Columbia River Basalt in the Riggins Quadrangle Western Idaho

By WARREN HAMILTON

CONTRIBUTIONS TO GENERAL GEOLOGY

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A study of the field, petrographic, and chemical characteristics of the lavas at the east margin of the Columbia Plateau

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COLUMBIA RIVER BASALT IN THE RIGGINS QUADRANGLE, WESTERN IDAHO

By Warren Hamilton

ABSTRACT

The Riggins quadrangle lies across the deformed east margin of the Columbia Plateau. It contains a number of remnants of Columbia River Basalt, a formation that consists of flows of silica-saturated basalt, and subordinate tuff and agglomerate. At one locality, interbedded lake sediments yielded a rich middle or upper Miocene flora.

The basalts consist of plagioclase, subordinate clinopyroxene, variable amounts of glass, opaque oxides, and deuteric minerals, and a little olivine. The rocks are typical tholeiites chemically, and have an average SiO_2 content of about 50 percent; however, they are more varied than are tholeiites in limited areas elsewhere, and porphyritic rocks containing phenocrysts of plagioclase are relatively common. Probable differentiation was recognized only in the accumulation of plagioclase phenocrysts.

The basalt sequence in and north of the northern half of the quadrangle is characterized by columnar-jointed flows of dark dense basalt, whereas the sequence in and south of the southern half lacks such flows and instead has abundant porphyritic light colored open-textured basalt; different sources are indicated.

INTRODUCTION

GENERAL STATEMENT

The ruggedly mountainous Riggins quadrangle of west-central Idaho (fig. 1) is underlain largely by pre-Tertiary metamorphic and granitic rocks, but large remnants of Columbia River Basalt of Miocene age are preserved in upland areas. These remnants represent the east edge of the Columbia lava plateau which was built up to a great thickness by fissure eruptions of basalt; in the Riggins quadrangle, the basalts thin eastward and cover an old topography that only locally had high relief. The basalts are broken by normal faults, which have displacements of as much as several thousand feet, and are warped into folds whose dips are generally less than 30°.

PRESENT WORK

The 30-minute Riggins quadrangle was mapped during parts of summers between 1952 and 1961; T. R. Lovett, D. G. Sherlock, and G. J. Klapper assisted for part of one season each. Fieldwork and subsequent office and laboratory studies were concentrated on the

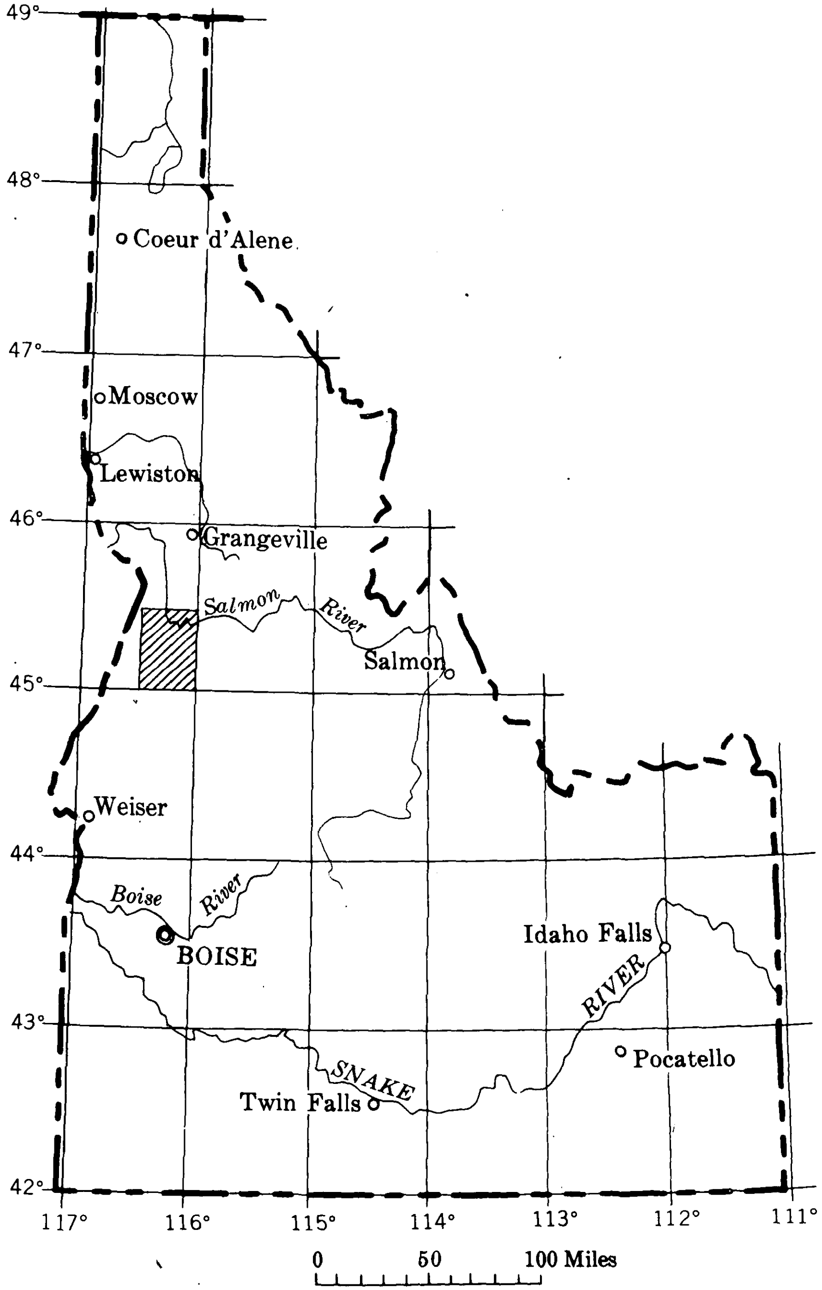

FIGURE 1.—Index map of Idaho showing location of the Riggins quadrangle (shaded).

pre-Tertiary metamorphic and plutonic rocks and structures; preliminary notes (Hamilton, 1958 and 1960) have been published on these, and a paper on the metamorphism in the Riggins region of west-central Idaho has been prepared for publication. A short paper describing the structure of the Columbia River Basalt in western Idaho has been published (Hamilton, 1962).

The Columbia River Basalt, widely distributed in the western two-thirds of the Riggins quadrangle, was mapped in semireconnaissance fashion. From the 100 specimens collected from the basalt, 25 thin sections were studied, and 9 specimens were analyzed chemically and spectrographically. Collections were made of a rich fossil flora from one locality.

Discussions with Howard A. Powers, Aaron C. Waters, and Ray E. Wilcox have been particularly helpful in formulating conclusions expressed here.

PREVIOUS WORK

Observations on several of the late Cenozoic faults in the Riggins quadrangle were published by Anderson (1934). A brief reconnaissance of the distribution and structure of the Columbia River Basalt in the quadrangle was made by S. R. Capps, and incorporated into the geologic map of Idaho (Ross and Forrester, 1947; see also Capps, 1941). The schematic map by Wagner (1945) included the northwestern part of the Riggins quadrangle. Weymouth (1928) identified the minerals in a xenolith in Columbia River Basalt, collected in the southern part of the quadrangle.

The little petrologic information about the Columbia River Basalt available in 1950 was summarized by Baldwin (1950), Campbell (1950), and Fuller (1950). A study with both broad and detailed aspects is being made by A. C. Waters (see also Waters, 1955, 1960, 1961).

NAME

Russell (1893) proposed the name Columbia Lava for the volcanic rocks of Tertiary age in central Washington and in the Snake River Plain of southern Idaho, but he (1901) subsequently revised the name to Columbia River Lava. Merriam (1901) recognized that volcanic formations of several ages and types were included in the one named unit and suggested that Columbia Lava be restricted to the unit that he thought to be exposed along the Columbia River. Many early workers continued to use the name so broadly, however, that it included a large proportion of the volcanic rocks of the Northwest, rocks that range in age from Eocene through Recent and that belong to several distinct petrographic provinces. Washington (1922) proposed the name Oregonian Basalts for this broad combination of volcanic rocks. Buwalda (1923) recognized that the basalts of the Columbia River are older than those of the Snake River Plain in southwestern Idaho and distinguished them as the Columbia River Basalts of Miocene age. Kirkham (1931a, 1931b) reached the same conclusion after more detailed work and called the Miocene rocks the Columbia River Basalt; this name has been in general use ever since, although Reed (1937) used the term Columbia River Lavas for the basalts near the east edge of the Columbia Plateau in western Idaho, a short distance north of the Riggins quadrangle. Columbia River Basalt was adopted by the compilers of the Idaho State geologic map (Ross and Forrester, 1947; see also Ross and Forrester, 1958).

Waters (1961) reviewed the nomenclature of the Columbia River Basalt, presented much new stratigraphic and petrographic data, and recommended that the formation be elevated to group status but that the name Columbia River Basalt not be modified. He also proposed subdividing the group into two formations, an older Picture Gorge Basalt and a younger Yakima Basalt. The validity of these formations was well established by Waters in a large region in Oregon and Washington, but not enough is yet known about their possible continuity between that region and the Riggins quadrangle to justify their use in the present report.

As the term is now used, the Columbia River Basalt, be it group or formation, forms most of the surface of the southern two-thirds of Washington and the northern one-third of Oregon east of the volcanic pile of the Cascade Range, and it laps onto the pre-Tertiary rocks of western Idaho; the basalt underlies an area nearly 250 miles in diameter (Baldwin, 1950; Fuller, 1950; Waters, 1961). The rocks are mostly tholeiitic [1] basalts of early Miocene to early Pliocene(?) age.

FIELD GEOLOGY

DISTRIBUTION AND THICKNESS

The southwestern one-ninth of the Riggins quadrangle (pl. 1) is underlain by a thick, generally south-dipping mass of Columbia River Basalt that extends far southwest beyond the quadrangle. Local relief within this mass in the quadrangle reaches 2,000 feet, and structural projections indicate a probable maximum thickness of basalt of about 3,000 feet; the minimum altitude reached by the base of the basalt is probably near 2,000 feet above sea level. Although

[1] The term "tholeiite" is used here, in the general sense of Turner and Verhoogen (1951, p. 181), to apply to basalt of relatively high SiO_2 content, but low Na_2O, K_2O, and MgO. Such basalt is saturated or slightly oversaturated in silica, although it may contain modal olivine, and contrasts with the undersaturated and more alkaline olivine-rich basalts. There are, of course, many types intermediate between tholeiite and olivine basalt, but most assemblages fall clearly into one group or the other, and the distinction is useful.

many hillsides in this part of the quadrangle are densely forested, there are wide areas of open forest and some of grassland, and the massive flows crop out as gently inclined risers that are traceable for long distances.

Other areas of basalt in the quadrangle are smaller, irregular in outline, and more complex in structure. Basalt remnants east of Meadows Valley and Round Valley are only about 1,000 feet thick; forest cover is thick, weathering is deep, and exposures are poor. A somewhat thicker west-dipping fault-bounded basalt mass is well exposed in cirque headwalls along its east and north margins.

A large mass that extends northward and southwestward from the center of the quadrangle forms an irregular syncline, near the axis of which flows the Little Salmon River; the mass veneers crests and ridges, has a maximum thickness of perhaps a little over 1,000 feet, and reaches a minimum altitude of about 1,500 feet. Exposures of basalt are in general good along the Little Salmon River, in the canyons tributary to it from the east, and along the cirque-indented rim from Elk Lake to Lake Creek Lookout (fig. 2*A*), but are poor west of the Little Salmon River.

A large mass of basalt in the northwestern part of the quadrangle is synclinal and bounded by faults. Exposures are excellent (fig. 2*B*) in much of this mass, and columnar-jointed flows crop out as vertical risers between other flows and pyroclastics hidden by talus slopes. The thickness of this basalt is at least 2,000 feet and may be 2,500 feet; the base of the basalts lies as low as 1,500 feet above sea level.

Small isolated remnants of Columbia River Basalt occur on a few ridges in other parts of the Riggins quadrangle.

The base of the basalt lies at altitudes that range from 1,500 feet to 8,100 feet above sea level, but no basalt is present on many of the peaks that stand higher than 8,000 feet. Most of this range in altitude is obviously due to deformation, although some is probably due also to the relief of the surface upon which the basalt was erupted. Lava flows lap against the slopes of Hard Butte (fig. 3*A*), in the center of the quadrangle, which probably stood 500 feet above the local base upon which the initial lavas were erupted. Local prebasalt relief of 100 to 200 feet—generally with much gentler slopes than near Hard Butte—is shown at many places where the base of the basalt is well exposed; flows fill old valleys, and lap out against their sides. The basalt thins eastward across the quadrangle.

The base of the Columbia River Basalt is thus not a stratigraphic horizon, but instead is a surface of considerable relief, at least locally, and no specific correlations will be suggested between the volcanic sections in the various areas of outcrop.

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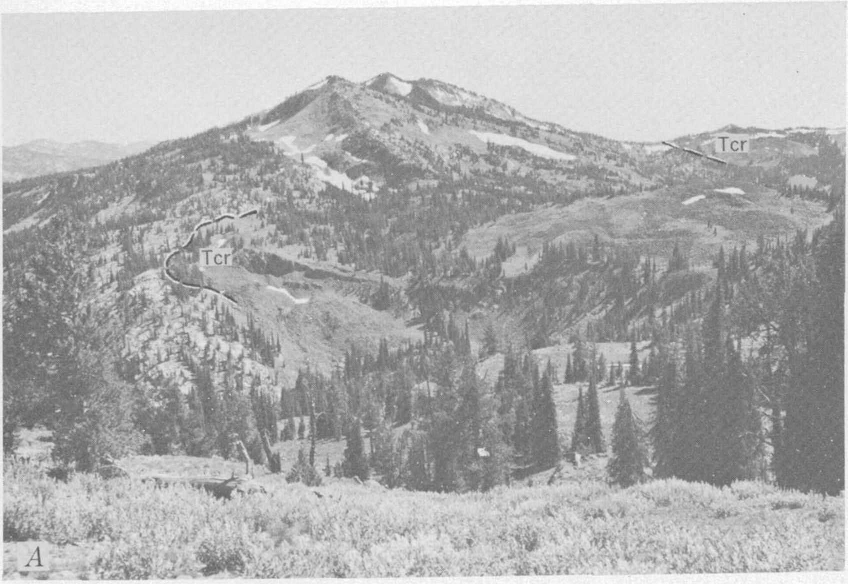
A. Basalt cap along Lake Creek Rim. Beneath the thin dark layer of basalt is gneissic quartz diorite. View northwest from saddle above Elk Lake.

B. Basalt north of Race Creek. Dense columnar-jointed lavas stand as cliffs. View north to hill 4315; relief in picture is about 1,600 feet.

FIGURE 2.—COLUMBIA RIVER BASALT, RIGGINS QUADRANGLE



A. Columbia River Basalt (Tcr) at Hard Butte. The peak stood above the basalt of the foreground area when the basalt was erupted, but the relief of the unconformity has been accentuated by gentle folding. Looking south.

B. Syncline in basalt north of Rapid River. Pre-Tertiary schist forms the inner canyon; base of basalt at left edge of picture is marked by a line. View north-northwestward across Little Salmon River, from east of Old Pollock; peak 4682 on left, 4638 on right.

FIGURE 3.—COLUMBIA RIVER BASALT, RIGGINS QUADRANGLE

LAVA FLOWS

The Columbia River Basalt consists largely of flows of basalt; breccia, agglomerate, and tuff are subordinate. In the northern half of the Riggins quadrangle, individual flows range from 6 inches to 100 feet in thickness, and flows as thin as 5 feet are abundant. The characteristic flows are columnar jointed and form vertical cliffs continuous for long distances (fig. 2*B*); these flows are of dark dense rock, are generally vesicular in their upper parts, and lack incorporated flow breccias.

In the southern half of the quadrangle, few flows are thinner than 20 feet, and most are at least 50 feet thick. Many flows are of breccia, and most others have flow breccias at their tops. Columnar-jointed flows and cliff outcrops are nearly lacking. Porphyritic basalt, bearing plagioclase phenocrysts, and light-colored open-textured basalt are abundant.

Many of the flows display flow structures, most commonly in the form of streaked-out, flattened vesicles or of vague partings within the rock. The coarsely porphyritic lavas have roughly parallel phenocrysts. Flow structures are formed in subhorizontal attitudes and are perpendicular to the regular columnar joints.

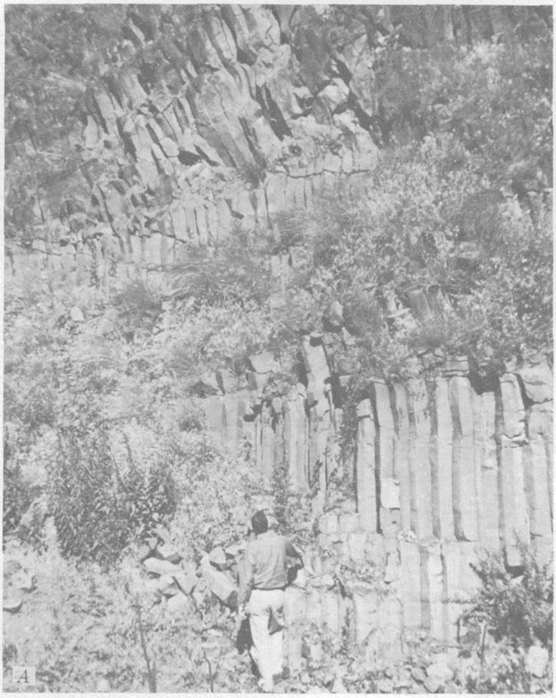
Flows as thick as 100 feet are probably present only where valleys were filled by ponded lava. An example of this is an outcrop along the Little Salmon River, 1.2 miles north of Elk Creek, where bluffs 100 feet high expose only a single flow; columnar jointing here is very irregular, being horizontal throughout one section, and varying wildly in another, which suggests nearness to irregular preflow valley walls.

The outcrop characteristics of the flows depend chiefly upon jointing. Most cliffs are formed on thick columnar-jointed flows (figs. 2*B* and 4*A*), although some are formed on very massive flows; spheroidal, platy, or irregularly jointed flows and most thin flows and fragmental rocks, are buried beneath colluvium.

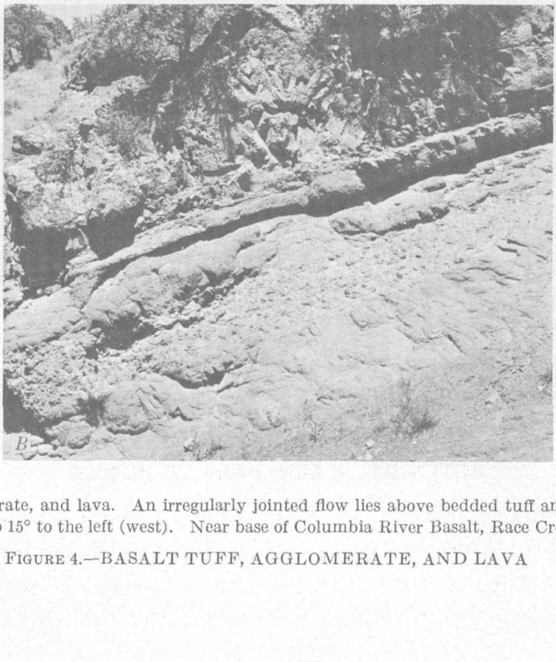
Most of the flows disintegrate to sharply angular, long-lasting rubble. Outcrops are lacking on dip slopes of cliff-forming flows in which bedrock lies a few inches below the surface, for even the columnar flows disintegrate to blocky rubble at the surface. Weathered surfaces on the basalts are typically yellow brown, but the rocks are highly resistant to weathering, and fresh rock is commonly within a small fraction of an inch of the outside surface.

CLASTIC ROCKS

Agglomerate, tuff, and water-laid tuff are of minor abundance. An outcrop of such rocks is illustrated by figure 4*B*. These clastic rocks are exposed in few places, as they are generally covered by



A. Columnar-jointed flow of basalt, near Race Creek.



B. Tuff, agglomerate, and lava. An irregularly jointed flow lies above bedded tuff and agglomerate; all dip 15° to the left (west). Near base of Columbia River Basalt, Race Creek.

FIGURE 4.—BASALT TUFF, AGGLOMERATE, AND LAVA

colluvium from overlying, bold-outcropping flows. Lake deposits were found only at one locality north of Hazard Creek; this material yielded a rich fossil flora described in a subsequent section.

Volcanic breccia with a yellow matrix is present in several places at or near the base of the Columbia River Basalt in the central and southwestern parts of the quadrangle. The breccia consists of shards and fragments of glassy basalt, generally microvesicular, and blocks and lenses of basalt in a soft mottled brownish-yellow to light-brown matrix. The basalt blocks, which occur in all sizes up to several feet in diameter, are generally vesicular; many blocks have aphanitic stony cores gradationally bounded against glassy rims. (Analyzed specimen 3, a relatively mafic granular-textured basalt, is from such a block.) Blocks are variably aphanitic or porphyritic, and black, gray, or red. The breccia is massive and displays little internal layering, even where several hundred feet thick; in some places, however, lenses and stringers of basalt within the breccia are parallel to the overall bedding, and some of these lenses have poorly developed pillow structures.

Yellow breccia crops out in the following places:

1. Along the north side of Mud Creek, 3.5 miles from the south edge of the quadrangle.
2. In highway cuts along the east side of the Little Salmon River, 8.5 miles from the south edge of the quadrangle, where 200 feet of breccia lies directly upon basement rocks, and is overlain by thin flows of basalt, in a small fault block.
3. At an altitude of 4,500 feet on a hillside east of Meadows Valley, 0.8 mile eastnortheast of Circle C Ranch.
4. At the base of the Columbia River Basalt, 0.5 mile south of Goose Lake.
5. Along the east face of Lava Ridge, south of Lava Butte Lakes, east of the center of the quadrangle, where about 100 feet of yellow breccia lies between flows of massive basalt.

The breccia apparently formed where lava flowed into lava-dammed lakes. Such an origin for similar breccia elsewhere in the Columbia River Basalt was suggested also by Fuller (1950) and Laval (1957). The yellow matrix is presumably palagonite—hydrated basaltic glass—as Weymouth (1928), Fuller (1950), and Laval (1957) have suggested for similar rocks in the region.

SOILS BETWEEN BASALT FLOWS

At most places where contacts between flows are exposed, the upper flow rests directly upon fresh rock of the lower; there was little or no weathering or formation of soils between flows. A possible exception is exposed at two places along the east side of the East

Fork of Lost Creek, 2.2 and 3.2 miles from the south edge of the quadrangle near its southwest corner. At these places, 1 foot of reddish-brown (almost brick-red) baked soft rock, with the texture of silt-rich fine-grained sandstone lies between a purplish vesicular flow beneath and a thick flow of dense porphyritic basalt above. This sand bed might have originated as a transported soil.

Another exception is exposed on the east side of the valley of the East Fork of Weiser River about 2.5 miles from the south edge of the quadrangle. At this locality, two vesicular flows of light-gray basalt are separated by 1 to 3 feet of similar baked soil(?) that is yellowish brown at the base and grades upward, as the effects of baking increase, to brick red. Both upper and lower surfaces of the sediment are irregular, and each displays about one foot of local relief.

DIKES

Dikes of basalt occur at scattered localities in the pre-Tertiary rocks of the Riggins quadrangle, but no dikes or sills are known within the lavas. All but 1 of the dikes seen are within 4 miles of the Little Salmon River or north of Riggins, the Salmon River; the one exception is 7 miles east of Riggins. Most of the dikes are only 2 or 3 feet thick. Presumably the dikes are related to the Columbia River Basalt.

A group of dikes containing xenocrysts(?) of biotite is in roadside cliffs about 1 quarter of a mile north of the mouth of the Rapid River. Four dikes, with maximum thicknesses of 3 feet, have steep dips and easterly strikes. Foliation in the wall-rock schists is nearly horizontal, and the dikes are broken and offset as much as 3 feet along fractures parallel to the foliation.

Another group of four or more dikes, which strike northward and dip steeply, is exposed in highway cuts along the east side of the Salmon River south of Chair Creek.

Representative of small single dikes is one exposed east of the Little Salmon River between Hailey and Captain John Creeks at an altitude of 4,000 feet. This dike is 2 feet thick and aphanitic throughout though the interior has a very finely granular aspect; near the margins, the rock has a pitchy luster because of abundant glass, but the actual margins are light-colored porcelaneous rock. Small xenocrysts(?) of biotite are strewn sparsely throughout the dike, as they are in most of the basalt dikes in the pre-Tertiary rocks.

A very large dike of basalt may be present on the west side of Meadows Valley near its lower end, where the contact between basalt and the underlying basement rock dips 65° westward, as indicated on the geologic map (pl. 1). This contact is exposed in fresh rock at two places; it is not faulted. Although the contact is interpreted as the depositional base, since tilted, of the Columbia River Basalt against a considerable initial slope on the basement rocks, it is possible that the basalt at this contact forms a steep composite intrusion, perhaps a very thick dike. As the basalt has abundant tiny irregular vesicles near the contact and sparse large vesicles as far as 30 feet from the contact, an intrusive origin appears unlikely.

STRUCTURE

The Columbia River Basalt has been warped and broken by normal faults. Dips are generally no steeper than 10°, but in the northwestern and south-central parts of the quadrangle the dips locally exceed 30°. The basalt of the northwestern area forms a syncline (fig. 3*B*), and another syncline crosses the Little Salmon River near Hazard Creek; basalt in any major anticlinal crests has been removed by erosion.

Two major normal faults, each dropped down on the east side, trend northward across the quadrangle. The eastern of these two faults displaces Columbia River Basalt about 3,000 feet vertically east of Hard Butte, and perhaps 500 feet near the south edge of the quadrangle. This fault is marked by hot springs at Riggins Hot Springs, by the Salmon River; on the Warm Springs Creek that is tributary to Hazard Creek; and on Goose Creek, just south of the quadrangle boundary. The fault is followed by alined valleys, the most striking of which are the straight canyons opposed across the Salmon River, and by a topographic scarp that is much modified by stream and glacier erosion. The fault dips steeply east where it is best exposed, east of Patrick Butte.

Another major north-trending normal fault has a displacement of at least 1,000 feet in the northwestern part of the quadrangle, about 1,000 feet in the central part, and only a few hundred feet in the southern part. Fault relations are particularly well shown north of the Rapid River and south of Boulder Creek. The fault is marked by several hot springs in Meadows Valley.

Another fault, dropped down 1,000 feet or so on the east side, trends southwest and south from Pollock Mountain to the south edge of the quadrangle.

Most of the other normal faults are oblique to the major faults. Near the western of the main faults in the southern part of the area, five minor faults strike northwestward; all are relatively downthrown on their southwest sides.

Topographic scarps along the faults are variably preserved, but at best are much eroded. No offsets of surficial materials nor any faceted spurs were seen. The variable quality of scarp preservation suggests different ages of faulting, none of which are younger than early Pleistocene.

REGIONAL ASPECTS OF STRUCTURE

The normal faults of the Riggins quadrangle lie within a belt about 30 miles wide of north-trending faults and monoclines. This belt separates the massive Salmon River Mountains of interior Idaho from the Columbia Plateau of northeastern Oregon and is coincident with the western border zone of the Idaho batholith. The west margin of the massive, uniform granodiorite and quartz monzonite of the Idaho batholith trends northward a few miles east of the Riggins quadrangle. The batholith is not broken by major late Cenozoic normal faults; faults that trend toward the batholith from the north and from the southeast die out as they reach the granitic terrane.

The border zone of the batholith consists of varied gneisses and, in the west, schists that strike generally northward and dip steeply east. At least within the Riggins quadrangle, the large normal faults are semiconcordant in plan to the gneissic foliation; and as the faults are mostly dropped down on their east sides, it is likely that they are semiconcordant in dip also.

West of the border zone of the batholith and the superimposed late Cenozoic normal fault blocks is the Columbia Plateau province of northeastern Oregon, in which the Columbia River Basalt is deformed by irregular domal and anticlinal uplifts and generally northwest-trending normal faults. Pre-Tertiary complexes are exposed in the uplifts. The young structures are superimposed across low-grade metamorphic rocks that trend eastward to northeastward and that were intruded by semiconcordant stocks and small batholiths in late Mesozoic time.

The late Cenozoic structure of the region is thus controlled by the orientation and competence of the pre-Tertiary rock complexes. The massive Idaho batholith is practically undeformed, but its gneissic border zone is broken by concordant normal faults. The heterogeneous pre-Tertiary complex to the west is cut directly across by young structures.

The extent of the Columbia River Basalt is also controlled in part by pre-Tertiary features. The basalt thins eastward across the border zone of the Idaho batholith and is virtually lacking upon the batholith itself, which must have stood as a highland during the period of basalt extrusion.

These and other aspects of the regional structure are described at greater length elsewhere (Hamilton, 1962).

PALEONTOLOGY

A rich fossil flora was found in diatomaceous tuff intercalated with basalt at one locality north of Hazard Creek. The occurrence is beside a rough road, about 4 miles by road from Hazard Creek and 0.6 mile beyond Tepee Springs, in the SE¼NW¼ sec. 31, T. 22 N., R. 2 E.

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The following leaves were identified by Roland W. Brown (written communication, 1954):

Carya egregia (Lesquereux) LaMotte [hickory]
Castanopsis perplexa (Knowlton) Brown [evergreen chinkapin]
Cedrela oregoniana (Lesquereux) Brown [cedrela]
Liquidambar pachyphyllum Knowlton [sweetgum]
Platanus dissecta Lesquereux [sycamore]
Quercus axelrodi Brown [oak]
Quercus payettensis Knowlton [oak]
Quercus simulata Knowlton [oak]
Ulmus speciosa Newbery [elm]
Zelkova oregoniana (Knowlton) Brown [Asiatic elm]

According to Brown,

> This collection represents a Miocene flora. Many of the species occur in the Latah Formation, and some in the Mascall Formation. The Latah Formation probably includes a sequence of beds ranging from early to late Miocene in age. This collection indicates a middle or late Miocene age.

Pollen and spores from the same locality were studied by Estella B. Leopold and Helen Pakiser, who recorded 73 grains and made the following identifications (written communication, 1960):

Angiosperms:	
Dicotyledons:	
Trees:	
Carya [hickory]	11
Zelkova [Asiatic elm]	8
Quercus [oak]	4
Betula [birch]	3
Alnus [alder]	2
Pterocarya [lingnut]	2
Ulmus [elm]	2
Castanea [chestnut]	1
Liquidambar [sweetgum]	1
Shrubs, vines, and herbs:	
Ostrya or *Carpinus* [hornbeam?]	5
Chenopodiaceae [saltbush family]	2
Corylus [filbert]	2
Allamanda?	1
Cardiospermum? [heartseed?]	1
Cedrela	1
Ericales undetermined [heath family]	1
Eriogonum?	1
Rhododendron?	1
Vitis? [grape]	1
Undetermined	1
Monocotyledons:	
Phoenix? [palm]	1
Graminae [grasses]	1
Undetermined	1

Gymnosperms:	
Picea [spruce]	6
Pinus [pine]	4
Abies c.f. *grandis* [fir]	3
Abies c.f. *lasiocarpa* [fir]	2
Juniperus? [juniper]	2
Ferns and fern allies:	
Lycopodium c.f. *cernum* [clubmoss]	1
Polypodiaceae [polypod fern family]	1

The leaves are humid-temperate forest forms, whereas the pollen and spores include montane and subalpine trees and shrubs as well. A large range in altitude of growth is represented by the flora, which indicates high total relief within the source region.

Chaney (1959) found that the Miocene floras of the Columbia Plateau belong to three main types: a swamp cypress forest, similar to that now growing in the valley of the Wabash River in southern Indiana, dominated by *Taxodium* (bald cypress); a *Glyptostrobus* (China cypress) forest, which occupied better drained ground but was similar to the swamp forest; and an evergreen oak-gordonia-maple forest, the most widely distributed type, similar to that of Tennessee today up to an altitude of perhaps 2,500 feet, which occupied low uplands. The Riggins macroflora is composed largely of forms typical of the upland type, and a climate like that of the present eastern interior of the United States is indicated.

Chaney suggested that the high-mountain plants, represented in the floras he studied (as in the Riggins flora) only by material which could have been carried a long distance by wind or water, grew on volcanoes which stood above the general level of the region. As the Columbia River Basalt laps eastward upon the pre-Tertiary rocks of western Idaho, it is also possible that central Idaho then stood as a highland region. In either case, a total relief in the region of at least 5,000 feet seems to be indicated, and it is quite possible that the Miocene peaks projected above timberline.

PETROGRAPHY

ROCK TYPES

Dark dense basalt characterizes the Columbia River Basalt of the Riggins quadrangle. Some contains phenocrysts of plagioclase; most contains sparse microphenocrysts of clinopyroxene and olivine, but none has conspicuous phenocrysts of these minerals. Groundmass textures are variably intersertal, intergranular, and diabasic. Conspicuously porphyritic basalt with small phenocrysts of plagioclase is a subordinate rock type in most parts of the quadrangle; but coarsely porphyritic basalt is limited to the large basalt sheet in the southwestern part, and light-colored basalt is abundant only in the same sheet.

Dark olive-gray basalt which has a finely granular appearance is widespread. These rocks are equigranular, or at least lack conspicuous phenocrysts of plagioclase, and are holocrystalline or nearly so. Only two specimens were examined in thin section; both have uncommonly "clean" appearances because of the scarcity of cryptocrystalline interstitial material. One of the specimens is diabasic, and its pyroxene ($2V=50°$) is a brownish-gray type uncommon in the area; it contains about 5 percent olivine and lacks both glass and chlorophaeite.[2] The other specimen has intergranular texture and has a total of about 10 percent glass and chlorophaeite.

Dark-gray dense, aphanitic basalt is the common rock in the bluff-forming flows that display regular columnar jointing and is widely distributed in the northern half of the quadrangle. Analyzed specimen 9 is the only sample of this rock studied in thin section; this specimen, the most silicic of those analyzed, consists of plagioclase laths (which are actually sodic enough, about An_{45}, to qualify the rock as a basaltic andesite) and pyroxene granules in a matrix of dark opaque-clouded glass that makes up about 45 percent of the rock.

Conspicuously porphyritic basalt is widespread in all major areas of Columbia River Basalt in the Riggins quadrangle; analyzed specimens 4, 7, and 8 are of this type. The porphyritic basalt occurs typically in flows with irregular columnar joints. These rocks are dark gray and generally display a greenish or olive-brown cast. Thin tablets of dark-appearing plagioclase make up 10 to 20 percent of the rocks and have an average size near 0.5 by 2 by 3 mm in some specimens and 1 by 3 by 5 mm in others. Of the 6 specimens studied in thin section, 2 have holocrystalline-intergranular groundmass textures, 2 have a little brown glass, and 2 have abundant mesostases that comprise hashes of feathery pyroxene, plagioclase microlites, glass, opaque specks and dendrites, chlorophaeite, and nontronite(?). The rocks contain olivine (or saponite presumably pseudomorphous after olivine) in amounts ranging from less than 1 percent to 4 percent.

Coarsely porphyritic basalt crops out in many places near the southwest corner of the area—along the upper reaches of East Fork of Lost Creek, both branches of the Weiser River, Boulder Creek and along the middle reaches of Mud Creek and Little Mud Creek. One such flow lies directly upon the pre-Tertiary basement rocks along Mud Creek. Another flow is traceable for several miles along East Fork of Lost Creek, and several are superimposed near the head of the West Branch of Weiser River. The tops of the flows of por-

[2] Conventional names are given the various submicroscopic mixtures of secondary minerals, although these names do not properly define mineral species. Chlorophaeite is discussed on p. L27.

phyritic basalt are vesicular and locally scoriaceous; interiors are dense, massive, and broken by widely spaced irregular joints. Feldspar phenocrysts are oriented in many places, the tablets lying subparallel to the margins of the flow.

This type of basalt is distinguished by abundant large thin tablets of plagioclase; the common size of these phenocrysts is about 1.5 by 7 by 10 mm, and the maximum size is 3 by 25 by 30 mm. The basalt tends to break along the (010) feldspar cleavages, parallel to the tablets of phenocrysts, and the crystals appear as large glistening surfaces. Where the color of the groundmass is dark greenish gray, as is most common, the apparent color of the feldspar is the same; where the groundmass is medium dark gray, lacking the green cast, the feldspar is light gray. The groundmass of analyzed specimen 5 is holocrystalline and consists largely of plagioclase laths and pyroxene granules; another specimen of holocrystalline basalt has subophitic pyroxene; the other two specimens studied in thin section have 10 to 20 percent of nearly opaque glass and cryptocrystalline material. Olivine uniformly makes up about 2 percent of each specimen, and is slightly to largely altered to iddingsite.

Light-colored basalt is most common and varied in the large basalt sheet in the southwestern part of the quadrangle. Many of these rocks owe their light color to the very abundant, irregular microvesicles they contain. Plagioclase crystals project into cavities and there appear white, so that the rocks are finely mottled and appear white around the microvesicles and dark gray elsewhere. Greenish or yellowish secondary minerals are also abundant about these microvesicles. In other light-colored rocks, the tiny plagioclase laths are nearly white, even though the rock is dense. Still other rocks are completely aphanitic, and the reason for their medium light gray color is not apparent. One of the two thin sections of dense but light-colored rock examined is of diabasic basalt that contains considerable chlorophaeite, and the other contains about 10 percent dark glass in an otherwise intergranular basalt; the rocks look much like the commoner dark basalts in thin section.

Scoriaceous red basalt is a minor rock type that occurs mostly in breccias, with or without associated gray scoria. The red scoria has a groundmass of glass crowded densely with tiny red opaque granules. Mafic minerals are fresh in one of the two thin sections studied, but are largely altered to green low-birefringent material; the mafic minerals are altered to red iddingsite in the other thin section.

Vesicles are either empty or lined only by films of late minerals in the great majority of flows in the Columbia River Basalt. An exceptional flow, spectacularly amygdaloidal, crops out in bluffs on the east side of the Little Salmon River south of Boulder Creek. Tiny veins and microamygdules are filled with granular heulandite(?), which locally encloses tiny roses of natrolite. Large vesicles have shells of granular heulandite(?) or radial-structured apophyllite (which has a marked anomalous brown interference color), and many of the large vesicles are filled by globular aggregates of radial prehnite. Analyzed specimen 1 is from this locality.

The abundance of porphyritic and light-colored basalt in the southern part of the quadrangle, as contrasted with the abundance of dense, dark basalt in the northern part, indicates that lavas from different sources are represented by the contrasted suites. All the rocks, however, are rather similar chemically.

ANALYZED SPECIMENS

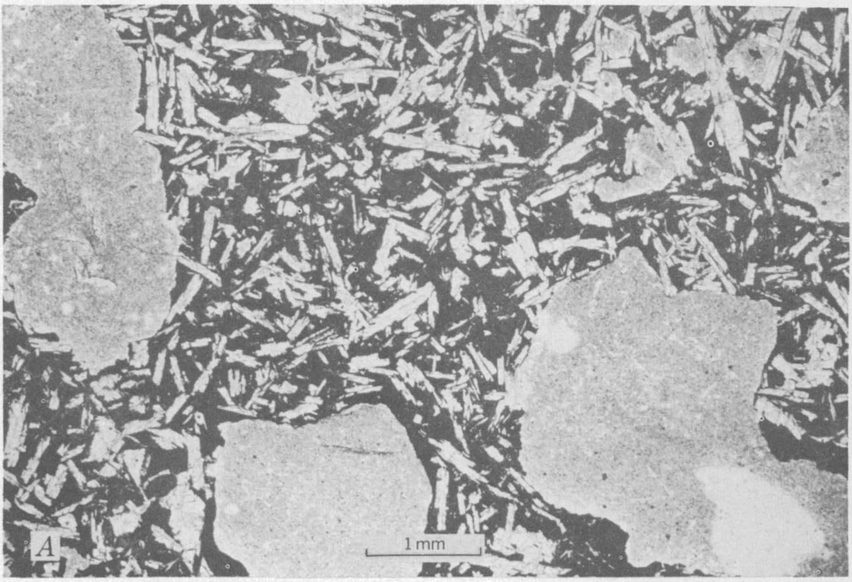
Data for the nine samples of basalt that were analyzed chemically are presented in a subsequent section. The localities from which those specimens were collected are shown on plate 1, and photomicrographs of all samples except No. 1 are given in figures 5, 6, 7 and 8. Descriptions of the samples, which are too fine grained to permit reliable point counts to be made, follow:

1. Greenish-black diabasic basalt. Sparse phenocrysts of plagioclase, up to 7 mm long, and small (0.5 mm) phenocrysts of olivine, lie in a groundmass of ophitic plates and blades of light-brown clinopyroxene, laths of plagioclase ($An_{\approx 55}$) 0.1–0.3 mm long, and interstitial birefringent brownish and greenish deuteric (?) alteration products. Olivine makes up about 3 percent of the rocks and is unaltered, but much of the groundmass plagioclase is flecked by secondary minerals. The few large vesicles contain shells of radial-structured apophyllite; the abundant tiny, irregular amygdules are filled by granules of heulandite (?) and tiny roses of natrolite. Collected from irregularly jointed flow by Little Salmon River at Boulder Creek.
2. Vesicular purplish-gray diabasic basalt, speckled by small white crystals of plagioclase. Laths of plagioclase ($An_{\approx 50}$) 0.1–0.5 mm long are partly enclosed in blades and subophitic plates of light-brown clinopyroxene that is variably clouded by dark dust. The rock contains about 5 percent pseudomorphs of reddish-brown iddingsite after olivine, but no unaltered olivine, and a few percent partly devitrified dark glass. Ilmenite occurs as small feathery-edged crosscutting plates. Vesicles are empty. Collected from flow near head of Little Mud Creek.

   Errors may have been made in several of the major oxide determinations (table 1) for this specimen. The ratio of Fe_2O_3

(8.9 weight percent reported) to FeO (3.6 percent) seems much too high, for a rock with such a ratio would normally be bright red. Further, the Al_2O_3 (17.6 percent) content seems too high and the MgO (4.2 percent) too low, when considered in terms of the minerals and other oxides present.

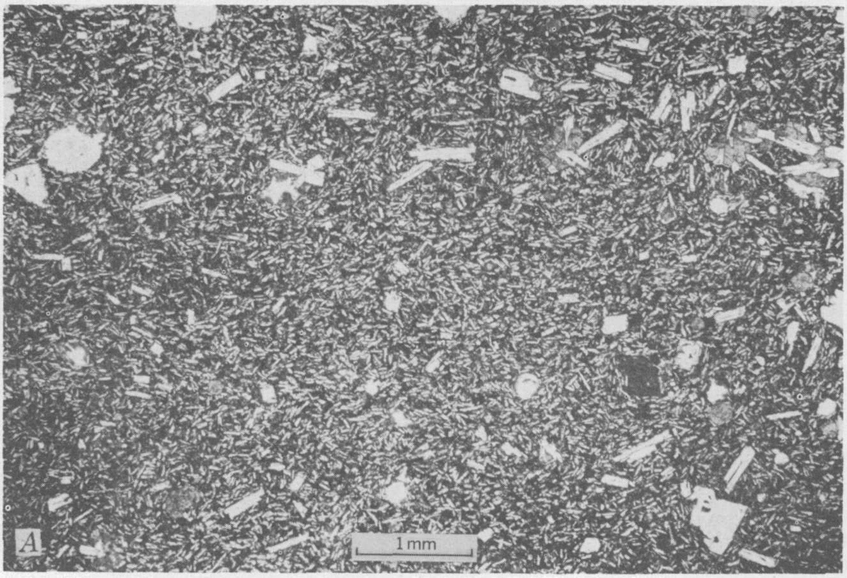
3. Vesicular chilled basalt. This specimen contains about 10 percent scattered, thin tabular phenocrysts of plagioclase ($An_{\approx 60}$), about 5 percent aggregates of larger phenocrysts of plagioclase, and 3 percent olivine as small phenocrysts, in a dark hash of minute granules of pyroxene and plagioclase, brown chlorophaeite, granules and tiny plates of oxides, and inclusion-clouded glass. The olivine is largely altered to light-brown iddingsite. Vesicles are empty. Collected from a block in yellow pillow breccia 0.8 mile east of Circle C Ranch, east of Meadows Valley.
4. Dense dark-gray intersertal basalt. Small phenocrysts of plagioclase (An_{55-60}, mostly smaller than 1 mm, making up 4 percent of the rock) and clinopyroxene (0.1–0.2 mm, 1 percent) rest in a groundmass of 0.02–.05 mm granules of pyroxene (pale greenish-yellow, 33 percent of the rock), 0.05 mm laths of plagioclase (An_{50-55}, 35 percent), brown glass (12 percent) clouded by minute opaque minerals, octahedra and tiny branching crystals of opaque minerals (about 7 percent), and orange to olive-brown chlorophaeite and nontronite (?) (about 6 percent). The rock also contains about 2 percent saponite and iddingsite that are probably pseudomorphous after olivine. Collected from columnar-jointed flow near mouth of Race Creek.
5. Medium-gray coarsely porphyritic intergranular basalt. Contains about 15 percent crystals of plagioclase about 1 cm long and about 7 percent smaller and thinner seriate phenocrysts of plagioclase ($An_{\approx 50}$) in a holocrystalline groundmass of tiny (0.01 mm) granules of pyroxene, 0.03 mm laths of plagioclase, and opaque granules. Margins of large plagioclase phenocrysts are slightly to very irregular, whereas those of the small phenocrysts are regular. The rock contains about 2 percent olivine, largely altered to reddish-brown iddingsite. Collected from massive flow near head of West Branch of Weiser River.
6. Dark-gray porphyritic intersertal basalt. Aggregated phenocrysts of plagioclase about 5 mm long make up about 15 percent of the rock. They rest in a matrix of: about 30 percent small laths of plagioclase (An_{50-55}) granules; 27 percent sparse, small phenocrysts of light greenish-yellow pyroxene; 16 percent glass, so crowded with inclusions as to be nearly opaque; about 8 percent granular oxides; 3 percent granules of olivine about half altered to brownish-green saponite; and a little nontronite(?).



A. Vesicular diabasic basalt. Specimen 2. Plane-polarized light. See text for full description.

B. Vesicular chilled basalt. Specimen 3. Plane-polarized light. See text for full description.

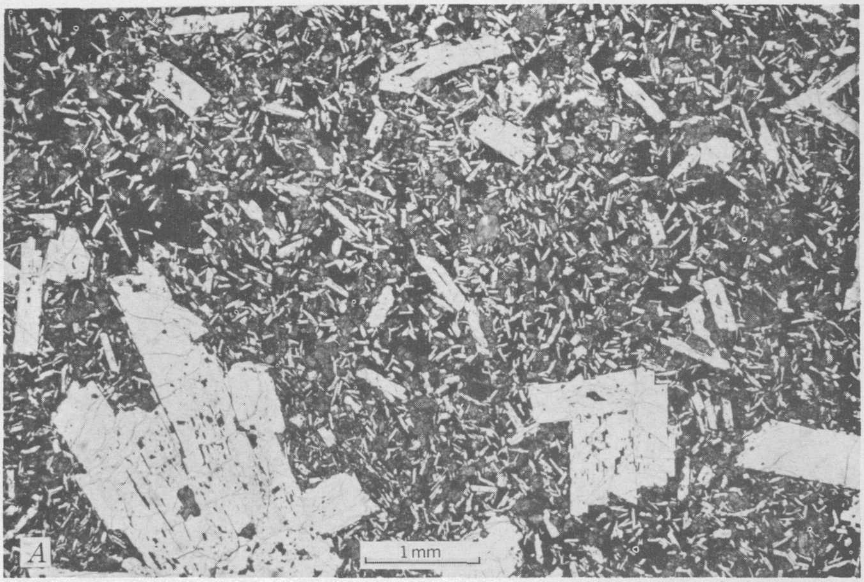
FIGURE 5.—PHOTOMICROGRAPHS OF ANALYZED SPECIMENS OF BASALT



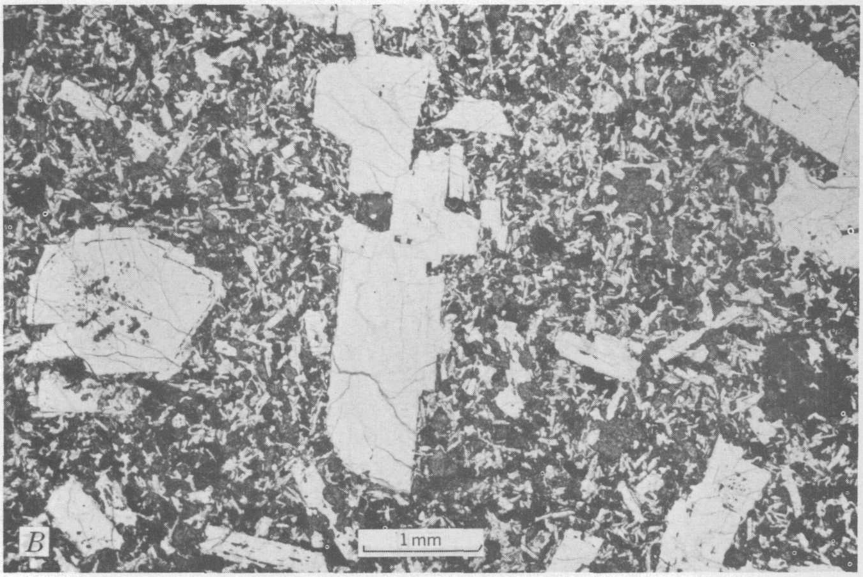
A. Dense intersertal basalt. Specimen 4. Plane-polarized light. See text for full description.

B. Coarsely porphyritic intergranular basalt. Specimen 5. Plane-polarized light. See text for full description.

FIGURE 6.—PHOTOMICROGRAPHS OF ANALYZED SPECIMENS OF BASALT

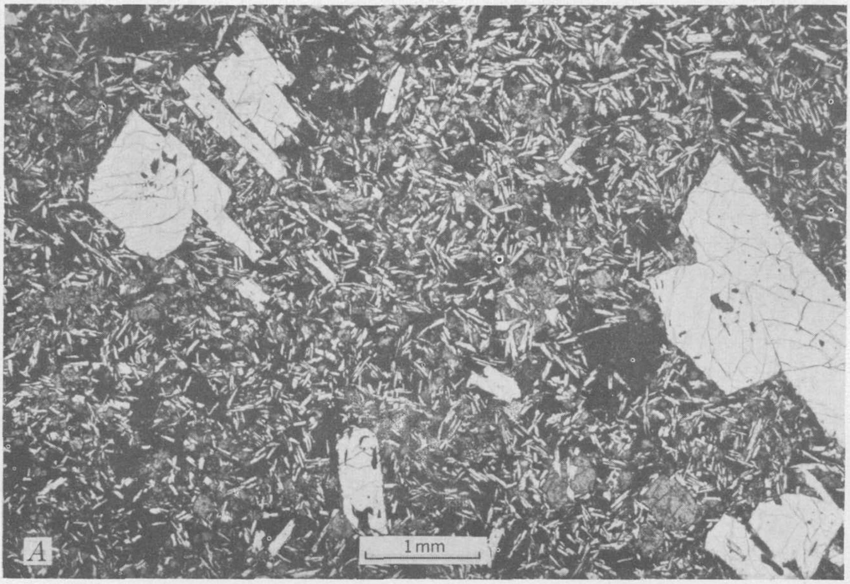


A. Porphyritic intersertal basalt. Specimen 6. Plane-polarized light. See text for full description.

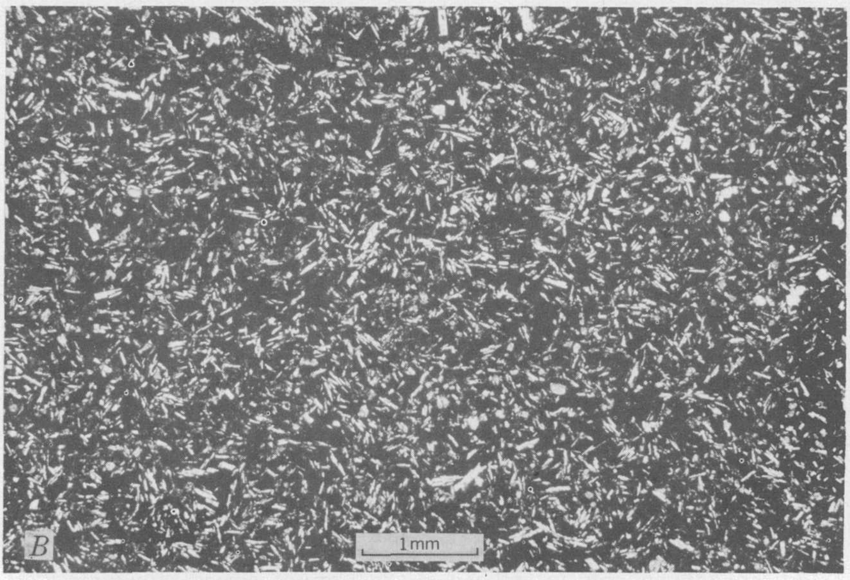


B. Porphyritic intergranular basalt. Specimen 7. Plane-polarized light. See text for full description.

FIGURE 7.—PHOTOMICROGRAPHS OF ANALYZED SPECIMENS OF BASALT



A. Porphyritic, diabasic-intersertal basalt. Specimen 8. Plane-polarized light. See text for full description.



B. Intersertal basaltic andesite. Specimen 9. Plane-polarized light. See text for full description.

FIGURE 8.—PHOTOMICROGRAPHS OF ANALYZED SPECIMENS OF BASALT

Collected from very thick columnar-jointed flow by Little Salmon River between Fall and Lockwood Creeks.

7. Dense dark olive-gray porphyritic intergranular basalt. Aggregated phenocrysts up to 5 mm long of plagioclase (An_{55-70}) constitute 15 percent of the rock. The groundmass consists of laths of plagioclase (An_{50-55}) 0.5–0.3 mm long and granules and small plates, 0.02–0.1 mm in diameter, of yellowish-gray clinopyroxene. Opaque oxides total about 4 percent of the rock and consist of magnetite equants and plates of ilmenite up to 2 mm long that nest around plagioclase laths. Small granules of unaltered olivine make up less than 1 percent of the rock. The pyroxene is locally replaced by brownish-green chloritic(?) material that has an anomalous reddish-brown interference color and low birefringence. A little brownish-green chlorophaeite is interstitial to plagioclase and pyroxene. Collected from flow 2 miles east of Little Salmon River on slope north of Hat Creek.

8. Dense very dark gray porphyritic diabasic-intersertal basalt. Aggregated phenocrysts of oscillatory-zoned plagioclase ($An_{\approx 60}$) make up about 10 percent of rock. It also includes groundmass laths 0.1 mm long of plagioclase ($An_{\approx 55}$) and 0.2 mm ophitic plates and 0.05–0.1 mm granules of grayish-yellow clinopyroxene. The mesostasis is nearly opaque glass, with opaque specks and dendrites, feathery pyroxene, plagioclase microlites, and chlorophaeite. The minor amount of olive-brown saponite may be pseudomorphous after olivine. Collected from columnar-jointed flow by Kessler Creek, 4.5 miles west of Salmon River.

9. Dense dark-gray intersertal basaltic andesite. Laths and tablets of plagioclase ($An_{\approx 45}$) 0.05–0.1 mm long constitute 30 percent of the rock, and small granules of light greenish-yellow pyroxene make up 20 percent. There is about 1.5 percent olivine ($Fo_{\approx 80}$), which is slightly altered to green saponite. Chlorophaeite, totaling only about 1 percent, lines microvesicles. The rest of the rock is dark glass, made nearly opaque by the abundant specks of opaque minerals within it. Collected from columnar-jointed flow 0.5 mile east of Circle C Ranch, east of Meadows Valley.

TEXTURE

The specimens can be placed in two main series—diabasic and granular—on the basis of their textures. Within each series, there is a range from holocrystalline basalt to basalt containing abundant glass. Phenocrysts of plagioclase are present in many of the granular rocks and may be large and abundant; in the diabasic rocks, plagioclase phenocrysts are small and sparse. Pyroxene in the diabasic types generally has a brownish appearance in thin section, whereas that in the granular rocks is invariably yellowish gray or light greenish yellow. Both types generally contain a little olivine and sparse microphenocrysts of pyroxene.

The holocrystalline diabasic basalt (as in analyzed specimen 1) consists of laths of plagioclase about 0.5 mm long and ophitic plates of pyroxene about 0.5 mm in diameter; both minerals are cut across by well-shaped plates of ilmenite. The rocks also contain octahedra of magnetite. In the diabasic-series rock with minor glass, such as specimen 2 (fig. 5*A*), the plagioclase is similarly in laths and the ilmenite plates are crosscutting, but the pyroxene is in blades and subophitic plates—the ophitic texture is much less developed than in the holocrystalline rock. In rocks with still more abundant glass, like specimen 8 (fig. 8*A*), plagioclase laths, mostly only about 0.1 mm long, lie in a hash of glass clouded by opaque dust, tiny feathery sheaves of inclusion-clouded pyroxene, plagioclase microlites, and opaque minerals in specks, small dendrites, and feathery needles. As the opaque material is clearly late crystallizing in the most glassy rocks, and as specimens can be placed in textural series between these rocks and the diabasic holocrystalline basalt, it seems likely that the crosscutting plates of ilmenite in the holocrystalline rocks are products of late-stage replacement rather than of early magmatic crystallization.

Rocks of the granular types are more widespread than are those of the diabasic textural series. In some of the holocrystalline granular rocks, as specimen 7 (fig. 7*B*), grain size approaches that of the diabasic basalt; plagioclase laths average about 0.3 mm long, and most pyroxene granules are 0.1–0.2 mm long; magnetite forms octahedra and granules, and ilmenite may occur either as sparse short plates or as long (up to 2 mm) plates that are interstitial to plagioclase, rather than cutting across it as in the diabases. In the coarsely porphyritic, granular-groundmass basalt (as in specimen 5), the groundmass is extremely fine grained even though it is holocrystalline; plagioclase laths are near 0.03 mm long, pyroxene granules near 0.01 mm, and opaque minerals are in granules of similar size. In the granular-type rocks with abundant glass, plagioclase laths and pyroxene granules rest in a groundmass mush of microlites of plagioclase, microgranules of pyroxene, and glass. Opaque minerals occur as granules and small plates (as in specimen 3), or as specks, tiny granules, and tiny dendrites so abundant as to make the glass nearly opaque (as it is in specimens 4, 6, and 9: figs. 6*A*, 7*A*, and 8*B*).

MINERALOGY

Plagioclase is the dominant mineral in all the basalts. It occurs chiefly in thin tablets, flat parallel to (010), in the groundmass; microphenocrysts of similar habit are present in nearly all specimens, and larger phenocrysts are in many. Most of the plagioclase (as determined by extinction angles in sections perpendicular to (010)) is sodic labradorite; some phenocrysts are calcic labradorite, and the plagioclase of the most silicic specimen analyzed (table 1, No. 9) is calcic andesine. Large phenocrysts of plagioclase are commonly in aggregates of intergrown crystals, and some of these aggregates share common cores of calcic material or cores containing abundant tiny inclusions of pyroxene or other minerals. Many of the large phenocrysts are embayed, or have irregular margins, whereas small phenocrysts and groundmass tablets are generally euhedral. The large phenocrysts typically display slight normal-oscillatory zoning, and the sodic rims of some specimens enclose granules of pyroxene. No alkali feldspar or quartz was recognized.

The pyroxenes are entirely monoclinic and occur as sparse microphenocrysts and as granules or subophitic plates in the groundmasses of well-crystallized rocks. They also occur as feathery aggregates in some of the diabasic-type rocks with abundant noncrystalline material. All the pyroxene of the intergranular rocks is light grayish yellow or greenish yellow and lacks apparent pleochroism. Only one type of yellowish pyroxene was recognized in some specimens, but several types, distinguishable by optic angle, are present in most. Optic angles are indeterminate in analyzed specimens 3 and 5. In the other specimens with yellowish pyroxene, 2V of microphenocrysts was measured on a universal stage, and 2V of groundmass granules was estimated by the spread of isogyres in *Bxa* (acute bisectrix) interference figures. The following angles were thus determined:

Specimen No.	*2V of microphenocrysts*	*2V of groundmass granules*
4	48°–51°	≈35°
6	45°–50°	≈35° or 40°
7	42°–44°	≈40°; and 0°
8	45°–49°	≈25° or 30°
9	50°	≈40°

Generally, the microphenocrysts are only slightly larger than the groundmass granules, but they nevertheless have consistently higher optic angles than do the granules. Presumably the granules are less calcic than the microphenocrysts. Only one specimen (No. 7) contains clinopyroxene with 2V low enough to be called pigeonite.

In specimens of less common type, the pyroxene is light yellowish brown or brownish gray and is subophitic or feathery, a habit uncommon in the yellowish variety. In the two analyzed specimens (Nos.

1 and 2, the least silicic of those analyzed) with brownish pyroxene, and in two other thin sections with similar pyroxene, the optic angle varies only between 50° and 53°. Presumably the brownish pyroxenes are richer in calcium and titanium than are the yellowish ones.

Magnesian olivine occurs as granules and microphenocrysts in most of the rocks and ranges in abundance from less than one percent to about 5 percent. The olivine is completely unaltered in some specimens, but generally it is altered along margins and cracks, or even altered entirely, to brownish-green saponite or reddish-brown iddingsite.

Metallic opaque minerals constitute only one to several percent, by volume, of the rocks in which they are in grains large enough to be counted with some confidence, but they may be considerably more abundant in those rocks with very fine grained groundmasses in which the oxide minerals occur as pervasive dust and minute granules that cannot be counted in thin section. In holocrystalline rocks, the opaque minerals are octahedra of magnetite and plates of ilmenite, the latter either cutting across other minerals or shaped around the plagioclase crystals. In intersertal specimens, much of the opaque material is in minute specks and dendrites and in tiny feathery edged plates.

Glass varies widely in abundance; chilled basalt in the yellow pillow breccia includes rock that is almost entirely glass, but in the flow rocks the maximum glass content is probably less than 50 percent. The glass is brown and generally is so densely crowded with minute specks of oxides as to appear almost opaque.

Materials conventionally termed deuteric are widespread, but are generally of minor abundance. Although such materials are commonly given specific mineral names (chlorophaeite, saponite, iddingsite, and others), detailed studies (for example, Wilshire, 1959) have shown them to be either composites of several distinct minerals or identical with minerals known by other names. Chlorophaeite and allied material is present in most of the rocks, generally in mesostases, where it occurs irregularly distributed in place of glass or in small irregular masses. The color is brown to greenish brown. The margins of the masses are typically chlorophaeite proper and are optically isotropic, but birefringence increases gradually toward the center, and the interiors are generally nontronite(?), with or without a radial structure. Such material is assumed by many petrologists to form entirely by alteration of previously solid material, but the zoned character and interstitial habit of much chlorophaeite in rocks that contain considerable glass suggest an origin during direct solidification from hot gels or solutions.

CHEMISTRY

ANALYTICAL DATA

Nine specimens of Columbia River Basalt from the Riggins quadrangle were analyzed for major and minor chemical components (table 1). The major oxides were determined by rapid colorimetric methods, similar to those described by Shapiro and Brannock (1956), by P. L. D. Elmore, S. D. Botts, K. E. White, M. D. Mack, and J. H. Goode.

The spectrographic analyses for minor elements were made by Paul R. Barnett. Five of these analyses were made by "quantitative" methods, in which internal standards are used for calibration, and the other four were made by the rapid "semiquantitative," visual-comparison method. In the semiquantitative method, determinations are reported as midpoints of logarithmic-third divisions (as 0.015, 0.03, 0.07, 0.15, 0.3, and so on). Tests have shown that semiquantitative and quantitative methods result in the assignment of the same interval in about 60 percent of the determinations. (This does not in itself demonstrate which of the two methods is more accurate.) In the analyses on table 1, comparison of the values obtained by the two methods suggests excellent agreement for barium, copper, gallium, nickel, vanadium, ytterbium, and zirconium, whereas semiquantitative determinations for cobalt and scandium scatter more widely than do the quantitative ones, and the semiquantitative values for chromium, strontium, and yttrium are consistently lower than the quantitative ones. Elements not listed were not detected.

MAJOR OXIDES

The basalt spans a considerable compositional range. Silica content, for example, varies from 46 to 53 percent as analyzed, or 49 to 54 percent as recalculated volatile free, despite the rather uniform mineralogic characteristics. Water content of the rocks varies from 0.9 to 5 percent. As the four least silicic of the analyzed specimens are also the most hydrous, the effect of recalculating the analyses volatile free (table 1, central part) is to decrease the range of components in the suite of nine analyses. Aspects of the variations are discussed in the subsequent section on comparative petrology.

Carbonate was detected in 5 of the samples analyzed, but an analytical bias rather than a true compositional difference seems to distinguish these 5 specimens from the other 4: the samples were analyzed in 2 groups, and CO_2 was reported from all of those in 1 group, but from none in the other.

TABLE 1—*Chemical analyses of specimens of Columbia River Basalt from Riggins quadrangle*

[Major-oxide analyses made by rapid methods in Washington, D.C., in 1957, by P. L. D. Elmore, S. D. Boots, and K. E. White (Nos. 1, 4, 6, 7, and 8), and by Elmore, Botts, M. D. Mack, and J. H. Goode (Nos. 2, 3, 5, and 9). Minor-element analyses made in Denver, Colo., by Paul R. Barnett, by quantitative (Nos. 1, 4, 6, 7, and 8, 1956) and semiquantitative (Nos. 2, 3, 5, and 9, 1957) spectrographic methods. Specimens described in text]

	Analysis No.									Average [1]
	1	2	3	4	5	6	7	8	9	
Major oxides (Weight percent)										
SiO_2	46.4	48.1	48.6	49.4	50.2	50.8	51.2	51.4	53.1	49.9
Al_2O_3	15.2	[2] 17.6	16.5	14.4	16.6	15.5	15.3	14.8	13.8	15.2
Fe_2O_3	4.0	[2] 8.9	5.0	5.2	4.6	2.7	3.6	3.2	3.2	3.9
FeO	8.1	[2] 3.6	6.6	7.1	6.9	8.8	8.2	8.8	9.4	8.0
MgO	6.2	[2] 4.2	5.6	5.7	5.2	5.4	5.2	4.9	4.2	5.3
CaO	8.3	8.6	9.4	10.1	9.5	10.4	9.5	8.9	7.7	9.2
Na_2O	2.8	3.0	2.6	2.7	3.0	2.7	2.9	2.9	2.9	2.8
K_2O	1.2	.56	.36	.30	.71	.80	.66	.96	1.5	.8
TiO_2	2.4	2.2	2.1	1.6	2.2	1.7	1.8	2.0	2.2	2.0
P_2O_5	.40	.32	.30	.19	.34	.24	.24	.32	.44	.3
MnO	.16	.17	.18	.19	.20	.18	.18	.18	.20	.2
H_2O	5.0	2.9	3.2	2.4	.88	1.3	1.3	1.7	1.6	2.3
CO_2	.10	<.05	<.05	.10	<.05	.06	.06	.08	<.05	~.05
Total	100	100	100	99	100	101	100	100	100	------
Major oxides (Recalculated volatile free to totals of 100)										
SiO_2	48.7	49.5	50.0	51.0	50.5	51.2	51.9	52.3	54.0	51.2
Al_2O_3	16.0	[2] 18.1	17.0	14.9	16.7	15.6	15.5	15.0	13.9	15.6
Fe_2O_3	4.2	[2] 9.1	5.1	5.4	4.6	2.7	3.6	3.3	3.2	4.0
FeO	8.5	[2] 3.7	6.8	7.3	6.9	8.9	8.3	8.9	9.5	8.1
MgO	6.5	[2] 4.3	5.7	5.9	5.2	5.4	5.3	5.0	4.3	5.4
CaO	8.7	8.8	9.7	10.4	9.6	10.5	9.6	9.1	7.8	9.4
Na_2O	2.9	3.1	2.7	2.8	3.0	2.7	2.9	2.9	2.9	2.9
K_2O	1.3	.58	.37	.31	.71	.81	.67	.98	1.5	.8
TiO_2	2.5	2.3	2.2	1.6	2.2	1.7	1.8	2.0	2.2	2.1
P_2O_5	.42	.33	.31	.20	.34	.24	.24	.33	.45	.3
MnO	.17	.17	.19	.20	.20	.18	.18	.18	.20	.2
Minor elements (Weight percent)										
Ba	0.04	0.03	0.03	0.03	0.03	0.07	0.05	0.06	0.07	
Co	.005	.003	.003	.005	.007	.006	.005	.004	.003	
Cr	.015	.015	.007	.02	.007	.015	.015	.01	.0015	
Cu	.02	.015	.015	.02	.007	.02	.02	.01	.015	
Ga	.0015	.0015	.0015	.002	.0015	.002	.0015	.002	.0015	
Ni	.006	.007	.007	.006	.007	.015	.006	.004	.003	
Pb	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	.0015	
Sc	.004	.003	.003	.005	.003	.004	.004	.005	.007	
Sr	.06	.03	.03	.06	.07	.07	.07	.08	.03	
V	.03	.015	.015	.03	.03	.02	.03	.03	.03	
Y	.006	.003	.0015	.006	.003	.007	.006	.006	.003	
Yb	.0006	.0007	.0003	.0006	.0007	.0006	.0006	.0006	.0007	
Zr	.015	.015	.007	.01	.015	.02	.015	.02	.015	
Field No.	SR 430-3	SR 611-2	SR 582-3	SR 2-2	SR 594-3	SR 428-2	SR 390B	SR 18	SR 581A-1	
Laboratory Nos.	148445 C647	151593 D1407	151591 D1405	148441 C643	151592 D1406	148444 C646	148443 C645	148442 C644	151590 D1404	

[1] Average of analyses 1-9; Al_2O_3, Fe_2O_3, FeO, and MgO omitted from analysis 2.
[2] See comments in text.

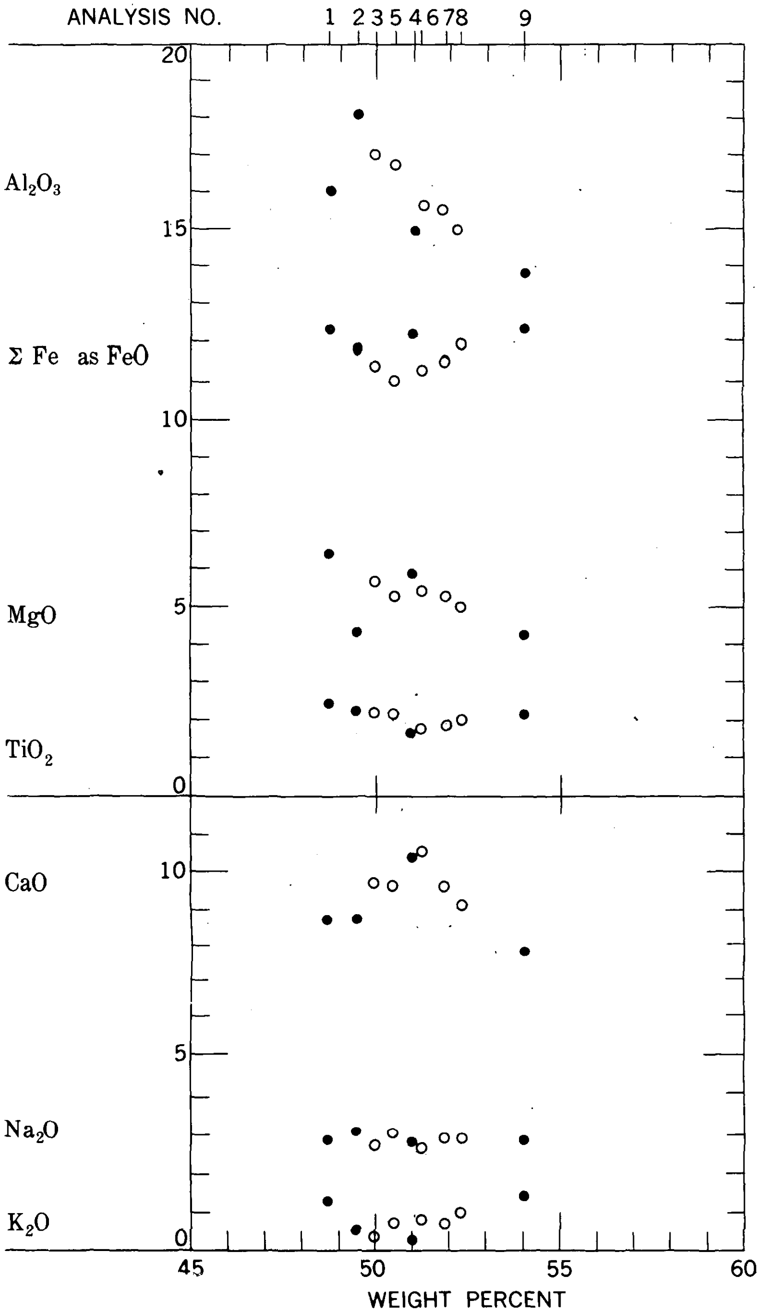


FIGURE 9.—Silica variation diagram of major oxides of Columbia River Basalt of Riggins quadrangle. Analyses recalculated volatile free. Circles, rocks with abundant phenocrysts of plagioclase; dots, nonporphyritic rocks.

Figure 9 is a silica variation diagram of the analyses. As SiO_2 increases, Al_2O_3 and MgO tend to decrease, Na_2O and total iron to remain constant, and K_2O to increase; CaO varies erratically. The conspicuously porphyritic rocks (numbers 3, 5, 6, 7, and 8), which contain 10 to 20 percent phenocrysts of plagioclase, are shown by circles on the diagram. The porphyritic rocks are in general higher in Al_2O_3 and CaO and a little lower in iron than are the nonporphyritic rocks. These distinctions might be explained in terms either of different initial magmas, and of forced early crystallization of plagioclase from magma rich in alumina and lime, or of accumulation of plagioclase crystals by partial differentiation.

Of the analyzed specimens, numbers 1 and 2 have diabasic, brownish clinopyroxene; they also have higher ratios of alkalis to lime than do most of the other specimens. Slight changes in the composition of plagioclase and pyroxene due to this distinction may in part cause the differing textures.

MINOR ELEMENTS

The suite of analyzed rocks varies relatively little in content of major components, so it is not surprising that a number of the minor elements similarly show little variation or vary erratically through a limited range. This seems true of cobalt, copper, gallium, yttrium, ytterbium, and zirconium.

The other minor elements detected show variations possibly correlative with major-component changes, although the correlations are poor and the number of samples so few that the ties may be illusory. Barium shows a general increase in the more silicic rocks and a tendency toward the expected correlation with potassium. Chromium is conspicuously low in the most silicic specimen, and nickel shows a moderate but erratic decline as silica increases. Lead was detected only in the most silicic specimen. Scandium, contrary to expectations, and possibly vanadium also, shows a slight, erratic increase with increasing silica. Strontium increases slightly with increasing content of calcium.

COMPARATIVE PETROLOGY

The Columbia River Basalt consists of contrasted sequences in the northern and southern halves of the Riggins quadrangle. The northern sequence, characterized by thin cliff-forming columnar-jointed flows of dark dense basalt, extends northward beyond the quadrangle at least 30 miles, as far as Grangeville. The southern sequence, characterized by thick flows with abundant flow breccia and by diverse lithologic types, extends at least the same distance south of the quadrangle. Different sources seem indicated for these contrasted assemblages of regional extent.

The Columbia River Basalt is similar to tholeiitic basalt of other regions and dissimilar to other basaltic rocks of Cenozoic age in the Northwest. Some aspects of such comparisons are given below.

A. C. Waters (1960, 1961) found the Columbia River Basalt exposed in the central part of the Columbia Plateau to consist of two main types. The older type, typified by the flows in Picture Gorge, "is characterized by about 5 percent olivine, a silica content of 47 percent, and by notably higher Al_2O_3, MgO, and CaO" contents than those of the younger type; the older type also has a "characteristic 'greasy' appearance because of the presence of saponite after olivine and of nontronite and other clay minerals after chlorophaeite * * *. The younger basalts are characterized by more than 20 percent of tachylite, little or no olivine, a silica content of 53–54 percent, and by notably greater amounts of K_2O and TiO_2," and are typified by the basalts near Yakima. Waters considers the contrasted types "to be products from separate magmatic hearths, and not differentiates of a hypothetical uniform magma" (Waters, 1960). Table 2 presents averages and ranges of chemical analyses of the Picture Gorge and Yakima types of Columbia River Basalt, as compiled by Waters (written communication, 1960; see also Waters, 1961) from both published and unpublished sources.

TABLE 2.—*Composition of Columbia River Basalt and basalt of the Snake River depression*

[Data from A. C. Waters and from H. A. Powers, written communications, 1960]

	Columbia River Basalt				Basalt of the Snake River depression
	Picture Gorge type		Yakima type		
	Average	Range	Average	Range	Average
SiO_2	49.5	47.5–50.0	52.8	49.1–54.7	46.1
Al_2O_3	15.3	14.5–16.0	14.0	13.3–14.4	14.5
Fe_2O_3	3.9	10.5–12.1 as FeO	2.5	10.8–14.2 as FeO	2.7
FeO	7.8		9.4		10.2
MgO	6.2	5.7–7.1	4.2	3.5–4.7	7.5
CaO	10.1	9.8–10.8	7.9	7.4–8.7	9.7
Na_2O	2.9	2.4–3.1	3.0	2.8–3.2	2.4
K_2O	.6	.4–0.7	1.5	.9–1.7	.6
TiO_2	1.5	1.2–1.7	2.1	1.4–3.6	2.9
P_2O_5	.26	.2–0.3	.4	.1–0.7	.7
MnO	.19	.16–0.14	.2	.1–0.4	.2
H_2O	1.8	1.0–3.8	1.2	.3–1.5	1.0
CO_2	--------	None–0.1	--------	nd	.04

Waters studied chemical analyses and several thin sections of rocks from the Riggins quadrangle and reported (written communications, 1960) that analyzed specimens 3, 4, and 6 (table 1) are chemically and petrographically similar to the Picture Gorge type of basalt in the central part of the Columbia Plateau, and that No. 9 is similar to the Yakima type, but that the other specimens do not match these two types. He suggested that the flows represented by specimens 3, 4, 6, and 9 came from vents within the Columbia Plateau to the west, and that the other, aberrant flows came from more local vents.

If, following Waters' classification, specimen 9 (Yakima type) is compared with specimens 3, 4, and 6 (Picture Gorge type), it is seen to be richer in lead and scandium, and possibly barium, and to be lower in chromium, nickel, strontium, and possibly cobalt. The analyses for minor elements are of course so few that this apparent distinction may be coincidental only.

The basalt of the Snake River depression in southern Idaho ranges in age from Pliocene to Recent, and is different from the basalt of the Columbia Plateau. H. A. Powers (1960; also written communication, 1960) found basalt of the Snake River depression to be low in silica and rich in iron; it has the unusual characteristic that the ratio of iron to magnesium generally increases as silica decreases. The basalt of the Snake River depression is high in titanium and phosphorus, relative to most other basalts. Table 2 presents the average of 38 analyses, published and unpublished, compiled by Powers (written communication, 1960) for basalt of the Snake River depression. (The rare, odd, highly alkaline mafic rocks of the Snake River depression are omitted from this average.)

The basalt of the Columbia Plateau in general, and of the Riggins quadrangle in particular, is much like that of other provinces of tholeiitic basalt. Representative compositions of such provinces on other continents are given in table 3. The Riggins basaltic rocks are more aluminous than most of the others and probably reflect the local abundance of porphyritic basalt in the Riggins quadrangle. The ratio of ferric to ferrous iron in basalt in the Riggins quadrangle is high and perhaps reflects surface oxidation over relatively long distances of magmatic flow. In their high content of iron and low content of magnesium, the Riggins rocks are like the Scottish and Indian tholeiites, but unlike the South African and Victorian ones.

The Riggins rocks are atypical in their relatively large variation within thin stratigraphic intervals, and in the abundance of porphyritic rocks containing feldspar phenocrysts. The difference between the basalt of the northern and southern parts of the quadrangle was emphasized in an earlier section.

The two most mafic basalts in the Riggins quadrangle (numbers 1 and 2) have a silica content similar to that of typical basalt of the Snake River depression, but are unlike it in other ways. The Riggins analyses were included with others from the Columbia River Basalt

TABLE 3.—*Average chemical composition of basalts in various tholeiitic provinces*

	Continental tholeiites					Oceanic
	1	2	3	4	5	6
SiO_2	51.2	51.6	51.9	51.5	50.7	50.9
Al_2O_3	15.6	14.3	15.5	13.5	14.6	12.8
Fe_2O_3	4.0	3.5	1.0	3.1	4.3	11.2 as FeO
FeO	8.1	9.2	9.7	10.5	7.1	
MgO	5.4	5.3	8.2	5.3	8.4	8.6
CaO	9.4	10.1	9.7	9.8	8.6	10.4
Na_2O	2.9	2.8	1.8	2.7	2.9	2.2
K_2O	.8	1.1	.7	.8	1.2	.4
TiO_2	2.1	1.6	1.1	2.4	1.6	3.0
P_2O_5	.3	.3	.1	.3	.4	.3
MnO	.2	.3	.3	.2	.2	--------

1. Riggins quadrangle (this report, table 1, col. A).
2. Nonporphyritic central magma type, Scotland (Walker and Poldervaart, 1949, p. 649).
3. Karroo basalt, South Africa (op. cit., table 16).
4. Deccan basalt, India (Sukheswala and Poldervaart, 1958, table 3, col. 2).
5. Tholeiite of central Victoria, Australia (Edwards 1950, p. 102, recalculated to 100).
6. Basalt of Kilauea and Mauna Loa, Hawaii (average of two weighted averages from Powers, 1955, p. 85).

in Powers' (1960) ternary plot of SiO_2–MgO–(FeO+Fe_2O_3+MnO). For these components, the Riggins rocks group within the field characteristic of Columbia River Basalt from other areas and do not overlap the field of basalt of the Snake River depression. None of the Riggins rocks are as high in TiO_2 or P_2O_5 as are most Snake River rocks, and the two most mafic basalts of the Riggins quadrangle have higher Na_2O/CaO ratios than do most basalts in the Snake River depression.

The volcanic rocks of the Cascade Range, west of the Columbia Plateau, are characterized by andesites which contain both hypersthene and clinopyroxene. The abundant basalt in this terrane is in general conspicuously richer in aluminum, calcium, and magnesium, and poorer in iron, than is such tholeiite as that in the Riggins quadrangle; but typical tholeiite is also widespread with the andesite. The Pacific Ocean is ringed discontinuously by such Cenozoic lavas, dominantly andesitic, but including both aluminous and tholeiitic basalt as well as dacite and other rock types. Some petrologists (for example, Byers, 1961) believe that the varied rocks of these associations are produced by a combination of differentiation of basaltic magma, dominantly tholeiitic, and assimilation in such magma of sedimentary and granitic rocks.

Tholeiitic basalt may be the fundamental magma type in the ocean basins despite long established assumptions that olivine basalt is the fundamental type there. Iceland, the largest island of oceanic structure (Båth, 1960), is composed principally of tholeiite; olivine basalt and feldspar-porphyry basalt are subordinate, and alkalic and silicic rocks are still less abundant (Walker, 1960). Powers (1955) demonstrated that the mafic alkaline basalt of the Hawaiian Islands is only a late-stage veneer erupted over foundations of silica-saturated basalt, typified by the lavas of Kilauea and Mauna Loa (table 3); this saturated basalt was erupted in rapid succession and varies relatively little in composition. During the decadent phases of activity of each volcano, however, olivine basalt and a wide variety of alkaline rocks, all undersaturated in silica and high in alkalies relative to magnesium, were erupted. The late stage lava was erupted in smaller volumes, and at longer intervals than were the primitive rocks, and Powers concluded that they formed partly, by fractionation, from silica-saturated magma that remained stagnant for long periods. If future work demonstrates, as now seems likely, that oceanic volcanoes generally have such a composite history, and that the widely sampled mafic alkaline basalt of the oceanic islands is only a veneer over much larger masses of silica-saturated basalt, then one obvious extrapolation will be that the associations of olivine basalt and trachyte of the continents are similarly complex derivatives of silica-saturated magmas. Relative to the silica-saturated basalt of the continental areas, as exemplified in table 3, that of Hawaii is low in aluminum and potassium, and high in titanium. Further data on the oceanic rocks are needed to determine whether or not such a difference separates oceanic and continental tholeiite in general.

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