jointed Frenchman Springs flow.

3.7   Port Kelly road. Turn right and park in turnout before railroad crossing.

STOP 1-1: Wallula Gap View Point at Port Kelly.

At this stop we are afforded an excellent view of the basalt cliffs on the west side of Wallula Gap. The cliff face mainly consists of Frenchman Springs Member flows (Wanapum Basalt) that are overlain by two Saddle Mountains Basalt flows (Umatilla and Ice Harbor Members; Fig. 2) visible at the top of the cliff. This is a good spot to view some of the rather unique characteristics of Columbia River flood-basalt flows, discuss how these flows were emplaced, and consider the role that structural geology played in controlling both CRBG flow distribution and the courses of the ancestral Columbia River and its major tributaries.

As discussed earlier in this guide, the factors that primarily control the overall geometry of an individual basaltic lava flow include (1) rate/volume of lava erupted, (2) lava composition and lava temperature (rheology), (4) vent geometry, and (5) topographic and environmental conditions (Reidel and Tolan, 1992; Reidel and others, 1994: Beeson and Tolan, 1996; Self and others, 1997, Reidel, 1998; Ho, 1999). There are two basic flow geometries, compound and sheet flows (Fig. 8). Visual inspection of the exposed CRBG flows in the cliff face reveals that individual flows have very regular, uniform, and laterally continuous internal arrangement of intraflow structures that is characteristic of sheet flows. Most CRBG flows display characteristics consistent with sheet flow emplacement, except near their margins (flow edge).

It is also important to remember that individual CRBG flows (especially Grande Ronde and Wanapum Basalts) are gigantic. Studies have shown that many of these individual flows covered many tens of thousands of square kilometers and traveled more than 400 km from their linear vent system in a matter of weeks to months (Tolan and others, 1989; Reidel and others, 1989, 1994; Reidel and Tolan, 1992; Reidel, 1998; Ho. 1999). These huge flows are Hundreds to thousands of times larger than any basaltic lava flow erupted during Human history (Fig. 6) and represent the largest lava flows know on Earth.

The emplacement of these gigantic flood-basalt flows also had profound impacts on the Miocene paleodrainage system. During the peak period of CRBG eruptions (approximately 17 to 14 Ma), these gigantic lava flows inundated vast portions of the flood-basalt province destroying the medial to distal reaches of the ancestral Columbia River system (Fecht and others, 1987). 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) the streams and rivers established new courses proximal to the margin of the CRBG flow. This pattern is clearly seen in the sedimentary record (Ellensburg Formation interbeds) found within the Grande Ronde Basalt and the Frenchman Springs Member of the Wanapum Basalt (e.g., Bentley, 1977; Fecht and others, 1987; Smith, 1988; Smith and others. 1989; Fig. 10).   The relatively rapid emplacement of the Grande Ronde flows, and later Frenchman Springs flows, forced the ancestral Columbia River and its major tributaries to re-establish paths around the margin of these gigantic flows. If the period of time between gigantic flows was relatively brief (1,000 to 20,000 years), the rivers would be forced to remain at the margin of the lava field. This would result is essentially no sediments being deposited on top of the flow within the central portions of the flow field. However if the period of time between gigantic flows was much longer (100,000 to several million years), regional structural subsidence and folding (Columbia Basin/Columbia Trans-Arc Lowland) and headward erosion would allow rivers to establish courses across the central portions of the flood basalt province.

Mapping of the CRBG in the Wallula Gap area (Gardner and others, 1981) has demonstrated that a number of CRBG flows either thin across or pinch out against, the Rattlesnake-

Wallula Alignment (e.g., Roza and Priest Rapids Members of the Wanapum Basalt and the Pomona and Elephant Mountain Members of the Saddle Mountains Basalt). This pattern of CRBG flow distribution and thickness can not be explained solely by regional-scale subsidence (i.e., Columbia Basin/Columbia Trans-Arc Lowland), but is related to contemporaneous deformation associated with Yakima Folds and northwest-trending faults (e.g., Bentley, 1977; Bentley and others, 1980; Gardner and others, 1981; Myers and Price, 1981; Vogt, 1981; Reidel, 1984; Beeson and others, 1985; Hagood, 1986; Fecht and others, 1987; USDOE, 1988; Reidel and others, 1989a,b; Beeson and others, 1989; Beeson and Tolan, 1990). Analysis of CRBG flow distribution and thickness, and associated sediments, has collectively provided the basis for figuring out the paleodrainage history of this region (e.g., Beeson and others. 1985; Hagood. 1986; Fecht and others, 1987; Smith, 1988; Beeson and others, 1989; Smith and others. 1989).

Return to Highway 730 and turn right.

5.5   Crossing Oregon/Washington border.

11.3   Entering Umatilla Basin. The uppermost CRBG flow across the river is the 13.5 Ma Umatilla Member of the Saddle Mountains Basalt.

14.5   Rest Stop.

15.3   Junction with Highway 37. Continue west on Highway 730.

17.1   CRBG flow exposed in borrow pit is the 12 Ma Pomona Member (Saddle Mtns. Basalt).

77.7   Crossing classic scabland topography developed on the Pomona flow.

23.7   Junction with Highway 395 and McNary Dam Road. Continue west on Highway 730.

24.5.1   Junction with Interstate 82. Turn right (northbound) onto Interstate 82 and cross the Columbia River into Washington.

26.1   Leave Interstate 82 at Highway 14 exit (Exit 131). Turn left

27.1   Intersection with Plymouth Road. Turn right onto Plymouth Road.

31.0   Road cut through crest of Columbia Hills. Park in right-side turnout on north side of road cut.

STOP 1-2: Columbia Hills Anticlinal Ridge -
Yakima Fold Geometry, Saddle Mountains Basalt flows, and Ellensburg Interbeds

Today we will be traveling through the western portions of the Yakima Fold Belt, along the Columbia Hills (Fig. 13). As the Landsat photograph shows (Fig.18), the anticlinal ridges in this portion of the Yakima Fold Belt are characterized by
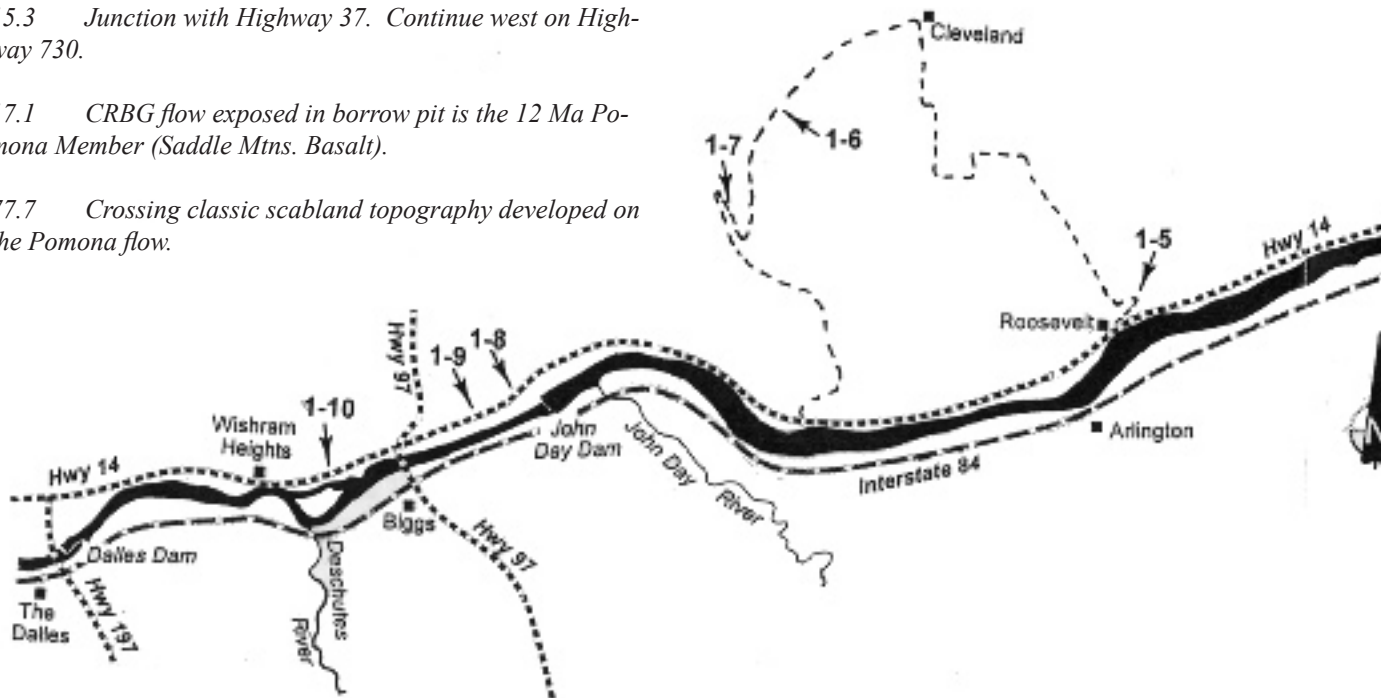

Figure 17 Field trip route map for Day One. Dashed numbers and arrows denote locations of planned stops.

narrow, northeast-trending, anticlinal uplifts separated by broad, synclinal basins. Toward the top of Figure 18 note that the trend of the anticlinal ridges abruptly changes to a N50°W trend and the spacing between anticlinal ridges is much shorter. This northwest-trending portion of the Yakima Fold Belt is called the Cle Elum-Wallula deformed zone (CLEW) and is part of the Raisz's (1945) northwest-trend Olympic-Wallowa Lineament (OWL). East of the CLEW, the Yakima fold (e.g., Saddle Mountains, Frenchman Hills) have an east-west trend and the relatively narrow anticlinal uplifts are again separated by broad, synclinal basins. Current models suggest that the Yakima folds are "wrinkle ridges". These models postulate that the Yakima folds were produced as a consequence of the regional stress regime which buckled the layered CRBG slab during early Grande Ronde time and set the locations and spacing of the folds (Anderson, 1987; Walters, 1989).

The Columbia Hills at this location consists of several parallel-trending anticlines (Fig. 13), but still display an asymmetrical, forelimb faulted, segmented, anticlinal geometry typical of most Yakima Fold anticlinal ridges. Here the amount of apparent vertical stratigraphic offset on the frontal thrust fault is very small (45 m (150 ft)) in comparison to the 730 m of apparent vertical stratigraphic offset that occurs on the frontal thrust fault on this same ridge west of The Dalles (see Day 2, Stop 2-

4). The view north from this locality is of the south-dipping limb of the Horse Heaven Hills.

In the road cut through the crest of the Columbia Hills are exposed folded and faulted Saddle Mountains Basalt flows (Elephant Mountain, Pomona, and Umatilla Members; Fig. 2) and the Rattlesnake Ridge and Selah Members of the Ellensburg Formation (Fig. 10). The sediments overlying the Elephant Mountain flow are considered to belong to the Alkali Canyon Formation because no other CRBG unit overlie these sediments at this locality.

Do the interbedded sediments exposed here provide any clues as to their origin and depositional environment? Retrace route back south along the Plymouth Road to the junction with Highway 14.

34.7   Junction with Highway 14. Turn right (west bound) onto Highway 14. Continue west on Highway 14 to Agri-
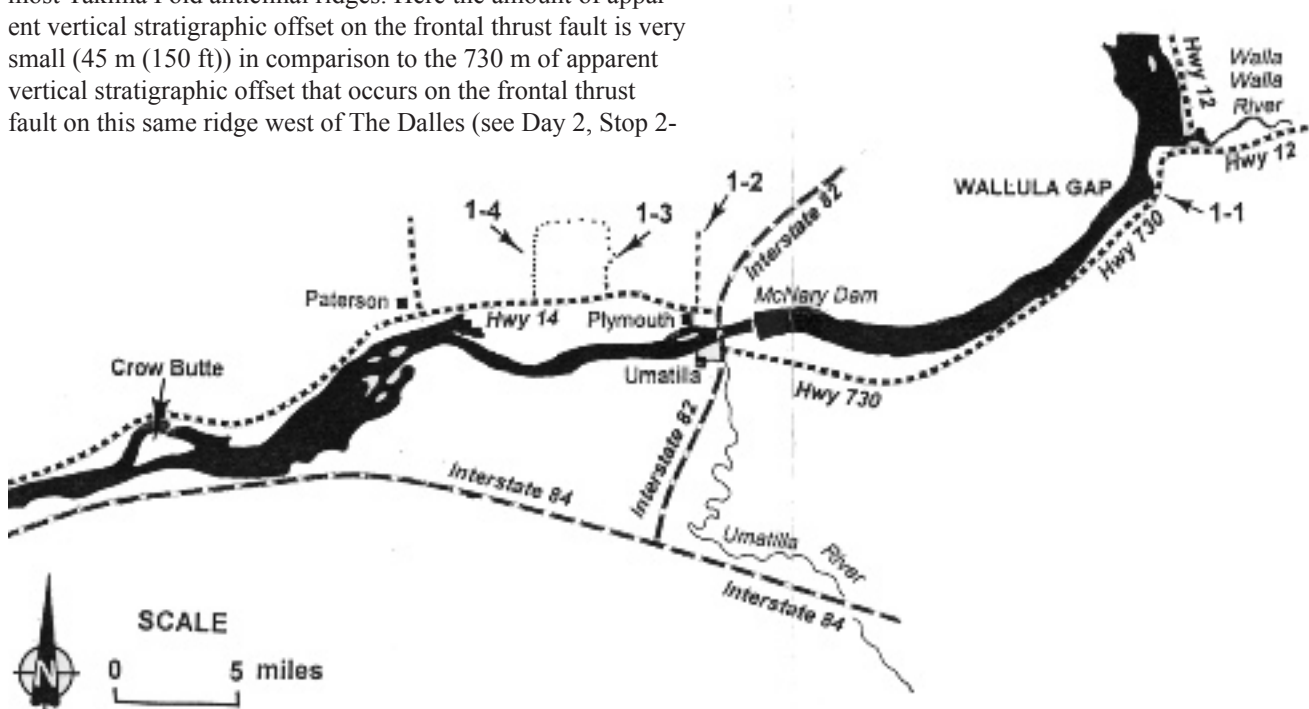
Figure 18. LandSat photograph of the west-central portion of the Columbia Plateau of Washington and Oregon showing the Yakima Fold Belt anticlinal ridges and basins and selected northwest-trending dextral wrench faults. Ridges: TYR = Tygh Ridge; CH = Columbia Hills; HHH = Horse Heaven Hills; TR = Toppenish Ridge; AR = Antanum Ridge; RH = Rattlesnake Hills; YR = Yakima Ridge; UR = Umtanum Ridge. Basins: DB = Dalles Basin; UB = Umatilla Basin; KV = Klickitat Valley; YV = Yakima Valley; MB = Moxee Basin; PB = Pasco Basin. Wrench faults: DBF = Dalreed Butte Fault; AF = Arlington Fault; LBF = Luna Butte Fault; GF = Goldendale Fault; WF = Warwick Fault; LF = Laurel Fault. Cities: Kennewick = K; Umatilla = U; Paterson = P; Goldendale = G; Blickleton = B; Roosevelt = R; The Dalles = TD; Lyle = L.

Northwest 's Prior Farm.

Note: The next two field trip stops are on private property belonging to AgriNorthwest. We have been granted special permission to enter the Prior Farm property for this field trip. Please obey all posted speed limits and yield the right-of-way to farm vehicles. Please do not return to these locations at a later time without express permission from AgriNorthwest.

39.1   Entrance to Prior Farms (AgriNorthwest). Turn right onto gravel road. Continue north past Substation No. 2 on main gravel road.

40.0   Entrance to gravel pit. Turn right and follow road into pit.

STOP 1-3: Alkali Canyon Formation

This stop is in a gravel pit excavated through a sequence of pedogenic calcrete, loess-like soil, and exotic lithology pebble-cobble conglomerate with a micaceous, felsic sand matrix. From the surface downward, the basic stratigraphy of this site is summarized as follows: (1) surficial deposits consist of loess and modern soil that ranges from 0.3 m- to 2 m-thick, (2) well defined, multiple layers of pedogenic calcrete, ranging from approximately 2 m- to 3 m-thick, (3) a thin (< 0.5 m-thick) paleosol interpreted to be at the top of the Alkali Canyon Formation, (4) Alkali Canyon Formation conglomerate forming the base of the gravel pit wall, consisting of variably cemented, indurated pebble gravel in a sand matrix approximately 3 m-thick, and (5) the eroded flow top of the Elephant Mountain Member (Saddle Mountains Basalt; Fig. 2) that forms the pit floor. These strata appear to form many of the subtle erosional benches east and west of this location.

The gravel exposed here is interpreted as an ancestral Columbia River or ancestral Salmon-Clearwater River deposit. Our position on the flanks of the Columbia Hills anticline (northern margin of the Umatilla Basin) and the thinness of the outcrop suggests we are on the edge of this channel tract. This is one of the few ancestral Columbia River/Salmon-Clearwater gravel deposits found to date within the Umatilla Basin. Erosion by the Pleistocene Cataclysmic Floods within the Umatilla Basin appears to have removed much of the Mio-Pliocene suprabasalt sediment section from the northern portion of this Basin.

Follow gravel road (north) that leads out of the pit.

40.2   Pit road rejoins main gravel farm road. Turn right onto main gravel road (north) and proceed through gap in the Columbia Hills.

At bottom of hill turn left onto gravel road (west).

Take left fork of gravel road.

Take left fork of gravel road.

Intersection with major north-south farm gravel road. Turn left (south) and proceed uphill.

Before starting up the hill, note the general appearance of the northern limb of this anticline. We are looking at the asymmetrically steep, faulted, limb of the fold.

Gate through fence. Turn right and proceed through gate. Turn left (south) and follow fire trail along the fence line to gravel road.

Turn right on gravel road.

Old gravel drill pad. Park vehicles and walk to summit of Hill.

STOP 1-4: Umatilla Basin and Klickitat Valley
View Point.

If it is not a "hazy" or dusty day, this spot provides an excellent view of the Umatilla Basin, Horse Heaven Plateau, Columbia Hills, Horse Heaven Hills, and the eastern Klickitat Valley. We will take a few minutes here, weather permitting, to point-out some of the geologic/geographic features we will be examining on this trip and discuss the geologic/paleodrainage evolution of this area.

This view point also offers a good spot to discuss the structural geometry of the Columbia Hills anticline. The ridge at this location has a broad, open, box-fold geometry. Note that the southern limb of the fold has a much more gentle dip than the northern limb we drove over to reach this spot. Another interesting aspect of this spot is the presence of scattered, angular, non-CRBG blocks. These are Cataclysmic Flood ice-rafted erratics. The hydraulic damming of floodwaters caused a temporary lake to formed that flooded the Umatilla Basin and southern portion of the Horse Heaven Plateau. This allowed the "icebergs" that carried these erratics to be grounded at this spot. The elevation of our observation point at the crest of the hill is approximately 235 m (770 ft) above mean sea level.

Retrace route back to gate.

Gate/main farm gravel road. Turn right onto gravel road and proceed to Highway 14.

Highway 14 intersection.   Turn right (west) onto Highway 14.

Junction with Highway 221. Continue west on Highway 14.

Glade Creek.

Canoe Ridge Estates Winery.

Intersection with Butte Road (Crow Butte State Park). Turn right onto Butte Road and follow it to Crow Butte State Park. Picnic Area

 LUNCH STOP

Retrace route back to Highway 14.

Butte Road/Highway 14 intersection. Turn right (west) onto Highway 14.

Alderdale/Mabton Road. Continue west on Highway 14.

Note the hummocky landslide topography and the light-colored sediments exposed along the Columbia Hills. Landslides (of various sizes) are common along this portion of the Columbia Hills. Anticlinal folding, interbedded sediment and basalt flows, and erosion of the southern flanks of the ridge by the Columbia River and Cataclysmic Floods have combined to created conditions that produced these landslides. The failure plane for many of these landslides appears to be either the sedimentary interbed/basalt flow top contact and/or at the top of siltstone/claystone beds found within the sedimentary interbeds.

Across river and immediately west of Interstate 84/Highway 74 interchange, note minor down-to-the west offset in the upper-most CRBG cliff. This is the northwest-trending Dalreed Butte Fault zone (Fig. 13). In Washington, the Columbia Hills anti-cline changes from a north-vergent to south-vergent fold across this fault zone.

Core of the Columbia Hills anticline. Southern (steep) limb has been largely removed by erosion.

Intersection with Roosevelt Grade Road. Turn right onto Roosevelt Grade Road. Proceed to turnout near summit of grade. White sedimentary interbed exposed in road cut is a diatomite indicating lacustrine environment. This diatomite overlies the Frenchman Springs Member and is overlain by the Rosalia flow of the Priest Rapids Member (Fig. 2). The Roza Member is not present here. This Ellensburg interbed spans the Squaw Creek-Quincy interval (Fig. 10).

Turnout near summit of grade. Park in turnout.

STOP 1-5: Columbia Hills View Point and Selah Interbed.

At this locality, we have an excellent exposure through the Selah Member (Ellensburg Formation; Fig. 10) and of the underlying flow top of the Lolo flow of the Priest Rapids Member *(Wa-*

napum Basalt; Fig. 2). Here the Selah interbed consists of a sequence of fluvial pebbly sandstone, sandstone, siltstone. claystone and reworked tuffs. The pebbly sandstone/sandstone beds represent a main channel facies of a major tributary to the ancestral Columbia River (ancestral Salmon-Clearwater and/or Snake Rivers). The finer sediments are overbank deposits of this river system. Remember that the variation we observe in this cut (2-dimensional view) also extends into a third dimension.

The maximum thickness of the Selah Member within this area (> 60 m-thick) occurs along the crestal portion of the Columbia Hills anticline; the Selah Member thins to the south into Umatilla Basin. These thickness data suggest that the depocenter of the Umatilla Basin during Selah time (14.5 to 12 Ma here) lay north of the axis of the Dalles-Umatilla Syncline (Fig. 13). Distribution of Selah gravel and sand facies also suggest that the primary paleodrainage tracts occupied this same area. These data would suggest that structural uplift associated with growth of the Columbia Hills anticline was not uniform along the entire length of the structure.

The presence of a very thick Selah Member section atop the Columbia Hills at this location was one of the major factors in citing the regional landfill atop this structure.
Continue north on Roosevelt Grade Road. 95.6   Intersection with Middle Road (gravel road). Head north (straight ahead) on Middle Road.

100.7   Intersection with Schranlz Road. Turn left onto Schrantz Road (gravel road).

103.1   Intersection. Stay on Schrantz Road.

105.9   Intersection with Dot Road. Turn right onto Dot Road (paved road).

113.2   Junction with Goldendale Highway. Turn left (west) onto Goldendale Highway.

119.8   Park in wide spot on left-hand side of highway. Watch for traffic!

STOP 1-6: Snipes Mountain Conglomerate and the Ancestral Columbia River

Throughout the area surrounding this stop, thin patches of gravel and sand are found unconformably overlying the Pomona Member (Saddle Mountains Basalt; Fig. 2). These gravels, like the one at this stop, consist of multi-lithologic, quartzite-rich, pebble-cobble gravel with a micaceous, felsic sand matrix. These gravels can be traced from the vicin-

ity of Sunnyside, Washington (Yakima Valley), through this area (Klickitat Valley), to Bingen, Washington (Fig. 16f). Age constraints on these strata are very poorly defined, with the best estimates being younger then 10.5 Ma, the age of the Elephant Mountain Member (Fig. 2) which they overlie at a number of locations. These strata are assigned to the Snipes Mountain Conglomerate.

The Snipes Mountain Conglomerate is interpreted to have been deposited by the ancestral Columbia River as it crossed the Horse Heaven Hills/Columbia Hills uplift prior to the river's shift to the east into the Pasco Basin (Fecht and others, 1987; Smith, 1988; Lindsey, 1996). The fact that these deposits are not found in a deeply incised valley or canyon (as correlative strata have been observed to do to the west in the Bridal Veil channel) is interpreted to mean that the highland we are now on was not undergoing significant uplift at the time these strata were deposited. Uplift of this part of the Horse Heaven Hills and Columbia Hills could have been occurring prior to deposition of these gravels as is suggested by thinning of many of the underlying CRBG flows through the area. Uplift was then renewed following migration of the ancestral Columbia River system to the east into the Pasco Basin after approximately 8 Ma.

Continue west on Goldendale Highway

Excellent view of the Klickitat Valley and Rock Creek -water gap.

Rock Creek Grade - time permitting, vehicles will off-load passengers here and proceed to bottom of grade (0.4 miles).

STOP 1-7A: Characteristics of Invasive CRBG Flows.

This sedimentary interbed exposed in the road cut (and also seen across the Rock Creek valley) occurs between the Ginkgo and Sand Hollow flows of the Frenchman Springs Member (Fig. 2). This interbed is actually the Vantage interbed that was invaded and rafted away atop the Ginkgo flow. Well logs and field data from this area (Sylvester, 1978) suggests that the "rafted" Vantage sediment is present throughout much of the central Klickitat Valley area. What features can be observed here that would indicate that this is a "rafted" interbed?

STOP 1-7B: Vantage Interbed and Ginkgo Flow

At this stop we will have an opportunity to examine the Vantage Member of the Ellensburg Formation. The Vantage Member here consists of a 5 m-thick siliciclastic sandstone (arkose) and represents the main channel facies of the ancestral Columbia River at about 15.5 million years ago (Fig. 16a). The path of the ancestral Columbia River through this area has been

determined based on the texture and lithology of the Vantage interbed from both outcrops and driller's logs (Sylvester, 1978; Anderson, 1987). Note that the degree of induration found within the Vantage sandstone is highly variable (poorly to well indurated) within this exposure. The cementing agent here is silica. How does the Vantage interbed at this location compare to that seen at Stop 1-7A?

The texture and lithology of the Vantage interbed at this spot indicates that these sands were deposited by the ancestral Columbia River. However the base of the Ginkgo exhibits a relatively "normal" flow bottom and does not display any features (e.g., pillow complex, hyaloclastic debris) to suggest that it encountered any water, much less a river, at this location. So what happened to the ancestral Columbia River? The ancestral Columbia River was temporary dammed by the Ginkgo flow in the northern Pasco Basin area. This allowed the Ginkgo flow to advance to the west over "dry ground".

729.0   Turn left onto the Rock Creek Road. Continue south on this Road to Highway 14.

133.4   Touchet Beds (slack-water Cataclysmic Flood deposits) in road cut.

134.2   Fork in road - continue on right-hand fork.

136.6   Frontal fault, Columbia Hills.

138.1   Junction with old Highway 8. Continue south on paved road.

138.5   Junction with Rock Creek Road. Turn right onto Rock Creek Road.

142.2   Junction with Highway 14. Turn right (west) onto Highway 14.

143.6   Note Alkali Canyon sediments exposed in slopes above the top of basalt. This reach of the Columbia River is controlled by the northwest-trending, Luna Butte Fault.

147.8   Highway 14 road cuts expose Luna Butte fault.

148.6   Road cut through fault breccia produced along the frontal fault of the Columbia Hills.

Scabland bench represents the eroded top of the Grande Ronde Basalt.

154. 7   Goldendale Aluminum Plant. 156.6   Optional Stop - park in turnout on left side of highway. Watch for traffic!

STOP 1-8 (optional): John Day Dam View Point.

This spot provides an excellent view east along the eroded southern flank of the Columbia Hills anticline. The lower "bench" that the Goldendale Aluminum Plant is built on is an eroded flow top breccia belonging to the uppermost Grande Ronde Basalt flow (Sentinel Bluffs Member; Fig. 2). This pronounced bench (sometimes termed the "Vantage bench") is seen along both sides of the Columbia River. This is an excellent example of the work of the Cataclysmic Floods and how they have modified the Columbia River Valley. The Vantage interbed is present in this area (ranging from 0.5 to > 2 m-thick; Anderson, 1987) and provided an easily erodable horizon for the Cataclysmic floodwaters.

Continue west on Highway 14. 158.1 Optional Stop - park in turnout on right side of highway before road cut.

STOP 1-9 (optional): Priest Rapids Pillow Complex, Quincy Diatomite, and Roza Flow Top.

Here we have an excellent exposure (from road level to the top of the cut) of the Roza vesicular flow top, a thin Quincy interbed, and the Rosalia pillow complex (Priest Rapids Member; Fig. 2). The Quincy interbed consists of diatomite and claystone that overlies a non-eroded Roza flow top. The Quincy interbed indicates that a lake existed at this location and that this lake must have existed long enough for the deposition of 0.3 to 1 m-thick diatomite.). We believe this lake (part of an extensive series of shallow lakes across the Columbia Plateau) formed because the emplacement of the Frenchman Springs and Roza Members prevented the ancestral Columbia River drainage from establishing an integrated channel tract across the central and western Columbia Platea*u*.

Continue west on Highway 14.

161.4   Highway 14/Highway 97junction. Continue west on Highway 14.

161.9   Stop sign. Continue west on Highway 14.

164.0   Maryhill Museum of Art.

165.0   Entering Columbia River Gorge Scenic Area.

165.4   Park in turnout on right side of highway just before the ravine.

STOP 1-10: Haystack Butte basalt flow and the Age of the Columbia River Canyon

Exposed in the road cut is a Simcoe basalt flow that was erupted from a vent (Haystack Butte) atop the Columbia Hills.

This lava flow traveled down the southern flank of the Columbia Hills and flowed to the Columbia River which was at essentially the same elevation as today's (pre-dam) river. The columnar jointed basalt at the eastern-end of Miller Island (directly below us) is the distal end of this Simcoe basalt flow. A K-Ar whole-rock age of $0.90 + 0.10$ Ma has been obtained on this basalt flow (Anderson, 1987) indicating that the Columbia River valley had been incised to its depth by this time.

This is the final field trip stop for day one.

Continue west on Highway 14.

168.2   Wishram Junction.

Continue west on Highway 14.

169.2   View of Fairbanks gap. Laura! Fault, Chenoweth Formation.

172.8   Crossing Laural Fault. Fault exposed in road cut. Columbia Hills vergence change.

174.3   Highway 14 on Tev bench - entering scabland tract.

177.2   Horsethief Lake State Park -for those people that have elected to camp, this is the campsite. The rest will proceed on to The Dalles, Oregon.

End of Day One Guide.

Day Two - Sunday September 29, 2002

Travel directions between field trip stops will be indicated by italic text. Figure 19 shows the route we will follow for today's field trip.

We will meet at the wide turnout on Highway 197 (south of Interstate 84, across Highway 197 railroad overpass - across from the pillow lava road cut) at the east end of The Dalles, Oregon.

Miles   Comments

0.0   STOP 2-1: Introduction to Day Two - Geologic Setting and Paleodrainage History.

The CRBG lava flows and the ancestral Columbia River both traversed the Cascade Range through the Columbia Trans-Arc Lowland on their way toward the Pacific Ocean. This

lowland was more than 60 km wide from the northern edge near the present-day Columbia River to the southern edge near the Clackamas River. Some CRBG units extend the breadth of this extent. This observation is made to counter a misconception that seems to arise that the CRBG flows traversed the Cascade Range in deep narrow gorges similar to the present Columbia Gorge. In fact, only a few of the Wanapum and Saddle Mountains flows were largely confined to stream canyons. The channels of the ancestral Columbia River followed broad Yakima fold belt synclines into the Cascade Range or cut channels marginal to earlier CRBG flows or at the contact between the CRBG and older highlands. Intracanyon flows of CRBG indicate that the ancestral Columbia River occupied at least four substantially different channels through the Cascade Range from 15.5 Ma to the present. Three of these channels (15.5 Ma. 14.5 Ma, and present-day) will be discussed at this stop.

The first of these channels was established during "Vantage time" which was a 100,000 to >300,000 year quiescent period between the end of Grande Ronde volcanism and the onset of Wanapum volcanism (~ 15.5 Ma). Prior to 15.5 Ma, the repeated emplacement of large volume Grande Ronde sheet flows had forced the ancestral Columbia River to the northern and northwestern margin of the province (Fecht and others, 1987; Smith, 1988). With the cessation of Grande Ronde volcanism and continued regional subsidence, the ancestral Columbia River began to shift towards the center of the Columbia Basin and Columbia Trans-Arc Lowland (Fig. 16a). Within the Columbia Trans-Arc Lowland, the ancestral Columbia River developed a channel along the Dalles-Mount Hood Syncline and then southwest along, and near, the margin of the Grande Ronde Basalt (Fig. 20). Prior to the emplacement of the Ginkgo flow (Frenchman Springs Member; Fig. 2), the ancestral Columbia River had been able to incise a canyon (by headward erosion) eastward along the Dalles-Mount Hood Syncline to just southwest of the present-day city of The Dalles.

The second paleodrainage pathway was established in mid to late Wanapum time between the Frenchman Springs and Priest Rapids Members (Figs. 2 and 16b). Here the Rosalia (Priest Rapids Member, ~ 14.5 Ma) pillow complex lies at the base of the columnar-jointed Rosalia sheet flow. The pillow complex overlies lacustrine deposits elsewhere in this area and here displays a westward imbrication. This geometry indicates that the Rosalia flow was advancing towards the west across a shallow lake that occupied the board low centered where the Dalles-Umatilla Syncline now lies (Tolan and Beeson, 1984; Fig. 16b). Because of the paleogeographic configuration of the land between the westernmost lake that occupied the Dalles-Mount Hood Syncline and its outlet into the ancestral Columbia River canyon (Fig. 20) near Mosier, Oregon, a unique situation developed when the Rosalia lava approached this area (Fig. 21).

As the Rosalia flow front advanced into the lake, it displaced a

large volume of lake water. This water could not escape rapidly enough through the outlet of the lake (probably a partially entrenched low spot through the anticlinal ridge between the two synclines) and began to back-up into the Dalles-Mount Hood Syncline. The pent-up waters eventually escaped across the active Rosalia flow front. The escaping waters chilled the molten lava causing phreatic brecciation, creating vast quantities of sand- to cobble-size fragments of glassy basalt that were carried in debris flow-like surges into, and down, the ancestral Columbia River canyon. The ratio of hyaloclastite to pillows increases westward toward the Mosier Syncline. We think that the increasing ratio of hyaloclastite to pillows indicates an environment of increasingly turbulent, or rapidly moving, water which interacted with the Rosalia flow front as depicted in Figure 21. We estimate that more than 8 km3 of hyaloclastic debris was generated and flushed in advance of the Rosalia lava flow (Tolan and Beeson, 1984). We will have an opportunity to examine the Rosalia hyaloclastite near the head of the ancestral Columbia River canyon (Mosier Syncline) at Stop 2-6.

The destruction of this canyon of the ancestral Columbia River forced the river to relocate northwards into another Yakima fold syncline (Bridal Veil channel; Fig. 20). From the vicinity of Hood River west to Bridal Veil, Oregon (Fig. 20), the ancestral Columbia River remained in this canyon until ~ 3 Ma. As discussed yesterday, the ancestral Columbia River did not occupy its present-day course through The Dalles area until ~ 6 Ma. However the ancestral Snake/Salmon-Clearwater Rivers did maintain tracts through this area from ~13 to 6 Ma. Surpabasalt sediments deposited in this basin by these major tributary rivers and "local" rivers/streams originating in the Miocene Cascade Volcanic Arc form the bluffs above the town and were originally mapped as the Dalles Formation (e.g., Piper, 1932; Hodge, 1938; Newcomb, 1966, 1969. 1971), but were redefined was the "Chenoweth Formation of the Dalles Group by Farooqui and others (1981a,b). We will have a chance to examine these suprabasalt sediments at our next stop.

The effects of the Cataclysmic Floods are very evident here in The Dalles area. Features to note: Looking west toward the water gap though the Columbia Hills, note that the soil has been largely stripped from the lower half of the southern flank of the Columbia Hills by flood-waters. Classic scabland topography.

Enter Highway 197 (southbound) and immediately turn right onto SE Frontage Road (old Highway 30).

1.8 Turn left onto Taylor Street. Then turn left onto

3nl Street and proceed up the hill
.

2.2   Intersection with Dry Hollow Road.   Turn right onto Dry Hollow Road and continue up the hill.

3.0   Intersection with 19'1' Avenue. Continue across 19'1' Avenue on Dry Hollow Road.

3.1   Park in lot on left side of Dry Hollow Road.   Watch for TRAFFIC!

STOP 2-2: Exotic Clast Lithologies in the Chenoweth (Dalles) Formation Conglomerate

The roadcut exposes a pebble-cobble conglomerate belonging to the Chenoweth Formation. This pebble-cobble conglomerate overlies a Cascadian debris flow and is overlain by a Cascadian air-fall tuff/volcan(elastic sandstone sequence (Fig. 22).

As previously discussed, the suprabasalt sediments in the Umatilla and Dalles Basins have been historically mapped as the Dalles Formation (Piper, 1932; Hodge, 1938; Warren, 1941; Newcomb, 1969, 1971). However based on their regional reconnaissance mapping of late Neogene sediments in north-central Oregon. Farooqui and others (1981a,b) proposed a major revision to the stratigraphic nomenclature for these sedimentary deposits. They proposed that the late Neogene suprabasalt sediments, north of the axis of the Blue Mountains anticlinorium in Oregon, that had been historically referred to as the "Dalles Formation" could be subdivided into five unique, mappable formations that occupy geographically discrete and separate basins (Farooqui and others, 1981b, p. 132-133). These five new formations would comprise the redefined "Dalles Group". The Dalles Formation of Newcomb (1966, 1969, and 1971) would be subdivided into the Chenoweth Formation (Dalles Basin) and the Alkali

Canyon Formation (Umatilla Basin). Farooqui and others (1981a,b) placed "divide" between the Dalles and Umatilla Basins along a north-south line just west of the lower canyon of present-day John Day River.

Based on the work of Newcomb (1966, 1969, 1971) and their own field work, Farooqui and others (1981a.b) concluded that only "locally derived" sediments (streams draining the northern flanks of the Blue Mountains and eastern slopes of the Cascade Range) comprise the suprabasalt sediment section within these basins. They concluded this based on the lack of any clasts within the conglomerates consisting of "exotic lithologies" - lithologies that could only be derived from beyond the boundaries of the drainage basin (e.g., quartzite, plutonic, metamorphic lithologies). Farooqui and others (1981a,b) further believed that the "local" rivers and streams that flow into the Umatilla Basin do not have any connection with streams and rivers in the adjacent Dalles Basin.

However re-examination of these late Neogene fluvial conglomerates in the Umatilla-Dalles Basins (Lindsey and others, 1993; Lindsey and Tolan. 1996; Tolan and others, 1996) has found conglomerate beds within these basins contain a significant percentage of exotic clasts (e.g., metavolcanic and
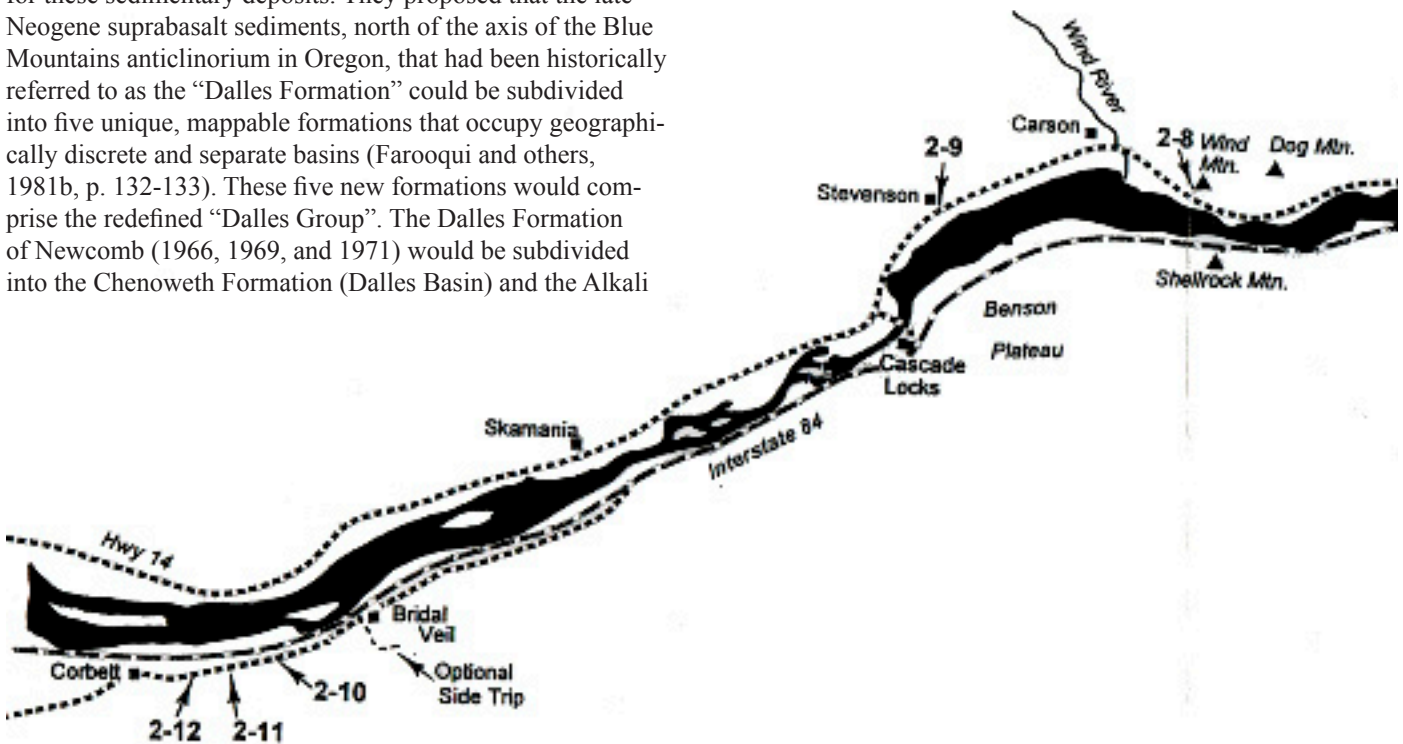

Figure 19 Field trip route map for Day Two. Dashed numbers and arrows denote locations of planned stops

metasedimentary lithologies - including quartzite) implying a distal provenance (Fig. 11). However if one is not careful, it is very easy to mistake exotic clasts for locally derived clasts. For example at this outcrop (Dry Hollow section - Fig. 22, Table 2), pebble counts indicate that approximately 62 percent of the clasts represent either CRBG or Cascadian lithologies - both "locally derived" lithologies. The remaining 38 percent consists of light- and dark-colored exotic lithologies (non-lo-

cally derived) which can be easily overlooked in a cursory examination.

Why Newcomb (1966. 1969, 1971) and Farooqui and others (1981a.b) failed to recognize the presence of exotic clasts within these deposits is not known. We speculate that it may be in some part related to the lack of "obvious exotics" (e.g.. Belt quartzite, gneiss, plutonic lithologies).

Clast Lithology Group	Dry Hollow Percentage	Signal Hill Percentage
Silicic Volcanics (andesite/rhyolite)	26	16
Silicic Meta-Volcanics	21	24
Plutonic	0	0
Chert	6	7
Laminated Meta-Sediments	1	2
Quartzite	8	27
Non-CRBG basalt	2	3
CRBG	36	21
Total number of clasts counted	316	225

Table 2. Clast-lithology groups and their abundance for two localities in the Chenoweth Formation in The Dalles area. See Figure 21 for site locations and measured sections.
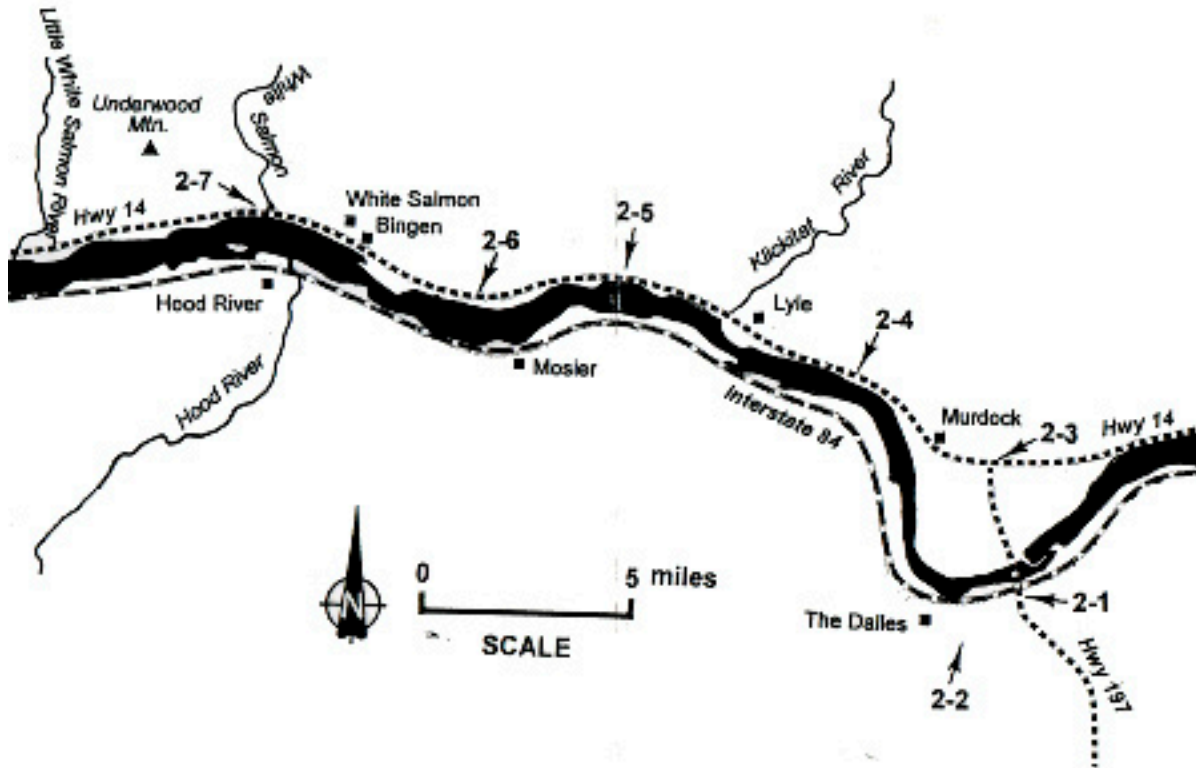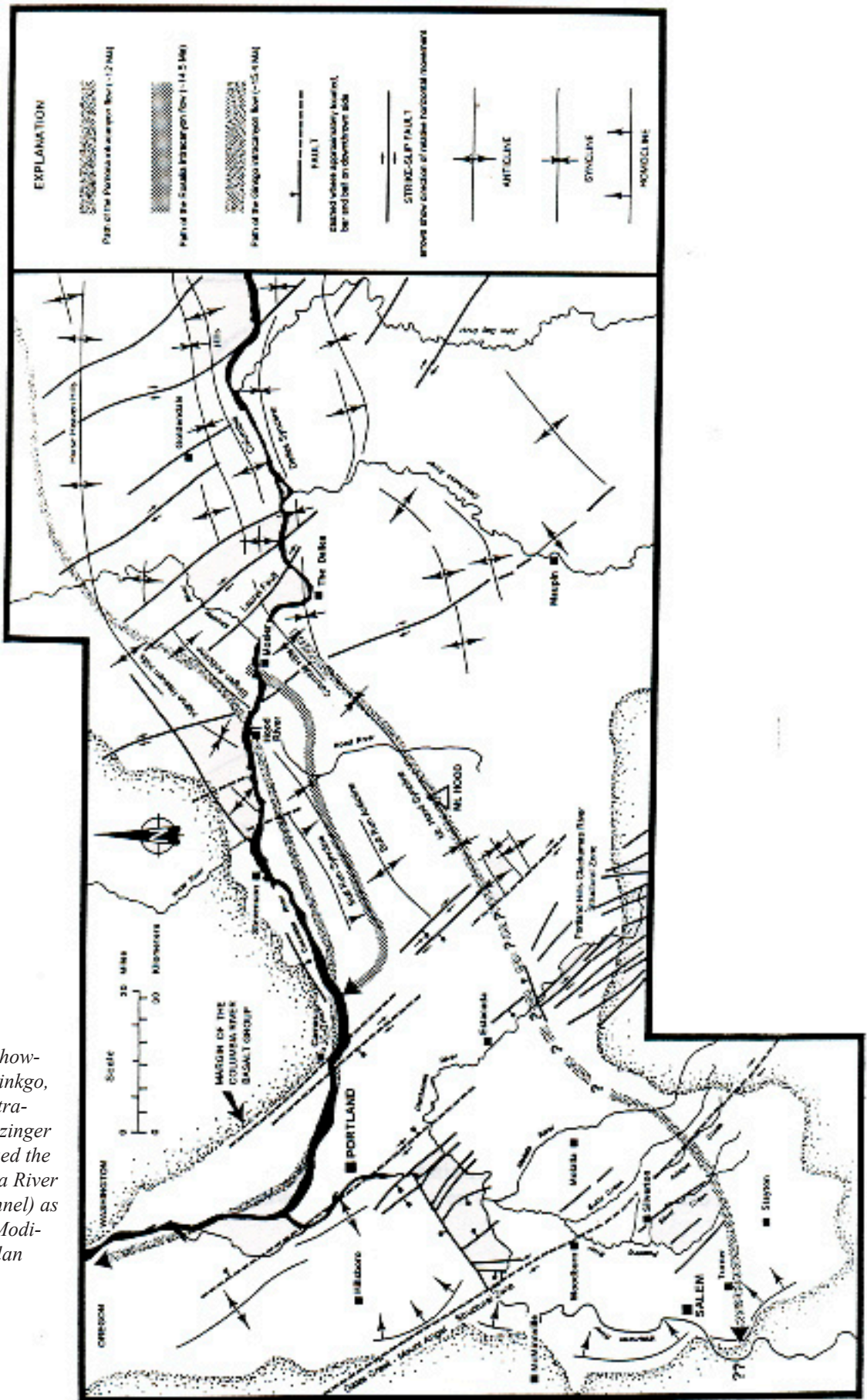
I igure 20. Sketch map showing the location of the Ginkgo, Rosalia, and Pomona intracanyon Hows. The I luntzinger flow (Asotin Member) used the same ancestral Columbia River canyon (Bridal Veil channel) as the later Pomona (low. Modified from Beeson and Tolan (1996).

Retrace route back to Highway 197

5.8   Junction of Highway 197 and Frontage Road (old Highway 30). Turn left onto Highway 197. Proceed north across Columbia River into Washington Highway 197.

9.6   Junction of Highway 197 and Highway 14. Turn left (west) onto Highway 14.

9.7   Parking in turnout on right side of highway.

STOP 2-3 (optional): Dalles-Mount Hood Syncline View point

On a clear day from this vantage point we have an excellent view down the axis of this major Yakima Fold syncline. The axis of this syncline trends southwest towards Mount Hood (on the skyline). During Vantage time (hiatus between Grande Ronde and Wanapum volcanism - ~ 15.5 Ma; Fig. 16a), the ancestral Columbia River established a channel along this structural low (Fig. 13) which was destroyed by the emplacement of the Ginkgo flow. Subsequent emplacement of additional Frenchman Springs flows within this synclinal low forced the ancestral Columbia River to establish a new course in the next syncline to the north - the Mosier Syncline (Fig. 20).

The light-colored bluffs rising above the city consist of interbedded volcaniclastic and epiclastic sediments of the Chenoweth Formation (formerly Dalles Formation). We also have a good view of the location of our previous stop (Stop 2-2). The Chenoweth volcaniclastic sediments are generally underlain by, and interbedded with, epiclastic fluvial sediments that contain quartzite-poor and quartzite-rich mixed-lithology conglomerate (Tolan and

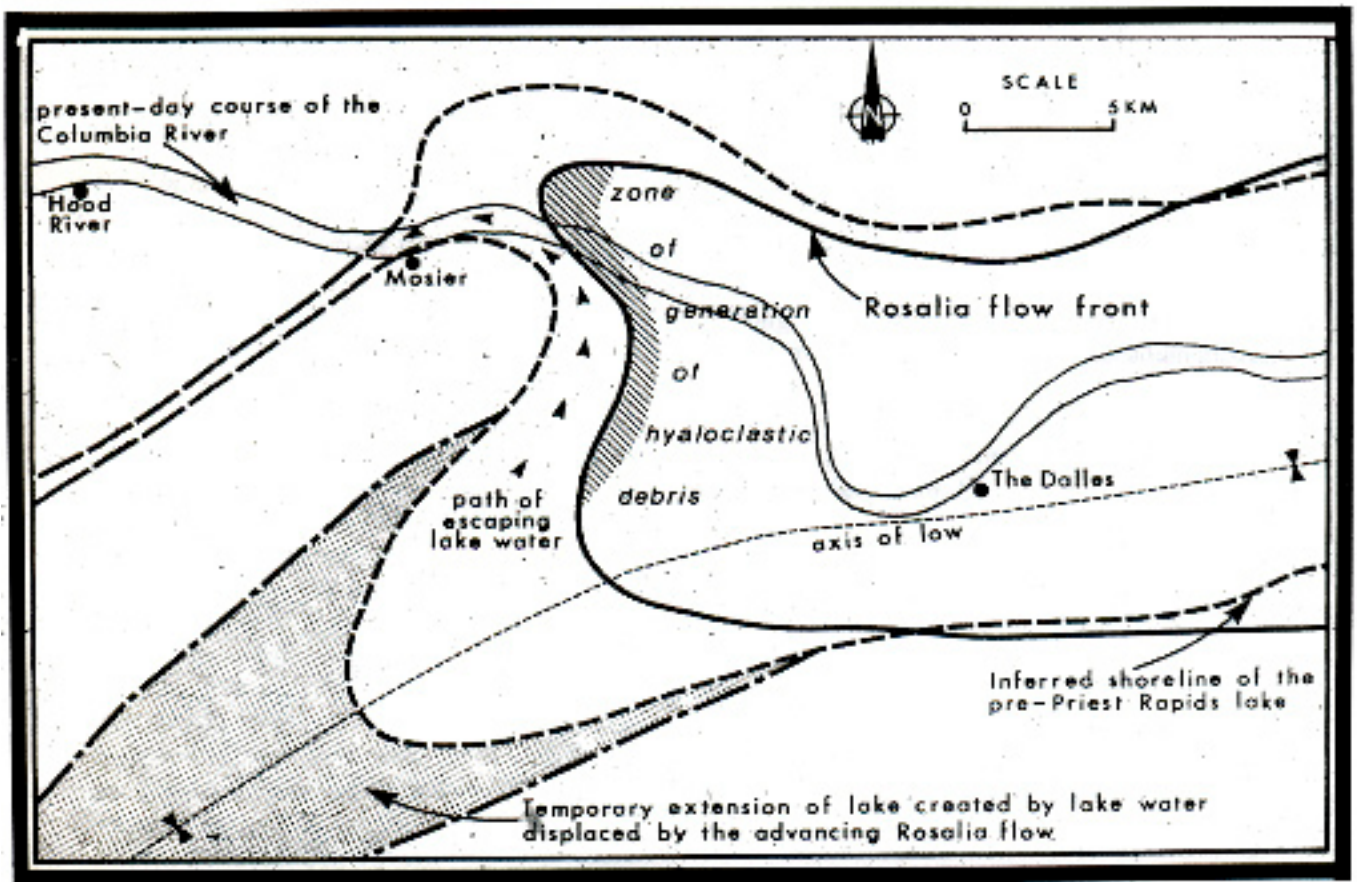**Figure 21**. *Sketch map showing the approximate location of the lake and head of the ancestral Columbia River canyon that existed when the Rosalia lava flow (Priest Rapids Member) approached this area. Arrows indicate path of escaping lake water where hyaloclastic debris was generated and transported when the Rosalia flow front advanced westward across this area. Modified from Tolan and Beeson (1984).*

DRY HOLLOW SECTION

Vertical
Scale (m)

Covered

St P B

C S Cb

Lithic (volcaniclastic)
Sandstone

Tuff

STOP 2-2

Covered Interval

Lahar with
pumice blocks

Covered Interval

Laminated Claystone

SIGNAL HILL SECTION

Vertical
Scale (m)

Covered Interval

St P B

C S Cb

Volcanic Debris Flow

Covered Interval

Lithic Sandstone
with lens of pumice pebbles

First Appearance of
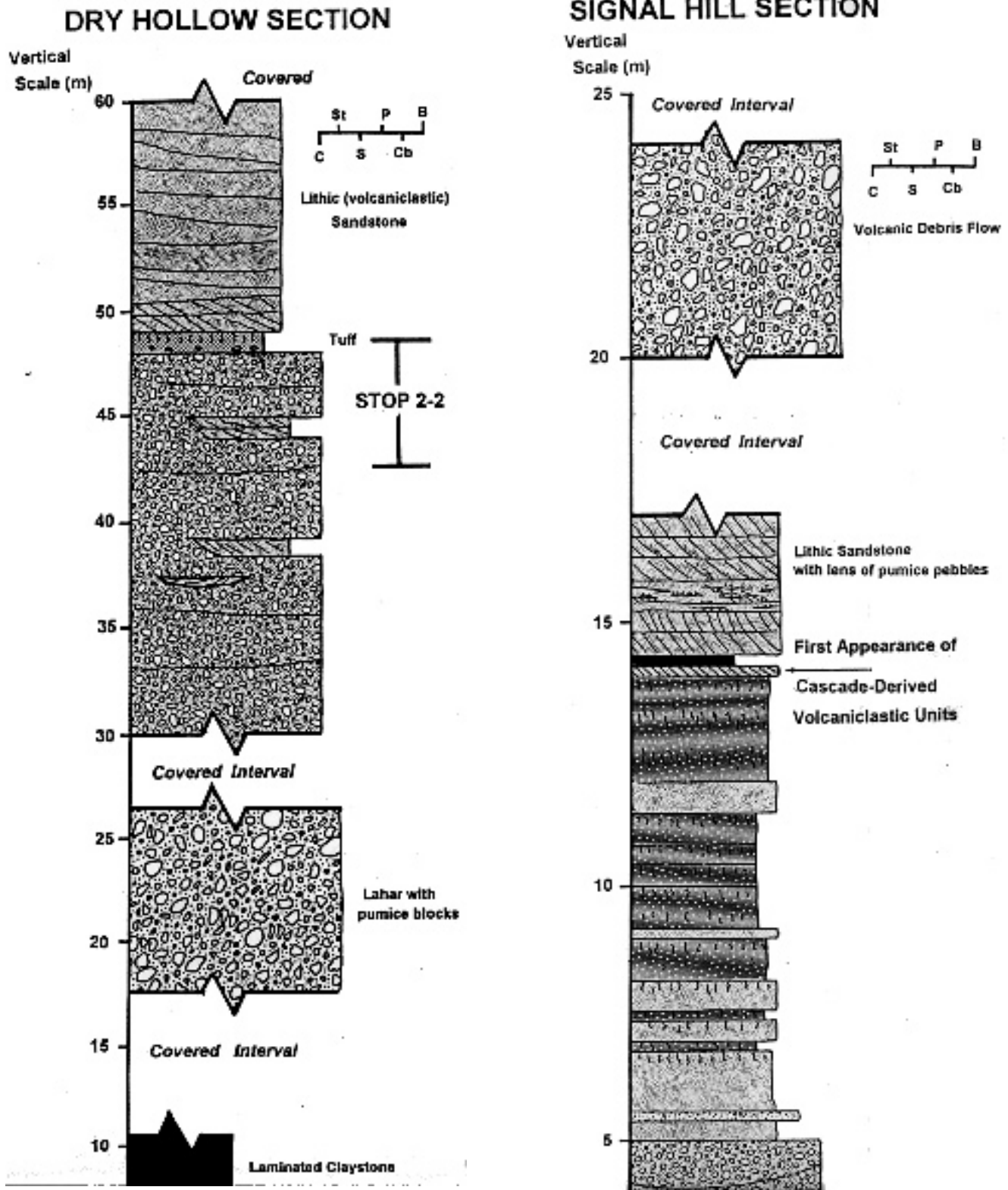
Cascade-Derived

Volcaniclastic Units

Figure 22 *Measured sections within the Chenoweth Formation, Dry Hollow and Signal Hill localities. Map to the right shows locations*

others, 1996). An excellent exposure of a quartzite/mixed-lithology, pebble-cobble conglomerate, capped by an andesitic debris flow, is found above the southern end (Oregon-side) of The Dalles Dam on Signal Hill (Fig. 22). These strata contain clast lithologies that are virtually the same as the quartzite/mixed-lithology facies of the Alkali Canyon Formation in the western Umatilla Basin (Fig.l 1). Like the Alkali Canyon Formation, the Chenoweth quartzite/mixed-lithology conglomerate contains a significant percentage of well-rounded metasedimentary and metavolcanic clasts. The matrix in this conglomerate is lithic, with some mica and variable mud content. The conglomerate beds are interstratified with lithic sandstone and siltstone beds that display evidence of pedogenic modification (burrows, root casts) that is interpreted as evidence of paleosol development. In outcrop, these strata display plane-bedding, cross-bedding, and channel cut-and-fill structures indicative of fluvial deposition. Paleocurrent indicators, typically clast imbrication and cross-bedding, indicate transport to the west. This evidence indicates that these epiclastic sediments were not locally derived, but instead represent deposits of a river whose headwaters lay beyond the margin of the CRBG. As discussed at earlier stops, we believe that these exotic lithology conglomerate beds were deposited by the ancestral Salmon-Clearwater & Snake Rivers. For much of the Neogene, these tributary rivers maintained a se-

ries of courses through the Umatilla-Dalles basin and joined the ancestral Columbia River in the Mosier/Hood River area (Lindsey and Tolan, 1996; Tolan and others, 1996). This tributary river system finally "captured" the ancestral Columbia River approximately 6 Ma (Fecht and others, 1987).

This exotic clast-bearing conglomerate at the Signal Hill locality is unconformably overlain by a Chenoweth (Cascadian) debris flow (Fig. 22) and capped (to the southwest) by Cascadian lavas that have been radiometrically dated at ~ 6 to 8 Ma (Farooqui and others, 1981a,b; Gray and others, 1996). The volcaniclastic sediments largely consist of flood- and debris-flow-deposited andesitic to dacitic detritus with minor air-fall ashes. Based on geochemical data, lithology, and superposition, Gannett (1982) established that the Dalles (Chenoweth) and Rhododendron volcanics were correlative and shared a common Cascadian source. More recent work by Gray and others (1996) suggest that much of the Chenoweth Formation (Dalles Formation) could be much younger, ranging from 8 to 6 Ma
.
Continue west on Highway 14.

10.3   Community of Murdoch

11.3   Entering the Columbia River water gap through the Columbia Hills (Ortley Anticline). Excellent natural cross-section through a Yakima Fold anticline.

14.9   Park in turnout on right side of Highway.

STOP 2-4 (optional): Frontal Fault Zone, Ortley Anticline (Columbia Hills)

The road cuts and natural cliffs provide an excellent opportunity to examine the characteristic of main frontal fault zones associated with Yakima Fold anticlines.
The blocky to columnar-jointed basalt flows seen immediately at highway level along the turnout belong to the Frenchman Springs Member of the Wanapum Basalt. These Frenchman Springs flows are overlain by a single Roza Member flow and two Priest Rapids Member flows (Fig. 2). The uppermost CRBG flow (entablature-colonnade-jointed flow) is the Pomona Member of the Saddle Mountains Basalt. The Pomona flow is overlain by more than 60 m of Chenoweth Formation sediments. As you walk east along the highway (Be careful - WATCH FOR TRAFFIC!), the blocky jointed Frenchman Springs flows
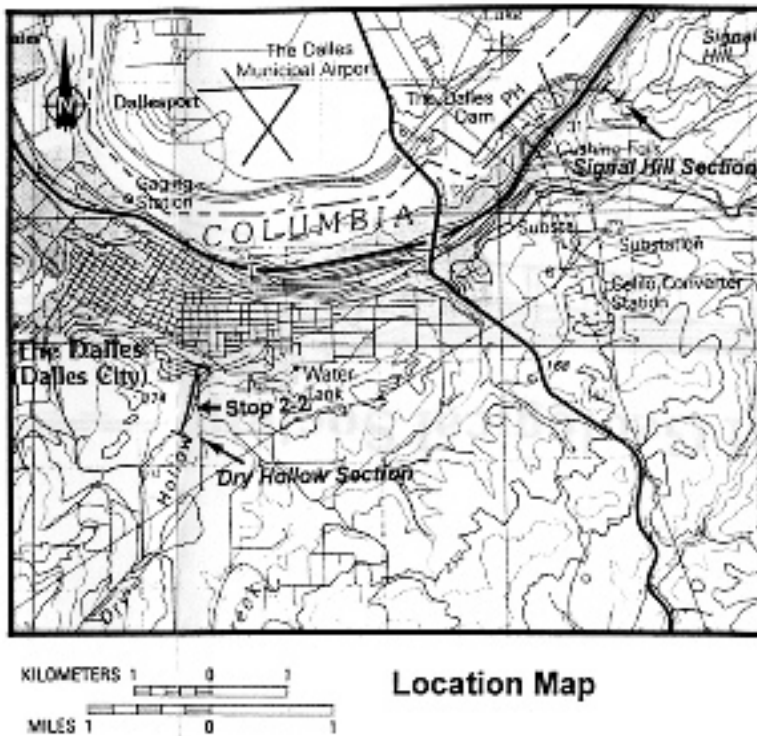

Figure 22 *(Continued)   Area map for the Dry Hollow and Signal Hill locales.*

terminate in a massive fault shatter breccia. The shatter breccia varies in thickness, but typically is 30 to 45 m-thick. As you proceed east, the fragments of basalt which compose the shatter breccia become progressively larger and grade into relatively "intact", basalt. This flow belongs to the Ortley Member of the Grande Ronde Basalt (Fig. 2) and has a near vertical dip. The apparent vertical stratigraphic offset on this fault is approximately 730 m.

Detailed mapping of this fold by Anderson (1987) found that the thickness of both the Frenchman Springs and Roza Members vary across this structure - thinning across the anticline and thicken in the adjacent synclines. These data indicate that these folds were growing during Wanapum time at this location. Development and growth of these folds by at least Vantage time is also suggested by the position of the ancestral Columbia River in the Dalles-Mount Hood Syncline.

Continue west on Highway

14. 16.8   Entering the town ofLyle, Washington.

17.1   Klickitat River

19.1   Rest Area

20.6   Park in small turnout on right side of highway

STOP 2-5 (optional): Pomona Member, Mosier Syncline.

At this stop we have another opportunity to examine the Pomona flow. The Pomona flow at this locality is a sheet flow that "back-filled" a portion of the Mosier Syncline. At the time the Pomona flow was emplaced, the course of the ancestral Columbia River lay on the north side of the Horse Heaven Hills/Bingen Anticline (Fig. 20). The ancestral Salmon-Clearwater/Snake Rivers joined the Columbia River to the northwest of this locality via a water gap in the Bingen Anticline (Anderson and Vogt, 1987; Fig. 16d). As the Pomona lava advanced down the ancestral Columbia River canyon it encountered this water gap and flowed back into the Mosier Syncline. Here the Pomona flow encountered a ''dry" river course because it had already "dammed" the ancestral Salmon-Clearwater River in the Levviston Basin area of western Idaho and the ancestral Snake River in the eastern Umatilla Basin/Horse Heaven Plateau area. The physical, textural, and lithologic appearance of the Pomona flow at this locality is virtually the same as seen yesterday at our second stop. The straight-line distance between yesterday's Stop 1 -2 and this locality is approximately 150 km.

Continue west on Highway 14. 22.8   Park on highway shoulder at west end of guardrail.

STOP 2-6: Rosalia (Priest Rapids Member) Hyaloclastite

The natural exposures and road cuts reveal a massive hyaloclastite at the base of the Rosalia flow. This deposit is composed of angular sand- to cobble-size fragments of Rosalia hyaloclastic debris that displays no evidence of normal fluvial transport (i.e., rounding, sorting, and bedding). The natural outcrops have the outward appearance of bedding, but close examination shows that the "bedding planes" are actually post-depositional cementation patterns that have been accentuated by differential weathering and erosion. Invasive lobes of Rosalia lava and fragments of broken or incipient pillows are also exposed here.

The Rosalia hyaloclastite here fills a canyon (ancestral Columbia River) eroded into the underlying Frenchman Springs flows. This erosional unconformity can be seen at the western end of the road cut. This is the easternmost known occurrence of the Rosalia hyaloclastite filling the river canyon and probably represents the head of the pre-Rosalia canyon where displaced lake water and lava dynamically interacted and created the hyaloclastic debris (Tolan and Beeson, 1984).

Exposures of the Rosalia hyaloclastite deposited within the ancestral Columbia River canyon have been found farther west in the Hood River Valley (Tolan and Beeson, 1984; Anderson and Vogt, 1987), the Bull Run River valley (Vogt, 1981; Anderson and Vogt, 1987), and at Crown Point in the western Columbia River Gorge (Waters, 1973; Tolan and Beeson, 1984). Between this locality and Crown Point (Fig. 20), the thickness of the hyaloclastite deposit changes little, but the stratification, degree of sorting, the rounding of clasts, and the number of foreign clasts (non-Rosalia basalt) increase. The texture and bed forms within the Rosalia hyaloclastite west of this locality are suggestive of debris flow/hyperconcentrated flood-flow depositional processes.

Continue west on Highway 14.

23.9   View of the Bingen Anticline.

26.4   Entering the town of Bingen, Washington.

23.9   Turn right at City Park sign. Proceed one block to Daubenspeck Park

Lunch Stop

Retrace route to Highway 14. Turn right (west) onto Highway 14.

28.2   Toll Bridge across the Columbia River. Continue west on Highway 14.

28.3   Good view of Underwood Mountain shield volcano. An olivine basalt flow from this volcano has yielded a K-Ar age of 0.85 ± 0.02 Ma (Korosec, 1987). Waters (1973) postulated that flows from this shield volcano dammed the Columbia River.

29.8   Junction with Highway 141 just before the White Salmon River. Continue west on Highway 14.

30.2   Park in wide turnout on left side of Highway. Be careful of on-coming traffic!

STOP 2-7: Ancestral Columbia River Deposits

The sandstone and conglomerate exposed in the road cut contain a high percentage of quartzite. granitic, and metamorphic clasts that clearly indicate that these sediments were deposited by the ancestral Columbia River (Buwalda and Moore, 1927; Warren, 1941; Waters, 1973; Allen, 1979; Bela, 1982). Mapping of this area by James Anderson (in Swanson and others, 1981) found that these fluvial deposits are confined to an ancestral Columbia River canyon (Bridal Veil channel of Tolan and Beeson (1984)) and overlie the 12 Ma Pomona intracanyon flow. This path of the Columbia River projects to the southwest (Fig. 20) and a remnant of this same channel is exposed at Mitchell Point (Fig. 23) on the Oregon side of the Gorge (Anderson, 1980). Note that the conglomerate that underlies the Pomona intracanyon flow at Mitchell Point contains very few quartzite clasts and a generally different assemblage of clasts. The fewer quartzite clasts suggests that some geologic time was required after an inundating CRBG lava flow for these exotic clasts to work their way across the Plateau. The pre-Pomona clast assemblage seems to reflect more of the Ancestral Snake River provenance that entered the system downstream of our present location.

Also note the presence of beds composed almost entirely of dark vitric and lithic sand within these fluvial deposits. As discussed earlier in this guide, these vitric and lithic sands were produced by the dynamic interaction between Cascadian high-alumina basaltic lava flows and the ancestral Columbia River from approximately 5 to 2 Ma (Tolan and Beeson, 1984). From here west, the presence of high-alumina, vitric/Iithic basaltic sands in the ancestral Columbia River deposits provides an excellent stratigraphic "marker" allowing them to be subdivided into mappable units (i.e., lower and upper member of the Troutdale Formation; Tolan and Beeson, 1984).

This locality is another spot where suprabasalt sediment

stratigraphic nomenclature has undergone many complex revisions that can (has) cause much confusion. This deposit has been called the ''Hood River Formation" by Buwalda and Moore (1927), "Dalles Formation" by Hodge (1938), "Hood River Conglomerate" by Warren (1941), "Troutdale Formation" by Allen (1979), "Snipes Mountain conglomerate" (Ellensburg Formation) by Bela (1982), and Ellensburg Formation by Korosec (1987). Much of the problem has stemmed from the fact that these deposits contain clasts of highly distinctive lithologies (e.g., quartzite, granite, gneiss). The presence of these distinctive clasts compelled past investigators to either define these deposits as new units and/or correlate them to units contain similar clast-lithologies. As Waters (1973, p. 143) succinctly pointed out, the presence of the exotic clasts can be found stratigraphically throughout the section, from pre-CRBG deposits, interbedded deposits within the CRBG, to post-CRBG deposits - so correlations based solely on the presence of these clasts are late often proved to be wrong. The mere presence of similar exotic clasts lithologies within deposits does not make them correlative, but simply means that they were deposited by a river system that headwaters lay beyond the boundaries of the Columbia River flood-basalt province in northern Washington, Idaho, or British Columbia. Since the 1980's, much work has focused on unraveling the paleodrainage history of this region using regional mapping of the CRBG to help provide time-stratigraphic control on these interbed deposits.

Continue west on Highway 14. 33.2   Road tunnels on Highway 14 are cut through dipping Grande Ronde Basalt flows. Across the river is Mitchell Point, Oregon (Fig. 23). Mitchell Point preserves the southern portion of the ancestral Columbia River canyon (the Bridal Veil Canyon, Fig. 20) which both the Huntzinger and Pomona flows used as a conduit to enter western Oregon and Washington. The northern portion of this canyon complex has been destroyed by the present-day Columbia River when it began to incise the Gorge. This exposure of the Pomona flow was first recognized by James L. Anderson (Anderson, 1980).

As shown in Figure 23, the jointing style exhibited by the Pomona intracanyon flow is nearly the same as that observed at Stops 1 -2 and 2-5 where the Pomona was emplaced as a sheet flow. The Pomona flow is unique in that its jointing style does not alter dramatically when its mode of emplacement (i.e., sheet flow verses intracanyon flow) changes. The reason for this is not known.

Also note that the base of Pomona intracanyon flow at Mitchell Point does not exhibit either pillow lavas or hyaloclastite deposits (Fig. 23; Anderson, 1980). This indicates that the Pomona flow advanced down a "dry" canyon. The canyon was dry because the Pomona flow had dammed the ancestral Columbia
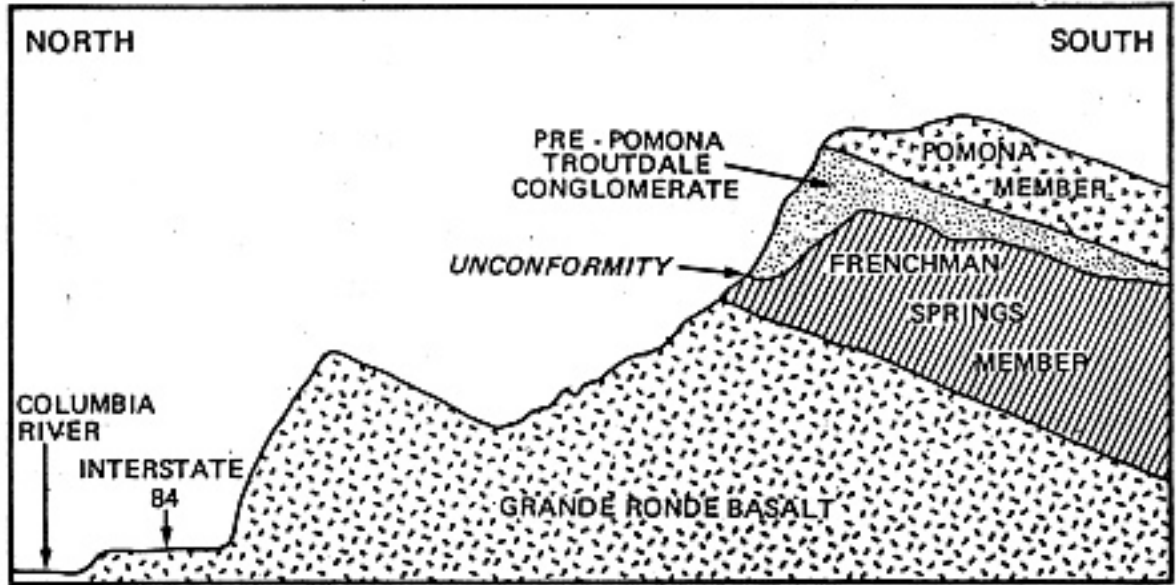
Figure 23. *Cross section through Mitchell Point showing preserved southern portion of the Bridal Veil channel of the ancestral Columbia River.*

River in the northern Pasco Basin and the ancestral Salmon-Clearwater River in the Lewiston Basin, thus temporarily shutting of the supply of water. The lack of extensive pillow complexes and hyaloclastic debris along the length of the Pomona intracanyon flow supports a rapid flow emplacement model (on the order of weeks to months) and not a long-duration empalcement model (on the order of many years to decades).

If the Pomona flow was emplaced over along period of time (years to decades), we should find ample evidence that the ancestral Columbia River had reestablished its presence in this canyon before the Pomona flow was completely emplaced. The lava dam created by the Pomona flow in the Pasco Basin (on the order of 15 to 30 m-high) would have resulted in an impoundment that would likely have over topped the lava dam in a period of a few months. In a long duration emplacement model, the waters of the ancestral Columbia River would have been able to overtop the lava dam long before the slowly advancing Pomona flow had reached its most distal point (Miocene Washington coast) and certainly long before it was inflated to its final thickness. Because the ancestral Columbia River did reoccupy this canyon, we would have expected to find, at some point, where the river waters overtook the slowly advancing flow front. Here the river would encounter molten Pomona lava. The consequences of the river encountering an active Pomona flow front would be the creation of large quantities of hyaloclastic debris and the presence of intraflow structures indicative of lava/water interaction. The hyaloclastic debris would be continuously created by this process as well as being transported and deposited downstream in advance of the

flow front. The absence of such features along the intracanyon complex here and even west of Longview, Washington, forces us to reject the long duration emplacement model for the Pomona flow.

36.4   Little White Salmon River (Drano Lake) Bridge. Continue west on Highway 14.

37.1   Cook-Underwood Road. Continue west on Highway 14.

38.6   Dog Mountain. This is the thickest, unrepeated, exposed section of Grande Ronde Basalt (more than 1.3 km) west of the Columbia Plateau and is the only exposed section that contains flows representing all four Grande Ronde magnetostratigraphic units (Anderson, 1987). The oldest Grande Ronde unit exposed belongs to the Teepee Butte Member (Reidel and Tolan, 1992; Fig. 2).

39.6   Dog Mountain Trailhead. Continue west on Highway 14.

40.3   Crossing the Collins Point (Wind Mountain) landslide complex. Over the past 50 years this landslide complex has had a history of repeated movement and has caused significant damage to Highway 14.

Continue west on Highway 14.

41.0   Park in turnout next to Wind Mountain quarry entrance.

STOP 2-8: Wind Mountain Intrusion.

Wind Mountain is one of several microdioritic intrusions in this area (e.g., Government Cove and Shellrock Mountain across the river in Oregon; Free, 1976; Swanson and others, 1981) that have a general northwest-trending alignment that coincides with the southern extension of Saint Helens seismic zone. Fragment of Grande Ronde Basalt (xenoliths) have been found in most all of these intrusions (Free, 1976), indicating they are younger than the Grande Ronde Basalt. K-Ar whole-rock ages of 6.6 + 0.7 Ma for Wind Mountain and 5.7 + 0.6 Ma for Shellrock Mountain. Most geologists who have studied Wind and Shellrock Mountains believe that magma from them reached the surface and formed volcanic edifices that were subsequently removed by erosion (Hodge, 1938; Lowry and Baldwin, 1952; Waters, 1973; Free, 1976; Allen. 1979). The age of the Wind and Shellrock intrusives provide a constraint on the maximum age of uplift and subsequent incision of the present-day Gorge. Stratigraphic relationships between Cascadian high-alumina basalts and the Troutdale Formation that will be viewed at the next stop (Stop 2-9) place the age of the onset of uplift and incision of the present-age Gorge at around 2 Ma.

Continue west on Highway 14.

42.9   Entering Home Valley. Continue west on Highway 14.

44.0   Wind River Bridge. 48.6   Entering Stevenson, Washington.

49.2   Turn left on Russell Avenue. Continue south (towards Columbia River) Shipboard Park and Stevenson Landing. Park in parking area located across railroad tracks. Walk down to waterfront.

STOP 2-9: View of Benson Plateau, Oregon.

The cliffs directly across the river consist of Grande Ronde Basalt overlain by Troutdale vitric sandstone and conglomerate (reddish-orange band atop the vertical cliff face) which are capped by Cascadian high-alumina basalt flows. The Benson Plateau surface (Fig. 24) was formed by Cascadian high-alumina basalt flows that flowed into the Bridal Veil channel of the ancestral Columbia River and eventually capped this former course of the Columbia River (Tolan and Beeson, 1984). It is the onset of Cascadian high-alumina basaltic volcanism, and resulting dynamic interaction with the ancestral Columbia River in the Bridal Veil channel in late Troutdale time, that resulted in the relatively rapid aggrading of the canyon and eventual shift of the river to its present-day position (Tolan and Beeson. 1984). Incision of the Gorge began with the onset of regional uplift.

So when did uplift begin? Based on field and relative age relationships, Tolan and Beeson (1984) speculated that the onset of uplift in this area could have begun as late as 2 Ma. Since then we have been able to obtain K-Ar whole-rock ages of 2.21 +0.10 Ma for the uppermost high-alumina basalt flow on Benson Plateau and 1.91 + 0.07 Ma for another high-alumina basalt flow capping the Bridal Veil channel at Nesmith Point, approximately 15 km west of Benson Plateau (Conrey and others, 1996). These data support our hypothesis that the present-day Gorge is a geologically "young" feature.

Retrace route back to Highway 14.

49.6   Intersection with Highway 14, downtown Stevenson. Turn left (west) onto Highway 14.

52.2   Cascade Locks Toll Bridge (Bridge of the Gods). Turn left and cross bridge into Cascade Locks, Oregon.

52.9   Junction with Cascade Locks Highway. Turn left and follow signs to Interstate 84 westbound.

53.5   On ramp to Interstate 84 westbound.

55.4   View of Bonneville Dam and the Cascade Landslide Complex on the Washington-side of the River. The Cascade Landslide Complex consists of a series of landslide lobes, with the youngest being the Bonneville Landslide lobe (Fig. 25) which dammed the Columbia River giving rise to the Native American legend of the "Bridge of the Gods" (Waters, 1973; Allen. 1979; Wang and others, 2002). This landslide buried the existing Columbia River channel and the river cut a new channel approximately 1.6 km south of its former position. There is some debate as to the exact age of the Bonneville Landslide. Recent radiocarbon ages (Pringle and Schuster, 1998) and lichen-growth studies (Reynolds, 2001) indicate a calendric age of AD 1500 to 1760. Schuster and Pringle (in Wang and others, 2002, p. 285) suggest that the Bonneville Landslide may have been triggered by the January 27, 1700 great subduction zone earthquake. Coring of upright, old-growth trees on the Bonneville landslide yields ages of >360 years, suggesting that this slide predates the 1700 subduction zone earthquake (Pat Pringle, personal communication, 2002).

56.0   Bonney Rock. Freeway cuts expose a diabase intrusion that was part of a feeder dike for Cascadian high-alumina basalts. This intrusion has yielded a K-Ar whole-rock age of approximately 3 Ma.

56.6   Excellent exposures of interstratified Cascadian

Figure 24. *View of the eastern side of Benson Plateau (north is to right). The plateau surface consists of high-alumina basalt flows that capped the Bridal Veil channel of the ancestral Columbia River from ~ 3 to 2 Ma.*

debris flow deposits and fluvial volcaniclastic sediments the lower Miocene-age (pre-CRBG) Eagle Creek Formation.

58.8   Across the river is Beacon Rock. Beacon Rock is a volcanic neck and is composed of olivine-bearing, high-alumina basalt. No reliable radiometric age dates have been obtained from Beacon Rock, but is likely between 4 and 2 Ma.

61.1   Take the Ainsworth Exit (Exit 35) off Interstate 84. Follow signs to Historic Columbia River

Highway. Continue west on Historic Columbia River Highway.

62.9   Horsetail Falls. Continue west on Historic Columbia River Highway.

63.2   Oneonta Gorge. Continue west on Historic Columbia River Highway.

65.5   Multnomah Falls. Continue west on Historic Colum-

bia River Highway.

66.0   Wahkeena Falls. Continue west on Historic Columbia River Highway.

68.5   Junction with Bridal Veil exit (Angel's Rest trailhead). Continue west on Historic Columbia River Highway.

68.6   Junction with Palmer Mill Road. Turn left here for start of optional side trip to examine the natural cross-section through the Bridal Veil channel or continue west on Historic Columbia River Highway.

Optional Side Trip

On this side trip you will have a chance to examine the Pomona intracanyon flow, Rhododendron debris flows/lahars. lower and upper members of the Troudale Formation, and Cascadian high-alumina basalt.

A NOTE OF CAUTION: Palmer Mill Road is a narrow, steep, gravel road that is not scenic but is geologically interesting. There is a turnaround at the top of the hill, and it is safer to

Figure 25. *View of the Bonneville landslide. Visible on the lower left side of photo is the north powerhouse of Bonneville Dam.*

stop and look at outcrops on the way back down the hill. For that reason mileages of stops and features of interest are given for coming down the road. Please park only in turnouts and do not block the road.

{0.0}   Palmer Mill Road and Historic Columbia River Highway intersection. Turn left onto Palmer Mill Road. Proceed to top of hill.

{1.6}   Turnaround at top of hill. Turnaround and begin down Palmer Mill Road.
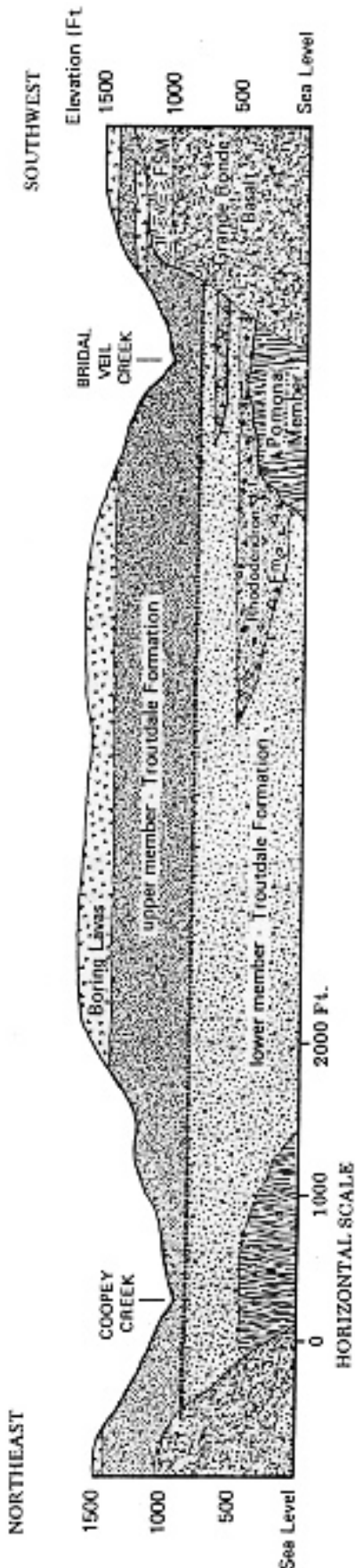
{1.9}   Park in turnout.

Side Trip Stop 1: High-Alumina Basalt and Upper Member of the Troutdale Formation.

This stop is located on the southwestern rim of the Bridal Veil canyon (Fig. 26). Here we can see Cascadian high-alumina basalt flows capping the Bridal Veil channel, excellent examples of the upper member of the Troutdale Formation vitric and lithic sandstone, and a high-alumina basalt flow that is interbedded with the upper member of the Troutdale Formation.

Walk back down the road approximately 0.1 miles to where the road grade begins to steepen. Exposed in the road cut (and road) is a blocky jointed, vesicular, plagioclase/olivine phyric. high-alumina basalt flow. This flow overlies a thin (5 m-thick) upper member Troutdale vitric sandstone that unconformably overlies Frenchman Springs Member of the Wanapum Basalt (Fig. 26), dated here as 15.2 Ma by K-Ar whole rock determination (Tolan, 1982). A K-Ar whole rock age of 3.00 + 0.44 Ma was obtained for this interbedded high-alumina flow (Conrey and others, 1996).

As you walk back up the road, examine the nature and character of the vitric sandstone overlying the high-alumina basalt flow. Note that the yellow to reddish-orange color of the exposure is due to the alteration of the basaltic glass that composes these sand beds.

In the hillside above the vitric sandstone exposure, are outcrops of high-alumina basalt flows that cap the Bridal Veil channel.   A K-Ar whole rock age of 2.06 + 0.05 Ma was obtained for this flow. The age of this flow capping the Bridal Veil channel here at Palmer Mill Road is consistent with other high-alumina basalt flows to the east that cap this

channel at Nesmith Point and Benson Plateau.

Continue down Palmer Mill Road.

{2.0}   Driving across high-alumina basalt flow interbedded with the upper member of the Troutdale Formation seen at the last stop.

{2.4}   Park in turnout on left side of road.

Side Trip Stop 2: Lower Member of the Troutdale Formation.

The contact between the upper and lower members of the Troutdale Formation is gradational and occurs across a 15 m-interval at approximately 800 ft elevation (Fig. 26). This stop is located at approximately 650 ft elevation and the sandstone and conglomerate exposed in the road cuts belong to the lower member of the Troutdale Formation (Tolan. 1982; Tolan and Beeson, 1984). The sediments exposed here are representative of the lower member of the Troutdale Formation. Here we can see poorly to moderately indurated, exotic lithology (exotic lithologies include quartzite, granite, gneiss, metavolcanics, cherts) pebble-cobble, framework conglomerates interbedded with poorly to moderately indurated, micaceous, quartzose-arkosic sandstone.

Continue down Palmer Mill Road

.
{2.8}   Park in turnout on left side of road.

Side Trip Stop 3: Pomona Intracanyon Flow and Rhododendron Lahars

The mound-shaped, entablature-jointed outcrop on the left is an erosional remnant of the Pomona intracanyon flow. The Pomona basalt at this locality is abundantly plagioclase phyric and sparsely olivine phyric. This change in lithologic appearance, in comparison to its appearance in the western Columbia Plateau, may have prevented early Columbia River basalt mappers (e.g., A.C. Waters and R.D. Bentley) from recognizing these exposures as Pomona basalt.

Overlying the Pomona flow here is a Rhododendron lahar. It is poorly exposed in the road bank on the right. To examine it you may have to scrape off a layer of colluvial soil and vegetation. If you do, please be careful to keep the drainage ditch clear of debris. The lahar consists of hornblende dacite clasts and carbonized

Figure 26. Generalized cross section through the Bridal Veil channel at Bridal Veil, Oregon. Here the ancestral Columbia River incised a canyon into Frenchman Springs Member (FSM) and Grande Ronde Basalt flows that was greater than 245 m deep. Remnants of the Pomona Member intracanyon flow indicate that it only partly filled the canyon at 12 Ma. In post-Pomona time, the ancestral Columbia River continued to deposit sands and gravels (lower member of the Troutdale Formation). The onset of Cascadian high-alumina basaltic volcanism is reflected in the composition of the upper member of the Troutdale Formation sediments. The total thickness of Troutdale sediments exposed here exceeds 335 m. High-alumina basalt flows (Boring Lavas) capped this channel and forced the ancestral Columbia River to its present-day position and prevented the river from re-occupying this former course when this region began to uplift about 2 Ma. Modified from Beeson and Tolan (1990).

wood set in a clay matrix (Tolan, 1982; Tolan and Beeson, 1984). This lahar is overlain by conglomerate and sandstone of the lower member of the Troutdale Formation (Fig. 26).

{3.2}   Junction with Historic Columbia River Highway. Turn left and resume main trip route.

END OF OPTIONAL SIDE TRIP

69.1   Pomona intracanyon flow.

69.2   Crossing Bridal Veil Creek. Bridal Veil Creek marks the southern margin of the Bridal Veil canyon. The CRBG outcrops in, and immediately west of, the creek are Wapshilla Ridge Member flows of the Grande Ronde Basalt (Fig. 2).

70.2   Shepards Dell.

70.3   Lava flow outcrops along the left side of highway are not CRBG, but Oligocene Skamania Volcanics.

71.4   Latourell Falls. Turn left and park in parking lot.

STOP 2-10 (optional): Latourell Falls and Skamania Volcanics.

Time permitting, we will take a short walk down the path to the base of lower Latourell Falls. An almost flat-lying, horizontally platy Skamania dacite flow is exposed at the parking lot and along the trail to the base of the falls. Given the viscous nature of dacite flows, we are proximal to a Skamania vent.

Latourell Creek spills over a 76 m-high entablature/colonnade-jointed Sentinel Bluffs Member flow (Grande Ronde Basalt; Fig. 2). This Sentinel Bluffs flow filled an old stream valley incised at the margin of the preceding CRBG flow and the older Skamania Volcanics highland. Note the presence of large rounded boulders exposed at the base of the Sentinel Bluffs flow, and the lack of a pillow complex, just below the colonnade. The well developed entablature/colonnade pattern is atypical for this flow; elsewhere in this region where it was emplaced as a sheet flow is displays a blocky-columnar jointing style. The entablature/colonnade jointing pattern appears to have resulted because this flow was emplaced as an intracanyon flow.

Continue west on the Historic Columbia River Highway.

73.1   Margin of the ancestral Columbia River canyon (incised into Skamania Volcanics) that was filled by the 14.5 Ma Rosalia intracanyon flow, eliminating that channel (Fig. 22).

73.3   Minor pillow complex at the margin of the Rosalia intracanyon flow. This pillow Complex formed when the Rosalia

intracanyon flow dammed and backfilled a small, local tributary stream that drained the Skamania highland.

73.5   Crown Point. Due to remodeling and restoration activities on the Vista House parking is limited. If no parking is available, proceed to next stop.

STOP 2-11 (optional): View of CRBG Intracanyon Pathways

Several features can be seen better from here than at our final field trip stop at Women's Forum State Park (Stop 2-12). The Pomona intracanyon flow is exposed in the quarry along the railroad tracks on the Washington side of the river. The Bridal Veil channel on the Oregon side of the river lies just east of the Bridal Veil Exit off of Interstate 84. The talus slope seen above the town of Bridal Veil is derived from outcrops of the Pomona intracanyon flow. The Vista House is built atop Crown Point. Here you are standing on the eroded top (eroded by Cataclysmic flood waters that topped Crown Point) of the 14.5 Ma Rosalia intracanyon flow, more than 215m above the former bottom of the ancestral Columbia River canyon. Here the Rosalia intracanyon flow consists 155 m of entablature/colonnade-jointed basalt overlying more than 60 m of bedded Rosalia hyaloclastite. Figure 27 is a photo of the north face of Crown Point below the Vista House. Note the lack of any pillow lavas at the base of the Rosalia flow indicating the ancestral Columbia River canyon was "dry" when this flow was emplaced.

Continue west on highway.

73.9   Vitric sandstone and conglomerate belonging to the upper member of the Troutdale Formation exposed in road cuts for the next 0.7 miles.

73.3   The blocky-jointed high-alumina basalt flow on the left is interbedded with the upper member of Troutdale Formation. This is also the headwall of the Crown Point landslide. The highway has subsided more than 7 m at this locality. We infer the failure plane for this landslide to be the unconformity between Skamania Volcanics and the overlying CRBG/Troutdale Formation.

75.0   Entrance to Women 's Forum State Park. Turn right and proceed to view point.

STOP 2-12: CRBG Intracanyon Flows and the Paths of the Ancestral Columbia River.

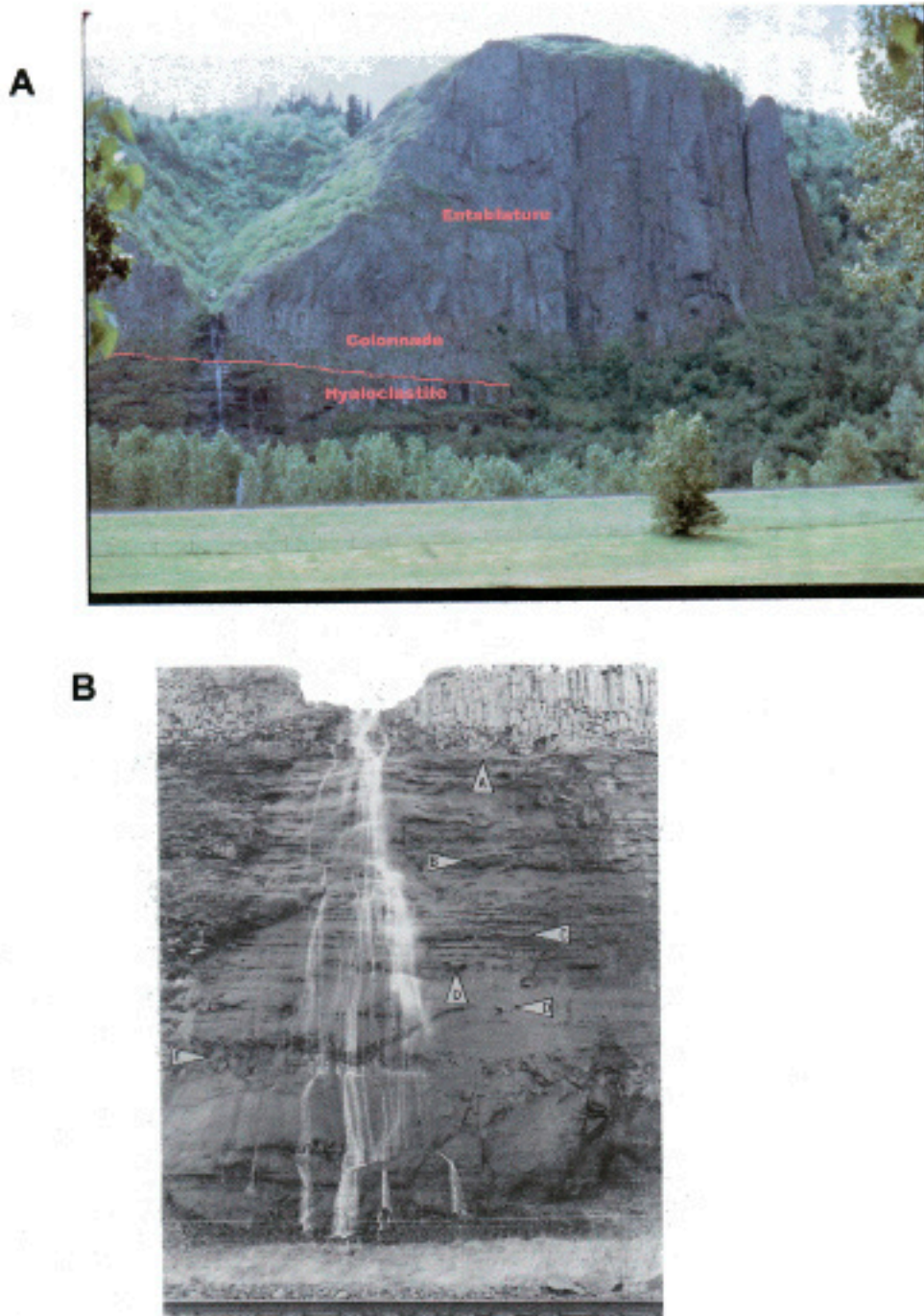Figure 28 is a photograph of the view from this location. From here we can see the intersection of 3

Figure 27. *A view of the northern face of Crown Point. A. Photo showing Rosalia basalt flow overlying bedded hyaloclastite. B. Close-up of bedded Rosalia hyaloclastite. Letter on photo: A - contact between Rosalia basalt and hyaloclastite, note lack of pillow lava. B - foreset-bedded hyaloclastite. C - laminar-bedded hyaloclastite. Differences in degree of induration (susceptibility to weathering) between hyaloclastite beds allow some beds to stand out in relief, producing the horizontal ridges seen here. D - scattered foreign boulders and cobbles of Skamania Volcanics, Grande Ronde Basalt, and Frenchman Springs Member of the Wanapum Basalt. The local availability of these rock types, their generally poor degree of rounding, and their relatively large size in comparison to the Rosalia hyaloclastic debris indicate that they were derived locally from the sides of the ancestral Columbia River canyon and not transported far. E - foreign boulder conglomerate.*
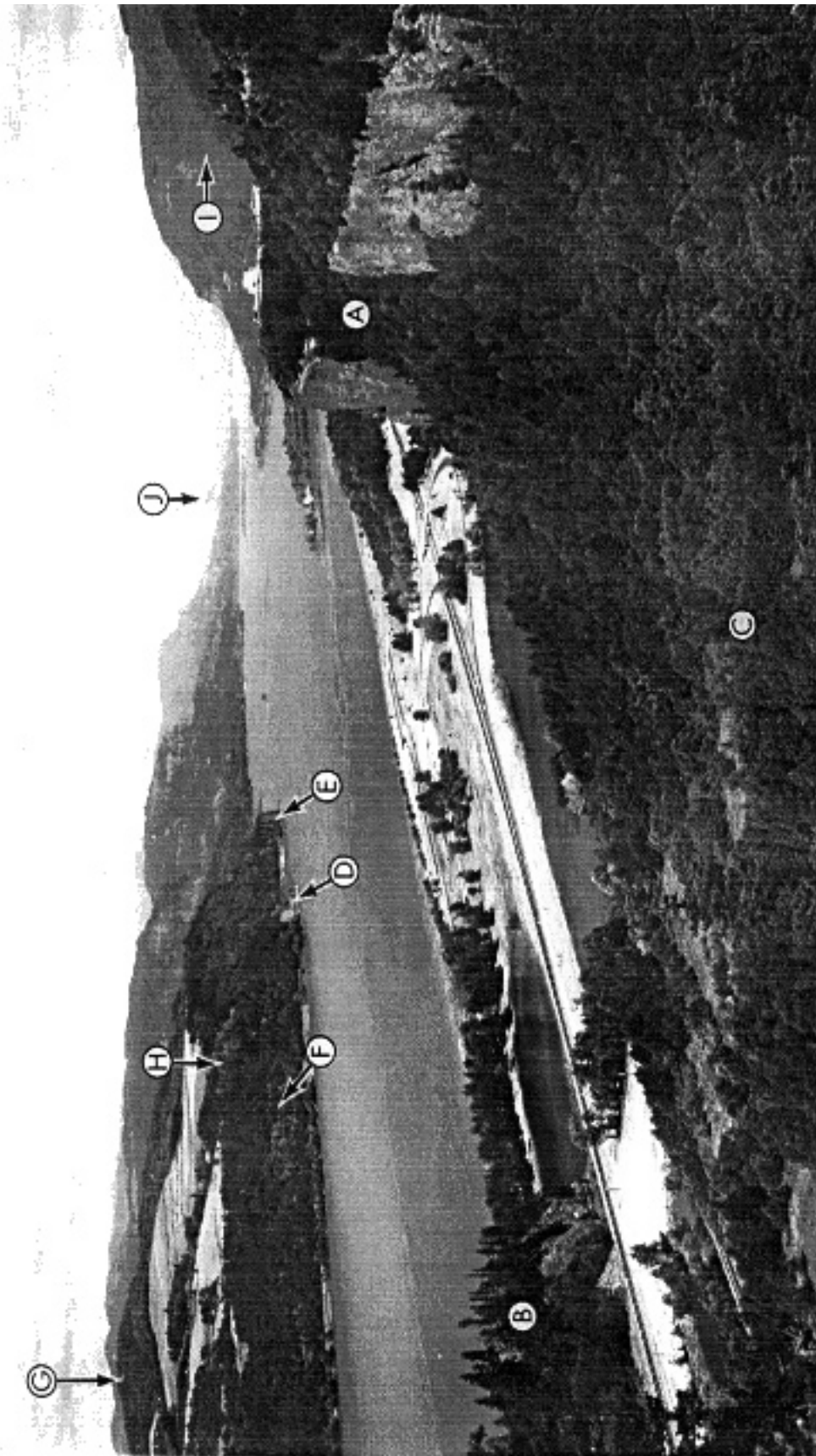
Figure 28. *View from Womens State Park (Stop 2-12). Features seen here are: A - Crown Point, a portion of the Rosalia intracanyon flow which overfilled the ancestral Columbia River canyon at 14.5 Ma. B - Rooster Rock landslide block. C - Crown Point landslide. D - Remnant of the Pomona intracanyon flow in the Bridal Veil channel of the ancestral Columbia River. E - Grande Ronde Basalt flows near Cape Horn that form the northern canyon wall of the Bridal Veil channel. The southern portion of the canyon wall was removed by the modern-day river. F - Lower member sandstone and conglomerate of the Troutdale Formation that were deposited within the confines of the Bridal Veil channel. G - Mount Zion, a Boring Lavas volcano that postdates the Troutdale Formation. H - small high-alumina basalt flow from the Mount Zion volcano. I - Location of the Bridal Veil channel on the Oregon side. J - Beacon Rock, a high-alumina basalt volcanic neck.*

Columbia River channels - the 14.5 Ma canyon filled and destroyed by the Rosalia flow, the Bridal Veil channel that the Huntzinger and Pomona flows used as a conduit to enter western Oregon and Washington, and the present-day canyon of the Columbia River.

END OF FIELD TRIP