

## STRATIGRAPHIC AND LITHOLOGIC VARIATIONS IN THE COLUMBIA RIVER BASALT

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**ABSTRACT.** The Columbia River basalt has been sampled by 28 stratigraphic sections and by the mapping of selected areas.

Petrographically, and also stratigraphically, the rocks assigned to this formation by Merriam, Lindgren, and Smith are divisible into two distinct varieties. The older, widespread in the Imnaha and John Day regions, is characterized by about 5 percent olivine, a silica content of 47 to 50 percent, and by notably higher  $Al_2O_3$ ,  $MgO$ , and  $CaO$  than the younger. Many outcrops have a characteristic "greasy" appearance because of the presence of saponite after olivine and of nontronite and other clay minerals after chlorophaeite. The basalts at Picture Gorge and Turtle Cove, described by Merriam in 1901, are typical.

The younger basalts are characterized by more than 20 percent tachylyte, little or no olivine, a silica content of 53 to 54 percent, and by notably greater amounts of  $K_2O$  and  $TiO_2$ . Nearly all the basalts that occupy the central and eastern part of the lava field north of the John Day and Imnaha areas are of this kind. They constitute the Yakima basalt as defined by Smith in 1901. In the lower part of the Imnaha River canyon, and also in the John Day basin, the Yakima basalt rests with distinct structural unconformity on flows of the older Picture Gorge type.

A late variant of the Yakima basalt emerged after warping and faulting had started to deform the Yakima flows in early Pliocene time. It contains more olivine and plagioclase and a distinctly higher percentage of iron and titania than normal Yakima flows.

Because of their separation in time, differences in chemical and mineral composition, and particularly because of the absence of transitional varieties between them, these lithologic and stratigraphic variations of the Columbia River basalt are considered to be products from separate magmatic hearths, and not differentiates of a hypothetical uniform magma.

### INTRODUCTION

The name Columbia River basalt was given to the basaltic lavas of the Pacific Northwest by Russell (1901, p. 28). Still earlier Russell (1893, p. 20-22) had described the basalt under the name "Columbia lava," and had noted that its best sections are "in the precipitous walls of the coulees or canyons in Douglas County,<sup>1</sup> and in the remarkable gates eroded by Yakima River through ridges" in the basalt, but he extended the name to include lavas that range in age from Eocene to Recent, and which spread over most of eastern Washington, eastern Oregon, the plains of southern Idaho, and the plateaus of northeastern California.

Merriam (1901, p. 303) held that only one unit of the several included by Russell should retain the formation name, and "This one should be the horizon which is most prominent along the Columbia River." He redefined the Columbia lava as follows: "In the John Day basin it is found that the lavas of the Columbia form a well-defined series which lies between the John Day [Oligocene and Lower Miocene] and the Mascall [Middle to Upper Miocene] formations. . . . This series is, moreover, that one of the several to which the name is applied which has the greatest lateral extent, forming probably the largest lava field of the world." Merriam stated that at Turtle Cove [Kimberly, Grant County, Oregon] 23 flows of basalt can be counted in the bluff.

Simultaneously with Merriam's work in the John Day basin, Smith (1901, p. 15) investigated the Yakima region of central Washington and faced the

<sup>1</sup> At the time Russell wrote, Douglas County, Washington, included the area later split off to form Grant County.

same problem. Here Russell (1900, p. 129-134) had described four "sheets" of basalt flows of different ages as constituting the Columbia River lava. Smith decided it was "inadvisable to use the general formation name, because the lavas of different ages must necessarily be separated" in the detailed mapping of the Yakima area, and he introduced the term *Yakima basalt* for the Miocene flows. The Yakima basalt, he wrote, "includes ten or more flows . . . . in the canyon of Yakima River where more than 2,500 feet is exposed in vertical section." Smith also noted that the Yakima basalt includes "flood after flood of molten rock, which covered the vast area between what is now the crest of the Cascade Mountains on the west and the mountains of Idaho on the east, and between the mountains of northeastern Washington and the Blue Mountains of Oregon on the south."

In the same year Lindgren (1901, p. 592), in his report on the gold belt of the Blue Mountains in Oregon, also suggested restricting the term Columbia River lava to basalts of Miocene age.

Although the U. S. Geological Survey (Wilmarth, 1938, p. 495) condoned the use of Columbia River basalt as a "blanket term, covering basalts of Eocene, Miocene, and Pliocene (?) age in the broad region described by

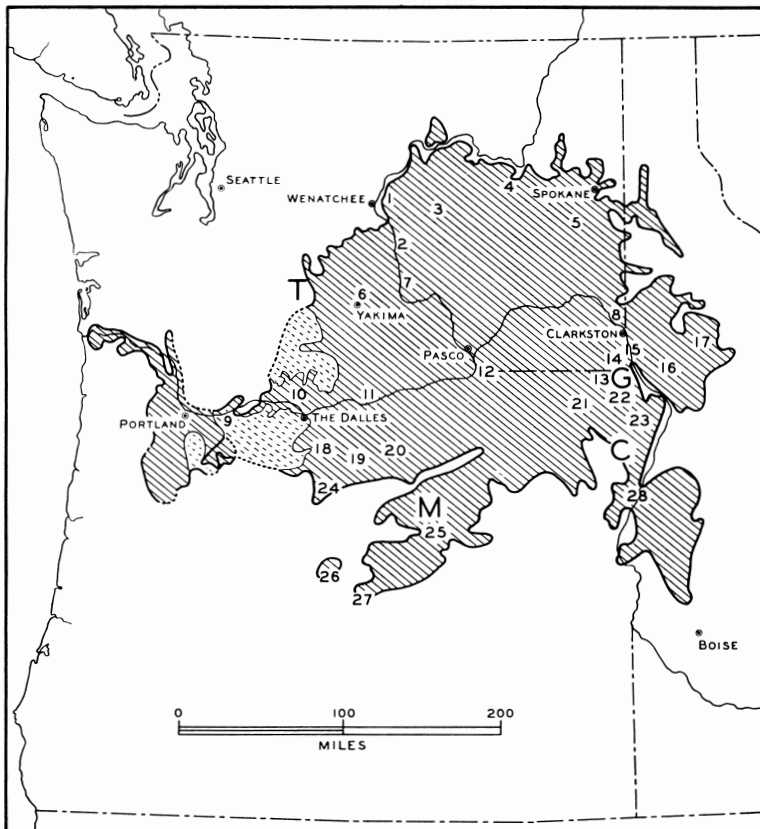


Fig. 1. Columbia River basalt. Area covered by the younger volcanic rocks of the Cascade Mountains is indicated by broken lines.

Russell," nearly all geologists since the time of Merriam, Smith, and Lindgren have restricted it to the dominantly Miocene flows that form the great area of flood basalts outlined in figure 1. In general, the terms Columbia River basalt and Yakima basalt have been used as synonyms, but there has been some tendency in the literature to apply Yakima basalt mainly to the western part of the lava field, particularly to the well-exposed flows along the eastern foothills of the Cascade Mountains. Moreover, the stratigraphic equivalence of the three areas named as "typical": (1) coulees and canyons of Douglas County (Russell), (2) canyon of Yakima River (Smith), and (3) Turtle Cove, John Day basin (Merriam) have never been demonstrated, and the general nature of the individual flows making up this vast assemblage of flood basalts remains little known.

In this paper some stratigraphic relations of the basalts in this vast lava field are summarized, together with data regarding the variation in composition of the basalts regionally, and with time. This summary is based on a sampling of the lava field by 28 measured stratigraphic sections whose locations and thicknesses are given in table 1, and whose positions are indicated in figure 1. Among these sections are the ones regarded as "typical" by Russell (numbers 1, 2, and 3), Smith (number 6), and Merriam (number 25), as well as the much thicker sections in the Columbia Gorge through the Cascade Mountains, and on the walls of the canyons of the Snake, Grande Ronde, Imnaha, and

TABLE 1  
Measured partial sections of Columbia River basalt

Section number (plate 1)	Name and Location	Thickness in feet	Number of flows
1.	Waterville-Douglas Creek, Douglas County, Washington	910	10
2.	Crescent Bar, Grant County, Washington	845	10
3.	Dry Falls, Grant County, Washington	450	8
4.	Lincoln, Lincoln County, Washington	330	4
5.	Rock Lake, Whitman County, Washington	250	3
6.	Roza Gap, Yakima County, Washington	845	9
7.	Sentinel Gap, Grant County, Washington	1190	16
8.	Uniontown Plateau, Whitman County, Washington	1735	25
9.	Multnomah Falls, Multnomah County, Oregon	730	8
10.	Klickitat River, Klickitat County, Washington	1195	15
11.	Rock Creek, Klickitat County, Washington	760	10
12.	Wallula Gap, Walla Walla County, Washington	1190	13
13.	Powatka, Wallowa County, Oregon	1470	19
14.	Grande Ronde, Asotin County, Washington	1460	32
15.	Snake River Bend, Asotin County, Washington	2080	25
16.	Keuterville-Salmon River, Idaho County, Idaho	1920	17
17.	Lawyers Canyon, Clearwater County, Idaho	1825	18
18.	Tygh Ridge, Wasco County, Oregon	610	8
19.	Beef Hollow, Gilliam County, Oregon	1555	22
20.	Sixmile, Gilliam County, Oregon	480	7
21.	Minam, Union County, Oregon	1077	20
22.	Joseph Creek, Wallowa County, Oregon	2010	23
23.	Imnaha, Wallowa County, Oregon	2465	31
24.	Cow Canyon, Wasco County, Oregon	750	11
25.	Picture Gorge, Grant County, Oregon	720	14
26.	Crooked River, Crook County, Oregon	830	11
27.	Mauray Mountains, Crook County, Oregon	410	5
28.	Pine Creek, Baker County, Oregon	1225	12

Salmon Rivers in the southeastern part of the plateau. A preliminary petrographic investigation of each flow in the 28 sections has been made, and a few chemical analyses of the rocks are herewith reported (tables 2, 3, 4, and 5). Geologic relations to contiguous formations are based on the mapping of 5 fifteen-minute quadrangles, and of all or part of 9 thirty-minute quadrangles, supplemented by considerable reconnaissance of other parts of the lava field. Only a few of the major results are given here; the purpose of this paper is to give a general, if still incomplete, picture of the regional variations in composition and stratigraphic position of the lavas within this huge area of flood basalts.

#### FISSURE ERUPTIONS AND DIKE SWARMS

The basalt flows emerged as fissure eruptions (Russell, 1901, p. 29; Merriam, 1901, p. 304; Lindgren, 1901, p. 741; Fuller, 1927, p. 228; Waters, 1950, p. 1533). The feeders are grouped in huge dike swarms concentrated within the limits of definite areas. In figure 1 the location of those dike swarms whose connection with the Columbia River basalt has been established are indicated by capital letters G, C, M, and T. None of these swarms have been thoroughly mapped or studied, and the following notes regarding them are based on reconnaissance.

*G. Grande Ronde dike swarm.*—This huge dike swarm, located near the northeast corner of the State of Oregon, is represented by scores of dikes, 10 to 70 feet thick, many of which can be traced for miles. They are magnificently exposed on the steep walls of the Grande Ronde River and its tributaries between Troy and Shoemaker Creek (pl. 2-B), and in the lower part of the canyon of Joseph Creek. Farther east dikes continue to appear, but in diminishing numbers, in the canyon of Snake River and at least as far east as Grave Creek near Keuterville, Idaho. Thus the dike swarm is at least 45 miles long and 10 to 20 miles wide.

Although individual dikes may curve or be irregular in detail, most have trends within the range north-south to north 30° east. A definite connection between a dike in this swarm and a flow of the Columbia River basalt has been reported and illustrated by Fuller (1927), and the writer has found additional examples. From the nature of fissure eruption, however, such unbroken connections must be extremely rare because a slight amount of withdrawal of the magma into the feeding fissure, or a resurgence of lava up the fissure after the flow has solidified will break the connection. Indirect but conclusive evidence of a genetic connection between dikes and adjacent flows has been seen at several localities. Criteria observed include an abrupt change from upright to inclined columnar jointing within the flow immediately adjacent to a dike, the cupping down of the top of some flows into a moatlike depression along the course of a dike, and the formation on the top of other flows of a raised edge or "levee" composed of thin gushes of lava and fragments of splattery clinker. In Shoemaker Canyon the direct connection of the chilled selvage of one dike with the chilled base of an adjacent flow was also observed, although the interior of this dike cuts upward through the flow with a sharp boundary. Many dikes are multiple (pl. 2-B) and fed more than one flow (Waters, 1950).

*C. Cornucopia dike swarm.*—The great swarm of dikes exposed in the eastern part of the Wallowa Mountains about 70 miles south of the Grande Ronde swarm was first described by Lindgren (1901, p. 593, 741-742). "At no place," he wrote, "are they exposed on such a magnificent scale as in the Bonanza Basin, near Cornucopia" and he also pointed out the relation of these dikes to the surrounding flows of Columbia River basalt. The dikes trend predominantly north-south. Goodspeed (1959, p. 213-229) has recently published some interesting petrographic details regarding some of the dikes in this swarm and has outlined the wide extent of the dikes to the north and northwest from Cornucopia. Stearns (1950, p. 55) reports a great swarm of dikes extending from Halfway (9 miles southeast of Cornucopia) to the Seven Devils region in Idaho. It appears, therefore, that the Cornucopia swarm may be fully as extensive and voluminous as the Grande Ronde swarm.

*M. Monument dike swarm.*—In his pioneer publication on the John Day basin Merriam (1901, p. 304) mentioned the occurrence of a group of basalt dikes which he considered to be feeders of the Columbia lava. This dike swarm is best exposed, and apparently the dikes are most numerous, in the canyon of the North Fork of John Day River between Monument and Kimberly. Near Monument sills and irregular cross-cutting masses of diabase also invade the John Day and Clarno formations. Thayer (1957) has traced the dike swarm between the Aldrich Mountains and the Monument-Kimberly area—a distance of about 40 miles—and has mapped the parts of the swarm that lie in the Mount Vernon and Aldrich Mountains quadrangles (Thayer, 1956a, b). Ray E. Wilcox is mapping the area near Monument. Most of the dikes in this swarm trend about north 30° west.

*T. Tieton dike swarm.*—Closely spaced dikes that trend north-south invade Oligocene and Miocene sedimentary and volcanic rocks along Tieton River from Rimrock to within about 5 miles of the junction of the Tieton with Naches River. From here they extend northward, and though not well exposed in the intervening area, probably connect with the group of dikes and irregular diabase intrusions about 25 miles to the north (headwaters of Manastash Creek) that Smith and Calkins mapped as feeders of the Yakima basalt (Smith, 1904, p. 8; Smith and Calkins, 1906, p. 7). Chappell (1936, p. 384) suggested that the huge Teanaway dike swarm, which lies still farther north in the Wenatchee Mountains, may contain feeders of the Columbia River basalt in addition to feeders of the Eocene Teanaway lavas (Smith, 1904; Smith and Calkins, 1906). Numerous dikes are found south of the Tieton, as well, but their southernmost limit is not known.

The Tieton dike swarm is much more complex than the ones previously described. This swarm, like numerous other belts of near-surface intrusions clustered along north-south zones within the Cascade Range, contains a wide assortment of igneous rocks of various ages and compositions. In addition to feeders of the Yakima basalt, this swarm includes great numbers of porphyritic olivine andesite dikes and olivine basalt dikes—perhaps feeders of the olivine-hypersthene andesites and basalts of the Fifes Peak formation that underlie the Yakima basalt of the Tieton area. Dikes and irregular masses of

diorite porphyry, dacite, and rhyolite are also minor components of this dike swarm.

*Lower Columbia River and Astoria regions.*—The writer has not worked on the Miocene basalts of the Lower Columbia Valley west of the Cascade Mountains. Dike feeders of these basalts have been reported in the Saint Helens quadrangle northwest of Portland (Wilkinson, Lowry, and Baldwin, 1946), and great numbers of basalt dikes can be seen across Columbia River between Woodland and Castle Rock, Washington. Some of the latter may be feeders of the Goble volcanic series of Eocene age. Dikes and sills genetically connected with the Columbia River basalt have been reported near Astoria (Warren, Norbistrath, and Grivetti, 1945) and in the upper part of the Nehalem River basin (Warren and Norbistrath, 1946, p. 233).

Returning to a consideration of the Columbia River basalt plateau as a whole, perhaps the most notable thing is the complete absence of feeders over great areas. Most parts of the huge lava field show no dikes. Even isolated dikes are not found far from the borders of the great swarms, and they could scarcely be overlooked among the excellent canyon exposures that prevail over wide areas of the plateau. To be sure other dike swarms may be hidden beneath a cover of soil or sedimentary rock, especially in the poorly exposed central part of the plateau. Moreover the topmost flows of flood basalt may hide dike swarms that contributed to lower flows in the lava sequence. It is interesting, however, that all the known dike swarms are concentrated near the southern and western margins of the great lava field (pl. 1). If the bulk of the lavas came only from these dikes, many flows must have traveled over 100 miles from their source. Evidence on the direction of movement of individual flows in the northern part of the lava field consistently indicates advance toward the highlands, which formed a shoreline for the encroaching sea of basalt on the north and east. (For criteria used in determining the direction of flow see Waters, 1960).

No shield volcanoes or cinder cones have been found, although both are common among the Pliocene-Quaternary olivine basalts that overlie the Columbia River basalt.

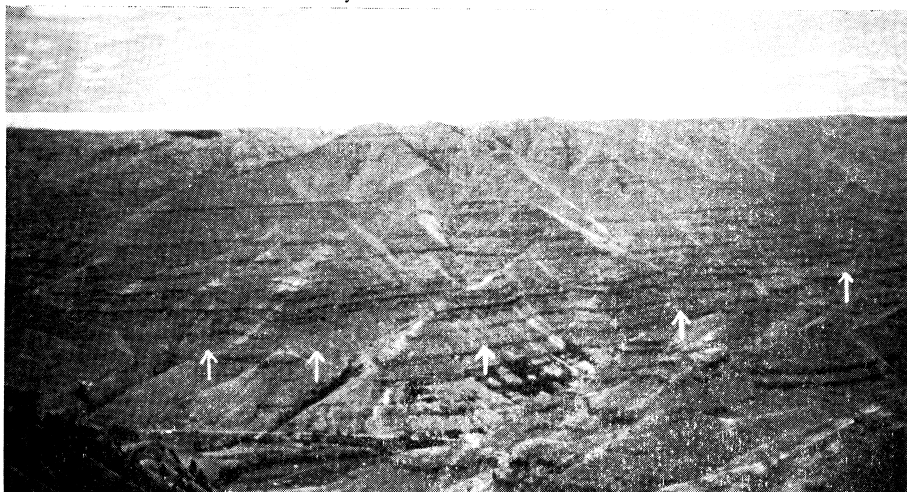
#### TWOFOLD DIVISION OF THE COLUMBIA RIVER BASALT

Remarkably homogeneous lava showing little variation in chemical and mineral composition except in relative amounts of glass (see tables 3 and 7) covers at least two-thirds of the area underlain by the Columbia River basalt floods. This is the Yakima basalt of Smith (1901, p. 15). Its monotony in composition is broken only by a late more basic variant that was erupted chiefly during the waning stages of vulcanicity after folding and faulting had started to deform the lava field in early Pliocene time. Typical Yakima basalt forms the characteristic flows described by Russell from Douglas County, the flows that banked against the plutonic and metamorphic highlands of northeastern Washington and western Idaho, the lavas at the surface of the plateaus of eastern Washington and northeastern Oregon, and all but the lower flows of the Grangeville plateau in Idaho.

But along the southern margin of the lava field the widespread and homogeneous Yakima basalt rests unconformably upon a more diversified and

PLATE 1

Unconformity within the Columbia River basalt

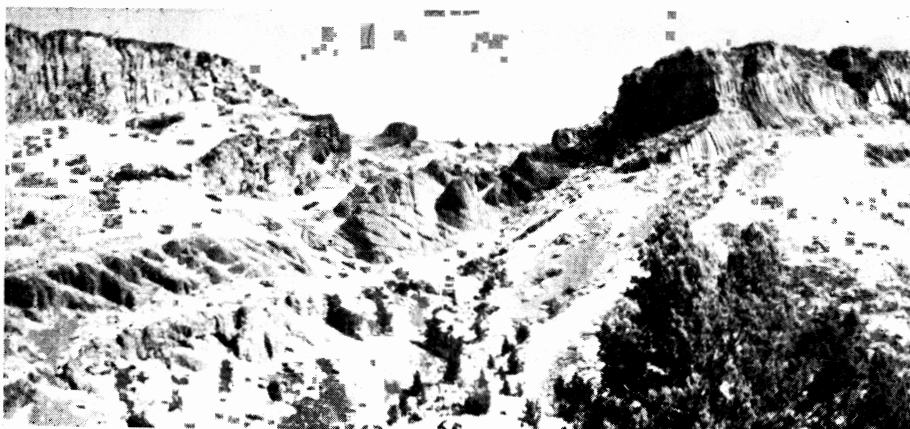


A. Slightly tilted and eroded flows of Picture Gorge basalt are overlapped toward the right by successively higher, nearly horizontal flows of Yakima basalt. The surface of unconformity is indicated by the arrow points. East wall of Imnaha River canyon at Grizzly Ridge. View shows a 3400-foot vertical section of basalt flows; lateral extent of view about 7 miles.



B. The upper limit of vegetation marks the emergence of springs at the unconformity between overlying permeable Yakima basalt and underlying nearly impermeable Picture Gorge basalt. Note the cliffed character of the Yakima flows and the more rounded slopes characteristic of the Picture Gorge flows. West wall of Imnaha River canyon one mile downstream from Imnaha, Oregon.

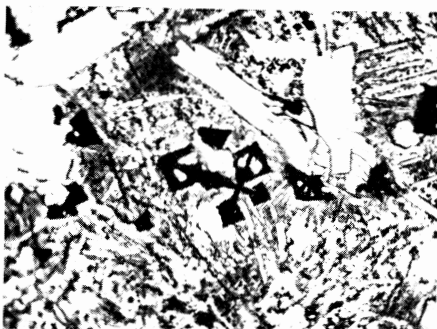
## PLATE 2



A



B



D



C

Structural and textural features of the  
Columbia River basalt.

somewhat older sequence of basalts (tables 2 and 6). This twofold division of the Columbia River basalt is subtle and easily overlooked in the field: in some places it can be picked up only after the observer becomes sensitive to rather elusive differences in physical appearance of the flows which reflect minor differences in mineralogy.

The division of the Columbia River basalt into two distinct formations is especially clear on the walls of the mile-deep canyons of the Salmon, Snake, and Imnaha Rivers of northeastern Oregon and adjacent Idaho. Here the junction between the two basalts is easily located by an unconformity between them (pl. 1), by the presence along the contact of local patches of coarse volcanic conglomerate containing fragments of the underlying basalt, and by the more impermeable character of the lower basalt, which, in places, causes a conspicuous line of springs and heavy vegetation along the contact (pl. 1-B).

Farther west, in the Ochoco Mountains and John Day basin, the older basalts are not confined to the deeper parts of canyons: they come to the surface over wide areas from which the younger basalts are generally absent. In the John Day basin the older basalt sequence makes up the sections at Picture Gorge and Turtle Cove that Merriam redefined as the "Columbia lava." But a few miles to the northwest it disappears unconformably beneath the homogeneous Yakima basalt.

Further discussion of structural and stratigraphic relations is deferred until the chemical and mineralogical differences between these two distinct sequences of lavas are outlined. In the following discussion the southern and older lavas will be called the Picture Gorge basalt, and the northern and younger the Yakima basalt. Near the end of this paper, proposals are made to formalize these terms as formation names and to elevate Columbia River basalt to the status of a stratigraphic group.

#### CHEMICAL AND MINERALOGICAL DIFFERENCES BETWEEN THE PICTURE GORGE AND YAKIMA BASALTS

The two divisions of the Columbia River basalt recognized on stratigraphic grounds also show characteristic differences in chemical and mineralogical composition. Table 2 lists available analyses of the older, or Picture Gorge basalt. Table 3 presents analyses of the Yakima basalt exclusive of its more basic late variant, a few analyses of which are listed in table 4. Table 5 gives the "average" analysis of each of the three chemically distinctive types of Columbia River basalt, along with averages of the Pliocene-Quaternary olivine basalts of the Cascade Mountains, the basalts from the Snake River Plain, and various "average" basalts from other parts of the world.

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A. Unconformity between tilted Columbia River basalt (center) and horizontal Pliocene-Quaternary olivine basalt (cliffed palisades on skyline). Crooked River canyon, 18 miles upstream from Prineville, Oregon.

B. Multiple basalt dike cutting Yakima basalt flows. Grande Ronde River near Shoemaker Canyon, Washington.

C. Unusual textural variant characteristic of the Late Yakima flows in the Cascade foothills. Note tangled coarse microlites of plagioclase enclosing large patches of partly crystallized glass (dark spots).  $\times 50$ .

D. Skeleton crystals of a titaniferous opaque in Late Yakima basalt.  $\times 140$ .

TABLE 2  
Chemical analyses, Picture Gorge type, Columbia River basalt

	1	2	3	4	5	6	7	8	A	B
SiO <sub>2</sub>	50.02	49.77	49.5	49.4	48.34	47.7	47.4	49.94	49.3	49.5
Al <sub>2</sub> O <sub>3</sub>	15.43	15.64	14.6	14.5	15.85	17.0	16.0	15.29	15.6	15.5
Fe <sub>2</sub> O <sub>3</sub>	4.20	3.00	2.5	3.1	2.75	3.5	3.3	4.23	3.5	3.8
FeO	8.31	8.19	9.4	8.3	8.54	7.4	8.5	7.82	7.8	7.8
MgO	6.01	6.32	7.1	7.1	6.74	6.5	7.6	5.73	6.5	6.2
CaO	9.93	9.77	10.8	10.4	10.46	11.2	10.0	9.91	10.3	10.2
Na <sub>2</sub> O	2.38	3.11	2.9	2.8	2.88	2.6	2.6	3.04	2.7	2.8
K <sub>2</sub> O	0.50	0.71	0.45	0.52	0.53	0.36	0.40	0.64	0.5	0.6
H <sub>2</sub> O <sup>+</sup>	1.02	0.62			0.73			0.36		
H <sub>2</sub> O <sup>-</sup>	0.48	0.93	1.0	1.9	0.88	2.2	2.4	0.98	1.8	1.6
TiO <sub>2</sub>	1.16	1.43	1.5	1.5	1.65	1.6	1.7	1.69	1.6	1.6
P <sub>2</sub> O <sub>5</sub>	0.26	0.24	0.27	0.26	0.29	0.34	0.32	0.26	0.3	0.3
MnO	0.24	0.19	0.22	0.20	0.19	0.18	0.19	0.20	0.2	0.2
CO <sub>2</sub>		0.01	0.08	0.05	0.02	0.05	0.04		0.04	
Sum	99.94	99.93	100.32	100.03	99.84	100.63	100.45	100.09		

1. Twelfth flow from top, Picture Gorge section (no. 26), Grant County, Oregon. Herdman, analyst. (New analysis).
  2. Fourteenth flow from base, Spray quadrangle, Wheeler County, Oregon, P. M. Montalto, analyst, USGS serial no. F-2536. (New analysis, courtesy D. H. Lindsley)
  3. Little Horse Spring, Post quadrangle, Crook County, Oregon, P. L. D. Elmore and K. E. White, analysts, USGS lab. no. 142176. (New analysis)
  4. One mile east of Drakes Butte, Maury Mountains, Crook County, Oregon. P. L. D. Elmore and K. E. White, analysts, USGS lab. no. 142177. (New analysis)
  5. Second flow from base, Spray quadrangle, Wheeler County, Oregon, P. M. Montalto, analyst, USGS serial no. F-2535 (New analysis, courtesy D. H. Lindsley)
  6. Third flow from base, Spray quadrangle, Wheeler County, Oregon, (New analysis, courtesy D. H. Lindsley)
  7. Sixth flow from base, Spray quadrangle, Wheeler County, Oregon. (New analysis, courtesy D. H. Lindsley)
  8. Composite analysis of weighed samples from each of 14 flows, Picture Gorge section (no. 26), Grant County, Oregon, B. Smith and R. B. Ellestad, analysts, Grout lab. no. R-966. (New analysis)
- A. Average of 16 analyses. Includes the analyses of Columns 1 to 7, plus the following nine unpublished analyses:
- 1) Picture Gorge, Grant County, Oregon, USGS Lab. no. 51-1715CW (T. P. Thayer)
  - 2) Picture Gorge, Grant County, Oregon, USGS Lab. no. 51-1717CW (T. P. Thayer)
  - 3) Picture Gorge, Grant County, Oregon, USGS Lab. no. 51-1718CW (T. P. Thayer)
  - 4) 1½ mi NE Mt. Vernon, Oregon, USGS Lab. no. ID-18385DCD (T. P. Thayer)
  - 5) Johnnycake Mt., Grant County, Oregon, USGS Lab. no. D-1779 (R. E. Wilcox)
  - 6) Johnnycake Mt., Grant County, Oregon, USGS Lab. no. D-1780 (R. E. Wilcox)
  - 7) Johnnycake Mt., Grant County, Oregon, USGS Lab. no. D-1781 (R. E. Wilcox)
  - 8) Riggins Quad, Idaho County, Idaho, USGS Lab. no. 148441 (W. B. Hamilton)
  - 9) Riggins Quad, Idaho County, Idaho, USGS Lab. no. 148444 (W. B. Hamilton)
- B. Average of two times Column A plus Column 8

As shown in these tables, and also in the standard variation diagram (fig. 2), there are significant chemical differences between the older Picture Gorge basalt and the Yakima basalt. The older lavas are higher in Al<sub>2</sub>O<sub>3</sub>, MgO, and CaO, and lower in SiO<sub>2</sub>, K<sub>2</sub>O, and TiO<sub>2</sub>. Moreover there appear to be no transitional varieties; the analyzed specimens fall distinctly into one group or another, and this is also true of the large number of modes measured from thin sections of these rocks.

TABLE 3  
Chemical analyses, Yakima type, Columbia River basalt

	1	2	3	4	5	6	7	8	A	B
SiO <sub>2</sub>	54.60	54.50	53.72	53.54	53.1	53.13	54.66	53.71	53.9	53.8
Al <sub>2</sub> O <sub>3</sub>	13.52	14.43	13.64	14.10	13.8	14.06	13.78	13.88	13.8	13.9
Fe <sub>2</sub> O <sub>3</sub>	1.96	2.17	2.46	1.73	3.2	2.25	2.12	3.65	2.3	2.6
FeO	10.46	8.80	9.96	10.33	9.4	9.45	9.30	8.27	9.8	9.2
MgO	3.52	4.24	4.63	4.59	4.2	4.72	3.69	3.93	4.2	4.1
CaO	7.45	8.01	8.27	8.54	7.7	8.39	7.44	7.59	8.0	7.9
Na <sub>2</sub> O	3.09	3.05	2.94	3.14	2.9	2.84	3.05	3.05	3.0	3.0
K <sub>2</sub> O	1.74	1.29	1.24	1.21	1.5	1.24	1.67	1.65	1.4	1.5
H <sub>2</sub> O <sup>+</sup>	0.87	1.09	1.05	0.26	1.6	0.79	0.99	0.69		
H <sub>2</sub> O <sup>-</sup>	0.10	0.29	0.40	0.03		0.54	0.29	0.53	1.1	1.2
TiO <sub>2</sub>	2.54	1.69	1.44	2.01	2.2	1.84	2.19	2.17	2.0	2.0
P <sub>2</sub> O <sub>5</sub>	0.09	0.21	0.31	0.35	0.44	0.33	0.36	0.47	0.3	0.4
MnO	0.13	0.10	0.21	0.22	0.20	0.19	0.18	0.20	0.2	0.2
CO <sub>2</sub>	None	tr	None		0.05				tr	
Sum	100.07	99.87	100.27	100.05	100.29	99.77	99.72	99.79		

1. Hackly basal flow, 5 mi west of Waterville, Douglas County, Washington. Herdsman, analyst. (new analysis)
  2. Clealum Ridge, 4 mi southwest of Cle Elum, Kittitas County, Washington. Geo. Steiger, analyst. (Smith, 1903a, p. 8)
  3. Eighth flow from top, Crescent Bar (No. 2) section, Grant County, Washington. Herdsman, analyst. (new analysis)
  4. East of Oregon State Training School, near Salem, Oregon. A. Willman, analyst. (Thayer, 1937, p. 1622)
  5. Five miles north of New Meadows, Riggins quadrangle, Adams County, Idaho. P. L. D. Elmore, S. D. Botts, and K. E. White, analysts, USGS Lab. no. 15190 (new analysis, courtesy, W. B. Hamilton)
  6. Composite analysis of weighed samples from each of 9 flows, Crescent Bar section (no. 2), Grant County, Washington. B. Smith and R. B. Ellestad, analysts, Grout Lab. no. R-964. (new analysis)
  7. Composite analysis of weighed samples from each of 19 flows, Lawyers Canyon Section (no. 17), Lewis County, Idaho. B. Smith and R. B. Ellestad, analysts, Grout Lab. no. R-964. (new analysis)
  8. Composite analysis of weighed samples from each of 32 flows, Grande Ronde section (No. 14), Asotin County, Washington. B. Smith and R. B. Ellestad, analysts, Grout Lab. no. R-965 (new analysis)
- A. Average of columns 1 to 5.  
B. Average of columns A + 6 + 7 + 8.

The chemical differences are clearly reflected in the mineralogy. Table 6 gives the modes of 14 flows of the older basalt exposed in the continuous section (number 25) at Picture Gorge, and of 13 flows that lie unconformably beneath the Yakima basalt in the thick section (number 23) on the west wall of the Imnaha River canyon near Imnaha, Oregon. Table 7 lists the same kind of data for two sections of the Yakima basalt, the first (number 2) at Crescent Bar in the northwestern part of the plateau, the other (number 14) a section comprising 32 flows on the north wall of the Grande Ronde Canyon in the southeastern corner of Washington. The Grande Ronde section lies within one of the areas of feeder dikes; the Crescent Bar section is far removed from any known dike swarm.

TABLE 4

Chemical analyses, Late Yakima and Ellensburg flows, Columbia River basalt

	1	2	3	4	A
SiO <sub>2</sub>	49.08	50.0	49.6	51.44	50.0
Al <sub>2</sub> O <sub>3</sub>	13.71	14.1	12.8	13.29	13.5
Fe <sub>2</sub> O <sub>3</sub>	1.25	2.1	1.9	2.16	1.9
FeO	13.02	11.6	13.2	12.00	12.5
MgO	4.58	4.3	4.4	4.28	4.4
CaO	8.44	8.1	8.4	8.28	8.3
Na <sub>2</sub> O	3.17	2.8	2.5	2.93	2.9
K <sub>2</sub> O	1.31	1.4	1.3	1.40	1.4
H <sub>2</sub> O <sup>+</sup>	0.90			0.66	
H <sub>2</sub> O <sup>-</sup>	0.20	1.8	1.0	0.07	0.9
TiO <sub>2</sub>	3.56	3.2	3.4	2.80	3.2
P <sub>2</sub> O <sub>5</sub>	0.73	0.79	0.81	0.61	0.7
MnO	0.25	0.24	0.27	0.23	0.25
CO <sub>2</sub>		<0.05	0.31		0.09
Sum	100.20	100.48	99.89	100.15	

1. The Dalles, Oregon, H. S. Washington, analyst (Washington, 1922, p. 779)
  2. Turtle Lake quadrangle, Washington, Specimen no. 6B-501. P. L. D. Elmore, S. D. Botts, and M. D. Mack, analysts (Becraft and Weis, in press)
  3. Turtle Lake quadrangle, Washington, Specimen no. 7B-261. P. L. D. Elmore, S. D. Botts, and M. D. Mack, analysts (Becraft and Weis, in press)
  4. 4 miles west of Stayton, Oregon. (Thayer, 1937, p. 1622)
- A. Average of columns 1 to 4

Most flows of Picture Gorge basalt are nearly holocrystalline, although some are exceedingly fine grained. Even the coarsely crystalline ones generally contain at least a little pale brown glass. The Yakima flows are rich in dark-colored tachylyte: most contain 20 percent or more, and many over 40 percent. The modes of all rocks listed in the tables were measured on specimens taken from the lower tier of columns, well above the basal chill zone, and so contain less glass than the flows as a whole. Nearly all flows of Yakima basalt are non-porphyrific or else have only tiny microphenocrysts. On the other hand about one-fourth of the Picture Gorge flows contain phenocrysts of plagioclase, pyroxene, and olivine.

Detailed studies of the minerals in the Columbia River basalt are under way but not yet complete; only a few of the main features are summarized here. Pyroxene, plagioclase, and olivine show some systematic differences in the two kinds of basalt. Most flows of Yakima type contain plagioclase close to An<sub>50</sub>, that in the Picture Gorge type is more calcic and shows more zoning. All pyroxenes are monoclinic and are optically positive. Most Yakima flows contain a clear to pale honey-colored pyroxene with a 2V of about 40 to 45 degrees. In many rocks it is zoned to a deeper honey-golden pyroxene. Pyroxene in rocks of the Picture Gorge type is more variable: pale golden-brown pyroxene with a 2V around 50 to 52 degrees is common, but in the coarser-

TABLE 5  
Average chemical composition of Columbia River basalts, and other basalts

	Columbia River Basalts					Nockolds (1954) World Averages			
	Picture Gorge basalt	Yakima basalt	Late Yakima and Early Ellensburg flows	Olivine basalts from central part of Cascade Range	Olivine basalts from Snake River Plain (compilation by H. Powers, 1960)	Normal tholeiitic basalt	Tholeiitic olivine basalt	Tholeiitic andesite	"Central" basalt
SiO <sub>2</sub>	49.3	53.8	50.0	49.79	46.11	50.83	47.90	51.43	51.33
Al <sub>2</sub> O <sub>3</sub>	15.6	13.9	13.5	16.74	14.54	14.07	11.84	13.05	18.04
Fe <sub>2</sub> O <sub>3</sub>	3.5	2.6	1.9	2.65	2.70	2.88	2.32	3.36	3.40
FeO	7.8	9.3	12.5	7.82	10.15	9.00	9.80	9.74	5.70
MgO	6.5	4.1	4.4	7.16	7.48	6.34	14.07	5.28	6.01
CaO	10.3	7.9	8.3	9.07	9.73	10.42	9.29	8.78	10.07
Na <sub>2</sub> O	2.7	3.0	2.9	3.32	2.41	2.23	1.66	3.18	2.76
K <sub>2</sub> O	0.5	1.5	1.4	0.82	0.61	0.82	0.54	1.04	0.82
H <sub>2</sub> O <sup>+</sup>	} 1.8	1.2	0.9	0.41	0.46	0.91	0.59	0.87	0.45
H <sub>2</sub> O <sup>-</sup>									
TiO <sub>2</sub>	1.6	2.0	3.2	1.71	2.93	2.03	1.65	2.60	1.10
P <sub>2</sub> O <sub>5</sub>	0.3	0.4	0.7	0.31	0.67	0.23	0.19	0.48	0.16
MnO	0.2	0.2	0.25	0.17	0.20	0.18	0.15	0.19	0.16
CO <sub>2</sub>	0.04		0.09	0.02	0.04				
Number of analyses	16	8	4	13	38	137	28	26	56

grained rocks it may be zoned to, or proxied for, by a pale purplish brown titanpyroxene of small (about 45°) 2V.

Analcime is a common accessory in the older basalts but is vanishing rare in Yakima flows. Cavity fillings of opal are common in the Yakima basalt, especially from areas near dike swarms, or where lava poured into water and formed pillow lava - palagonite complexes.

The Picture Gorge flows are characterized by a small (about 5 percent) but uniform content of iron-rich olivine, which in most rocks is wholly or partly altered to saponite. Except for its late basic variant, the Yakima basalt shows only traces of olivine, or at most less than 2 percent. The Picture Gorge basalt also contains more chlorophaeite and its characteristic decomposition products than does the Yakima basalt. Chlorophaeite, first described from the Columbia River plateau by Peacock and Fuller (1928), is an apple-green iron-rich mineraloid, completely isotropic to light and X-rays when fresh. It is unstable, however, and freshly broken surfaces alter within a few months to a sooty black material, or after long-continued weathering to waxy dark brown

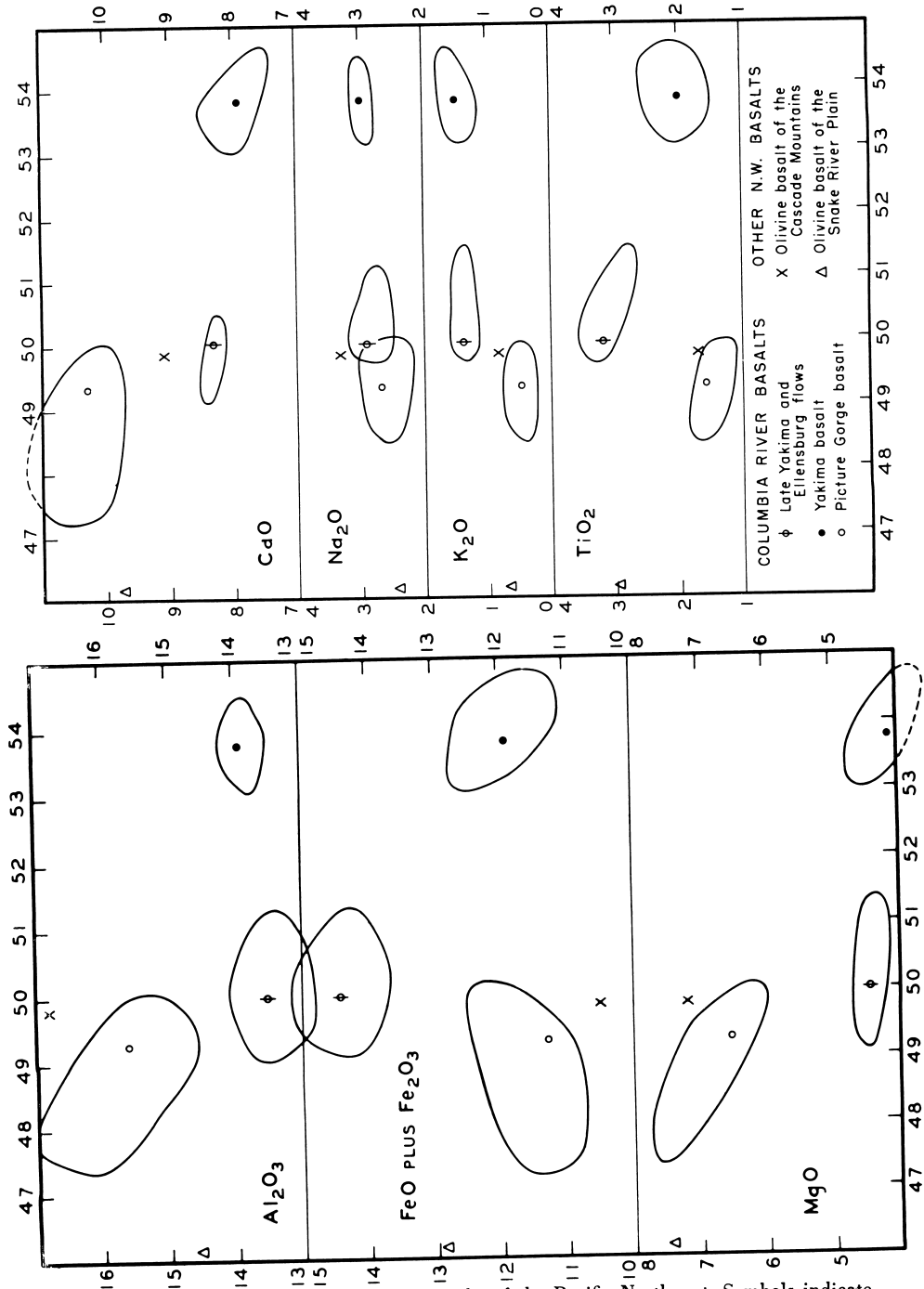


Fig. 2. Variation diagram, basaltic rocks of the Pacific Northwest. Symbols indicate average composition of: (a) the three chemical variants of the Columbia River basalt, (b) the olivine basalt of the Cascade Mountains, and (c) the olivine basalt of the Snake River plain (from table 5). Spaces enclosed by lines show areas within which available chemical analyses of the three variants of the Columbia River basalt fall.

TABLE 6  
 Modes, Picture Gorge basalt: no. 25, Picture Gorge section; no. 23,  
 lower part of Imnaha section

(Top No. 25 Picture Gorge	Plagioclase	Monoclinic Pyroxene	Olivine (including saponite)	Glass	Chlorophaeite (including decomposition products)	Opagues	Zeolites
25-1	43.6	42.2	2.6	1.8	1.2	7.6	1.0
25-2	40.0	37.0	6.2	6.2	4.8	3.6	2.2
25-3	40.4	30.2	7.6	3.8	13.6	3.8	0.6
25-4	41.4	33.6	5.4	6.0	7.8	5.0	0.8
25-5	39.6	42.0	2.8	1.4	6.2	7.6	0.4
25-6	37.2	37.0	6.8	4.2	8.0	6.0	0.8
25-7	33.2	39.2	2.2	10.4	4.0	10.8	0.2
25-8	36.8	37.0	2.4	20.2	0.2	3.4	none
25-9	42.8	37.0	6.2	4.4	3.4	6.0	0.2
25-10	37.8	36.4	8.2	3.8	7.8	6.0	none
25-11	39.0	34.6	4.2	13.8	2.0	6.4	none
25-12	39.0	42.0	1.6	4.6	3.6	8.6	0.6
25-13	40.6	36.4	7.4	2.8	6.2	6.2	0.4
25-14	39.2	40.2	2.4	4.6	5.4	7.4	0.8
Average	39.2	37.5	4.7	6.3	5.3	6.3	0.6
<b>No. 23 Imnaha</b>							
23-20	41.0	33.6	4.4	10.8	3.0	7.2	none
23-21	46.5	30.5	2.7	7.0	7.3	6.1	trace
23-22	46.4	32.9	2.1	5.0	5.1	7.6	0.9
23-23	54.2	27.6	2.2	7.4	0.4	7.4	0.8
23-25	44.0	37.7	6.3	1.8	1.7	8.5	trace
23-26	56.4	25.4	12.6	1.0	0.2	2.8	1.6
23-27	54.4	20.0	13.0	2.0	1.2	6.4	3.0
23-28	49.2	31.2	4.0	4.0	0.4	10.8	0.4
23-29	34.2	29.2	6.6	19.2	1.8	9.0	trace
23-30	39.2	25.0	7.4	13.2	6.6	8.2	0.4
23-31	45.6	31.8	11.4	5.6	0.8	4.8	none
Average	46.5	29.5	6.7	7.0	2.6	7.2	0.7

or reddish brown substances. In about half of the flows it is decomposed, even in the fresh rocks from deep excavations; in some of these it is fresh in the chilled base of the flow but decomposed in the flow interiors and along the margins of vesicles where volatiles could break it down during the last stages in the cooling history of the flow. X-rays show that the decomposition products are chiefly iron oxides and clay minerals, among which nontronite, saponite, montmorillonite, and celadonite appear to be most common. Peacock held that chlorophaeite replaces olivine, but his work was done before X-ray identifications became routine, and it seems almost certain that he confused the abundant deep greenish iron-rich saponite, which pseudomorphs ferriiferous olivine in many Picture Gorge basalts, with chlorophaeite. The writer's observations

TABLE 7  
 Modes: Yakima basalt: No. 2, Crescent Bar section; No. 14,  
 Grande Ronde section

No. 2 Crescent Bar (Top)	Plagio- clase	Mono- clinic pyroxene	Olivine (including saponite)	Glass	Chlorophaeite (including decomposition products)	Opagues
2-2	36.2	29.1	1.4	22.2	4.8	6.3
2-4	30.5	25.9	none	30.6	5.7	7.3
2-51	30.9	28.6	trace	28.6	2.9	9.0
2-52	28.5	29.0	0.7	29.9	2.6	9.2
2-8	30.4	25.9	none	35.5	1.8	6.5
2-10	29.8	31.0	0.4	29.2	0.6	8.9
2-11	30.4	26.4	none	32.8	0.4	10.0
Average	31.0	28.0	0.03	29.8	2.7	8.2
No. 14 Grande Ronde						
14-1	27.8	41.0	none	19.5	3.5	8.2
14-2	23.7	37.2	trace	29.6	1.1	8.5
14-2a	26.8	20.8	2.2	32.4	5.9	11.9
14-4	18.2	23.0	1.8	41.8	6.8	8.2
14-6	30.0	24.1	1.7	28.2	5.1	10.8
14-8	37.8	39.3	1.7	12.0	5.5	3.6
14-8a	24.3	44.5	0.4	16.0	6.9	7.9
14-9	27.2	28.8	none	30.3	3.1	10.5
14-10	33.3	35.0	none	23.5	none	8.1
14-11	30.8	29.6	none	24.7	2.7	12.2
14-12	33.0	31.1	0.4	18.2	3.8	13.5
14-13	31.1	34.4	none	23.8	none	10.7
14-14	35.2	30.2	none	21.8	4.5	8.3
14-15	24.2	32.8	2.1	27.6	3.7	9.5
14-16d	16.0	37.2	0.2	32.6	1.4	12.6
14-17	13.6	30.3	none	43.5	1.8	10.8
14-18	33.2	21.0	1.0	31.9	5.9	7.1
14-19	25.0	35.2	trace	27.0	none	12.7
14-20	32.0	30.2	0.6	23.6	7.5	6.1
14-21	36.5	25.9	0.6	25.4	5.4	6.6
14-22	28.5	29.6	1.4	24.0	5.6	10.8
14-23	44.2	34.2	1.6	10.2	3.0	6.8
14-24	46.8	36.2	0.4	9.8	none	6.8
14-25	36.8	33.2	1.8	17.6	3.0	7.6
14-26	40.4	33.6	0.6	16.4	4.4	4.6
14-27	33.8	47.4	1.6	10.4	2.2	3.6
14-28	39.0	33.6	0.6	19.0	4.4	4.2
14-29	41.2	37.0	0.6	10.8	1.8	8.6
14-30	39.4	37.2	none	14.0	1.2	8.2
14-31	42.2	39.4	0.2	14.4	none	3.8
14-32	32.4	52.6	none	9.4	none	5.6
14-33	45.0	37.6	0.4	10.8	none	6.2
Average	32.1	33.9	0.7	21.9	3.1	8.3

are that chlorophaeite is invariably interstitial, or else is confined to oval segregations within basalt glass. Its decomposition products may wander widely, however, producing stains on feldspars and ferromagnesian. Flows containing abundant chlorophaeite weather to a deep orange brown; flows without it generally weather to neutral gray or greenish gray shades.

The richness of the Picture Gorge flows in olivine and in chlorophaeite is responsible for one of the most useful criteria to distinguish them from the Yakima basalt in the field: most of the olivine and chlorophaeite-rich flows have undergone a slight deuteric alteration that gives the lava a dark color and a characteristic greasy or waxy appearance. On weathering this greasy type of lava swells and develops innumerable small cracks much like the craze on the surface of some kinds of pottery. Continued swelling and opening of the cracks causes the lava to disintegrate into a coarse grus of small angular fragments. The decomposition and disintegration of the rock is more intense in the interiors of joint columns than along their edges, and is more prevalent in the centers of flows than in their chilled tops and bottoms. The immediate cause of the crazing and swelling of the rock is its content of clay minerals derived mainly from the breakdown of olivine and chlorophaeite. The disintegration of the coarsely columnar interiors of the flows by these alterations causes the Picture Gorge basalts to weather into generally rounded slopes with softened and blurred profiles in contrast to the bold cliffs of "rimrock" carved from the resistant lower tier of columns in the flows of Yakima basalt.

In the older, greasy-appearing basalts that occupy the lower part of the Imnaha Canyon (pl. 1-B) such alterations significantly affect the joint pattern. Columnar joints in the lower parts of the flows are swelled shut, and alteration of the flow centers has produced a massive tightly jointed rock that is practically impermeable to water. Therefore many springs emerge on the walls of the Imnaha Canyon at the unconformity between the overlying well-jointed Yakima basalt and the Picture Gorge basalt.

In general the Yakima basalt is nearly free of these alterations. Near dike feeders some flows show blotchy streaks where collapsed vesicles contain a little chlorophaeite and have retained enough volatile material to produce a slight amount of montmorillonitic alteration of the vesicle walls. Some of these blotchy flows also contain opal in cavities, and a few show small ball-like clusters or pseudocubic aggregates of cristobalite. Opal was disregarded in making the modes shown in table 7, but it is unquestionably responsible for the higher silica content shown in the chemical analysis of the rocks from Waterville (column 1, table 3) and from Clealum ridge (column 2, table 3). Each of these flows contains about 1 percent of hyaline opal as cavity fillings.

The complete lack of transitional flows between the Picture Gorge and Yakima types is noteworthy, and so is their separation in time. The conclusion seems inescapable that on the Columbia River plateau two distinct and separate batches of magma were poured forth in volume from different magmatic hearths at different periods of time. Yet the differences are of a kind that could be approximated by selective removal of early crystallizing plagioclase, olivine, and magnesian pyroxene from the Picture Gorge magma. The case against the Yakima type's being a differentiate from the Picture Gorge type is chiefly the lack of transitional rocks between them. Noteworthy, too, is the rarity of porphyritic flows of Yakima basalt, indicating that the parent magma had not undergone a long and complex crystallization history prior to extrusion.

TABLE 8  
Modes: Klickitat River section (no. 10) of the Columbia River basalt

Specimen number	Plagio-clase	Mono-clinic pyroxene	Olivine (including saponite)	Glass	Chlorophaeite (including decomposition products)	Opaques
10-1	40.4	43.4	5.6	2.6	1.8	6.6
10-2	45.4	36.8	5.0	8.0	1.6	3.2
250 feet of sedimentary rocks (Ellensburg equivalent)						
10-4	45.6	20.6	3.2	18.0	5.4	7.2
110 feet of sedimentary rocks (Ellensburg equivalent)						
10-5	42.6	25.4	1.0	23.0	0.8	7.2
40 feet of sedimentary rocks						
10-6	49.0	19.8	4.8	21.6	0.8	4.0
10-7	45.4	34.8	none	8.2	5.6	6.0
10-8	41.2	33.0	none	14.0	6.4	5.4
10-9	39.8	21.2	none	31.4	2.2	5.4
10-10	36.2	27.0	none	25.0	8.0	3.8
10-11	37.4	28.6	none	32.6	0.8	0.6
10-12	37.8	26.4	0.4	26.0	4.8	4.6
10-13	44.6	33.6	1.0	13.0	5.6	2.2
10-14	47.8	33.0	1.4	6.2	8.8	2.8
10-15	31.2	19.2	none	44.8	0.2	4.6
10-16	31.4	16.8	none	51.8	none	(in glass)
10-17	43.4	36.8	none	9.4	5.0	5.4

#### LATE TEXTURAL AND MINERALOGIC VARIANT OF THE YAKIMA BASALT

In the southwestern part of the lava field, chiefly along Columbia River and in the area lying west of Columbia River between Wenatchee and Pasco, a textural and mineralogic variant of the Yakima basalt appears, which seems to have had a slightly different crystallization history than normal Yakima flows. It is characterized by a coarse but open network of large plagioclase microlites and of granular to elongate clinopyroxenes. The large plagioclase microlites have well-developed 010 faces but show ragged skeletal ends—a feature that was also noted by Wilkinson (Wilkinson, Lowry, and Baldwin, 1946, p. 20) in the Columbia River basalt west of the Cascades. Filling the openings between these coarse tangled microlites are patches of glass, varying from 1 to 4 millimeters in diameter (pl. 2-C). In most flows this glass has partly crystallized, and is half filled with flamboyant variolitic sheaves of feldspar needles and with a titaniferous opaque in large skeletal growths (pl. 2-D).

Pahoehoe tops and flow unit separations are more common in these flows than in the normal Yakima basalt. They also show a higher content of vesicles. In some flows, moreover, the glass mesostasis does not completely fill the voids between the large feldspar microlites but leaves a complicated maze of interconnected miarolitic cavities. This miarolitic texture is transitional to the coarse diktytaxitic texture (Fuller, 1931b, p. 116) so common in the olivine-rich basalts of the Cascade Mountains and southern Oregon plateaus. On weathering the interstitial glass is the first thing to decompose; weathered rock strongly resembles diktytaxitic-textured olivine basalt, but the mineralogy is quite different.

Older flows of this textural type (represented by flows 10-5, 10-9, and 10-12 to 10-14 in table 8) vary only slightly from normal Yakima flows in mineral composition, although they do contain a little more olivine (generally 0.5 to 3 percent), and a distinctly higher ratio of plagioclase to pyroxene than the normal Yakima basalt. But near the top of the sequence several flows containing 5 to 15 percent of olivine are interstratified with the less olivinic flows. These have more normal textures, and less glass. Some contain pigeonite as the groundmass pyroxene. Modes of 14 of these flows are given in table 9, and 3 more (specimens 10-1, 10-2, and 10-6) are in table 8. The flows richer in olivine are among the youngest of the Yakima basalt; some are interstratified with the overlying Ellensburg formation. Even those that occur below the Ellensburg are commonly interlayered with thin interbeds of arkose, siltstone, and diatomite, or they show ancient soil zones and other evidence of weathering between flows. Some interbeds consist of coarse sand and gravel derived from a metamorphic-plutonic terrain. This indicates that stream gradients were being steepened by warping of the plateau at the time these late olivinic flows emerged.

Some of the late olivinic flows are confined to synclines that apparently were just beginning to form when these flows were erupted. Examples are: (A) Two flows that overlies beds equivalent to the Ellensburg formation in the Klickitat section (number 10), modes of which are given in table 8, specimens 10-1 and 10-2. (B) Several late flows that occupy the axial part of a syncline followed by Columbia River in the Arlington-Roosevelt area. Two of these flows lie above sediments equivalent to the Ellensburg formation. Others lie below the Ellensburg but contain intercalations of diatomite and micaceous sandstone. Modes of 4 of these flows are given under samples 1 to 4 in table 9. (C) The topmost flows in the axial part of the same syncline at The Dalles, Oregon. One of these flows, well exposed in the northwest part of The Dalles, was chemically analyzed by Washington (1922). The analysis is listed in column 1, table 4, and a mode from a thin section of this flow is listed as sample 13 in table 9.

Although most of these olivinic flows are found in the southwestern part of the lava field, they occur elsewhere. The chemical analyses (columns 2 and 3 of table 4) given by Becraft and Weis (in press) of two basalts from the Turtle Lake quadrangle near the northeastern margin of the basaltic plateau are of this type of rock. Becraft (written communication) reports that the analyses are of the topmost flow of Yakima basalt in each area, and he kindly

TABLE 9

Modes: Late Yakima and Ellensburg flows, Columbia River basalt

Location of Samples	Plagioclase	Monoclinic pyroxene	Olivine (incl. saponite)	Glass	Chlorophaeite (including decomposition products)	Opakes	Zeolites
1. 2½ mi NE Roosevelt, Washington	43.0	19.3	10.4	10.1	5.9	8.9	2.4
2. Top flow Yakima basalt, Wood Gulch	46.7	24.4	12.1	4.9	6.3	5.0	0.6
3. Rock Creek, Goodnoe, Washington	45.0	25.1	9.0	10.7	2.8	6.8	0.5
4. Rock Creek, Goodnoe, Washington	42.7	26.3	6.3	11.7	5.0	7.6	0.4
5. 5 mi S of Mabton, Washington	42.1	26.4	10.6	9.0	3.6	7.4	0.9
6. Roza flow, Selah Tunnel, Yakima, Washington	43.6	19.4	12.4	14.8	2.4	7.4	none
7. Wenas flow near Pomona, Washington	34.2	25.6	7.0	22.2	1.6	9.4	none
8. Platy flow, Frenchman's Springs, Washington	39.6	27.4	6.6	16.8	0.3	7.7	1.6
9. 2 mi NE Frenchman's Springs, Washington	50.1	22.0	12.5	5.5	2.4	7.0	0.5
10. Babcock Ridge, Quincy, Washington	34.6	21.4	8.0	27.7	1.4	6.9	none
11. Rock Island, Washington	31.6	23.8	5.2	31.0	trace	8.4	none
12. Turtle Lake quad (Becraft, in press)	39.1	21.3	5.6	24.7	0.9	8.2	none
13. The Dalles, Oregon	39.8	24.0	3.2	23.0	4.8	6.2	none
14. Intracanyon flow, Clarkston, Washington	42.4	36.0	6.8	8.4	1.4	4.6	0.4
Average	41.0	24.5	8.3	15.7	2.8	7.2	0.5

lent a thin section cut from one of the analyzed rocks. The mode listed as sample 12 in table 9 was made from this thin section. Another olivinic flow of Late Yakima type (mode listed as sample 14, table 9) is well exposed west of Clarkston, Washington. This flow was extruded after uplift and considerable erosion of the normal Yakima basalt, for it half fills a deep canyon cut in Yakima flows by an earlier stage of Snake River (Lupher and Warren, 1942). Another olivinic flow caps 250 feet of sedimentary rock that rest on top of Yakima basalt east of Buford Creek in Wallowa County, Oregon.

One of the two kinds of Stayton lava (see column 4 of table 4), reported by Thayer (1937) from the west side of the Cascade Range near Salem, Ore-

TABLE 10  
Chemical analyses and modes: typical Quaternary olivine basalts

	1	2	3	4	5	6	Average
SiO <sub>2</sub>	48.71	49.0	49.38	49.44	49.6	49.95	49.35
Al <sub>2</sub> O <sub>3</sub>	16.92	14.7	16.92	16.85	16.0	16.81	16.37
Fe <sub>2</sub> O <sub>3</sub>	3.49	6.0	1.05	5.05	1.3	3.39	3.38
FeO	7.65	4.2	8.82	5.58	9.9	6.72	7.15
MgO	7.98	8.2	8.56	7.25	7.4	8.60	7.98
CaO	9.68	11.0	9.80	9.15	9.6	8.79	9.34
Na <sub>2</sub> O	2.96	2.5	3.10	3.25	3.3	3.01	3.02
K <sub>2</sub> O	0.40	1.8	0.40	0.66	0.53	0.49	0.71
H <sub>2</sub> O <sup>+</sup>	0.22		0.04	0.25		0.38	
H <sub>2</sub> O <sup>-</sup>	0.18	0.54	0.05	0.26	0.18	0.22	0.39
TiO <sub>2</sub>	1.38	1.3	1.40	1.80	1.5	1.21	1.43
P <sub>2</sub> O <sub>5</sub>	0.22	0.59	0.19	0.39	0.34	0.17	0.30
MnO	0.18	0.18	0.17	0.17	0.20	0.16	0.18
CO <sub>2</sub>	0.02	0.26	0.01	0.01	<0.05	0.02	0.06
Sum	99.99	100	99.89	100.01	100	99.92	
Plagioclase	51.6	38.8	47.1	45.0	50.0	47.1	46.6
Pyroxene	17.7	30.6	20.4	26.0	19.0	22.1	22.6
Olivine	18.0	21.8	18.4	19.1	18.0	19.1	19.1
Glass	6.3	1.2	9.9	3.9	9.4	6.3	6.2
Chlorophaeite	none	none	0.9	none	none	none	trace
Opauques	6.3	4.0	3.3	6.0	3.6	5.3	4.8
		3.6(K.Spar)					
Zeolites	none	none	none	trace	none	trace	—

1. Porphyritic olivine basalt. Sec. 36, T 2 S, R 8 E, west of Black Lake, Hood River quadrangle, Oregon. V. C. Smith, analyst. USGS Lab. no. E2101. (new analysis)
2. Conant butte lava flow, Sec. 11, T 17 S, R 18 E, near Post, Oregon. P. L. D. Elmore and K. E. White, analysts. USGS Lab. no. 142180. (new analysis)
3. "Big Lava Bed," a recent flow. Lava Creek, Sec. 34, T 4 N, R 9 E, west of Willard, Washington. V. C. Smith, analyst. USGS Lab. no. E2093. (new analysis)
4. Postglacial olivine basalt flow, South Pine Creek, Hood River quadrangle, Oregon. Sec. 25, T 2 S, R 10 E. V. C. Smith, analyst, USGS Lab. no. E2100. (new analysis)
5. Top flow, olivine basalt, Ochoco State Park, 1 mile west of Prineville, Oregon. P. L. D. Elmore and K. E. White, analysts. USGS Lab. no. 142182. (new analysis)
6. Wind River lava flow, Trout Creek Hill, northwest of Carson, Washington. Sec. 7, T 4 N, R 7 E. V. C. Smith, analyst. USGS Lab. no. E2094 (new analysis)

gon, appears to be identical in chemical and mineral composition, and also in texture, to these Late Yakima olivinic flows.

Only a few chemical analyses of the late olivine basalts have been reported (table 4), but from them and the many modes that have been measured (tables 9 and 8), it is apparent that these rocks are lower in silica and notably higher in iron and titanium than normal Yakima basalt. They also show more variation among themselves, yet have a definite easily recognized consanguinity in chemical composition and mineralogy.

As to their source and origin, the more basic nature of these flows and their appearance during the waning stages of vulcanicity seems to rule out the idea that they are late differentiates of the Yakima basalt magma unless, perhaps, one assumes that the "chamber" which supplied the Yakima basalt was

so thoroughly eviscerated that the last final flows were clogged with crystal accumulates carried up with the final liquid dregs. But most of these flows are not strongly porphyritic. The few that are, such as the Roza flow of the Yakima-Vantage area, are so conspicuous that they are used as stratigraphic markers. Neither do these flows contain large glomeroporphyritic clots nor cognate inclusions of gabbro, troctolite, or similar rocks. In fact most are non-porphyritic and closely similar in appearance to the normal Yakima basalt. In their richness in olivine and plagioclase, the "Late Yakima" rocks show some resemblance to the widespread Pliocene-Quaternary olivine basalts that lie unconformably upon the Yakima basalt and spread over wide areas in the Cascade Mountains and central Oregon plateaus. The "Late Yakima" flows, however, are much less feldspathic and contain less than half the olivine found in these younger Pliocene-Quaternary olivine basalts (tables 9 and 10).

Could the accelerating tectonic movements that began in early Pliocene time have opened new fissures and brought the "Late Yakima" flows to the surface from a different, possibly deeper, site of magma generation than did the feeders for the main bulk of the Yakima basalt?

#### LATE STRUCTURAL MOVEMENTS AND ASSOCIATED OUTPOURING OF THE PLIOCENE-QUATERNARY OLIVINE BASALTS

This is not the place to discuss structural changes produced by isostatic movements connected with the withdrawal of vast volumes of magma from relatively few dike swarm centers, and the loading of the crust by lava in areas far removed from the feeders. That such movements did occur is suggested by the pronounced basining of the basaltic plateau. At the end of the period of extrusion the Yakima basalt must have had the form of a great plano-convex lens with its upper surface nearly flat, and its bottom a curve. Warping has continued until now the upper surface of the basalt stands from 2000 to well over 5000 feet above sealevel on all parts of its periphery (the extension of the Miocene basalts along the lower course of Columbia River west of the Cascade Mountains excepted). But in the central part of the plateau (Pasco and Umatilla basins) the surface of the basalt is still near sealevel.

How thick the basalt may be in the center of this great lens can only be conjectured. Nowhere except along the uplifted margins of the plateau has erosion bitten deeply enough to expose the floor on which the basalt was poured. Near the southeastern margin of the basaltic floods 3000 to 4000 feet of the Yakima basalt is exposed on the precipitous walls of the Snake, Salmon, Grande Ronde, and Imnaha River canyons. In some parts of this area another 1000 feet or more of Picture Gorge basalt lies unconformably below it. Sections of Yakima basalt over 2000 feet thick can be seen in the Columbia River gorge, where it crosses the Cascade Mountains, and also in the eastern foothills of the Cascades where rivers such as the Yakima have eroded deep water gaps through anticlinal ridges in the basalt (Smith, 1903b; Waters, 1955a). But all these thick natural sections are near the margin of the lens. The floor, where exposed, is a hilly to mountainous erosion surface with centripetal regional slopes. All the available evidence indicates that the basalt thickens rapidly toward the center of the plateau, but geophysical measurements are not available

to indicate the total thickness. One deep well drilled in Section 15 Township 11 North Range 24 East at the eastern end of the Rattlesnake Hills, not far from the center of the plateau, is reported to have bottomed in basalt at a depth of 10,655 feet.

As already noted, tectonic activity connected with the upheaval of the Cascade Range began to affect the western margin of the plateau during the waning stages of the outpouring of the Yakima basalt. Furthermore, faults of the Basin and Range province began to spread into the southern and southwestern margins of the lava field. Both folding and faulting grew in intensity during the Pliocene, raising the great east-west anticlinal ridges that characterize the western half of the plateau and breaking its southern part into a mosaic of fault blocks. The faults continue northward along the eastern slope of the Cascades, where they block out the east side of the upper Metolius and Hood River valleys, and extend far north of Columbia River into the Cascade Mountains of Washington.

Many of the Pliocene-Quaternary olivine basalts that cover great areas of the Cascade Range and that form the dominant rocks in the block-faulted plateaus of south-central Oregon rose to the surface along these faults. Although the younger olivine basalts were frequently confused with the Columbia River basalt in early reconnaissances, they are strikingly different in both field habit and mineralogy. At many places, moreover, they rest with strong structural unconformity upon upturned and eroded Columbia River basalt (pl. 2-A).

Many of the olivine basalts spread from fissure eruptions, but unlike the Columbia River basalt they also built numerous low shield volcanoes dotted with satellitic cinder cones. In places these shields are so closely spaced that they overlap. Some are lined up along major fissures: among the many examples are the NNW-SSE lines of basalt shields and cinder cones of the Simcoe Mountains in south-central Washington, and the lava shield and associated cinder cones that grew at the intersection of two faults south of the great bend of the Metolius River in the Cascade Mountains of Oregon. This shield fed the voluminous intracanyon flows of olivine basalt so conspicuous along the lower Metolius. Other centers of olivine basalt extrusion appear to be entirely independent of faults and fractures.

The Pliocene-Quaternary olivine basalts differ from the Columbia River flows in other ways than their mode of eruption. They occur in thin lava flows and flow units averaging less than 20 feet thick instead of the huge flows, averaging 77 feet thick, that characterize the Columbia River basalt. Many olivine basalt flows are complexly intertongued by filled lava tubes and narrow overlapping flow unit streams (Waters, 1960). Pahoehoe tops are common. Some flows spread out to smooth surfaces without either ropy tops or surface clinker. The most striking feature of their mineralogy is the high content of plagioclase and olivine, and the corresponding diminution in the amount of pyroxene (table 10). About half of them are light gray, and they show the characteristic open network of plagioclase laths with voids between (diktytaxitic texture). Table 10 gives chemical analyses and modes of 6 flows of

olivine basalt collected from near the southwestern margin of the Columbia River basalts.

Because of these striking differences in field habit, mineralogy, (tables 6, 7, and 10), and chemical composition (table 5), and also because of their separation in time, it appears that the Pliocene-Quaternary olivine basalts did not arise as a differentiation product of either of the two major divisions of the Columbia River basalt. It is also interesting that olivine basalts of the same physical and chemical characteristics as the Pliocene-Quaternary olivine basalts reached the surface in the Hart Mountain area and other parts of southern Oregon during the Miocene at approximately the same times that the petrographically different Yakima basalt and Picture Gorge basalt was accumulating to the north (George W. Walker, personal communication). These regional relations appear to point to fundamental differences in either the depth, or else in the area of source of supply of the magmas, rather than to changes imposed on a single uniform molten mass during the course of its cooling history. Such suggestions are, of course, purely speculative, but as more data are accumulated about these interesting rocks we may be able to confine the speculations within a more rigorous framework. Present evidence, admittedly inconclusive, appears to favor the idea that the differences in the three types of lava that have been included in the Columbia River basalt, and also the difference between them and the olivine basalts of the Cascades and central Oregon plateaus, are to be sought in differences at the point of magma generation rather than as steps in the crystallization-differentiation of a single uniform parent magma.

#### STRATIGRAPHIC RELATIONS

We return now to a discussion of the stratigraphic relation of the two main divisions of the Columbia River basalt to one another, and to contiguous sedimentary formations.

From the evidence already outlined it is apparent that the "Columbia lava" of Merriam is somewhat older than the Yakima basalt of Smith. The two are separated both on the basis of chemical and mineralogical differences, and because of a structural unconformity between them. Moreover, the basalts that Merriam (1901, p. 303) described are not "the horizon which is most prominent along Columbia River" nor are they "that [series] of several to which the name [Columbia] is applied which has the greatest lateral extent, forming probably the greatest lava field in the world." Instead the basalt of the John Day basin seems to be restricted to areas of only moderate size which lie along the southeastern margin of the great area of flood basalts. It may, of course, have extensive underground extensions beneath younger lavas to the north, south, and west.

On the other hand Smith's claim (1901, p. 15) that the Yakima basalt is composed of "flood after flood of molten rock, which covered the vast area between what is now the crest of the Cascade Mountains on the west and the mountains of Idaho on the east, and between the mountains of northeastern Washington and the Blue Mountains of Oregon on the south" is confirmed.

To further restrict the name Columbia River basalt to the Yakima rocks, however, would only make additional confusion in an already confused term-

nology. Since Merriam's time the basaltic rocks that he studied in the John Day basin have consistently been called the Columbia River basalt, and although Merriam did not designate a type section, the well-exposed section at Picture Gorge, Oregon has informally served as the type over the years. The present danger of confusion lies not so much in the use of the term "Columbia River" for these basalts as in the widely held but erroneous assumption that the rocks of the John Day basin are the time and mineralogical equivalents of the Yakima basalt to the north, plus the added fact that the Yakima basalt has also been considered as synonymous with Columbia River basalt in the literature. There is indeed good justification for such usage, since it was to this group of lavas that Russell (1893, p. 20-22) first applied the term "Columbia lava," and designated the canyons and coulees in Douglas County, Washington, as "typical."

These dilemmas in nomenclature are easily resolved if we elevate the *Columbia River basalt* to group status, and recognize two distinct formations within it: (1) The *Yakima basalt* as defined by G. O. Smith, and (2) the older basalts of the John Day Basin, called the "Columbia Lava" by Merriam, but herein renamed the *Picture Gorge basalt*, with the section at Picture Gorge designated as the type section. This nomenclature also provides the flexibility to add additional formations or other stratigraphic subdivisions as the need may arise, for, as will now be shown, there are still numerous stratigraphic problems which cannot be resolved until the entire Columbia River plateau has been geologically mapped.

#### GEOLOGIC AGE

At Picture Gorge, the Picture Gorge basalt is overlain by the Mascall formation of middle to late Miocene age (Merriam, 1901; Berry, 1929, p. 235; Chaney, 1925; Downs, 1956, p. 321-329; Chaney and Axelrod, 1959, p. 119-134). Farther northwest it disappears unconformably beneath the Yakima basalt of the Condon area.

The relation of the Yakima basalt to the Mascall formation is not clear, but at many points along its northern and eastern margin the Yakima basalt overlies, or is intercalated with, fluvial and lacustrine beds that carry an abundant Latah flora (Berry, 1929, 1931, p. 32; 1934, p. 101; Brown, 1937, p. 163-164; Chaney and Axelrod, 1959, p. 119-134). This middle or late Miocene flora is regarded by most paleobotanists to overlap that of the Mascall. The Ellensburg formation, first assigned to the Miocene, but now regarded to be early Pliocene on the evidence of both fossil vertebrates and the ecological relations of its fossil plants (Axelrod, 1950, p. 239-243) rests on the Yakima basalt at its type area, but also contains in its lower part some basalt flows (the Wenas basalt) that were considered to be the final outpourings of the Yakima basalt floods (Smith, 1903a). Moreover the uppermost flows of Yakima basalt are intertongued with sediments of the lower Ellensburg at many other localities in south-central Washington (Smith, 1904, p. 7; Waring, 1913, p. 19-21; Waters, 1955a, p. 670-673).

Below the base of the Ellensburg formation the Yakima basalt contains several interbeds of diatomite (Mackin, 1947). From one of these exposed in

a roadcut two and three-fourths miles north of Satus Pass in south-central Washington, Kenneth Lohman (*in* Sheppard, 1960, p. 10-13) reports 43 species of diatoms. The diatom flora indicates that this part of the Yakima basalt is of Early Pliocene age.

Bruce Foxworthy (Waters, 1955a, p. 664) has found fossils of fresh-water molluscs, tentatively identified as of Pliocene age, in sediments intercalated with the upper part of the Yakima basalt in Ahtanum valley west of Yakima.

The Latah formation and the Ellensburg formation consist chiefly of sediments of local derivation dropped by streams that were flowing from adjacent highlands toward the encroaching sea of basalt. These sedimentary rocks are now found as a discontinuous fringe that borders the basalt on the west, north, and east. Flows of lava repeatedly dammed the lower courses of the rivers, forming shallow lakes that spread over the margins of the lava plain and served as traps for fluvial and lacustrine sediments. Basalt flows from later eruptions entered and in many places completely over-ran these marginal lakes, building great pillow lava - palagonite complexes along the margin of the volcanic field (Fuller, 1931a). During the waning stages of volcanism, however, these relations were modified and even locally reversed. Many late flows did not spread the full distance from dike swarm to margin of the lava field, and still others were confined to deepening basins and to shallow synclinal troughs between growing anticlines.

The marginal interdigitation of the Yakima basalt flows with the sedimentary rocks of the Latah formation and lower Ellensburg formation suggests that the time of accumulation of the basal part of the Yakima basalt was somewhere in the range from middle to late Miocene, but the uppermost flows were erupted during the early Pliocene.

The age of the older Picture Gorge basalt can also be fixed within broad limits. At Picture Gorge this basalt lies unconformably upon the John Day formation (considered to be of Oligocene and early Miocene age) and is overlain by the middle to upper Miocene Mascall formation. This indicates a probable early or middle Miocene age for this section of basalt. We cannot be sure, however, that the basalt which lies unconformably beneath the Yakima basalt in the Imnaha canyon of northeastern Oregon is necessarily the precise age equivalent of that at Picture Gorge. Although similar in petrographic character it shows slight differences (table 6), perhaps indicating derivation from a different dike swarm. Petrographic similarity, moreover, is a very dubious criterion for the correlation of volcanic rocks.

Basalts considered to be part of the Columbia River basalt are widespread in the Lower Columbia valley west of the Cascade Mountains (Treasher, 1942; Wilkinson, Lowry and Baldwin, 1946; Lowry and Baldwin, 1952; Snavely, Brown, Roberts, and Rau, 1958, p. 58-61). On the Washington side of Columbia River, Weaver (1937, p. 178-180) found these basalts to be interstratified with marine sandstones containing fossils of the Middle Miocene Astoria formation and Lowry and Baldwin (1952, p. 5) found the same relationship on the Oregon side. Moreover, they report (p. 3) the occurrence of two "varieties or phases" of the Columbia River basalt west of the Cascades, and Parke

D. Snively (personal communication) reports a thick sandstone interbed separating two sequences of the Columbia River basalt north of the river.

Ultimately it may be desirable to extend the twofold division of the Columbia River basalt outlined in this paper to areas west of the Cascade Mountains. The terminology proposed gives the flexibility necessary to add further stratigraphic details. Meanwhile, until more of the Columbia River plateau and contiguous areas on the west and south are geologically mapped, we can have only an imperfect picture of the detailed distribution and age relations of the two basalt formations described herein to adjacent sedimentary formations. We need also additional information on the relations of the Columbia River basalt to the generally younger and more diversified sequences of olivine-rich basalt which spread over much of the Cascade Mountains, southeastern Oregon plateaus, and Snake River plain. When additional details have been supplied by field investigations and mineralogic work, we may have the basis for sound deductions regarding the fascinating problem of the relations between structural movements and magma generation during late Tertiary time in this tectonically and magmatically active province of the Pacific Northwest.

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Kenneth Lohman responded to the writer's request for an age determination of the diatomite from Satus Pass.

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