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Chapter 3

Bedrock Geology of The Northern Columbia Plateau and Adjacent Areas

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ABSTRACT

The Columbia Plateau is surrounded by a complex assemblage of highly deformed Precambrian to lower Tertiary continental and oceanic rocks that reflects numerous episodes of continental accretion. The plateau itself is comprised of the Columbia River Basalt Group, a tholeiitic flood-basalt province of moderate size covering an area of about 2 x 10^5 km^2 with an estimated volume of 2 x 10^5 km^3. The Columbia River basalt, formed between about 16.5 x 10^6 years B.P. and 6 x 10^6 years B.P., is the youngest known flood basalt. More than 99 percent of the basalt was erupted during a 2.5-3 x 10^6 years interval centered about 15 x 10^6 years B.P., building a featureless plateau that sloped toward its center, reflecting concurrent subsidence and volcanism. Eruptions were infrequent between about 14 and 6 x 10^6 years B.P., allowing time for erosion and deformation between successive outpourings. The present-day courses of much of the Snake River, and parts of the Columbia River, across the plateau date from this time. Basalt produced during this waning activity is more heterogeneous chemically and isotopically than older flows, reflecting its prolonged period of volcanism. Most of the flows are thick and ponded behind natural levees. They were erupted from north-northwest-trending linear fissure systems tens of kilometers long, revealed today by dikes and relic vent areas. Eurption rates are estimated for various flows as between 1 km^3/day and 10^{-4} km^3/day per linear kilometer of active fissure, with flow rates of 5 to 15 km/hr down slopes of 1:1,000 considerd typical. Current magma production rates in Hawaii could have produced the basalt in the allotted time. No available models adequately account for the tectonic setting of the province and its relation to coeval calc-alkaline volcanism in the Cascade Range.

INTRODUCTION

The Columbia Plateau is perhaps the best area on Earth to view evidence of catastrophic flooding of truly impressive magnitude. The youngest series of floods produced the famed Channeled Scabland, which we will examine during this field conference. But an earlier episode of repeated flooding left telltale marks of a totally different but equally impressive kind; this flooding, involving lava, not water, deposited the flood basalt that built the Columbia Plateau in Miocene time. It is a remarkable coincidence that two such large yet unrelated inundations occurred in the same area and that evidence for both of them can be examined in many of the same outcrops.

This paper attempts to summarize briefly the bedrock geology of the northern Columbia Plateau and its surroundings, emphasizing the deposits of the lava floods, the Columbia River Basalt Group.

ROCKS BORDERING THE NORTHERN COLUMBIA PLATEAU

The Miocene basalt overlies and encroaches upon a diverse assemblage of Precambrian to lower Tertiary rocks (Figs. 3.1 and 3.2). The depositional, intrusive, and structural histories of these rocks are very complex and poorly known.

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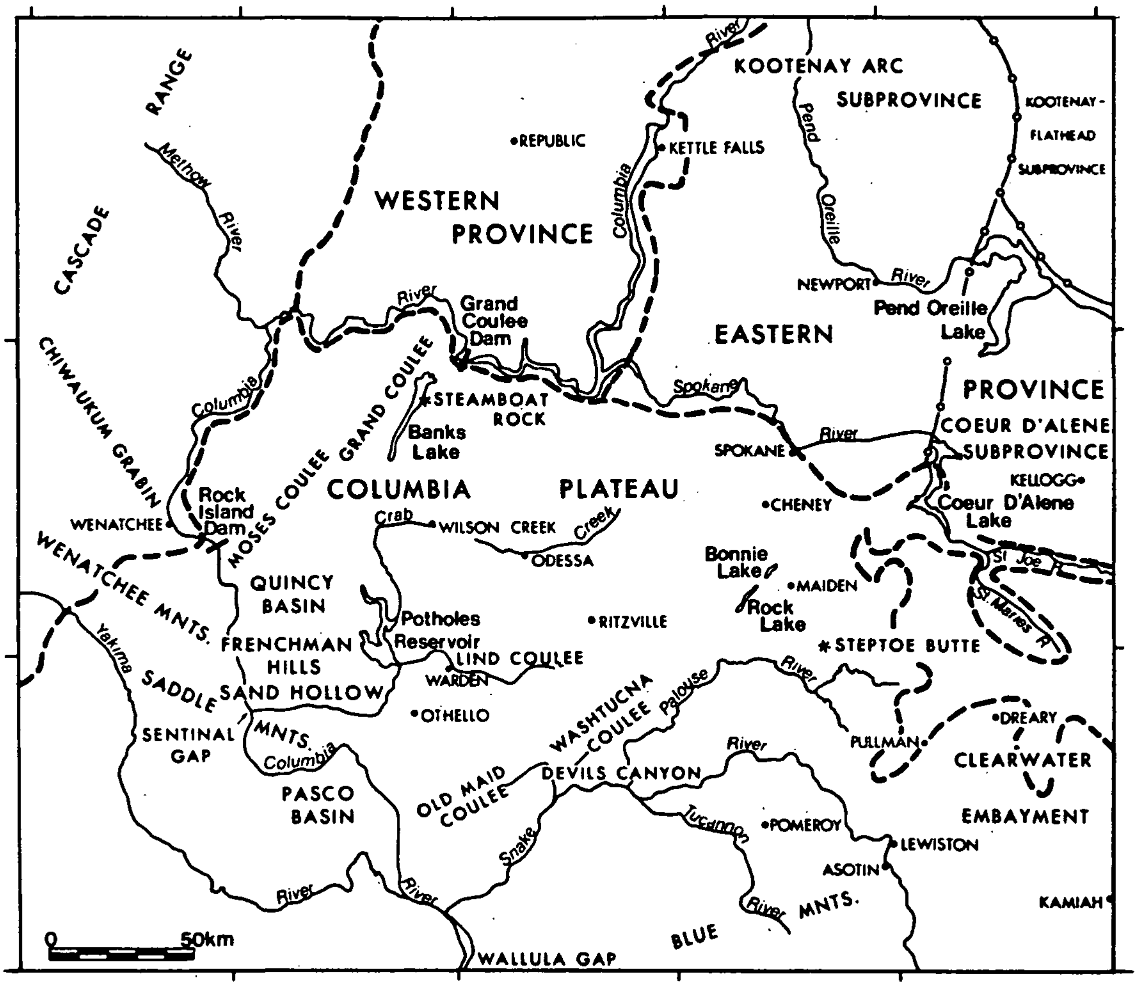


Figure 3.1. Index map showing localities and boundaries of provinces and subprovinces mentioned in text. Boundaries north of Columbia Plateau from Yates and others (1966). Other province boundaries based on Newcomb (1970).

They form highlands that rise abruptly from the margins of the plateau. No glacial floods coursed across them, except between the ice dam across the Clark Fork River and the plateau near Spokane. Glaciers descending from the highlands blocked major drainages and played an important role in scabland development by diverting water onto the plateau.

Yates and others (1966) provide an excellent summary of the pre-Miocene rocks north of the plateau and east of the Okanogan Valley. They have subdivided the region into the geologically distinct Eastern and Western Provinces, separated by the valley of the Columbia River (Fig. 3.1).

The Eastern Province is structurally divisible into three subprovinces, which Yates and others (1966) designated the Kootenay-Flathead, Coeur d'Alene, and Kootenay Arc subprovinces (Fig. 3.1). The *Kootenay-Flathead subprovince* is characterized by subparallel, broad, open folds trending northwest to north-northwest; normal faults with displacements of hundreds of meters or more parallel the folds. The major folding is of Laramide age, but the faults are somewhat

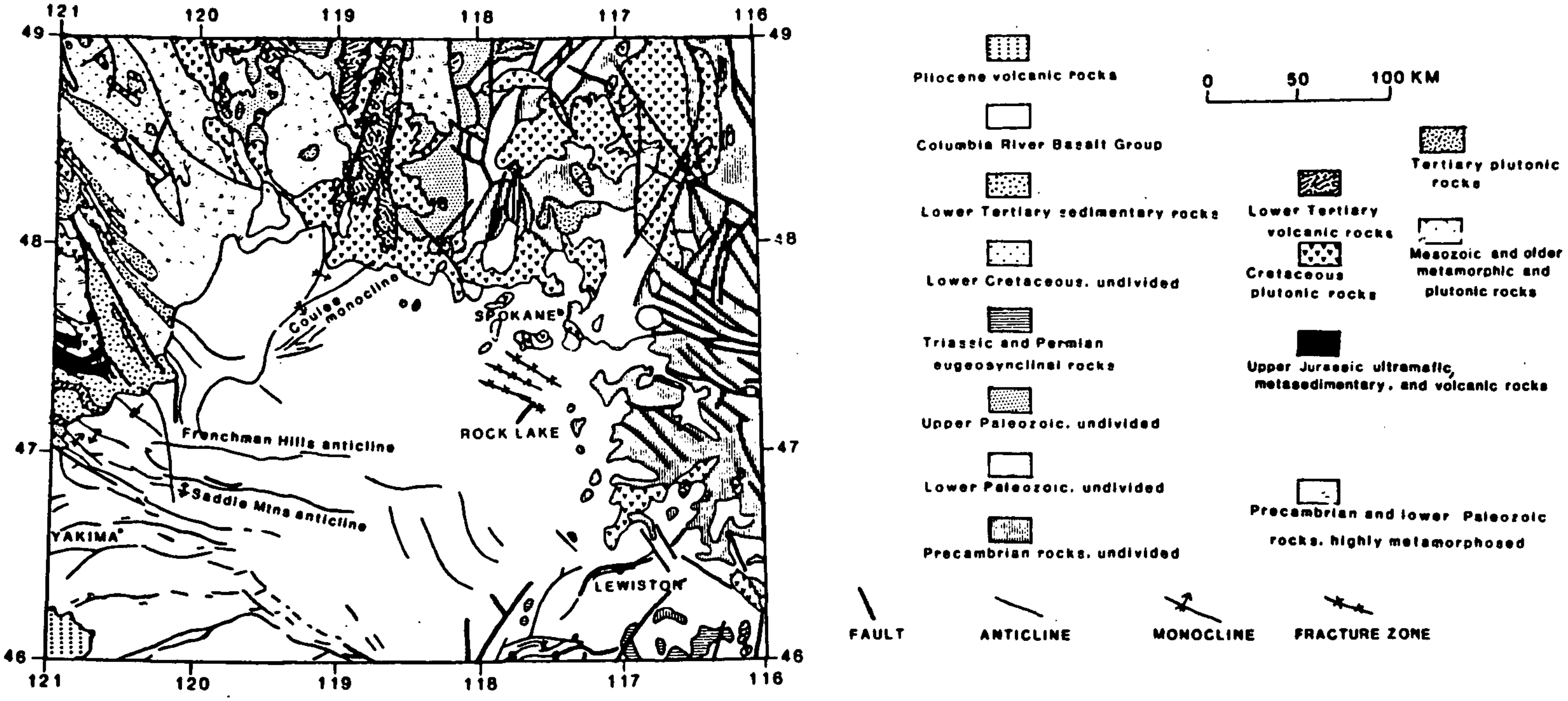


Figure 3.2. Geologic map of northern part of Columbia Plateau and surrounding area, simplified from King and Beikman (1974). Anticlinal axes, shown only on Columbia Plateau, from Newcomb (1970) with additions from Bond (1963), Griggs (1973), Swanson and others (1977), and Tabor and others (1977).

younger. The *Coeur d'Alene subprovince* contains numerous west-northwest-trending strike-slip faults (Fig. 3.2), the most notable being the Hope fault forming the northern boundary to the subprovince and the Osburn fault, both of which have right-lateral displacement of at least 25 km. This set of strike-slip faults defines a part of the Lewis and Clark line, which shows evidence of repeated movement from Precambrian to Cenozoic time (Reynolds and Kleinkopf, 1977). The subprovince contains the famed Coeur d'Alene mining district in the Wallace and Kellogg area of Idaho. The Purcell Trench separates the *Kootenay Arc subprovince* from the other two subprovinces. The Purcell Trench appears to be a major north-trending fault or fault zone separating highly metamorphosed Belt rocks on the west from mildly metamorphosed Belt rocks on the east. This contrast in metamorphic grade can be seen on either side of Rathdrum Prairie northeast of Spokane, just downstream from the site of the ice dam that impounded Lake Missoula (Griggs, 1973). Folds in the Kootenay Arc show an overall northeast trend and are of either Late Jurassic or Early Cretaceous age. The southern part of the Kootenay Arc subprovince is complex, with numerous strike-slip and thrust faults and, locally, large overturned folds cut by high-angle dip-slip faults (Miller, 1975). Deformation here has occurred intermittently since the Precambrian.

The Western Province of Yates and others (1966) contains a eugeosynclinal assemblage of graywacke, greenstone, dark shale and slate, thin chert layers, conglomerates, and pods and lenses of limestone. This assemblage represents a fundamental contrast with the miogeosynclinal character of the rocks in the Eastern Province, but the nature of the boundary between the two provinces is unknown. The age of the eugeosynclinal rocks ranges from Carboniferous to Middle Jurassic. No major unconformities reflecting orogenies during accumulation of these rocks have been recognized in the Western Province. The entire assemblage was folded and faulted, commonly along north to northwest trends, during Late Jurassic or Early Cretaceous time. The Western Province also contains high-grade metamorphic rocks of unknown age; some of these have been interpreted as gneiss domes (Fox and others, 1977; Rinehart and Fox, 1976).

Extensive batholiths intruded both the Western and Eastern (mainly the Kootenay Arc subprovince) Provinces in Late Triassic to Eocene time (Miller, 1975), with perhaps the main pulse of intrusive activity in the middle Cretaceous. These plutonic rocks vary from quartz diorite to quartz monzonite, including a distinctive two-mica quartz monzonite (Miller, 1975). Batholithic rocks comprise more than 50 percent of the exposed terrane over much of the Western Province and the Kootenay Arc subprovince. Similar plutonic rocks underlie much of the area between the Okanogan River and the Methow graben and occur south of the graben as far as the Entiat River drainage system.

Volcanic rocks, chiefly dacite to quartz latite, were erupted principally during the early and middle Eocene (Pearson and Obradovich, 1977) north of the Columbia Plateau. They are associated with clastic sedimentary rocks composed of material eroded from the uplifted batholithic rocks and their wallrocks. These Eocene rocks are best preserved north of Grand Coulee Dam along the north-northeast-trending Republic graben, which was apparently forming during the period of volcanic activity. Volanic rocks of comparable age, which may be erosional remnants of an originally extensive field, occur in Washington in the Toroda Creek graben northwest of Republic (Rinehart and Fox, 1976), along the Okanogan River, at several localities near Kettle Falls, along the Pend Oreille River northwest of Newport, and in a north-northwest belt near the mouth of the Spokane River (Pearson and Obradovich, 1977).

The eastern margin of the northern Columbia Plateau south of the Couer d'Alene subprovince is developed against the Belt Supergroup and, south of about latitude 46° 45′, the Bitterroot lobe (Armstrong, 1975) of the Idaho batholith and its highly metamorphosed wallrock. The Bitterroot lobe, just east of the area shown in Figure 3.2, consists mainly of granodiorite and granite of probable Late Cretaceous age (Hyndman and Williams, 1977). A younger, Eocene suite of granite is volumetrically subordinate. The wallrock of the Bitterroot lobe has generally been considered to be strongly metamorphosed Belt Supergroup, but Armstrong (1975) recently showed that at least the southern and western parts of the lobe intruded pre-Belt high-grade metamorphic rocks about 1,500 x 10^6 years ago. Minor volumes of lower Cenozoic volcanic rocks of intermediate and silicic compositions occur near Deary and Kamiah, Idaho, in the Clearwater embayment (Bond, 1963).

The northwestern and western parts of the northern Columbia Plateau abut against the Cascade Range. The north Cascades, north of about latitude 47° 15′, consist mainly of pre-Cretaceous gneiss and schist intruded by Mesozoic and Tertiary plutons. The parent material for the metamorphic rocks is mostly Paleozoic sedimentary and volcanic rocks (Misch, 1966, 1977). Several periods of metamorphism are known. The dominant structural trends are north to northwest and include major strike-slip, thrust, and dip-slip faults and fault zones (Misch, 1966; Yeats, 1977). Ultramafic rocks, considered by some workers to be parts of ophiolite complexes, occur in a few fault-bonded blocks. Sedimentation and lesser volcanism occurred in the Methow graben from Jurassic to early Tertiary, and in the Chiwaukum graben in early Tertiary times (Gresens and others, 1977; McKee, 1972). South of about latitude 47° 15′, the Cascades are composed dominantly of Tertiary volcanic rocks, calc-alkaline in character, intruded by shallow plutons and overlain in places by Quaternary basalt, andesite and dacite. The Columbia River Basalt Group overlies, interfingers with, and underlies volcanic rocks of Cascade derivation most of which is related to ongoing subduction of the Juan de Fuca or Farallon plate (Christiansen and Lipman, 1972; Dickinson, 1970).

COLUMBIA RIVER BASALT

Introduction

The Columbia River Basalt Group comprises a tholeiitic flood-basalt province of moderate size, covering an area of about 2 x 10^5 km^2 with an estimated volume of 2 x 10^5 km^3 of basalt (Waters, 1962). The province is commonly referred to as the Columbia Plateau, although some physiographers prefer to distinguish the Blue Mountains area in southeast Washington and northeast Oregon, large parts of which are underlain by the basalt, as a separate geomorphic province (see Baker, Ch. 2, this volume).

The group is the youngest assemblage of flood basalt known. Radiometric ages indicate that it was formed between about 16.5 and 6 x 10^6 years B.P. (Watkins and Baksi, 1974; McKee and others, 1977); early Miocene to late Miocene by modern geologic time scales (Berggren and van Couvering, 1974). More than 99 per cent of the basalt was erupted during a short 2.5-3 x 10^6 years interval centered about 15 x 10^6 years B.P. This activity built up a rather featureless plateau whose gentle regional slope was directed toward the central part of the area from all sides, reflecting concurrent subsidence and volcanism. Eruptions were far less frequent between about 14 and 6 x 10^6 years B.P., allowing time for considerable erosion and deformation between outpourings. The present courses of much of the Snake River and parts of the Columbia River were established at this time.

Relatively little erosion, other than along major drainages and in mountainous uplifted areas, has taken place in the last 6 x 10^6 years. Thus the original surface of the plateau is preserved with remarkable fidelity in some areas, especially in the eastern and northern parts of the province, where only the Channeled Scabland lends much variety to the otherwise monotonous Miocene surface covered with a relatively thin blanket of Quaternary loess.

The Columbia Plateau is a typical flood-basalt province. Flows are voluminous and cover large areas. They advanced as sheetfloods, were fed by fissure eruptions, and generally form thick cooling units composed on one or more flows, rather than compound lava flows in Walker's (1972) terminology. Cinder cones were not formed. Small spatter ramparts are present but poorly preserved. In most of these features, the province contrasts with that produced by basaltic plains volcanism, such as the Snake River Plain, discussed by Greeley (1977).

The basalt flows covered an erosional surface of considerable local relief near the margin of the plateau, 1000 m or more in many places. Some of the pre-basalt hills and ridges today still stand hundreds of meters above surrounding lava flows. The geomorphic term, steptoe, a hill of older rocks surrounded by a lava flow, was coined for Steptoe Butte 70 km south of Spokane (Fig. 3.1).

The nature of the pre-basalt surface and the rocks on which it was developed is unknown beneath the central part of the plateau. Sparse evidence suggests that a thick weathered or altered zone caps an older sequence of mafic to intermediate, lower Tertiary volcanic rocks beneath the Pasco Basin (Raymond and Tillson, 1968; Newman, 1970; Jackson, 1975).

Stratigraphy

The Columbia River Basalt Group has recently been subdivided into five formations, three of which are lumped into one subgroup corresponding to the Yakima Basalt of Waters (1961) and Swanson and others (1977). The stratigraphic nomenclature is given in Figure 3.3, with those units that occur within the area of the field conference indicated with asterisk. The Imnaha and Picture Gorge Basalts are restricted to the southwestern and southern margins of the province, respectively (Fig. 3.4), and appear to have a much smaller combined volume than the Yakima Basalt Subgroup. Papers dealing with the Imnaha Basalt are written by Hooper (1974) and Holden and Hooper (1976). The Picture Gorge Basalt is discussed by Nathan and Fruchter (1974) and Fruchter and Baldwin (1975). The formations are not discussed further in this paper.

The Yakima Basalt Subgroup underlines virtually all of the Columbia Plateau in Washington. The Channeled Scabland is developed exclusively in this unit. Representatives of its three formations, the Grande Ronde, Wanapum, and Saddle Mountains Basalts, occur in areas to be visited during the conference (Fig. 3.4). References on the Yakima Subgroup include papers by Waters (1961), Bond (1963; his "upper basalt"), Swanson (1967), and Diery and McKee (1969), on the Grande Ronde Basalt; by Mackin (1961) and Lefebvre (1970) on the Wanapum Basalt; and by Schmincke (1967a) on the Saddle Mountains Basalt.

Grande Ronde Basalt

The Grande Ronde Basalt, equivalent to the lower Yakima basalt of Wright and others (1973), is the most voluminous and areally extensive formation in the group (Fig. 3.4), covering most of the plateau with a volume of more than 150,000 km^3. Its thickness varies considerably depending on buried topography and the amount of erosion. The thickest known section exceeds 1000 m in drill holes in the Pasco Basin. Across the northern plateau, exposed thicknesses are no more than 750 m, generally much less. The formation probably contains hundreds or even a few thousand different flows.

The Grande Ronde Basalt consists mostly of non-porphyritic, fine-grained, tholeiitic basalt. Most flows carry scattered plagioclase microphenocrysts and plagioclase-clinopyroxene microphyric clots. Olivine occurs in small amounts (less than 0.5 percent) in the ground mass of all but the lowest magnesian flows.

Few flows are distinctive enough in the field to serve as stratigraphic markers, except in relatively limited areas. Criteria such as jointing habit and weathering color are tempting but unreliable for flow recognition over long distances. Chemistry is an important adjunct to correlation studies but needs to be examined in an independent framework because of repetitive compositional changes with time in the section (see paragraph on chemistry).

Flows were erupted from dikes found throughout the eastern half of the plateau (Fig. 3.4). One such dike apparently connects with its flow above the highway along the east side of Banks Lake in the Grande Coulee, 8 km southwest of the south end of Steamboat Rock (Swanson and others, 1975b).

The formation can be subdivided into four magnetostratigraphic units based on different magnetic polarities (Fig. 3.3). These four units, mappable in the field with a portable fluxgate magnetometer, are each as much as 350 m thick. They are not fine subdivisions of the formation but do provide both regional correlations and a framework for attempting chemical correlations.

The top of the Grande Ronde is generally well defined by a zone of weathering (a saprolite) or a thin sedimentary interbed separating the formation from overlying flows. For example, a poorly exposed sandstone, the Vantage Member of the Ellensburg Formation, separates the Grande Ronde and Wanapum Basalts along the Grand Coulee. The saprolite and interbed sandstone indicate a significant time break but magnetic polarities above and below the contact are similar.

Series		Group	Subgroup	Formation	Member	K-Ar age (m.y.)	Magnetic polarity
MIOCENE	UPPER MIOCENE	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Saddle Mountains Basalt*	Lower Monumental Member	6[3]	N
					Erosional unconformity		
					Ice Harbor Member		
					basalt of Goose Island	8.5[3]	N
					basalt of Martindale	8.5[3]	R
					basalt of Basin City	8.5[3]	N
					Erosional unconformity		
					Buford Member		R
					Elephant Mountain Member*	10.5[3]	N,T
					Erosional unconformity		
					Pomona Member*	12[3]	R
	MIDDLE MIOCENE				Erosional unconformity		
					Esquatzel Member		N
					Erosional unconformity		
					Weissenfels Ridge Member		
					basalt of Slippery Creek		N
					basalt of Lewiston Orchards		N
					Asotin Member		N
					Local erosional unconformity		
					Wilbur Creek Member*		N
					Umatilla Member		N
					Local erosional unconformity		
				Wanapum Basalt*	Priest Rapids Member*		R_3
					Roza Member*		T,R_3
					Frenchman Springs Member*		N_2
					Eckler Mountain Member		
					basalt of Shumaker Creek		N_2
					basalt of Dodge		N_2
					basalt of Robinette Mtn.		N_2
				Grande Ronde Basalt*			N_2
	LOWER MIOCENE					14-16.5[2]	R_2
				Picture Gorge Basalt[4]	(basalt of Dayville basalt of Monument Mtn. basalt of Twickenham)[1]	(14.6-15.8)[1,2]	N_1
				?			R_1
				Imnaha Basalt[4]			R_1 T N_0 R_0?

[1] Information in parentheses refers to Picture Gorge Basalt

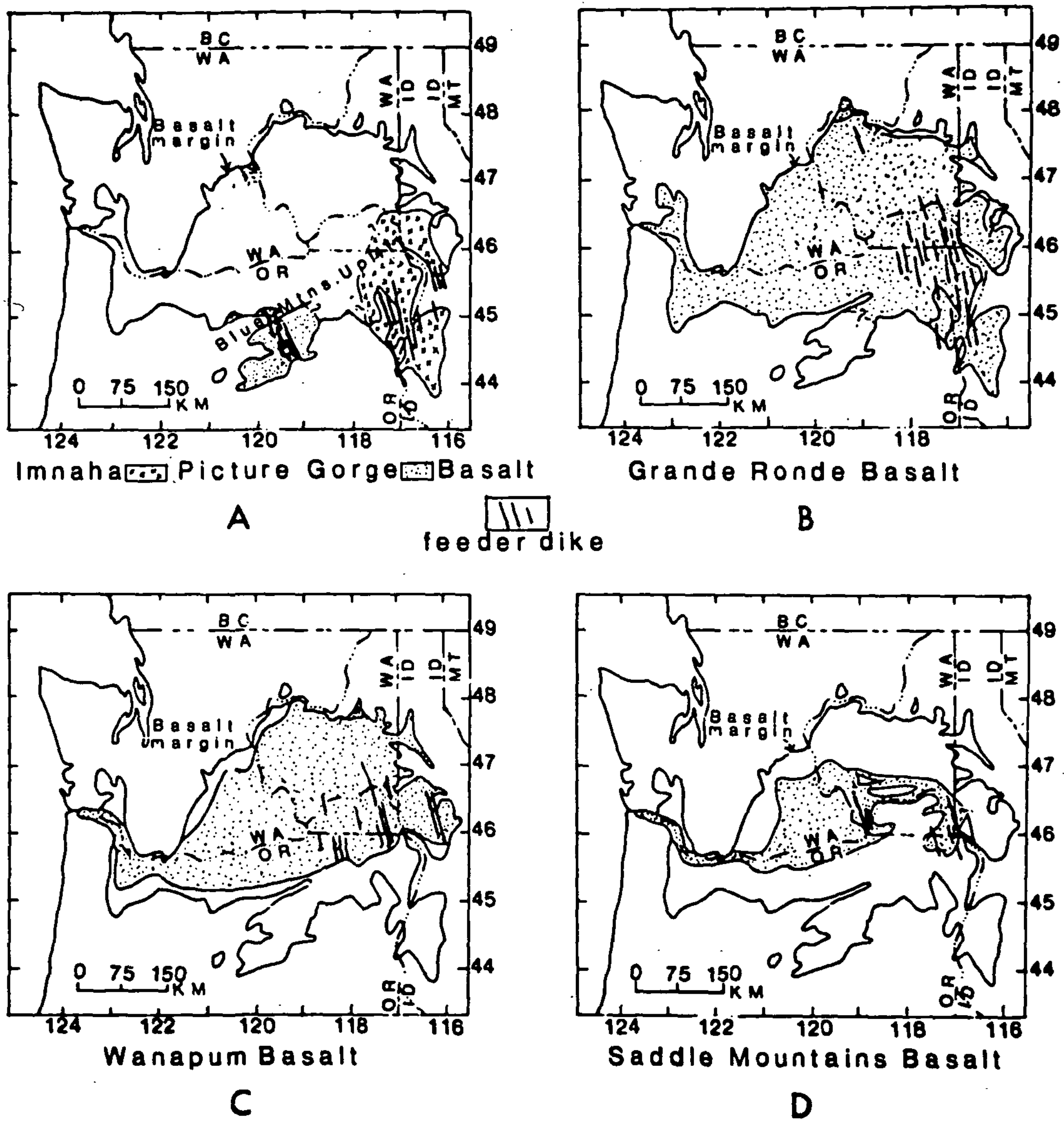
[2] Data mostly from Watkins and Baksi (1974)

[3] Data from McKee and others (1977)

[4] The Imnaha and Picture Gorge Basalts are nowhere known to be in contact. Interpretation of preliminary magnetostratigraphic data suggests that the Imnaha is older.

Figure 3.3. Stratigraphic nomenclature, age, and magnetic polarity for units within the Columbia River Basalt Group. N—normal polarity, R—reversed polarity, T—transitional polarity. Subscripts refer to magnetostratigraphic units of Swanson and others (1977). Geologic time scale from Berggren and van Couvering (1974). * designate units in the area of the field conference.

Moreover, the Grande Ronde and overlying Wanapum Basalts are interbedded at one locality, Benjamin Gulch, 3 km south of Pomeroy, in southeast Washington (Fig. 3.1). Thus, the evidence suggests that the time break occurred within one magnetic polarity interval and probably



Imnaha ▨ Picture Gorge ▨ Basalt

A

Grande Ronde Basalt

B

▥ feeder dike

Wanapum Basalt

C

Saddle Mountains Basalt

D

Figure 3.4. Maps showing generalized distribution and feeder dikes for the formations in the Columbia River Basalt Group. Distribution queried where uncertain.

lasted no more than a few tens of thousands of years, with eruptions continuing locally during this period.

The Grande Ronde crops out only in the more deeply eroded parts of the plateau within the area of the field trip. The lower flows in the Spokane area and up the St. Joe and St. Maries Rivers belong to this formation (Griggs, 1976), although previous workers had considered them younger (Pardee and Bryan, 1926; Dort, 1967; Bishop, 1969). The formation crops out along the lower parts of some of the deepest scabland channels southeast of Spokane, such as the channel containing Bonnie and Rock Lakes. The lowest flows all along the Grand Coulee belong to the formation, as do those along Moses Coulee. The valley of the Columbia River is eroded into the Grande Ronde; particularly good sections are exposed in the water gaps across the Saddle Mountains and Frenchman Hills. The formation is well exposed along the Snake River canyon upstream from Devils Canyon.

Wanapum Basalt

The Wanapum Basalt, approximately equivalent to the middle Yakima basalt of Wright and others (1973), covers a wide part of the Columbia Plateau (Fig. 3.4) including most of the area to be seen during this field conference. It is much less voluminous than the Grande Ronde Basalt, probably containing less than 10,000 km^3 of lava flows. On a local scale, the Wanapum overlies the Grande Ronde conformably or with very slight, local erosional disconformity, except for the interbedded relation in Benjamin Gulch already described. On a regional scale, however, the Wanapum overlies progressively older basalt from the center toward the margins of the plateau; this is especially apparent in southeast Washington (Swanson and others, 1977). We interpret this to mean that the central plateau was subsiding during accumulation of the Grande Ronde, so that progressively younger flows of the Grande Ronde were confined to the deepening center of the basin.

The Wanapum is distinguished from the Grande Ronde because it consists of a sequence of generally medium-grained, olivine-bearing flows that commonly contain a few percent plagioclase phenocrysts. Most of the flows have high Fe and Ti contents, in contrast to those in the Grande Ronde.

Feeder dikes for flows in the Wanapum Basalt occur widely in the eastern half of the plateau (Fig. 3.4), although feeders for an individual flow or a sequence of related flows are rather localized (Fig. 3.5).

The formation is divided into four members on the basis of petrography and magnetic polarity (Fig. 3.5). The oldest, the Eckler Mountain Member, does not crop out in the northern plateau except for a possible occurrence near St. Maries, Idaho (Griggs, 1976). The Frenchman Springs, Roza, and Priest Rapids Members are considerably more extensive (Fig. 3.5) and are described below.

Frenchman Springs Member—This is the most extensive member of the Wanapum (Fig. 3.5) and probably contains 3,000 to 5,000 km^3 of basalt. As many as ten flows, generally three to six, of normal magnetic polarity occur in any one section. Mackin (1961) named the three flows in the Quincy Basin, from bottom to top, the Ginko, Sand Hollow, and Sentinel Gap.

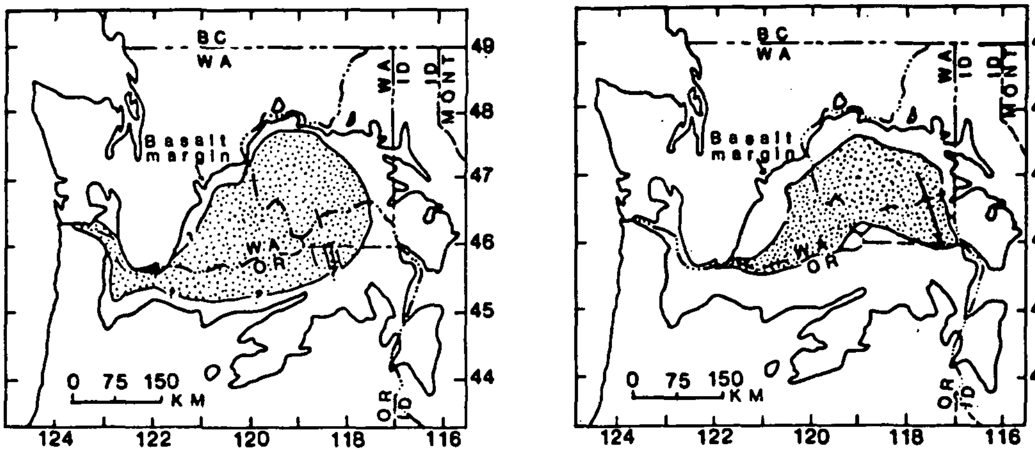
Most flows in the Frenchman Springs contain scattered glomerophyric clots of plagioclase a centimeter or more across. The clots are generally very unevenly distributed through a flow and may be hard to find. Many flows were erupted from dikes north and south of Walla Walla (Fig. 3.5).

The Frenchman Springs Member apparently never covered the northeast part of the province (Fig. 3.5). It is not found in the Spokane area or in the Cheney-Palouse scabland north of Rock Lake. The member crops out in some of the deeper channels west of Odessa, for example along Crab Creek. It occurs widely along the upper Grand Coulee, underlying the visitor overlook at Dry Falls, but pinches out to the north about 13 km southwest of the south end of Steamboat Rock. The Frenchman Springs borders the Quincy Basin in the north, south, and west (Grolier and Bingham, 1971) and is well exposed in Lind and Washtucna Coulees, Devils Canyon, and along the Snake River.

Roza Member—The flows within the Roza Member, which overlies the Frenchman Springs, are probably the best known and certainly some of the most widespread of all flows on the plateau

(Fig. 3.5). The following is taken from Swanson and others (1975b).

> "The Roza is characterized by abundant plagioclase phenocrysts, averaging more than 5 mm in length; the phenocrysts are distributed quite uniformly, generally about 10 per 150 cm² (Lefebvre, 1970), and are mostly single crystals. This texture serves to distinguish the Roza Member from almost every other unit and, when stratigraphic relations are considered, is virtually diagnostic . . . [Work by many geologists shows that] the Roza Member originally covered an area of at least 40,000 km² and contained a volume of lava greater than 1500 km³.
>
> The member typically consists of one or two thick flows . . . [totalling about 50 m thickness] . . . but in some places contains three or more. Thin flow units are abundant only near vent areas. Successive flows can be recognized by the

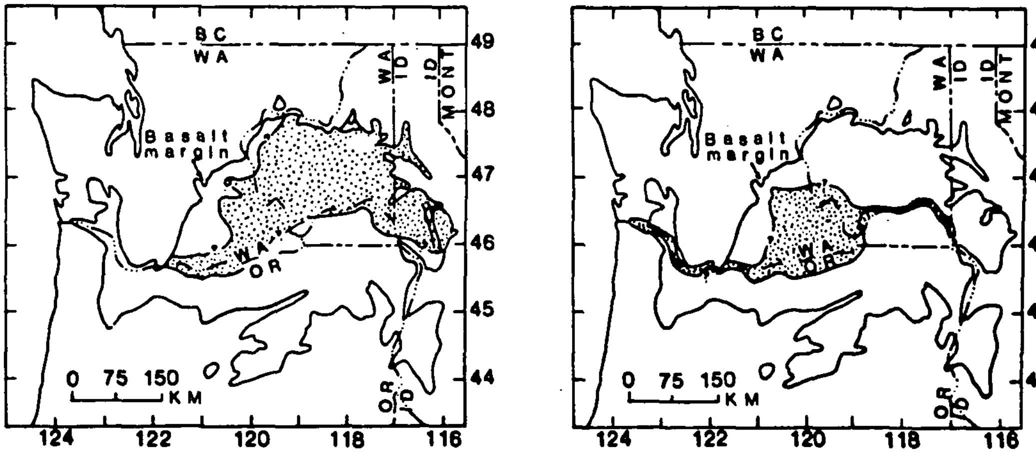


Frenchman Springs Member

A

Roza Member

B



Priest Rapids Member

C

Pomona Member

D

Figure 3.5. Maps showing generalized distribution and feeder dikes for the Frenchman Springs, Roza, and Priest Rapids Members of the Wanapum Basalt and the Pomona Member of the Saddle Mountains Basalt.

> presence of intervening vesicular and ropy zones on the upper surface of the lower flow or by small differences in the number and size of plagioclase phenocrysts. Multiple flows may have been overlooked in some places where only one flow has been reported, perhaps because so little time elapsed between successive eruptions that cooling and solidification tended to obscure flow contacts. In general, such terms as simple, compound, single-flow, or multiple-flow cooling units, originally applied to ash-flow tuffs (Smith, 1960a, b), are thought to be equally applicable to the Roza Member and to flows of the . . . [Columbia River Basalt Group] . . . In this scheme, the Roza Member is commonly a simple cooling unit, but in places consists of a multiple-flow, compound cooling unit or several different cooling units.
>
> A variety of evidence suggests that the Roza Member was erupted during a short period of time, perhaps of the order of a few hundred . . . (to a few thousand) . . . years for the entire member and a matter of days for single flows and cooling units. Interflow sediments, except locally derived tephra, have not been found, even though epiclastic sediments of extra-plateau derivation, as well as biogenic sediments, were deposited both before and after Roza time in many places on the Columbia Plateau . . . Evidence of significant erosion between successive Roza flows has nowhere been found, and delicate surface textures are commonly preserved. The transitional magnetic polarity (Reitman, 1966) of the Roza Member is further permissive evidence of its rapid accumulation. Such a polarity is apparently produced during a reversal in the Earth's magnetic field, which is thought to take place rapidly, possibly within 10^3 yrs (Rikitake, 1972) . . . [Recently, a magnetically reversed flow and dike of Roza affinity have been found in southeast Washington; they are interpreted to represent a late stage of Roza volcanism after the magnetic field had completed its change from normal (Frenchman Springs Member) through transitional (Roza Member) to reversed (Roza and Priest Rapids Members) polarity (Choiniere, 1977)]."

We have found numerous vent and near-vent areas and feeder dikes that define a linear, north-northwest trending, vent system in the eastern plateau (Fig. 3.5). The zone is probably less than 5 km wide and at least 130 km long. The northernmost known vents occur in the Cheney-Palouse scabland northwest of Winona (Bingham, 1970). The vent and near-vent areas are defined by accumulations of airfall spatter, some welded or agglutinated, and pumice of Roza lithology. Remnants of spatter cones and ramparts are recognizable in places; some have been bulldozed or burrowed into by a younger flow of the member. Thick mounds of platy, relatively dense flows form low hills at presumed vents in the southern part of the vent system and are interpreted to be some of the latest cooled and/or degassed material to be erupted. This is the material with reversed magnetic polarity.

The Roza, like the Frenchman Springs Member, failed to advance into the Spokane area (Fig. 3.5); its northeast terminus can be observed in one place just south of Bonnie Lake in the Cheney-Palouse scabland. The member is widespread elsewhere in the northern plateau, however. It is well exposed along Crab Creek in the Odessa-Wilson area, where it hosts peculiar ring structures, 50 m to 500 m in diameter, interpreted by McKee and Stradling (1970) as sag flowouts, formed by foundering of crust on a partly solidified flow, and by Hodges (1976) as reflecting interaction of water and lava. The Roza is prominent along the Grand Coulee, where it extends farther north than the Frenchman Springs Member and rests directly on the Grande Ronde Basalt. It occurs throughout the Quincy Basin (Grolier and Bingham, 1971); in the Potholes Reservoir area, where much of the dam consists of riprap from the Roza; along the walls of the Columbia Valley; and throughout the southern part of the Cheney-Palouse scabland.

Priest Rapids Member—The Priest Rapids Member overlies the Roza and contains the youngest flows throughout most of the scabland country (Fig. 3.5). It typically consists of one or two flows totalling 30-50 m thick. The entire member may have a volume of 2,000-3,000 km^3. Flows in the Channeled Scabland typically contain small olivine and scattered small plagioclase phenocrysts. All flows have reversed magnetic polarity.

Flows of two different compositions occur in this member throughout the scabland country. One has high Fe and Ti (Rosalia chemical type of Table 3.1). The Lolo-type flow(s) appear to be younger, but considerably more mapping is needed to definitely establish the age relations. Sources for the Lolo-type flows are known in western Idaho (Fig. 3.5); sources for Rosalia-type flows have not been found.

Table 3.1. Chemical types of basalt discussed in text and present in Channeled Scabland (oxides in percent; trace elements in ppm)

	Grande Ronde Basalt		Wanapum Basalt			Saddle Mountains Basalt		
				Priest Rapids Member				
	High-Mg Grande Ronde (one flow)	Low-Mg Grande Ronde (one flow)	Roza	Lolo	Rosalia	Wilbur Creek	Pomona	Elephant Mountain
SiO$_2$	53.56	55.80	50.97	49.96	50.09	54.41	51.77	50.89
Al$_2$O$_3$	14.58	14.00	14.01	14.32	13.63	14.51	14.85	13.52
FeO [1]	11.10	11.74	13.85	13.71	14.98	11.07	10.52	14.66
MgO	5.23	3.35	4.37	5.15	4.28	4.51	6.98	4.26
CaO	9.08	6.86	8.42	8.83	8.27	8.32	10.63	8.31
Na$_2$O	2.90	3.13	2.71	2.56	2.66	2.69	2.35	2.45
K$_2$O	1.15	1.98	1.21	1.03	1.15	1.77	.64	1.23
TiO$_2$	1.70	2.26	3.11	3.13	3.54	1.95	1.62	3.51
P$_2$O$_5$	.26	.43	.67	.78	.80	.56	.25	.58
MnO	.19	.19	.24	.20	.21	.21	.18	.20
Cr	100.2	12.8	54.5	97.0	15.5	36 [2]	110 [2]	20 [2]
Cs	0.8	1.40	1.0	0.7	.95			
Hf	3.75	5.10	4.3	4.45	5.35	7.1	3.6	6.5
Rb	27.5	45.0	25.0	21.0	28.0			
Ta	.74	1.0	.99	1.18	1.11			
Th	3.50	6.30	3.8	3.55	4.05	6.6	2.6	6.0
Zn	133.0	145.0	171	214	220			
Sc	37.1	31.2	35.45	35.5	36.7	27.0	35	31
La	18.5	28.5	27.0	29.5	33.5	41.0	17	34
Ce	38.5	58.5	54.5	59.5	69.5			
Sm	5.40	7.80	7.8	8.85	9.1	7.9	4.8	9.6
Eu	1.69	2.19	2.34	2.68	2.81	2.4	1.5	2.6
Yb	2.6	3.65	3.20	3.50	4.25			
Lu	.51	.63	.60	.65	.73	0.69	.42	.76

[1] FeO + 0.9 Fe$_2$O$_3$.

[2] Trace element data from J. S. Fruchter (written commun., 1977).

The rimrock flows near Spokane, and the younger flows up the St. Joe and St. Maries Valleys, are of the Rosalia chemical type. Similar flows extend far southwest into the Cheney-Palouse scabland and west at least as far as the Odessa area. Farther south, similar high Fe and Ti flows occur near Othello. The high Mg, Lolo-type flows crop out in the lower Cheney-Palouse scabland, for example in the Devils Canyon-HU Ranch area, and within the Quincy Basin. Flows *of unknown composition occur in the member all* along Grand Coulee. The Priest Rapids is commonly hidden beneath loess along the margins of many scabland channels, with the underlying Roza Member the most prominent flow displayed.

Saddle Mountains Basalt

The Saddle Mountains Basalt, approximately equivalent to the upper Yakima basalt of Wright and others (1973), is the youngest formation in the Yakima Basalt Subgroup. It contains flows of diverse chemistry, petrography, age, and paleomagnetic polarity (Fig. 3.3). It was erupted between about 13.5 ± 0.5 x 10^6 and 6 x 10^6 years ago (McKee and others, 1977; Atlantic Richfield Hanford Company, 1976), during a period of waning volcanism, accelerated folding, canyon cutting, and development of thick but local sedimentary deposits between flows. The Saddle *Mountains Basalt has a volume of only about* 2000 km^3, less than 1 percent of the total volume of the Columbia River Basalt Group, yet contains by far the greatest chemical diversity, including major and trace element and isotopic abundances, of any formation in the group.

The Saddle Mountains Basalt has been subdivided into 10 members based on petrographic, magnetic, and chemical characteristics. These 10 members are listed in Figure 3.3, together with several informally named subunits. Four of the members, the Wilbur Creek, Asotin, Weissenfels Ridge, and Buford, occur principally in extreme southeast Washington and adjacent Idaho and Oregon. The Wilbur Creek and Asotin, however, also are found as intracanyon flows toward the center of the Columbia Plateau (Swanson and others, 1977), probably channeled westward by ancestral valleys of the Palouse River (Figs. 3.1 and 3.4). Two other members, the Esquatzel and Lower Monumental, occur chiefly as intracanyon flows along the ancestral Snake River. They therefore cover only a very small total area but extend for tens of kilometers along the canyon. The Esquatzel spilled from the mouth of the old canyon and covered part of the Pasco Basin. The other four members, the Umatilla, Pomona, Elephant Mountain, and Ice Harbor, cover relatively wide areas and also occur, at least locally, as canyon fills.

Of the 10 members of the Saddle Mountains Basalt, only the Wilbur Creek, Pomona and Elephant Mountain members are likely to be encountered during the conference and are described below.

Wilbur Creek Member.—The Wilbur Creek is fine-grained and has sparse phenocrysts of plagioclase less than 5 mm across. It was apparently erupted in the eastern part of the province, where it is most widespread and flowed westward down an ancestral valley system. The member occurs as a remnant of a valley-filling flow in the Warden-Othello area, where it forms a prominent, sinuous ridge owing to erosional inversion of topography.

Pomona Member.—The Pomona Member consists of one principal cooling unit characterized by small, commonly wedge-shaped phenocrysts of plagioclase (generally less than 5 mm long), together with scattered clinopyroxene and olivine. Some plagioclase phenocrysts are riddled with clinopyroxene inclusions.

Schmincke (1967a) showed that the Pomona occurs as a sheetlike flow throughout much of south-central Washington (Fig. 3.5), and our work indicates its presence in nearly 50 remnants of an intracanyon flow along an ancestral Snake River canyon from Asotin (Fig. 3.1) to the central Columbia Plateau (Swanson and Wright, 1976; Swanson and others, 1977). Figure 3.6 presents an example of an intracanyon flow remnant. The flow presumably advanced down the canyon from a source in western Idaho, emptying from the mouth of the canyon in lower Old Maid Coulee into a broad basin across which the flow moved as a sheetflood.

A peperite, a mixture of sediment and chilled, fragmented lava, is commonly developed where the Pomona plowed into unconsolidated vitric ash near the margin of the flow (Schmincke, 1967b). Good examples of this relation occur along Crab Creek northwest of Othello, about the only place where the member crops out in the area of the field conference.

The Pomona averages about 30 m thick outside of the ancient canyon. Its maximum preserved thickness in the canyon is 110 m near the mouth of the Tucannon River. It covers more than 18,000 km^2 and has a volume of more than 600 km^3. The flow advanced nearly to the Pacific Ocean along the Columbia River Valley, more than 500 km from its suspected but unproven source area in western Idaho (Fig. 3.5). It is truly one of the monumental basalt flows on Earth.

Elephant Mountain Member.—The Elephant Mountain Member overlies the Pomona and consists of several nearly non-porphyritic and generally fine-grained flows that are physically nondistinctive but chemically recognizable (Table 3.1). The member occupies more or less the area covered by the Pomona, although it did not advance west of the Cascades. Flows advanced down the ancestral Snake River Canyon from sources in southeast Washington and adjacent Idaho and Oregon (Swanson and others, 1975a). Its thickness averages about 30 m, in intracanyon remnants reaching 150 m, and its volume is 200-250 km^3. The member is the youngest flow exposed south and west of Othello.

Physical characteristics of flows

Flows within the Grande Ronde, Wanapum, and Saddle Mountains Basalts range from a few tens of centimeters to more than 100 m thick, averaging 30-40 m. The thick flows generally record ponding in pre-basalt valleys, in structurally controlled basins that developed during volcanism, or in narrow canyons eroded into older flows; such intracanyon flows are common only in the Saddle Mountains Basalt. Even the thinner flows generally show evidence of being ponded. This evidence con-

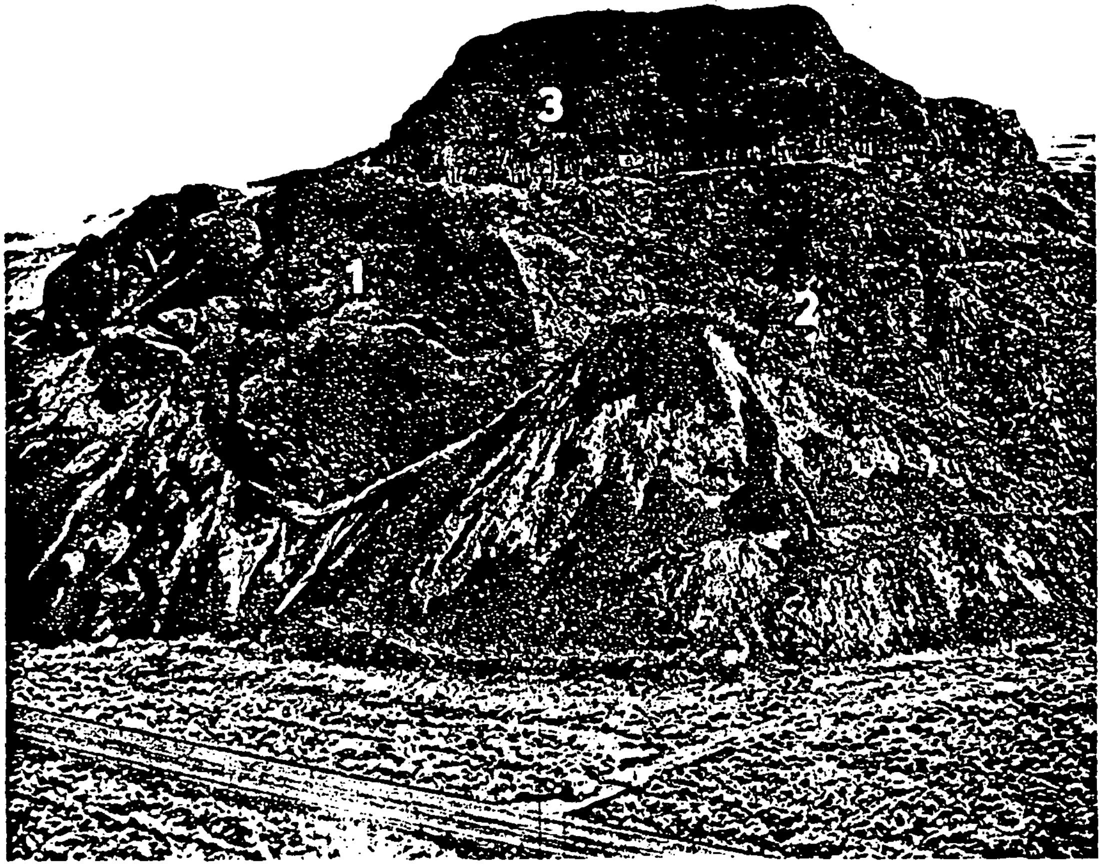


Figure 3.6. Photograph showing cross section of an ancient canyon of the Snake River and three flows of Saddle Mountains Basalt that were successively deposited in it. 1 designates the oldest intra-canyon flow which partly filled a canyon eroded into the Frenchman Springs Member, which is visible in the background at the extreme left edge of the photo. This oldest intracanyon flow was itself incised, and flow 2, the Pomona Member, makes up the columnar basalt against the steep wall of that paleocanyon. The Pomona (2) and flow 1 were then beveled by erosion to a nearly flat surface, and flow 3, in the Elephant Mountain Member, moved down-canyon (toward observer) and covered both older flows. Exposure is on the east wall of Devils Canyon and is about 100 m high.

sists of the columnar-jointed nature of the basalt (Fig. 3.7). Such columns can apparently form only under static cooling conditions; their development therefore implies that the lava had ponded. What impounded the lava can rarely be determined. Natural levees several meters high have been observed in places and probably account for most of the ponding. Elsewhere, flows could have pinched out against opposed topographic slopes.

Flows that cooled under stagnant conditions contracted and developed a characteristic jointing habit, shown in idealized form in Figure 3.7. The terms colonnade and entablature were borrowed from classical architectural usage by Tomkeieff (1940). Columns in the colonnade are from 10 cm to 5 m in diameter, averaging about 1 m, and can be as long as 50-75 m although generally 5-10 m. Most are straight, but curved columns are rather common and generally unexplainable in terms of simple cooling models. Columns in the colonnade are commonly subdivided into prismatic blocks by cross or blocky joints, and platy joints may form in the coarsest-grained part of a flow.

The colonnade-entablature contact is relatively sharp, the change commonly taking place within 1-2 cm. The contact is traceable in many places for several kilometers before other complexities obscure it. The glass content of the groundmass increases abruptly from the colonnade to the entablature for an unknown reason (Swanson, 1967). The entablature consists of columns of smaller diameter, generally less than 25 cm, and less consistent orientation than those in the colonnade. Columns in many entablatures are bundled into fan-, synclinal-, tent-, or other unusually shaped arrangements. Most columns in an entablature are highly segmented by irregular cross joints, so that the columns can be readily broken in fist-size pieces. The entablature generally comprises about 70 percent of the thickness of a flow but can make up 100 percent (one example that we know of) to zero percent. The upper part of the entablature is scoriaceous and commonly merges into a zone of short, wide, generally poorly defined columns that some workers call the upper colonnade. A rubbly, clinkery zone occurs at the top of some flows locally; such a zone is, in our experience, much more common near vent areas than elsewhere.

Idealized jointing patterns can be satisfactorily explained by existing theory for the cooling of bodies of igneous rock (Jaeger, 1961), but such patterns are seldom found in nature. Acceptable thermomechanical explanations for the typically complex jointing patterns, particularly in the entablature, are not available despite considerable descriptive information (Tomkeieff, 1940; Waters, 1960; Mackin, 1961; Spry, 1962; Swanson, 1967; Schmincke, 1967a). Problems such as mutual interference of columns growing inward from irregular contacts, ponding of water on a flow surface and percolation down joint planes during solidification, the influence of chemical composition on tensile strengths and heat conduction, and inadequate knowledge of rock mechanics under high temperature-low pressure conditions are some of the difficulties that plague attempts at analysis of natural jointing habits.

Some flows have a tiered appearance defined principally by alternating layers of vesicular and relatively nonvesicular rock rather than by joints. These layers may record separate gushes or thin flows that piled up and solidified as a single compound cooling unit.

Many flows entered water and formed pillows. Recent studies (Jones, 1968; Moore, 1975) have demonstrated conclusively that pillows are nothing more than the subaqueous equivalent of pahoehoe toes. Many of the pillowed flows occur near the margin of the plateau at the time of eruption, apparently because lakes resulted from flows ponding rivers draining marginal highlands. Other pillowed flows are much more extensive, perhaps signifying entry into shallow lakes standing on the plateau surface. An example of such a flow is one of the Priest Rapid flows, which is pillowed throughout an area of tens of square kilometers in the Cheney Palouse scabland, although the

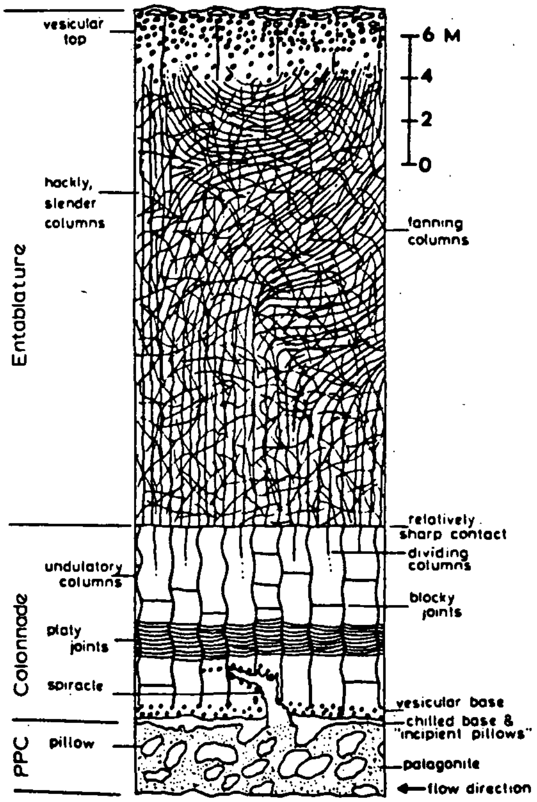


Figure 3.7. Cross section of typical flow in the Yakima Basalt Subgroup showing, in idealized form, jointing patterns and other structures. PPC, pillow-palagonite (hyaloclastite) complex, present at base of flows that entered water (from Swanson, 1967).

pillows were stripped away by the Pleistocene floods in many places and are not very apparent.

In places, lava deltas (Fuller, 1931; Moore and others, 1973) formed as lava poured into shallow lakes and ponded streams. The direction of dip of foreset "bedding," defined by elongate pillows and thin sheet flows, in the lava deltas indicates the local flow direction of the lava. Some classic lava deltas can be seen near Malden south of Spokane (Griggs, 1976), near the mouth of Moses Coulee (Fuller, 1931), and at the mouth of Sand Hollow south of Vantage.

Other criteria for defining flow directions include inclined pipe vesicles, which plunge upcurrent, and bent spiracles (Fig. 3.7), formed by steam blasts beneath a flow, which tail out downcurrent. Flow directional data for basalts must be treated in the same way as those for current-produced structures in sedimentary rocks—carefully. A few data in a small area show the local direction but say little about regional patterns. Nonetheless, careful studies by Schmincke (1967c) and ongoing work by others are succeeding in defining patterns of lava advance within the plateau.

Basalt flows burrowed into deposits of unconsolidated sediments, forming peperites and even sills, in many places on the plateau (Schmincke, 1967b). Excellent examples of such flows, called invasive flows (Byerly and Swanson, 1978), are exposed in the diatomite mines in the Quincy Basin (Roza Member), near Rock Island Dam southeast of Wenatchee (Fig. 3.8; the Hammond sill in the Grand Ronde Basalt; Hoyt, 1961), and in many areas near Spokane where flows burrowed into sediments of the Latah Formation. In our experience, nearly half of the examples of basalt-sediment contacts on the plateau record invasion by the basalt and inversion of the stratigraphy.

Invasive flows are particularly common in the Wenatchee-Ellensburg area, where they have been studied by Byerly and Swanson (1978). Some of these 5-120 m thick flows cover hundreds of square kilometers. Their tops have thick glass selvedges, generally are nearly planar, and contain few vesicles. Locally, thin dikes and sills sprout from the top and intrude the host sedimentary rock. All sill-like bodies intrude 3 to 20 m thick sedimentary deposits; none cuts an older flow, nor have any feeder dikes been found. Exposures show lateral gradations over hundreds to thousands of meters from surface flows through pillow-hyaloclastite complexes and peperites into invasive flows. Flow directional data show that the lava flowed toward the sill-like bodies. Microprobe analysis of glassy selvedges confirms correlations made across these facies changes and shows that the invasive flows fit perfectly into the chemical stratigraphy established for the basalt in nearby areas. Likewise, magnetic stratigraphy shows no anomalies; all flows and interlayered invasive flows in the lower and upper parts of the section have normal polarity, all in the middle part have reversed polarity. Each invasive flow apparently formed prior to the next higher flow, as lava advanced into a low area and burrowed into unconsolidated sediments.


Figure 3.8. Tongues of basalt invading silt and fine sand (now lithified). Satellite sill associated with the Hammond invasive flow near Rock Island Dam.

Chemistry

Study of the chemistry of the Columbia River Basalt Group has gone hand in hand with field work. Major element chemistry has been obtained for hundreds of samples collected in the field (Brock and Grolier, 1973; Hooper and others, 1976; T. L. Wright and D. A. Swanson, unpub. data, 1978), and trace element chemistry has been obtained for selected sections and also for

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representative samples of all parts of the stratigraphic section (Osawa and Goles, 1970; Nathan and Fruchter, 1974; T. L. Wright and D. A. Swanson, unpub. data, 1978). Sr-isotope data have been published by McDougall (1976), and studies are being completed by D. O. Nelson (unpub. data, 1978; Nelson and others, 1976). Lead isotope data are available from S. E. Church (written commun., 1975).

We and others have used major element chemistry to define the variation between and within stratigraphically defined flows in the Yakima Basalt Subgroup. Flows in the Saddle Mountains Basalt all have distinct major compositions termed chemical types. Flows in the Wanapum and Grande Ronde Basalts are chemically distinguished from each other, but flows of similar chemistry are repeated within each formation. Representative chemical types from each unit are shown in Table 3.1 and representative intra-flow chemical variation is shown in Figure 3.9. Within the three formations, trace element and major element compositions correlate closely. Some flows at different stratigraphic levels in the Grande Ronde Basalt have virtually identical major and trace element compositions, indicating that magmatism was broadly cyclic. A few flows of Saddle Mountains Basalt are similar in major element abundances to flows of Wanapum or Grande Ronde Basalt but differ significantly in minor and trace element abundances; one example is shown in Table 3.2.

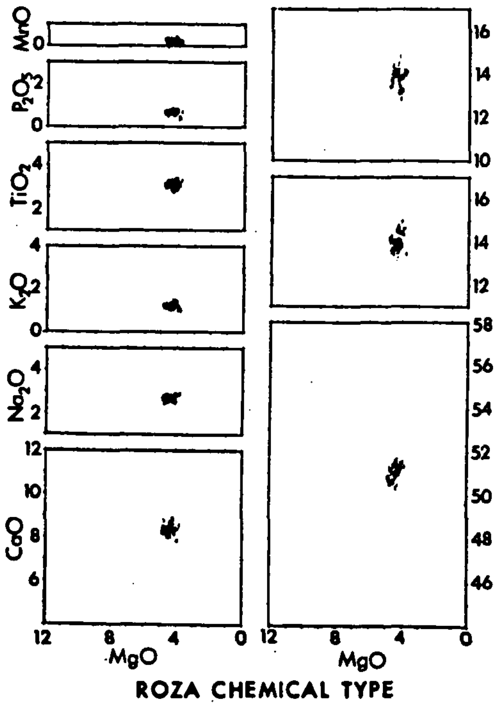

Figure 3.9. MgO-variation diagrams for the Roza Member, showing representative intraflow variation, to a large degree due to analytical uncertainty and alteration. Abundances are in weight per cents.

Table 3.2. Comparison of two chemical types with similar major element but different minor and trace element compositions (oxides in percent; trace elements in ppm)

	Chemical type	
	Intermediate-Mg Grande Ronde (Grande Ronde Basalt)	Wilbur Creek (Wilbur Creek Member of Saddle Mountains Basalt)
SiO_2	54.45	54.41
Al_2O_3	14.43	14.51
FeO [1]	11.53	11.07
MgO	4.49	4.51
CaO	8.14	8.32
Na_2O	2.99	2.69
K_2O	1.44	1.77
TiO_2	1.79	1.95
P_2O_5	0.30	0.56
MnO	0.20	0.21
Cr	17.2	36 [2]
Hf	4.1	7.1
Th	1.36	6.6
Sc	35.9	27.0
La	19.5	41.0
Sm	6.1	7.9
Eu	1.84	2.4
Lu	0.54	0.69

[1] $FeO+0.9 Fe_2O_3$.

[2] Trace element data from J. S. Fruchter (written commun., 1977).

Chemical compositions are used extensively for purposes of flow correlation. A scheme by which flows are identified using their major element chemistry to define chemical types has been recently published (Wright and Hamilton, 1978). Major element chemistry is routinely used to back up field identification of samples, and with few exceptions is of equal or greater effectiveness than comparisons made on the basis of trace elements, which are commonly determined with less precision. Chemical compositions alone are insufficient for flow correlation within the Grande Ronde Basalt, however, and reliable correlations involve consideration of stratigraphic position, magnetic polarity, and petrography. Such correlations in the Grande Ronde indicate that individual flows in southeast Washington are of relatively restricted extent, traveling at most about 30 km from their source. Another application of major element chemistry to field studies is the correlation of dikes and flows. This is successful insofar as the chemistry is distinctive, but there is ambiguity within the Frenchman Springs and Grande Ronde Basalts, where stratigraphically separated flows of similar chemistry exist.

Sr isotopes are uniformly low (.704-.705) in the Grande Ronde and Wanapum Basalts and variably higher (.707-.715) in the Saddle Mountains Basalts, suggesting a fundamental change in the source material during the waning stages of volcanism on the Columbia Plateau. Lead isotope data are consistent with the Sr data, becoming more radiogenic in the Saddle Mountains Basalt.

We have an incomplete understanding of the petrogenesis and evolution of the Columbia River basalt, but modeling of the chemistry leads to the following broad generalizations:

1. Crustal fractionation is not an important process, and magma storage at high levels in the crust is probably minimal.
2. The lava chemistries, assuming that they represent relatively unmodified partial melts, are consistent with a mantle that is heterogeneous both with respect to mantle compositions and mineral proportions.
3. Chemical compositions are more consistent with derivation from a pyroxene-rich (e.g., garnet pyroxenite) rather than olivine-rich (e.g., peridotite) source rock and could represent moderate (10-20 percent) degrees of partial melting in a nondepleted source.

Mode of Eruption

The Columbia River basalt flows were erupted from fissures, now exposed as dikes (Fig. 3.10). Several hundred such dikes have been found, and many others must be buried by younger flows or unexposed in forested areas. Taubeneck (1970), who has done the best work on the dikes to date, estimates that a minimum of 21,000 dikes are present. This number seems somewhat excessive but even if accurate would not necessarily imply 21,000 separate eruptions, as many flows were doubtless fed by several offset dikes extending along the length of the fissure system.

Feeder dikes are known to occur within the eastern two-thirds of the province (Fig. 3.4). Many more have been found in the southeast part of the area than elsewhere, where they comprise the Chief Joseph dike swarm (Taubeneck, 1970), a name for the combined Grande Ronde and Cornucopia dike swarms of Waters (1961). Topography is much more rugged in this area, however, so that more of the basalt section is exposed than elsewhere; this alone may account for the seeming concentration of dikes in this area. We have recently discovered scattered feeder dikes for all formations within the Yakima Basalt Subgroup west and north of the Chief Joseph dike swarm, despite generally subdued topographic relief and relatively poor exposure. One such dike occurs along the east wall of the Grand Coulee 8 km south of the south end of Steamboat Rock; some others are listed in Swanson and others (1975b). We feel that the evidence, evaluated in

Figure 3.10. Feeder dike for flow in Frenchman Springs Member, along the Snake River about 14 km downstream from the mouth of Devils Canyon. Concave-upward columnar joints reflect influence of cooling at the ground surface, which was only about 40 m above level of exposure at the time of intrusion. Dike is about 10 m thick.

terms of quality of exposure, suggests that dikes occur more or less evenly distributed beneath the eastern two-thirds or more of the province. The Picture Gorge Basalt was erupted from a separate swarm, the Monument dike swarm in north-central Oregon (Waters, 1961; Fruchter and Baldwin, 1975).

No dikes of Columbia River basalt have been found in the Cascade Range, as discussed by Swanson (1967) and confirmed by subsequent work. This is of some importance, as the Cascades were erupting calc-alkaline rocks at this time. The distinction between the Cascades and Columbia Plateau clearly has a magmatic as well as physiographic basis, with no known overlap.

The feeder dikes average about 8 m wide but vary from a few centimeters to more than 60 m. They may tend to thin upward, but this is far from certain. The dikes cannot be traced far laterally, in part because of exposure problems. Obviously related dike segments, offset a few meters to form an en echelon pattern, form systems extending tens of kilometers. Compound or multiple dikes, consisting of two or more pulses of magma related to the same intrusive event, are common, but composite dikes, containing two or more phases of contrasting compositions, have not been reported. In other words, each fissure was utilized just once, not repeatedly.

The chance of finding a dike connecting with a flow it fed is small, owing to problems of exposure and to the fact, observed repeatedly at Kilauea, that lava drains back down a fissure after the end of an eruption, thus tending to break the contact between dike and flow. Nonetheless, several examples have been found of such a connection. In most cases, the top of the dike is rubbly, apparently consisting largely of slabs of crust once floating on a flow before it poured back into the fissure (for example, Plate 1a in Swanson and others, 1975b). In one example lacking such rubble, the dike merges imperceptibly with its flow of the Frenchman Springs Member (Fig. 1, Number 6, in Swanson and others, 1975b).

Many other dikes can be correlated with particular flows, or at least sequences of flows, on the basis of chemical and magnetic-polarity similarity. In this way, dikes have been found for most of the named stratigraphic units.

It is possible to reconstruct the nature of the vent systems for some units from the distribution of feeder dikes as well as accumulations of pyroclastic material and, in places, the preservation of spatter cones and ramparts. The results show that eruptions of single flows or related flows took place from fissures concentrated in long, narrow vent systems on the order of tens of kilometers long and several kilometers wide (Swanson and others, 1975b, and later work).

Attempts have been made to estimate the rate of eruption and advance for single flows. The estimates take into account the observation that flows, even those that advanced tens to hundreds of kilometers from their sources, quenched to a crystal-poor sideromelane glass when they entered water; this indicates little cooling during transport and hence rapid advance, since the lava apparently moved as sheet floods rather than through insulating tube systems. Application of rheologic models, developed in part from this observation by Shaw and Swanson (1970), to vent systems of known dimensions suggests eruption rates of about 1 km^3/day per linear kilometer of active fissure for the largest flows, such as those in the Roza Member, and about $10^{-4}km^3$/day/km for the smaller flows (Swanson and others, 1975b). For flows of "average" volume, probably several tens of km^3, rates of 10^{-1} to $10^{-2}km^3$/day/km may be inferred. By comparison, sustained rates of eruption at Kilauea and Mauna Loa are 10^{-3} to $10^{-4}km^3$/day/km. Using observed dike widths, theoretical modeling suggests that such eruption rates could indeed have been sustained by supply from depth (Shaw and Swanson, 1970). Such eruptions probably lasted a very few days. Flow rates of 5 to 15 km/hr down slopes of 1:1000 are calculated from the model, adequate to allow thick flows to move far with little cooling.

Rapid eruption rates do not necessarily imply rapid melting rates in the mantle. Flows were erupted only once every ten thousand years or so on the plateau during even the peak of volcanic activity, as estimated by counting the number of flows in a magnetostratigraphic unit of assumed duration based on comparison with seafloor magnetic anomalies of roughly comparable age. Calculations show that continuous melting at the Hawaiian rate, $10^{-1}km^3$/yr (Swanson, 1972) or a little less (Shaw, 1973), could account for the volume of Columbia River basalt in the allotted time. Unusually rapid melting events cannot be excluded but are not required.

If melting progressed at the Hawaiian rate, then large, deep storage reservoirs are required in order to account fo the large volume of single flows. This contrasts with the Hawaiian situation, where eruptions are much more frequent and lava "leaks" to the surface more or less continuously. The presence of large, deep storage reservoirs may be a principal and distinguishing characteristic of flood-basalt provinces in general.

SEDIMENTARY DEPOSITS

Sedimentary deposits are interlayered with the basalt in places, particularly near the margins of the plateau. Schmincke (1967c) conducted the best study of these interbeds to date, finding two dominant provenances. One is the older rocks that surround the plateau. Rivers draining these highlands carried detritus out onto the flat constructive surface of the plateau, dumping it there and then having it covered by the next flow. The second main source was the erupting calc-alkaline volcanoes in the Cascade Range. Large volumes of pyroclastic debris were blown, carried by lahars, or, most commonly, transported by rivers and distributed across the western part of the plateau in both Oregon and Washington. The thickness of such interbeds increases with decreasing age, reflecting either the slowed rate of basalt outpouring, possibly accelerated rate of Cascade volcanism, or both. A third, minor source of interbeds was the collection of diatom tests in shallow lakes that stood for thousands of years on the plateau surface. A fourth, minor source was the basalt itself, which was eroded particularly during the period of uplift during Saddle Mountains time (about 13 to 6 x 10^6 years ago).

Interbeds in the Spokane area are assigned to the Latah Formation. They are subarkosic and derived from nearby pre-basalt hills. These interbeds present a certain geologic hazard, as they frequently have failed beneath the heavy basalt layers and given rise to large landslides along steep-walled valleys. Griggs (1976) describes these slides in some detail.

A particularly important interbed is the Vantage Member of the Ellensburg Formation, to which all interbeds in the northwestern part of the province are assigned. The Vantage, primarily a subarkosic sandstone, separates the Grande Ronde and Wanapum Basalts. It is poorly exposed because of talus cover, but its erosion leads to a prominent stripped structural surface on top of the Grande Ronde in Grand Coulee, along the Columbia River, and elsewhere.

An extensive diatomite deposit occurs in the Quincy Basin and may be observed during the conference (e.g. Stop 14, Ch. 7, this volume). It is being mined north of I-90 and west of George. This diatomite was apparently deposited on top of the Frenchman Springs Member and burrowed into by the Roza Member, forming a peperite. Blocks of this diatomite were carried a short distance eastward by an old Missoula flood and deposited with gravel just east of George, as seen at Stop 13 (Ch. 7, this volume).

None of the interbeds is as extensive as most of the basalt flows. Moreover, each interbed displays lateral facies changes that make correlation based on lithology difficult. Thus, the interbeds are of little use in regional stratigraphic studies, although they are good marker beds locally. The interbeds deserve considerably more attention than they have received recently, because they hold the key for unraveling ancient drainage patterns that, in turn, reflect the tectonic disturbance of the province.

Most known faults on the plateau are closely associated with sharp folds and are considered to have formed in response to the folding. These faults approximately parallel fold axes and have thrust-type displacements. A few normal faults and fault zones, however, are neither spatially nor geometrically related to steep folds and may indicate independent zones of rupture (Fig. 3.2).

The Columbia River cuts across the anticlinal ridges in a series of spectacular water gaps, as does the Yakima River near Yakima. These gaps themselves are structurally controlled by shallow north-south synclines that cross the ridges. Some of these water gaps began to form at least 8-12 x 10^6 years ago, as shown by fluvial conglomerates of those ages confined to the area of the gaps (Wallula and Sentinel Gaps (Fig. 3.1) are good examples); later uplift of the ridges carried these deposits several hundred meters above present river level.

DEFORMATION AND TECTONIC SETTING

The northern Columbia Plateau is far from the flat, featureless area implied by its name. The plateau is actually a structural basin, with its low point in the Pasco Basin near the center of the province. Stratigraphic evidence indicates that this basin was forming during basalt emplacement and continued to subside into Pliocene and possibly Pleistocene times. The eastern half of the plateau has not sagged appreciably since 6 x 10^6 years ago, however (Swanson and others, 1975a). Regional slopes toward the Pasco Basin are variable but average about 2.5 m/km from the north and east. Slopes from the south are steeper because of the Blue Mountains uplift (Swanson and others, 1977).

The western part of the northern plateau is creased by a series of gentle to sharp, even overturned, folds with structural amplitudes as great as 1,800 m but averaging about 1,000 m (Fig. 3.2). These folds, so young that the anticlines form ridges and the synclines valleys, have trends varying from almost due north to about 20 degrees of east-west (Newcomb, 1970). The folds were forming during Saddle Mountains time, as demonstrated from field relations in a number of places (Waters, 1955, 1961; Schmincke, 1967a; Bentley, 1977); some, such as the Naneum Ridge anticline in the Wenatchee Mountains (Fig. 3.2), were probably active as early as Grande Ronde time.

Anticlines and synclines are the dominant structures, but monoclinal flexures are common. One of the most prominent monoclines is the Coulee Monocline (Fig. 3.2) which controlled the erosional etching of the lower Grand Coulee (Stop 8, Ch. 7, this volume). Its structural relief is more than 300 m. Many of the folds are boxlike, consisting of two or more monoclinal flexures with opposed directions of dip. This type of structure is thought to form under little confining pressure, consistent with the evidence for the youth of the structures and the lack of indication that much overburden has been stripped off the plateau. Bentley (1977) contends that "in gross character, the anticlines are 'drape' folds caused by vertical breakup of basement rocks probably coincident with the major . . . uplift of the Cascades."

The regional tectonic setting of the Columbia Plateau is complex and poorly understood. The plateau occupies a position inland of the partly coeval Cascade Range and in this manner resembles marginal basins of the western Pacific. Furthermore, east-west extension, indicated by dike orientations, is consistent with such an analogy. However, this zone of extension apparently continues, with local breaks, north into interior British Columbia and south into the Basin and Range province far beyond the limits of Cascade volcanism. Moreover, other flood-basalt provinces on Earth appear to have formed in areas of incipient continental rifting, not marginal basins. By analogy, then, the Columbia Plateau may occupy part of an incipient or slowly developing continental rift. Neither of these settings, however, explains adequately the complex contemporaneous deformation of the province. We have a long way to go before sense can be made of the tectonic setting of the plateau, and it will only be understood after integrated studies of the Cenozoic volcanic and tectonic history of the entire Pacific Northwest.