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DIVISION OF MINES AND GEOLOGY
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Report of Investigations
No. 19

A Stratigraphic Section In The Yakima Basalt And The Ellensburg Formation In South-Central Washington

By
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FOREWORD

An important duty of the Division of Mines and Geology, as set out in the law that established the Division, is the preparation and publication of maps and reports on the geology and mineral resources of the State. Report of Investigations No. 19 is a part of the program that fulfills this duty.

Geologic mapping is, of course, the framework upon which all mineral exploration is based. But geologic maps are valuable only when the mapped formations or other map units are fully and carefully described. The present report is an important contribution of this kind. In it are described the igneous and sedimentary rocks that are exposed at the surface in a large area in central Washington. These rock units include several that have been important sources of valuable nonmetallic mineral resources. Particularly noteworthy are pumicite (volcanic ash) and diatomite (diatomaceous earth); the production value of these has been several million dollars. Of value also has been stone from certain stratigraphic units, which because of its jointing characteristics is excellent building stone. Report of Investigations No. 19 should be helpful also in any continuation of the search for oil or gas in the central part of the State.

Dr. Mackin, the author of this report, has carefully studied the geology of central Washington over a period of many years, both in his capacity as a professor in the Department of Geology at the University of Washington and as a consultant for several private and public agencies that own mineral resources and have developed the water-power resources of the area. We feel that this contribution by Dr. Mackin to the knowledge of the geology of central Washington will be a significant aid in the future development of mineral resources here.

Marshall T. Huntting, Supervisor
Division of Mines and Geology

August 1, 1961

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A STRATIGRAPHIC SECTION IN THE YAKIMA BASALT AND THE ELLENSBURG FORMATION IN SOUTH-CENTRAL WASHINGTON

By J. Hoover Mackin

INTRODUCTION

Field studies in the Columbia Plateau over a period of years by me and a number of students at the University of Washington and Washington State University have resulted in the working out of the detailed stratigraphy of the upper 2,000 feet of the Yakima Basalt and the lower part of the Ellensburg Formation at a number of places in south-central Washington, mostly within an area of about 600 square miles approximately defined by lines connecting Vantage, Priest Rapids, Yakima, and Ellensburg (fig. 1). Individual flows and sedimentary units have been named in theses and private reports (Twiss, 1933; Mackin, 1946, 1955; Mason, 1953; Alto, 1954; Galster, 1955; Gray, 1955; Laval, 1956; Sargent, 1956; Grolier and Foxworthy, 1959), but none of these constitutes formal publication, and some of the terms are colloquialisms or are for other reasons invalid or unsuitable as stratigraphic names. The set of stratigraphic terms published by Cook (1957) includes some of our field names that are no longer in use, and none of the units is adequately described as to rock content. Several workers need stratigraphic names for articles now in preparation dealing with various phases of the geology of the Columbia Plateau, but they are unwilling either to introduce the names now in use or to propose new names for the familiar units; the purpose of this paper is to formalize the nomenclature.

The part of this report dealing with the Yakima Basalt is limited to a brief description of each stratigraphic unit at the type locality and a statement of the lateral extent of the unit or other factors that justify assignment of a formal name. Citations are restricted to earlier contributions that bear directly on the proposed terminology; for discussions of age, petrology, primary structural features, magnetism, and other properties of the Yakima Basalt the reader is referred to articles by Waters (1955a; 1955b; in press), Campbell (1950), and papers cited therein.

The Ellensburg Formation consists of fluvial and lacustrine sediments from several different sources, and intercalated basalt flows. The stratigraphic complexity that is to be expected in this type of accumulation is further increased by contemporaneous folding. For this reason an explanation of the proposed nomenclature requires description of several sections rather than one, and discussion of problems of correlation between them.

Some of the basalt flows to be described in this paper are many thousands of square miles in areal extent. It should be noted by way of background that neither the knowledge of the great size of individual flows, nor the concept of a flow-by-flow stratigraphy of basalts on a regional scale, is new. While the reconnaissance nature of their work did not permit the tracing of individual flows, all three geologic pioneers in the Columbia Plateau were clearly aware of the magnitude of the flows (Russell, 1893, p. 21; Smith, 1901, p. 15; and Calkins, 1905, p. 31). Calkins says, "Their extent, considered separately, must have been enormous, for it is rare to see the edge of a layer thinning out." Waters (1955b, p. 708) reports a single flow several thousands of square miles in extent in the eastern part of the Columbia Plateau. Regional stratigraphic studies based on basalt sheets of the same order of magnitude as those of the Columbia Plateau have been carried on in the Keweenawan lava field with remarkable success by Cornwall (1951) and White (1960). It is necessary to change only the geographic names to make White's description of the Keweenawan lavas, as "an example of flood basalts," fit those of Eastern Washington.

Acknowledgments

Many data that otherwise would not have been available were obtained in the course of work as geologic consultant on the Priest Rapids and Wanapum Dams on the Columbia River. I am indebted to Public Utility District Number 2 of Grant County, Washington, and the Harza Engineering Company of Chicago, Illinois, for permission to publish these data. The stratigraphic studies at the dam sites were advanced in many ways by R. B. Jackson, Resident Engineer; Clifford Willis, Harza Staff Geologist; Giles Thompson, Project Geologist; and Richard Galster, Assistant Geologist. Most of the photographs were taken for me by Carl Lewis, Project Photographer. Thanks are due the Northern Pacific Railway Company for permission to publish photographs of the diatomite deposits. The report has benefited in substance and in form as a result of field discussions or critical reading of the manuscript by H. A. Coombs, Roald Fryxell, M. J. Grolier, W. N. Laval, S. C. Sargent, F. C. Calkins, Dwight Schmidt, Aaron Waters, and H. E. Wheeler.

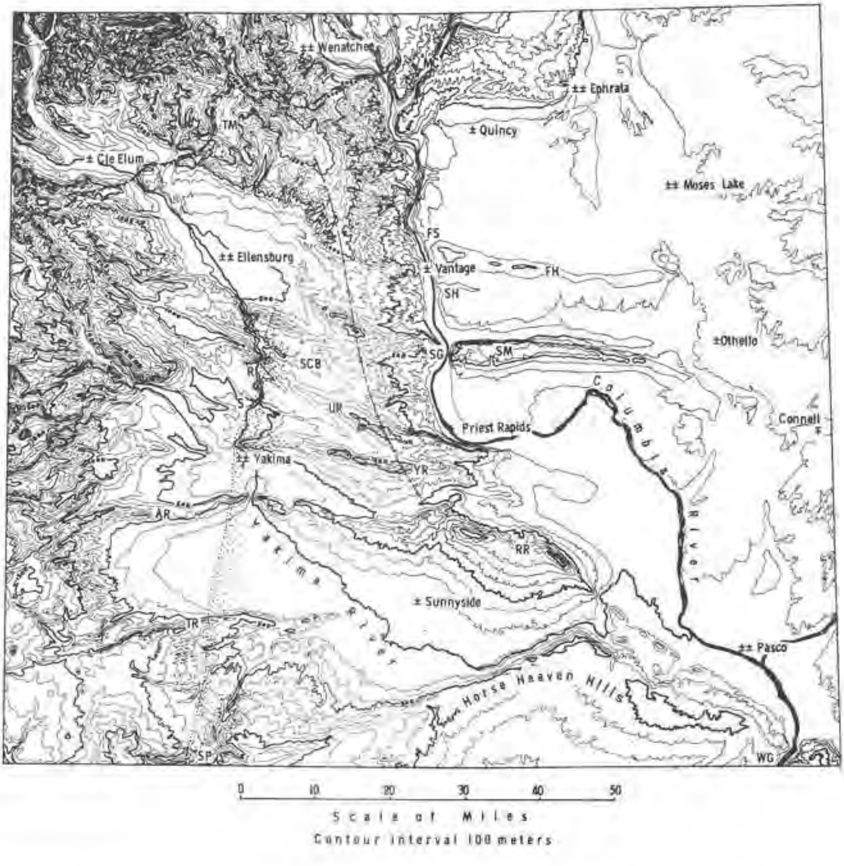

Figure 1.—Location map. AR, Ahtanum Ridge; FH, Frenchman Hills; FS, Frenchman Springs; MC, Moses Coulee; R, Roza Station; RR, Rattlesnake Ridge; S, Selah Creek; SCB, Squaw Creek Basin; SG, Sentinel Gap; SH, Sand Hollow; SM, Saddle Mountains; SP, Satus Pass; TM, Table Mountain; TR, Toppenish Ridge; UR, Umtanum Ridge; WG, Wallula Gap; YR, Yakima Ridge. The northwestern border of the Yakima Basalt is indicated by a hachured line southeast of Cle Elum and Wenatchee. The stippled zone west of Yakima is the western limit of known occurrences of quartzite gravel in the Ellensburg Formation and is interpreted as the approximate western margin of the Beverly-Selah alluvial plain of the ancestral Columbia River. The dash-dot line between the Yakima and Columbia Rivers is the Hog Ranch axis; the southeastward-trending ridges are folds of Plio-Pleistocene age, and the surface contours serve, as approximate structure contours, to show that the Hog Ranch axis is a culmination of plunge on each of the major anticlines.

YAKIMA BASALT

Yakima Basalt vs. Columbia River Basalt

Smith (1901, p. 15) defined the Yakima Basalt as basalt flows of Miocene age, which are typically exposed in Yakima Canyon between Ellensburg and Yakima, and which he believed to extend from the Cascade Range in Washington eastward to the Rocky Mountains and southward to the Blue Mountains of Oregon. He regarded the Yakima Basalt as one division of the "Columbia Lava" ("Columbia River Lava," "Columbia River Basalt"), defined originally by Russell (1893, p. 2) as including a number of basalt sequences in the Northwest ranging in age from Eocene to Pliocene. "Columbia Lava" was restricted by Merriam (1901, p. 303) to the succession of basalt flows between the John Day and Mascall formations in the John Day Basin in Oregon, and "Columbia River Basalt" was applied by Buwalda (1923, p. 2) and Kirkham (1931, p. 570) to the sequence of Miocene flows in southwestern Idaho. "Columbia River Basalt" has come to be widely used for the Miocene (and Early Pliocene?) basalt that underlies most of the Columbia Plateau in Washington, apparently on the assumption that the lavas of the Plateau are the same as those of the John Day Basin or southwestern Idaho. But this assumption has never been checked by tracing of individual flows, and Waters (in press) recognizes an unconformity between the Columbia Lava of Merriam in the John Day Basin and a younger sequence of flows which probably corresponds with the Yakima Basalt. Yakima Basalt is used here in the sense of Smith's original definition, because most of the flows of the Vantage-Priest Rapids area, in the central part of the Plateau, are definitely correlatable with those of Smith's type section in Yakima Canyon.

Rock Content

The base of the Yakima Basalt was defined by Smith (1903, p. 3) as the unconformable contact with the Eocene Manastash sandstone, but the context indicates that the formation was intended to embrace the whole succession of mid-Tertiary basalt flows and interbedded sedimentary rocks which rest unconformably on a wide variety of sedimentary, igneous, and metamorphic rocks around the borders of the Columbia Plateau. As flow-by-flow mapping proceeds, the base will doubtless need to be redefined in some places, but this possibility needs no consideration here because, as indicated above, the units to be described are parts of a single sequence, with nothing to suggest a hiatus of significant duration during the depositional history.

Where the Yakima flows advanced against the pre-existing drainage, fluvial and lacustrine sediments were deposited along the borders of the lava field (Waters, 1955a, and papers cited therein). In most places these deposits consist chiefly of materials derived from erosion of older rocks (e. g., the Latah Formation of the

Spokane area), but in the Ellensburg-Yakima area they are made up chiefly of hornblende andesite pyroclastic detritus from eruptive centers in what is now the Cascade Range. Russell (1900, p. 127) applied the term "Ellensburg" to a sequence of these sedimentary rocks, "possibly 1,000 feet" thick, that overlies the Yakima Basalt in the vicinity of Ellensburg, and Smith (1903, p. 3) used the term for a 1,600-foot section of the same beds, measured by Calkins northwest of Yakima. Lava flows intercalated in this sedimentary sequence in the valley of Wenas Creek, near Yakima, were named by Smith (1903, p. 4) the "Wenas Basalt."

In most places in the part of south-central Washington studied by Russell, Smith, and Calkins there is no difficulty in following their usage in distinguishing between the Yakima Basalt, consisting predominantly of basalt flows with minor interbedded sedimentary units, and the Ellensburg Formation, consisting predominantly of volcanic-derived sediments with or without interbedded basalt flows. Detailed stratigraphic studies make it evident that the uppermost flows of the sequence near Priest Rapids did not extend westward to Yakima Canyon, and this raises a question as to the definition of the top of the formation. The question answers itself: the uppermost flows at Priest Rapids are described later in this paper as the Priest Rapids Basalt Member of the Yakima Basalt, for they are clearly part of the Yakima Basalt as defined by Smith. The top of the Yakima Basalt is thus explicitly recognized as a lithostratigraphic boundary (Wheeler and Mallory, 1953) rather than a time-stratigraphic boundary.* There is of course no _a priori_ reason why lava flows with minor interbedded sedimentary units should give way upward in a vertical section to fluvial and lacustrine sediments with only minor flows or none at all, but this happens to be true throughout most of south-central Washington, and the change is a good stratigraphic boundary.

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*Since this was written this point has been confirmed and extended by independent observations by M. J. Grolier, and jointly by him and me, in the course of field excursions in the northern part of the Ellensburg 30-minute quadrangle. The Roza flow, which is overlain by four Priest Rapids flows at Priest Rapids, constitutes the top of the Yakima Basalt for most of the distance of about 7 miles from the Yakima River westward to the vicinity of Kelly Hollow, in a belt of outcrop along the north side of Wenas Creek (Smith, 1903, areal geology sheet). The Frenchman Springs Member, which underlies the Roza flow and consists of three flows near the Columbia River, is represented by a single flow where it forms the top of the Yakima Basalt west of the termination of the Roza flow at Kelly Hollow. The Frenchman Springs flow terminates about 5 miles beyond this point, and the Yakima-Ellensburg contact steps down to the surface of the next lower flow; the sedimentary unit mapped by Smith in this area as "the Ellensburg under the Wenas Basalt" is the Vantage Sandstone Member of the Yakima Basalt. It is noteworthy that the sediments at the base of the Ellensburg commonly rest on the vesicular surface of the flow that locally forms the top of the Yakima; that is, there is no evidence of any considerable lapse of time at the contact. It appears that 10 flows which compose the upper 1,000 feet of the Yakima Basalt at the Columbia River are about the same age as most of the Ellensburg Formation in sections west of the Yakima River.

General Stratigraphic Relations

The Yakima Basalt in south-central Washington seems at first to be a monotonous sequence of flows with so limited a range in lithology as to offer poor material for regional stratigraphic studies. Along the walls of Grand Coulee and Moses Coulee, however, where parts of the sequence are almost completely exposed, reconnaissance even from a car window shows that individual flows are continuous and of substantially uniform thickness for 10 miles or more. These exposures also make it evident that habits of cooling-contraction jointing differ markedly from flow to flow, and that distinctive arrangements of joint patterns in a given flow tend to be so persistent laterally that the flow can be identified with confidence across a covered area on the basis of the jointing alone.

The flows exhibit distinctive features of several other kinds: (1) absence or presence of phenocrysts and degree of crystallinity of the groundmass; (2) shape, size, and percentage of vesicles and diktytaxitic openings (see below); (3) nature of the upper surfaces, which range from aa to pahoehoe types; (4) weathering and erosion characteristics, such as breakage habit and color of the weathered product; and (5) weathering and erosion effects at interflow contacts, and other evidence regarding the duration of the time interval between successive flows.

The description of a flow in this paper is limited to these features and others, such as thickness, that are needed for its identification as a stratigraphic unit; no attempt is made to describe the flow as such, or to discuss questions of origin. Most flows show marked variations from base to top in percentage of crystals, glass, empty spaces, and mineraloid fillings in the spaces; in grain size, identity, and degree of endomorphic alteration of the minerals; in degree of devitrification and alteration of the glass; and so on; but these properties, and especially their differences in development from level to level, are largely disregarded in this paper except those that are distinctive of a given flow. "Fine-," "medium-," and "coarse-grained" (basalt) mean that the average larger sized plagioclase laths are less than 1 mm., 1 to 2 mm., and more than 2 mm. in length, respectively. Freshly broken surfaces commonly show a sprinkling of irregularly angular voids, usually less than 1 mm. in diameter, seen under the microscope to be interstitial spaces in a meshwork of feldspar and pyroxene grains; some of these voids are made conspicuous by fillings of black or dark-green mineraloids. The angular voids in the Yakima flows are as a rule somewhat smaller than similarly shaped openings, 0.5 to 1.5 mm. in diameter, that characterize the texture of certain olivine basalt flows of the Steens Mountain area, called "diktytaxitic" (net-arrangement) by Fuller (1931b, p. 116), but the size ranges overlap, and it seems preferable to extend Fuller's term rather than to invent a new one for the meshwork textures of the Yakima flows. "Dense," as used here, means that the rock is virtually free of diktytaxitic openings, and the degree of development of the diktytaxitic texture is indicated by adverbs or by estimates of the percentage of openings. Some Yakima flows (for example, the Rocky Coulee flow) are consistently dense through the entire thickness, while others (as the Roza flow) are notably diktytaxitic except for a thin zone of dense basalt at the base and, at the top, a somewhat thicker zone of dense basalt with numerous vesicles. In general, the degree of development of the diktytaxitic texture varies directly with the degree of crystallization of the rock; it is likely that the openings represent a "second boiling," caused by increased vapor pressure resulting from continued crystallization within the flow after crystallization was halted by chilling at the base and top.

It should be emphasized that lithology and jointing are suggestive guides rather than criteria for correlation. Jointing habits in many of the flows are remarkably persistent for long distances, but may change abruptly and drastically for reasons that are not understood. Theoretically, marked changes are likely in such properties as grain size, crystallinity, and mineralogy in a single flow from near its source to its distal margins; for example, Fuller's (1939) demonstration that olivine may settle out while a flow is in motion means that a flow that is olivine-rich in one place may be olivine-poor in another place, farther from the source. Most of the other properties listed above are secondary effects of compositional differences and cooling history, and may be expected to change with them.

Because of the lateral variability of the flows, the surest check on the identification of a unit is its position relative to other distinctive units in a familiar sequence. Thus one widespread porphyritic flow, discovered by W. H. Irwin (oral communication) in the Grand Coulee area and independently by me in the Squaw Creek area, 70 miles to the southwest (Mackin, 1946), is immensely helpful in confirming correlations of overlying and underlying flows, and the distinctive features of these flows, in turn, tend to confirm the identification of the porphyritic flow. Three sedimentary units, the Vantage Sandstone, the Squaw Creek diatomite, and the Quincy diatomite, play the same role; although these units make up only a small part of the section in the upper 2,000 feet of the Yakima Basalt, they are almost indispensable keys to the stratigraphy of the flows because they have great lateral extent and are identifiable with certainty wherever two or more are present in the same exposure. The basal part of the Ellensburg Formation, which in most places includes one or more widespread beds of pumicite, similarly provides a check on the identification of the uppermost Yakima flows.

Regional stratigraphic studies in the Yakima Basalt thus depend, not on the tracing of any individual units, but on relations seen in sequence; it is only after the basic stratigraphy has been worked out that vertical and lateral variations of various kinds, in selected units, can be investigated adequately.

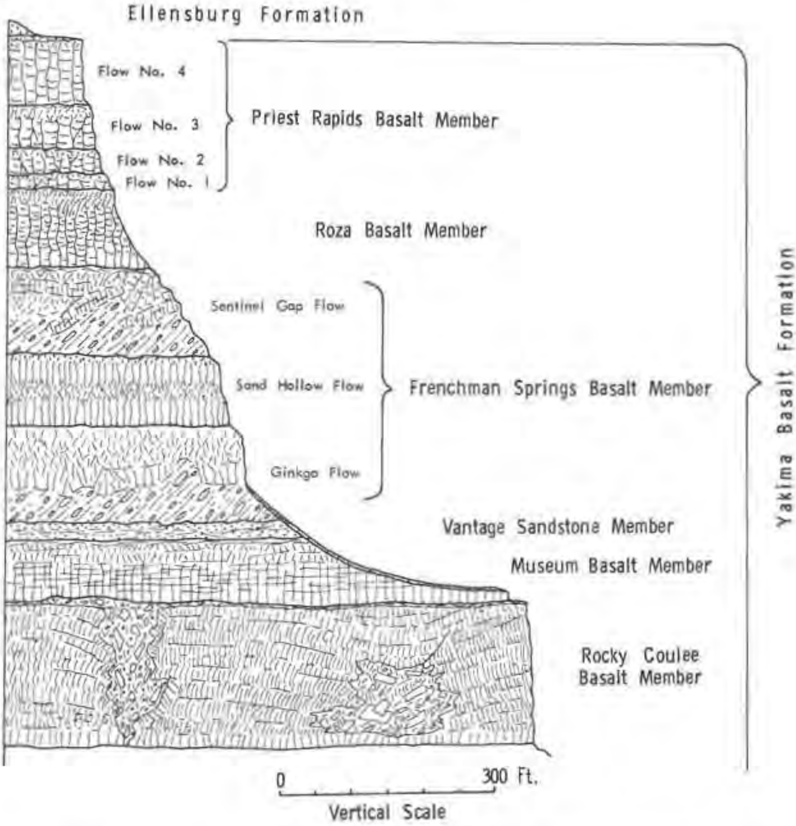


Figure 2.—Stratigraphic sequence in the Vantage-Priest Rapids area. The most prominent topographic feature of the area is a stripped structural surface, the Museum Platform, developed on massive columns at the base of the Museum flow. The Squaw Creek diatomite (not shown) is the lateral equivalent of the Sentinel Gap flow, and the Quincy diatomite (not shown) is the lateral equivalent of one or more of the Priest Rapids flows.

The columnar section (fig. 2) illustrates why the Vantage-Priest Rapids area is a good place to begin regional stratigraphic studies in the Columbia Plateau. Far from being monotonous, the sequence is highly varied, with no two units exactly alike. It is exposed, moreover, in deep cuts made by the Columbia River across three major anticlinal structures—Frenchman Hills, Saddle Mountains, and Umtanum Ridge (fig. 1). The lowest flow described, the Rocky Coulee Basalt, is underlain conformably by other flows that are seen only in the cores of the anticlines and that are too little known in this area to justify assignment of formal stratigraphic names. These and still lower flows are best exposed in Moses Coulee and around the margins of the lava field to the north and west.

Rocky Coulee Basalt Member

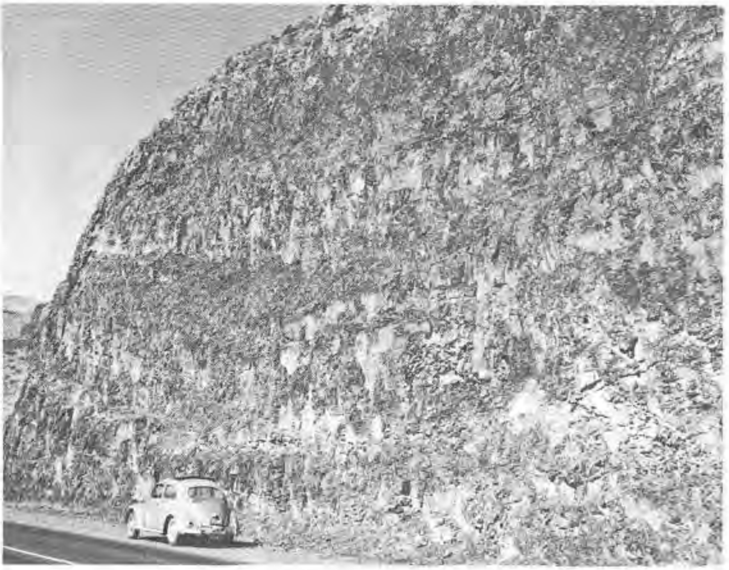
Although the type locality of the Rocky Coulee Basalt Member is at the mouth of Rocky Coulee, just west of Vantage, this flow is best exposed in a deep highway cut on the east side of the Columbia River about 1 mile south of Vantage. Its thickness in the Vantage-Priest Rapids area is 200 ±10 feet. Its lithology is not distinctive except that the flow is somewhat finer grained than other Yakima flows of comparable thickness in this area; its plagioclase microlites are commonly less than 0.3 mm. in length. Feldspar phenocrysts as much as 5 mm. long are present, but are so extremely rare as to be of little use for purposes of identification.

Vesicles as much as 2 inches in diameter, with flattened amoeboid shapes or with flat floors and arched roofs, make up as much as 20 percent of some highly vesicular layers in the upper 25 feet of the flow. The degree of vesicularity generally decreases downward; the lower half of the flow normally contains round vesicles a few millimeters in diameter, one or two to a square yard of exposure, but vesicular layers and lenses a few inches to many feet in thickness, gradational at both base and top, may occur at any level in the flow. The rock is generally dense, but may contain as much as 5 percent of diktytaxitic openings.

The top is typically pahoehoe; glassy-surfaced convolutions with a few feet of local relief are split open in some places (pl. 1B), and usually there is some upbuckling, but no rafting of slabs has been seen. In the foundation for the Wanapum Dam the flow was mantled locally by several feet of scoriaceous clinker.

The most distinctive feature of the flow in the Vantage-Priest Rapids area is its jointing habit, particularly a tendency for a great overdevelopment of what Tomkeieff (1940) calls the entablature at the expense of the colonnade. The colonnade, consisting of well-formed columns 3 to 4 feet in diameter, is commonly less than 30 feet thick; that is, something less than one-tenth of the thickness of the flow. The blocky- and splintery-breaking small columns of the entablature are arranged in wavy tiers, which may, in areas of poor exposure, give an impression of separate flow units (pls. 1A, 3); in some places spectacular fan jointing, described by Fuller (1931a), occurs within the tiers or crosses their boundaries.

In highway exposures just south of Vantage the Rocky Coulee flow is cut by a rudely cylindrical spiracle, as much as 40 feet in diameter, in which slabs and pillowlike masses of basalt occur in an openwork structure or in a matrix of palagonite breccia. Columnar joints in the adjoining solid basalt curve sharply, tending to approach the sides of the spiracle at right angles. As shown by Fuller (1931a, p. 299), these features probably were formed by rapid upward movement of a large volume of steam, rising from underlying wet places after the flow had come to rest. The Rocky Coulee cliff on the east side of the river south of Vantage shows a "flowout structure," formed by sagging and collapse of semisolid parts of the flow



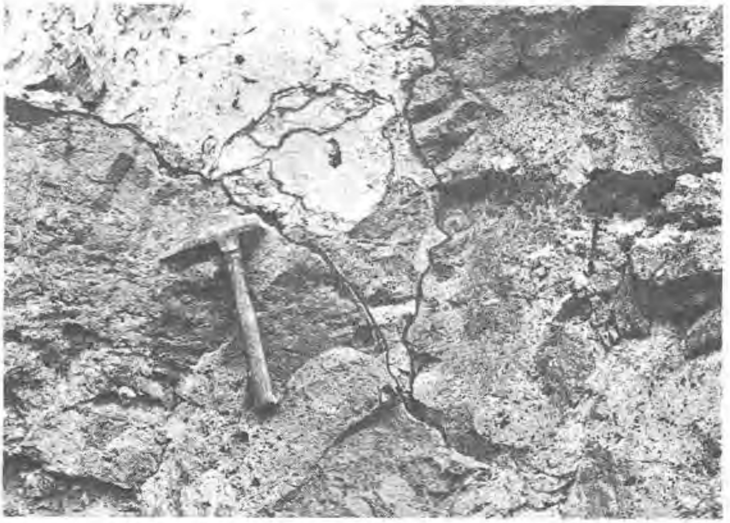


Plate 1. Structural Features of the Rocky Coulee Flow.

A. Small splintery columns and "brickbat" jointing in the entablature of the Rocky Coulee flow, in a highway cut 1 mile south of Vantage on the east side of the Columbia River. Note tiered arrangement of joint zones (compare with plate 3).

B. "Flowdown" projection of the Museum flow into a wedge-shaped crack in the upper surface of the Rocky Coulee flow, near A. The high fluidity of the Museum flow is indicated by penetration of the lava to where the crack is only 5 mm. wide.

into a lava tunnel (pl. 3). Spiracles and "flowout structures" are seen in the Rocky Coulee flow at many other places in south-central Washington, but they are of little value for purposes of identification because both occur in other flows in the Yakima sequence.

Museum Basalt Member

The type locality of the Museum Basalt Member is the Washington State Ginkgo Petrified Forest Museum southwest of Vantage; the Museum building is on a stripped structural surface developed on the basal 10 to 20 feet of the colonnade of the Museum flow (pl. 3). The contact between the top of the flow and the overlying Vantage Sandstone is exposed in highway cuts just to the west, and scattered outcrops on the sides of Rocky Coulee provide a poor composite section, but the middle and upper parts of the flow usually form soil-covered slopes. The flow is best known from holes drilled on the Columbia valley floor in a 4-mile segment south of Vantage during an investigation of alternative sites for the Wanapum Dam. Several complete core sections of the Museum flow indicate that it is 90 ±5 feet thick; that the vesicles are similar in size, shape, and distribution to those of the Rocky Coulee flow; that it is crowded with feldspar laths 1 to 2 mm. in length, making it medium-grained; and that the lower, nonvesicular part is notably open textured, with as much as 15 percent of microvesicles by volume. As in the Rocky Coulee flow, there are feldspar phenocrysts as large as 5 mm. in length, but they are very rare.

In the vicinity of the Museum building the basal part of the flow contains numerous pipe vesicles averaging ½ inch in diameter and 5 feet in length. Many of the pipe vesicles grade upward into cylinders of vesicular lava as much as 4 inches in diameter, which continue upward into the middle part of the flow; the total lengths of these vesicular cylinders and the nature of their upper terminations are not known because this part of the flow rarely crops out. Pipe vesicles and vesicular cylinders occur at the base of many of the Yakima flows, apparently being localized above sources of steam bubbles at the base of the flow, as shown by Du Toit (1907). The vesicular cylinders in the Museum flow are nearly vertical, but the pipe vesicles are rather consistently inclined northwestward, suggesting that the flow advanced in that direction (Waters, 1960, p. 358).

There is no weathering on the surface of the Rocky Coulee flow, or any other evidence that much time elapsed before it was covered by the Museum flow. The very high fluidity of the Museum flow is indicated by apophyses which penetrate nearly to the ends of narrow wedge-shaped cracks in pressure ridges on the Rocky Coulee flow (pl. 1B). This contact is tight in most places and, except where the top of the Rocky Coulee flow is highly scoriaceous, the contact zone is as resistant to erosion as the solid basalt above and below.

The upper part of the Museum flow in a number of surface exposures is deeply weathered to a yellow-brown silty clay. The absence of this weathered zone in drill-core sections below the valley floor of the Columbia River suggests that it does not represent a hiatus prior to deposition of the Vantage Sandstone but is the work of ground water moving through the permeable sandstone during the present erosion cycle.

The Rocky Coulee and Museum flows are definitely identifiable throughout the Vantage-Priest Rapids area. A flow that resembles the Rocky Coulee flow in jointing habits and other characteristics occurs at about the same stratigraphic horizon as much as 30 miles to the north in Moses Coulee, and 40 miles to the west along the western border of the lava field, but much more study is needed before the correlation can be regarded as certain.

Vantage Sandstone Member

The Vantage Sandstone Member is typically exposed in highway cuts west of Vantage, and has been transected by many drill holes at the Wanapum Dam site. It is weakly cemented and rarely crops out except in steep cliffs; it is the "light-colored bed" noted by Calkins (1904, p. 34) as being interstratified with basalt flows in the bluffs on both sides of Sentinel Gap. In the Vantage-Priest Rapids area it is 30 ±10 feet thick and consists chiefly of quartz-feldspar-mica sand and (or) tuffaceous sand of hornblende andesite composition. Either kind of sand may predominate in a given place, or the two may be interbedded in cut-and-fill structures and mixed in all proportions. Most sections include massive or laminated silt or clay, which may be bentonitic and may include leaf impressions and peat layers. The unit is yellow brown where exposed under oxidizing conditions, and gray to bright green below the level of active ground-water circulation.

Sedimentary units in many places in south-central Washington which are believed to be correlative with the Vantage Sandstone have been described in the reports and theses cited earlier. As noted by Laval (1956, p. 23), the pyroclastic phase is closely similar in mineralogy to tuffs in the Ellensburg Formation, and has been quite certainly derived from the same eruptive centers in the Cascade Range to the west. The quartz-feldspar-mica sand could have been derived directly from granitic rocks to the north, or "second-hand" from the Swauk and other Cretaceous to Early Tertiary sandstones and arkoses which border the lava field on the northwest.

Frenchman Springs Basalt Member

General statement.—The Vantage Sandstone Member is overlain in the near-vertical walls of Frenchman Springs Coulee by two flows, the Ginkgo flow and the

Sand Hollow flow, which were named for nearby localities. At an early stage in the stratigraphic study these flows were regarded as parts of a single stratigraphic unit, the Frenchman Springs Basalt Member, because several lines of evidence, particularly the presence of the same distinctive phenocrysts, suggested that both were spread from a common source during the same eruptive period. A third flow, which overlies the Sand Hollow flow on Saddle Mountain but did not extend as far north as Frenchman Springs Coulee, has been treated in some unpublished reports as a separate unit of member rank, the Sentinel Gap Basalt, even though it contains the same kind of phenocrysts. The Sentinel Gap flow is now regarded, in accordance with Laval's usage (1956, p. 26), as part of the Frenchman Springs Basalt; the advantages of having a common term for all flows with the Frenchman Springs type of phenocrysts outweighs the technical defect that the complete Frenchman Springs sequence is not present at the type locality. One of the advantages of this usage is that one or more flows with these phenocrysts, seen at this horizon at a number of places in south-central Washington, can be confidently mapped as Frenchman Springs Basalt prior to the detailed study required for flow-by-flow correlation with the Ginkgo-Sand Hollow-Sentinel Gap succession in the Vantage-Priest Rapids area. The general term is useful also because the Frenchman Springs flows tend to subdivide into flow units, especially in the vicinity of flowout structures.

Most of the phenocrysts are aggregates of partly resorbed, weakly zoned, plagioclase crystals; the aggregates tend to be roughly equidimensional in overall shape, averaging 10 mm. but reaching a maximum of 25 mm. in diameter. They are so shattered internally as to appear white—or if, as is commonly the case, the internal cracks are limonite stained, yellowish white. The phenocrysts are very unevenly distributed; they may be present in the proportion of several to a hand specimen, but so rare in adjoining parts of the same ledge that none or only a few are seen in many square yards of exposure. Clusters may occur near the top, near the base, or anywhere within the flow; their erratic distribution suggests that concentrations formed by gravitative rise of the crystals may have been swirled down into the flow by eddies, or rolled under caterpillarwise as it advanced. This, and the fact that the phenocrysts have substantially the same size and other characteristics in chilled parts as in the interiors of the flows, the resorption effects, and the intense shattering, indicate that they are intratelluric. But, as in most questions relating to internal features of the Yakima flows, a complete understanding must await study of the individual flows, as such, from near their sources to their distal margins.

Ginkgo flow.—The Ginkgo flow takes its name from the Ginkgo Petrified Forest, described by Beck (1945) and developed into a state park largely through his efforts. The petrified logs occur in a layer of pillows and palagonite breccia

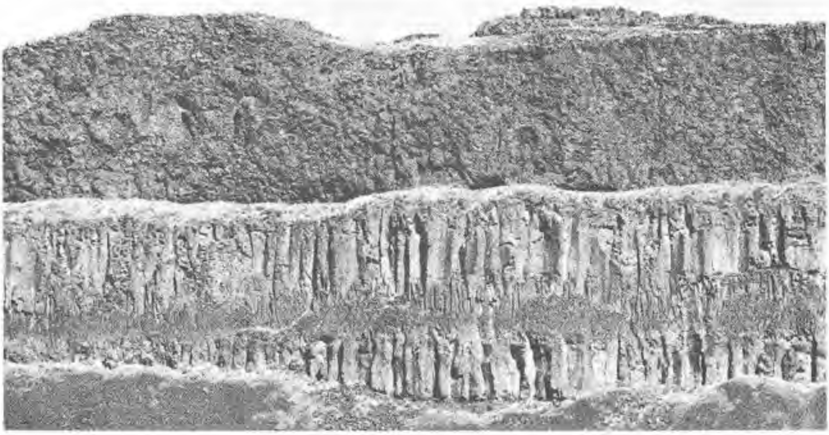


Plate 2A

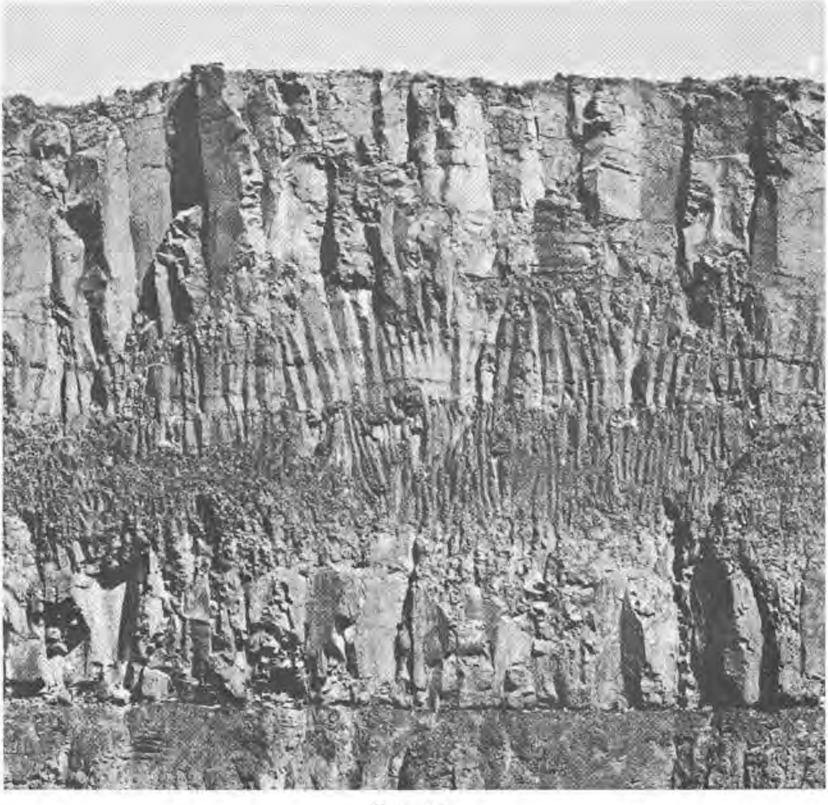


Plate 2B

which rests directly on the Vantage Sandstone Member at most places in the Vantage-Priest Rapids area. These relations conform with Fuller's (1931a) view that the pillow-palagonite layers in the Yakima sequence were formed where the flows advanced into lakes; the logs were probably lying waterlogged on the bottom of the "Vantage Lake" when it was destroyed by the advance of the Ginkgo flow. The pillow-palagonite layer is overlain in the type area by a sheet of solid basalt that is clearly the part of the Ginkgo flow that spread "in-the-dry" over the top of its own pillow-palagonite delta. The contact between the pillow-palagonite complex and the solid basalt may be a planar surface corresponding with the water plane of the lake; or the solid basalt may be complexly disrupted by upward extensions of the pillow palagonite formed by rising steam; or irregularly shaped masses of solid basalt may extend downward into the pillow-palagonite sheet as a result of displacement of the lake water by rapid advance of lava tongues. Where there was no lake, the Ginkgo unit is an ordinary flow. Depending on the scale and purpose of the mapping, it may be convenient and useful to distinguish between a pillow-palagonite phase and a flow phase.

The type locality is in the lower part of Schnebly Coulee west of Vantage, but both the pillow-palagonite and the flow phases are best exposed in the new road cuts near the mouth of Sand Hollow, 1 mile south of Vantage. The overall thickness in the Vantage-Priest Rapids area is 150 ±20 feet, of which the lower 50 to 75 feet is pillow palagonite in most places. Phenocrysts of the Frenchman Springs type are unevenly distributed throughout the unit. The jointing habits of the flow phase are so variable as to be of little use for purposes of identification. Occurrence of petrified wood in combination with Frenchman Springs phenocrysts is a good basis for float mapping of the Ginkgo flow in much of south-central Washington, but since petrified wood occurs at other horizons in the Yakima Basalt and is not everywhere present in the Ginkgo pillow palagonite, this criterion must be used with caution.

Sand Hollow flow.—The field term for this unit, the "double-barreled" flow, expresses the jointing habit that is its most distinctive feature: in cliff exposures on

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Plate 2. Structural Features of the Frenchman Springs Basalt.

A. Sand Hollow and Sentinel Gap flows in the scarp east of the Columbia south of Sand Hollow. The contact between the Sand Hollow flow and the underlying Ginkgo flow is exposed above the top of the talus at the center. The three zones of cooling-contraction joints in the Sand Hollow flow are, from the base upward, the lower colonnade, about 25 feet; the entablature, about 30 feet; and the upper colonnade, about 35 feet. The joints of the upper colonnade extend to within a few feet of the top of the flow, which here is ropy and shows minor ruptures on low pressure ridges.

The Sentinel Gap pillow-palagonite complex shows no foreset structure at this place. The solid ledges at the top are in the flow phase of the Sentinel Gap flow.

B. Details of jointing in the Sand Hollow flow, near A. The zones of jointing are sharply defined, but continuity of the rock from zone to zone makes it evident that the zones are parts of a single flow. The entablature at this place consists of columns of two sizes, larger above and smaller below. Note the planar surface of the underlying Ginkgo flow.

Plate 3. Yakima Basalt Sequence on the South Limb of the Frenchman Hills Anticline.

The cliff overlooking the river consists entirely of the Rocky Coulee flow except for a thin (5- to 15-foot) capping made up of massive columns at the base of the Museum flow. The disturbed part of the Rocky Coulee flow in the center of the photograph Is a "flowout structure." The Museum Platform is a stripped structural surface formed by erosional removal of the weak upper part of the Museum flow, the Vantage Sandstone, and the pillow-palagonite phase of the Ginkgo flow; these weak units are concealed by fans and talus. The dashed line marks the top of the Sand Hollow flow. South (to the right) of the draw this flow is overlain by the Sentinel Gap flow, represented mainly by a pillow-palagonite complex with well-developed foreset structure. The solid ledges above the pillow-palagonite complex are in the lava phase of the Sentinel Gap flow. The highest hills consist of the Roza flow, which overlies the Sentinel Gap flow south of the draw. North of the draw the Roza flow rests directly in the Sand Hollow flow; the Roza flow was spread "in-the-dry." The lake in which the Sentinel Gap flow terminated should be represented by sediments at the Sand Hollow-Roza contact; the fact that none are present is taken to mean that they were removed by erosion prior to spreading of the Roza flow. The Priest Rapids flow, which overlies the Roza flow, has been eroded back so far from the valley side that it is not possible to make certain measurements of thickness of the Roza flow that would be of special interest; namely, (a) above the flattish surface of the Sentinel Gap flow, (b) above the sloping front of that flow, and (c) on the flattish surface of the Sand Hollow flow.

the east side of the Columbia Valley north and south of Sand Hollow the colonnade, consisting of regular prismatic columns 4 to 6 feet in diameter and 20 to 30 feet in height, is almost exactly matched by a columnar zone 30 to 40 feet thick near the top of the flow (pl. 2). The entablature, consisting of one or more tiers of small columns, is about 30 feet thick. The presence of an upper zone of large columns is not unusual in Yakima flows; what distinguishes the Sand Hollow flow is the unusual thickness and perfect development of this zone, and the reduction of the entablature to less than one-fourth of the overall thickness of the flow.

The top of the flow, as seen in highway cuts along the south side of Frenchman Springs Coulee, is a jumble of broken blocks and rafted slabs of scoriaceous lava, with local relief of as much as 5 feet (pl. 5A). Numerous interconnected openings as much as a foot across in this aa lava help one to understand the extreme permeability of some interflow contacts in basalt.

Sentinel Gap flow.—Because the Sentinel Gap flow terminates within the Vantage-Priest Rapids area, it requires somewhat different treatment from that accorded the older units, which are, in this area, merely parts of a sequence of strata with no boundary effects.

At Sentinel Gap this unit is 125 ±10 feet thick, consisting mostly of solid basalt characterized by disorderly joint patterns, but containing irregularly distributed masses of pillow palagonite. It thins northward and pinches out completely in about 10 miles. The distal mile, well exposed in the scarp on the east side of the Columbia River north of Sand Hollow, is a gradually tapering wedge of palagonite breccia made up of pillows and lava slabs arranged in a northward-dipping foreset structure; near the thin end of the wedge the light-yellow color of the palagonite contrasts sharply with the dark underlying and overlying flows (pl. 3). In the 8 miles between Sand Hollow and Sentinel Gap the unit is composed of solid basalt and pillow palagonite, in all proportions, the extreme irregularity of the contact between the two kinds of rock probably being due to emplacement of lava tongues below the surface of the lake. The thickness relationships, the dip of the deltaic foresets, and the absence of any considerable thickness of quiet-water sediment at the base of the unit indicate that the flow advanced northwestward into a lake of its own making.

The Sentinel Gap flow is overlain by the highly distinctive Roza Basalt, to be described below. North of the end of the flow, for example in Frenchman Springs Coulee, the Roza Basalt rests directly on the blocky surface of the Sand Hollow flow (pl. 5A) or on a thin and discontinuous sedimentary unit consisting chiefly of peaty silt and (or) diatomite (pl. 5B). The absence of pillow lava at the base of the Roza flow in this area, and the fact that some of the patches of sediment at the contact stand mesalike as much as 3 feet above the surface of the Sand Hollow

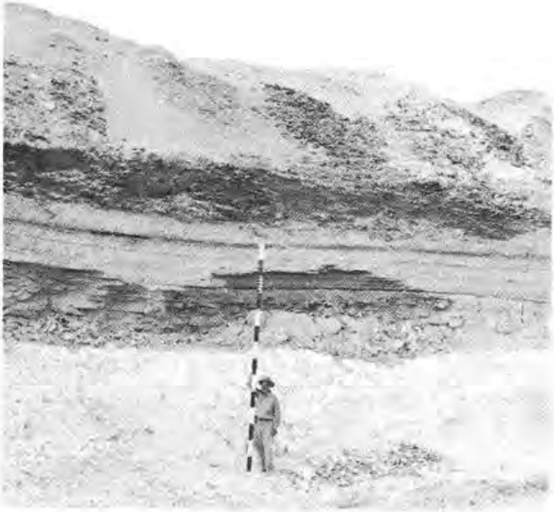

Plate 4. Diatomite Beds.

A. Working face in the Squaw Creek diatomite (NW¼ sec. 15, T. 15 N., R. 20 E.). The diatomite bed is 13 to 14 feet thick at this place. There is a sharp transition to the overlying shale. The dark rock above the top of the rod is the base of the Roza flow; in some places this flow fills shallow channels cut in the shale. It is evident that the flow spread in the dry after disappearance of the lake and after channeling of its floor.

B. Working face in the Quincy diatomite (NE¼ sec. 21, T. 18 N., R. 23 E.). Base of the rod rests on the surface of the Roza flow. The overburden consists of angular blocks and pillows of a Priest Rapids flow. Note cluster of blocks and pillows which appear to have been injected into the diatomite on the right. The Priest Rapids flow clearly advanced into the lake in which the diatomite was formed.

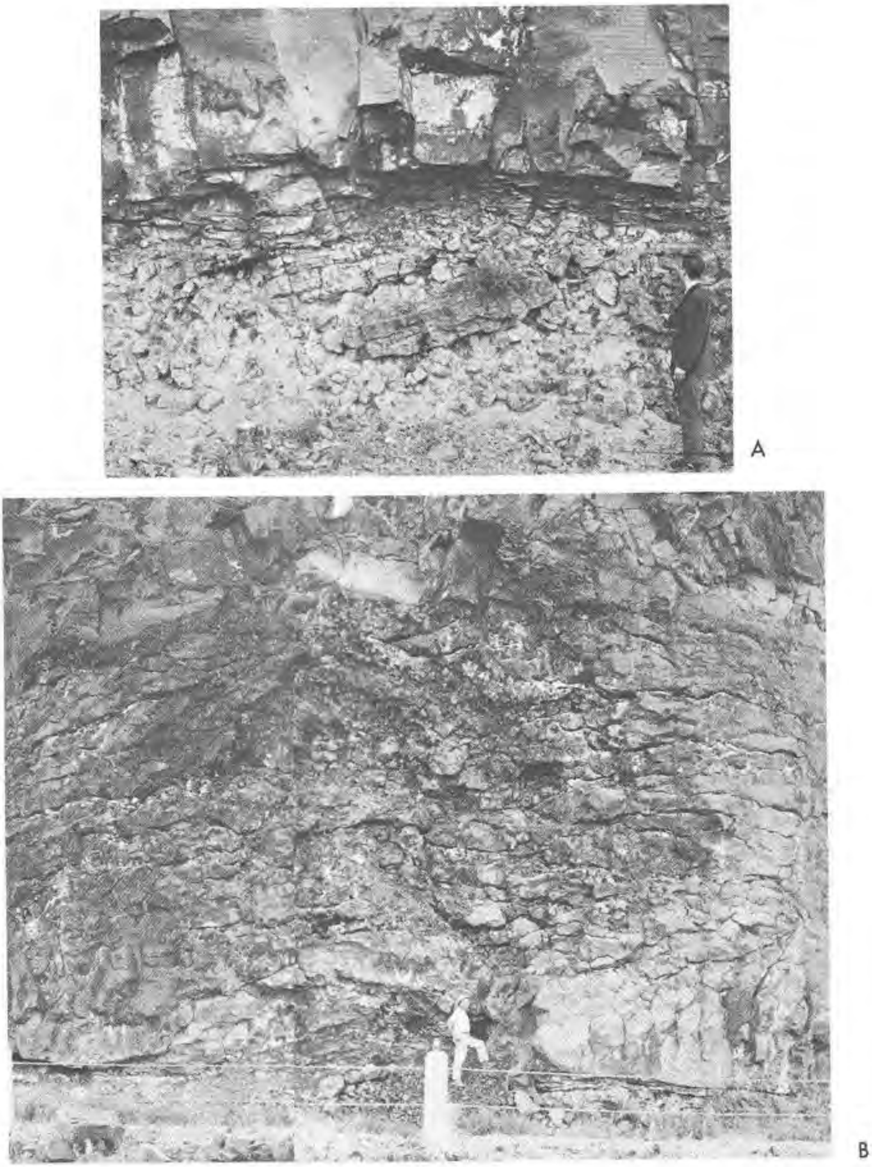

Plate 5. Base of the Roza Flow.

A. Roza flow resting on the blocky surface of the Sand Hollow flow in a highway cut on the south side of the north alcove in Frenchman Springs Coulee. At this place there are no sediments at the contact.

B. Spiracle at the base of the Roza flow, a short distance west of A. The spiracle is localized over a low mound of sediments which include peat and diatomite.

Plate 6A

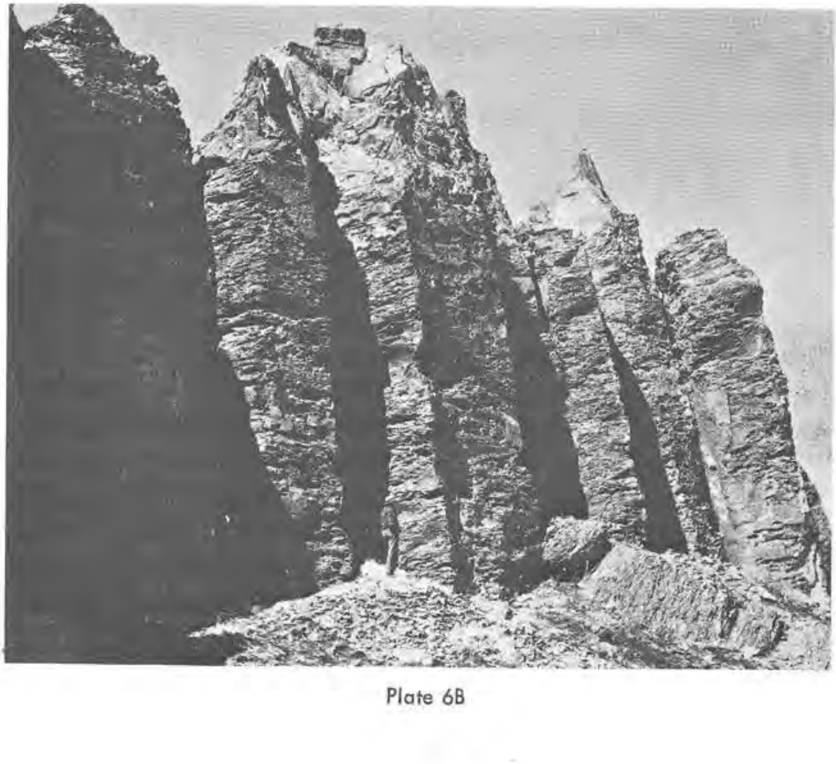

Plate 6B

flow, show that the ponded water body in which the sediments were deposited had been drained, and that there had been at least a brief period of erosion, before the advent of the Roza flow.

Squaw Creek diatomite.—A similar record is preserved about 30 miles west of the Vantage-Priest Rapids area. In the Squaw Creek drainage basin (fig. 1), a bed of diatomite which rests on a Frenchman Springs flow is about 5 feet thick at the Yakima River and thickens eastward in 12 miles to about 17 feet near the Yakima-Columbia divide (Mackin, 1946). The thick end of the diatomite wedge abuts against the terminus of the Sentinel Gap flow. A bed of diatomaceous siltstone 5 to 10 feet thick, which overlies the diatomite in most sections east of the Yakima River, thickens and coarsens westward to a sandstone and pea conglomerate, in part tuffaceous and in part consisting of granitic detritus. The overlying Roza flow was spread on dry land; in some places the surface of the siltstone had previously been channeled by rivers (pl. 4A). The relationships are taken to mean that the diatomite was deposited in a lake impounded by the Sentinel Gap flow, and that the lake had been drained and the lake plain trenched by rivers before the spreading of the Roza flow. On the basis of this interpretation, the Squaw Creek diatomite is considered a part of the Frenchman Springs Basalt Member.

Roza Basalt Member

The type locality for the Roza Basalt Member is a scarp on the east side of the Yakima River opposite Roza Station (fig. 1), where the Roza flow overlies the Squaw Creek diatomite. The thickness of the flow in the Roza-Squaw Creek area is 100 ±10

Plate 6. Columnar Jointing in the Roza Flow.

A. Colonnade on the north wall of the south alcove at Frenchman Springs. The columns are 90 ±10 feet high and 10 ±2 feet in diameter. In the left half of the photograph the pinches and swells are arranged in a diagonal pattern which slopes about 30° to the left. In other parts of the same wall there is no pattern or the pattern slopes in the opposite direction; the angle of slope varies widely. The pinch and swell patterns seem to be random rather than systematic.

Note that the subhorizontal platy parting which characterizes the Roza colonnade is evident wherever the smooth surface of the columns has been destroyed by weathering (see B).

In a channel-shaped area to the left of center the columns give way to complex patterns of whirling platy parting that may mark the site of a late surge of flow.

B. Detail of colonnade near the end of a narrow septum between the north and middle alcoves at Frenchman Springs. Note the subhorizontal platy parting in the columns and the talus of conchoidally fractured spalls beneath the figure in the center. The swirling pattern at the top of the columns is in an irregular zone about 10 feet thick which lies between these and an overlying zone of large columns. The swirling zone is here 40 to 60 feet above the base of the flow.

feet. Its most distinctive feature is the presence of lath-shaped plagioclase phenocrysts averaging about 1 cm. in length and 5 mm. in thickness. The crystals are transparent, and therefore look dark on fresh fractures. They are in the same compositional range as the Frenchman Springs phenocrysts but can be distinguished from them on the basis of size, shape, and color. They differ from them also in this important respect—they are uniformly distributed from base to top of the flow in the proportion of several to a hand specimen. They are clearly intratelluric; their uniform distribution suggests that the mass of these relatively small crystals was not sufficient to cause the gravitative segregation that seems to have occurred in the Frenchman Springs flows.

The colonnade commonly makes up one-half to three-fourths of the thickness of the Roza flow; the columns are as much as 10 feet in diameter, and, except near the base, they are usually cut by a very strongly developed platy parting normal to the axes (pl. 6). In many places the ordinary blocky jointing of the entablature gives way to sharply recurved and swirling patterns of plates, suggesting that directional stresses were set up in still viscous lava by a surge of movement after partial consolidation of the colonnade. Chiefly because of the platy jointing, the lower and middle parts of the flow are easily eroded, forming covered slopes surmounted by ledge outcrops of short massive columns near the top. The surface, in the few places where it has been seen, is ropy, locally displaying some upbuckling and splitting of pressure ridges. Except for a fine-grained vesicular zone at the top, the rock is medium to coarse grained and contains 10 to 20 percent diktytaxitic openings. It weathers to a deep red-brown color.

Talus derived from the colonnade and the zones of swirling platy jointing consists of slabs and splinters, mostly between 1 and 2 feet in length and a few inches in thickness, bounded by curving fracture surfaces. Because of its breakage habit and attractive color, this rock has recently come into wide use in the Northwest, both as a building stone and in ornamental masonry. Some of the Priest Rapids flows (see below) yield spalls that are similar in form and color but lack the Roza phenocrysts. The lithology and breakage habit of the Roza and Priest Rapids rocks are so distinctive that it is possible to recognize them in buildings, whereas identification of most of the Yakima flows depends on a knowledge of stratigraphic sequence and other field relations.

The Roza flow has been used for many years as a key unit, "the porphyritic flow," or as one of several porphyritic flows, in study of dam and reservoir sites in the Grand Coulee and Quincy Basin by W. H. Irwin, Fred O. Jones, W. E. Walcott, George Neff, and other Bureau of Reclamation geologists. Correlation between the Grand Coulee and Squaw Creek areas was first indicated by similarity in lithology and sequence, and has been confirmed by study in various parts of the intervening area by Alto (1954) and Gray (1955). The known area of outcrop has been extended southward to the Horse Heaven Hills by Laval (1956, p. 28) and eastward to Connell by Grolier (oral communication). Because the flow is definitely identifiable in drill cores, it has been much used in working out the subsurface geology at the Priest Rapids dam site by Mackin (1955) and in ground-water studies in south-central Washington by Grolier and John Robinson (oral communication). It was tentatively identified by S. C. Sargent (1956) while studying the engineering geology of The Dalles dam site; it is probably Flow R of the sequence at The Dalles. It was seen in a number of places between Yakima and The Dalles by Waters, Grolier, Sargent, and me in the course of a field conference in the spring of 1960. Although there are of course some variations, the properties outlined above are remarkably persistent over the presently known extent of 10,000 square miles. As the flow is conservatively estimated to be 150 feet in average thickness, its volume is more than 300 cubic miles. Its source is probably east of the known outcrop area, but is as yet unknown.

Priest Rapids Basalt Member

Four flows that overlie the Roza Basalt Member at Priest Rapids Dam are referred to collectively as the Priest Rapids Basalt Member, for the practical reason that a family resemblance between them is so strong that they cannot be identified separately except where the full sequence is present. Thicknesses based on diamond drill holes at the dam site are, from the base upward: Priest Rapids flow no. 1, 30 ±5 feet; no. 2, 40 ±5 feet; no. 3, 60 ±5 feet; and no. 4, 90 ±10 feet. Priest Rapids flow no. 4 is overlain directly by the Ellensburg Formation or by basalt flows interbedded in the Ellensburg. Much of the dam site area is now covered by buildings or water, but the Roza and Priest Rapids flows and the Ellensburg Formation are exposed in a south-dipping homocline on the west side of the reservoir.

As indicated earlier, the Priest Rapids flows are closely similar to the Roza flow in lithology, differing only in the virtual absence of phenocrysts; Roza-type phenocrysts are present but are very rare. Except in the vesicular tops and chilled bases, the flows are medium to coarse grained and contain a high percentage (15 to 20) of diktytaxitic openings. The columns of the colonnade are very large in diameter; in the thinner flows, columns that are only a few tens of feet in height may be as much as 10 feet in diameter (pl. 7A). Depending on the degree of development of the platy parting, the flows range from very weak to very resistant; the rapids in the Columbia River at the dam site were held up by relatively massive columns in Priest Rapids flow no. 4 (pl. 7B). As in the case of the Roza flow, the weathering color is red brown.

Plate 7A

Plate 7B

Laval (1956) assigns to the Priest Rapids Basalt Member a thick sequence of strata measured in many sections in an area of several thousand square miles in south-central Washington, south of Priest Rapids. His section near Mabton, for example, includes three "basal Priest Rapids flows," aggregating 216 feet; the Mabton sedimentary interbed, 75 feet; the Umatilla flow, about 285 feet; and the Sillusi flow, about 100 feet; the total thickness is 650 to 700 feet. His suggestion that these units be considered parts of the Priest Rapids Basalt is a workable arrangement; any or all of them can readily be raised to member or formational rank as our understanding of the stratigraphy develops. The presence of intermediate percentages of Roza-type phenocrysts in some of the flows assigned by Laval to the Priest Rapids Basalt complicates the descriptive stratigraphy, but is of special petrogenetic interest. The great thickness of the Priest Rapids flows in the central part of the lava field has an important bearing on the subsidence that accompanied the spreading of the flows, a matter to be considered later.

Quincy diatomite.—In the vicinity of the Columbia River only one of the Priest Rapids flows extended north of the Frenchman Hills. Throughout the western part of the Quincy Basin this flow rests, not directly on the Roza flow, but on a widespread sheet of diatomite, as much as 20 feet thick, here designated the Quincy diatomite. The diatomite bed extends southward across the axial part of the Frenchman Hills anticline, terminating on its south flank; the Quincy diatomite lake evidently predates the arching of this structure. The contact is not exposed, but it is probable that the diatomite bed ends against the front of a Priest Rapids flow and that the lake was impounded by this flow; that is, the relationships are believed to be similar to those between the Squaw Creek diatomite and the Sentinel Gap flow. In most places in the Quincy Basin a sheet of palagonite breccia between the diatomite and the flow phase of the overlying Priest Rapids flow indicates that the flow advanced into the lake rather than over the dry lake bed (pl. 4B). On

Plate 7. Structural Features of the Priest Rapids Basalt.

A. Colonnade of Priest Rapids flow no. 3 in a draw 1 mile north of Priest Rapids on the west side of the Columbia River. The jointing is definitely columnar, but the columns are poorly formed, being bounded and in some places transected by curving joint planes. The colonnade is 35 ±5 feet high, and the columns average about 10 feet in diameter; that is, they are notably short and stout.

B. Massive columns of Priest Rapids flow no. 4, which formed Priest Rapids in the Columbia River. The columns average about 10 feet in diameter and are cut into slabs 1 ±0.5 feet thick by joints normal to the axes.

the assumption that the Quincy lake was impounded by one Priest Rapids flow and destroyed by another, the Quincy diatomite is considered to be a part of the Priest Rapids Basalt Member.*

ELLENSBURG FORMATION

The Saddle Mountains-Priest Rapids Section

The Ellensburg Formation is represented in the Vantage-Priest Rapids area by basalt flows that are probably at about the same horizon as Smith's (1903) Wenas Basalt at Wenas Creek near Yakima, and by sedimentary rocks that may be approximately equivalent to the "sub-Wenas Ellensburg" at Wenas Creek. On the basis of general lithologic similarity, the terms "Wenas" and "sub-Wenas" have been used in a number of theses (Mason, 1953; Gray, 1955; Laval, 1956) and reports (Mackin, 1947, 1955), but no time-stratigraphic unit has as yet been walked out through the intervening 30 miles; it is preferable to assign different formal names in the two areas because use of the same names begs a number of questions as to correlation. A flow that is believed to be continuous over much of the area, and that was called the "Wenas Basalt" in the earlier reports, is here designated the Saddle Mountains Basalt Member of the Ellensburg Formation; the type locality is the scarp on the east side of Sentinel Gap (fig. 3, section 4). The term "Beverly," originally used by Twiss (1933) for a pumicite bed in the sedimentary rocks beneath the Saddle Mountains Basalt in the Sentinel Gap section, is here redefined to include all the sedimentary rock and intercalated basalt between the top of the Yakima Basalt and the base of the Saddle Mountains Basalt in that section.

Beverly Member.—Excavations below the bed of the Columbia River at the Priest Rapids dam site, now covered by buildings or flooded, afforded excellent exposures of the base of the Beverly Member. In most places under the eastern part of the channel Priest Rapids flow no. 4 is overlain by peaty siltstone, sandstone, and conglomerate deposited directly on the scoriaceous surface of the flow (fig. 3, section 1). Near the west bank, however, the same types of sediments lie in an ancient channel cut entirely through flow no. 4 (fig. 3, section 2); these channel-filling deposits include partly petrified logs and fresh-water shells of several types.

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* M. J. Grolier has discovered that in some parts of the Quincy Basin the palagonite breccia which caps the Quincy diatomite contains a percentage of feldspar phenocrysts approaching that which is characteristic of the Roza flow, and much higher than in the immediately overlying "solid" Priest Rapids basalt. This may mean merely that the phenocrysts were concentrated in the upper part of the Priest Rapids flow by floating upward as it advanced, and that the palagonite breccia was formed chiefly by the rolling under of the phenocryst-rich zone where the flow entered the diatomite lake. It may, on the other hand, mean that there are two "Quincy diatomites," or two "Roza flows," or other stratigraphic complexities missed by me in the reconnaissance on which this paper is based.

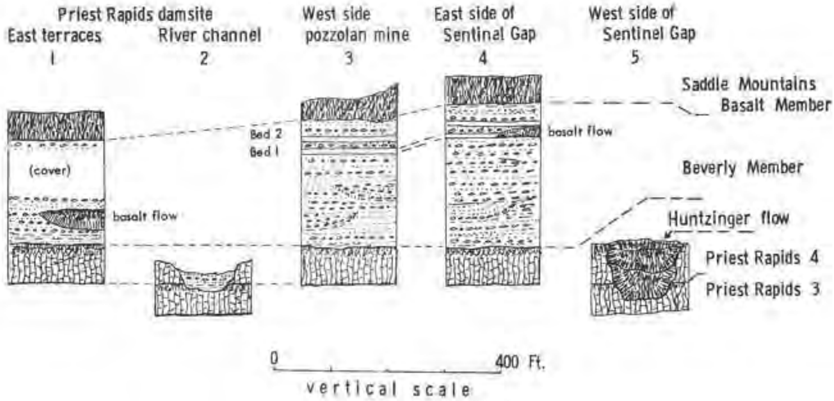

Figure 3. —Columnar sections of the lower part of the Ellensburg Formation in the Sentinel Gap-Priest Rapids area.

It is not certain whether the sediments which rest on the surface of flow no. 4 slightly predate the cutting of the channel or were deposited shortly after the channel was filled; in either case, it is evident that there was no considerable lapse of time between the spreading of the last Priest Rapids flow and the deposition of the Beverly sediments.

The conglomerate that makes up most of the Beverly Member at Priest Rapids and in the other sections in figure 3 consists of pebbles of varied felsite porphyries, 40 to 50 percent; granitic and metamorphic rocks, 30 to 40 percent; basalt, 10 to 20 percent; and gray, pink, and purple quartzite, 5 to 10 percent. In rock types, size and degree of rounding of the pebbles, and depositional features such as channeling and torrential bedding, the conglomerate is similar to the channel gravel of the modern Columbia River. They differ in that the conglomerate is indurated in some places, is commonly interbedded with fine-textured tuffaceous sediments, is in places deformed, and contains a smaller percentage of basalt and a larger percentage of the felsite porphyries. The Beverly pebbles and sand grains found in drill holes and exposures below the river bed are commonly coated with a green mineraloid (celadonite or an iron-rich nontronite?), but color alone is not a criterion, because the sediments may be tan colored along routes of deep circulation of ground water.

The granitic and metamorphic pebbles clearly come from the north, and the quartzite pebbles are Belt or early Paleozoic rocks from the Northern Rockies.

Plate 8. Basalt Flow and Pumicite in the Beverly Member.

Air photograph looking southward down the dip on the south limb of the Saddle Mountains anticline just east of Sentinel Gap. A dip slope formed by stripping of Beverly sediments from the surface of the uppermost Priest Rapids flow shows in the right foreground; the angle of depression of the camera is the same as the dip, hence the slope looks like a straight line. The mine workings are in Beverly pumicite, chiefly bed no. 1, which forms light-colored outcrops extending part way across the photograph. The dark ledges farther east are a basalt flow at the same horizon as bed no. 1. The Saddle Mountains flow forms two lines of ledges, a continuous line where the base of the flow is sapped by removal of the Beverly sediments and a discontinuous line formed by a poorly developed upper colonnade.

The Saddle Mountains flow is overlain by Ellensburg conglomerate. It is not known whether the Ellensburg at this place is a basalt or a quartzite (that is, ancestral Columbia River) conglomerate; though there is an abundance of quartzite pebbles in the soil, it is not certain whether these are "in place" or are a lag accumulation derived from a higher sheet of pediment gravel which was in turn derived from quartzite conglomerate in the Beverly Member.

The dip flattens at about the latitude of the mine workings, and the Saddle Mountains flow can be seen extending 3 miles to the south, where it passes beneath a mantle of glacial flood gravel. Light-colored barchan dunes in the right background are moving eastward from the Columbia valley floor.

Similar quartzite gravel occurs at about this horizon at a number of places in south-central Washington, and has long been recognized as the signature of an ancestral Columbia River (Warren, 1941; Waters, 1955a, and papers cited therein). The quartz-feldspar-mica sand of the Vantage Sandstone is also of northern derivation, but could have been deposited by short streams heading in older rocks northwest of the lava field; the first appearance of the quartzite pebbles in the Vantage-Priest Rapids area signals the birth of the Columbia as a major river, heading in the Northern Rockies, formed by the linking together of drainage lines that had been disrupted by spreading of the Yakima flows.

Not exposed at Priest Rapids, but conspicuous in both natural and artificial cuts on the east side of Sentinel Gap, is a bed of gray pumicite that is the most distinctive lithologic unit in the Beverly Member (fig. 3, section 4, bed 1; pl. 8). The bed has been described by Carithers (1946, p. 64-65) in a report on pumicite occurrences in Washington. The pumicite has been mined as a source of pozzolan for both the Priest Rapids and Wanapum Dams, and has been investigated in the concrete laboratories on both jobs. It consists almost entirely of glass shards, predominantly within a very narrow range in size (0.02 to 0.2 mm.). The index of refraction of the glass is 1.50 to 1.51. The similarity of the material to a coarser, lapilli-bearing pumicite at about the same horizon farther west (see p. 35) indicates that it was derived from Cascade volcanoes. The very perfect sorting suggests that it was airborne; lamellar bedding, crossbedding, and ripple marks at different levels indicate that it probably was deposited in part in quiet water and in part on dry land. Laval (1956, p. 52) notes that the crossbedding is similar to that in wind-drifted silt and sand on the present flood plain of the Columbia.

Bed no. 2 in the same exposures is superficially similar to bed no. 1, but consists of very fine grained mineral matter, chiefly quartz and feldspar, and contains about 20 percent clay. It clearly is lacustrine, and probably represents a mixture of volcanic dust from the Cascades with nonvolcanic material that came from the north. Bed no. 2 is generally inferior to bed no. 1 as a pozzolan, but the test data include a number of anomalies, discussion of which is beyond the scope of this paper. A laboratory study of samples from bed no. 1 and other Washington State pozzolans is reported in a recent paper by Klemgard (1958).

A pozzolan mine on the west side of the Columbia 7 miles south of Sentinel Gap exposes a similar section; i. e., two beds of fine-grained sediments interlayered with conglomerate (fig. 3, section 3). Correlation between the two sections, suggested by similarity in the megascopic properties of the two beds, is confirmed by their being virtually identical in composition as determined by study with the microscope. These beds are usually covered by float on all except the steepest slopes, but scattered exposures indicate that they occur widely in the Vantage-Priest Rapids area.

Laval (1956) describes a section on the Saddle Mountains east of Sentinel Gap in which the Saddle Mountains Basalt Member is overlain by conglomerate consisting predominantly of subangular pebbles of basalt. He interprets this conglomerate as indicating that the Saddle Mountains anticline had by that time gained sufficient height to shed aprons of basaltic detritus; he refers to the basalt conglomerate as the "tectonic phase of the Ellensburg." Assignment of formal stratigraphic names in this part of the section depends in part on how the top of the Ellensburg Formation is defined, and this in turn depends on regional stratigraphic studies of the Ellensburg and Ringold Formations now being carried on by M. J. Grolier and R. E. Brown, respectively. The point that is of especial interest here, namely the date of the beginning of arching of the Saddle Mountains structure, does not depend on whether Laval's basalt conglomerate is considered to be Ellensburg; the relations of the Huntzinger flow (see below) on the south limb of the structure west of Sentinel Gap indicate that arching began during Beverly time.

Basalt flows.—The Saddle Mountains Basalt Member and the three lava flows in the Beverly Member (fig. 3) are dense, black, and very fine grained, with rare plagioclase phenocrysts as much as 2 mm. in length. Small round vesicles occur throughout the middle and lower parts of the flows. The flows are particularly characterized by a jointing habit in which the entablature is developed to the complete or almost complete exclusion of the colonnade; the small splintery columns and brickbat jointing differ markedly from the massive columns of the Priest Rapids flows, and make it possible to tentatively identify the flows of this suite from a distance, even in isolated exposures.

As was noted by Laval (1956, p. 55), a flow in the upper part of the Beverly Member on the south flank of Saddle Mountains terminates a short distance east of Sentinel Gap. The end of the flow consists of detached pillows or tongues of basalt, which rest on the basal pumicite layers of bed no. 1 and are overlapped by the upper layers, as if the lake in which the pumicite was deposited had been dammed by the flow (fig. 3, section 4; pl. 8).

A lava tongue which crops out near river level on the east side of the Columbia just downstream from Priest Rapids Dam has been proved by drilling to lie in a channel cut in Beverly sediments about 40 feet above the top of Priest Rapids flow no. 4 (fig. 3, section 1). Prior to construction of the dam the tongue was represented by a lag deposit of huge boulders scattered over the bed of the Columbia at the dam site.

A tongue of basalt, here designated the Huntzinger flow, lies in a channel cut several hundred feet into the Yakima Basalt on the south limb of the Saddle Mountains anticline just west of Sentinel Gap (fig. 3, section 5; pl. 9). The base of the tongue is seen only at its updip end; the gravel of the river that cut the

Plate 9A

Plate 9B

channel, if present, is concealed by talus. The Beverly conglomerate has been entirely removed by erosion, but a litter of quartzite cobbles in the vicinity of the tongue indicates that the conglomerate was probably present when the channel was cut. The tongue trends southward in alignment with the basalt tongue which occupies a channel cut in Beverly sediments at Priest Rapids, and is tentatively correlated with it.

The Yakima East Section

The Ellensburg sequence in the Yakima East quadrangle, described by Waters (1955a), is shown diagrammatically in figure 4. Waters' "sub-Wenas Ellensburg" consists of conglomerate and tuffaceous sandstone 250 ±25 feet thick, with a thin basalt flow near the base. As this stratigraphic unit occurs in places where the Wenas Basalt is not known to be present, an independent name is needed; the term "Selah Formation," applied to it earlier (Mackin, 1947), is here changed to "Selah Member of the Ellensburg Formation." The type locality is on the west side of the Yakima River on the south flank of the Selah anticline (Waters' measured section). The Wenas Basalt is about 100 feet thick at this place. Waters assigns formal stratigraphic names to two other flows in the Ellensburg sequence—the Selah Butte Basalt, about 125 feet above the top of the Wenas Basalt, and the Elephant Mountain Basalt, in the lower part of the Ellensburg in another part of the Yakima East quadrangle.

Plate 9. Huntzinger Flow.

A. Air photograph looking southward down the dip on the south limb of the Saddle Mountains anticline just west of Sentinel Gap. The dark ridge is a composite tongue of basalt, the Huntzinger flow, which fills a valley that was cut in the upper part of the Yakima Basalt during Beverly time. At the up-dip end, in the foreground, the valley was cut entirely through the several flows composing the Priest Rapids Basalt; the first flow, which is continuous beneath the channel, is the Roza Basalt. As seen in B, the surface of the lava tongue near the north end slopes southward about 5° and the dip of the Priest Rapids flows at the same place is 4°; because the surface of the lava tongue is a stripped but little-modified initial surface, and because the original slope of that surface and of the Priest Rapids flows was very low, the difference in dip, about 1°, is an approximate measure of the deformation that preceded the emplacement of the lava tongue.

Differences in width of the surface of the lava tongue express the form of the valley walls, which were generally steep but in some places, as in the middle distance on the right, flared out widely. Continuity of the Roza and older flows in the foreground shows that the dark ridge is a valley fill, not a dike.

The exposed part of the lava tongue is about two miles long. An additional half mile is represented by a narrow rock island that formed a rapids in the Columbia River prior to filling of the Priest Rapids reservoir. Seven miles farther south a tongue of similar lava fills a channel cut in Beverly sediments.

B. View west across the Columbia River. The dark ridge is the Huntzinger flow.

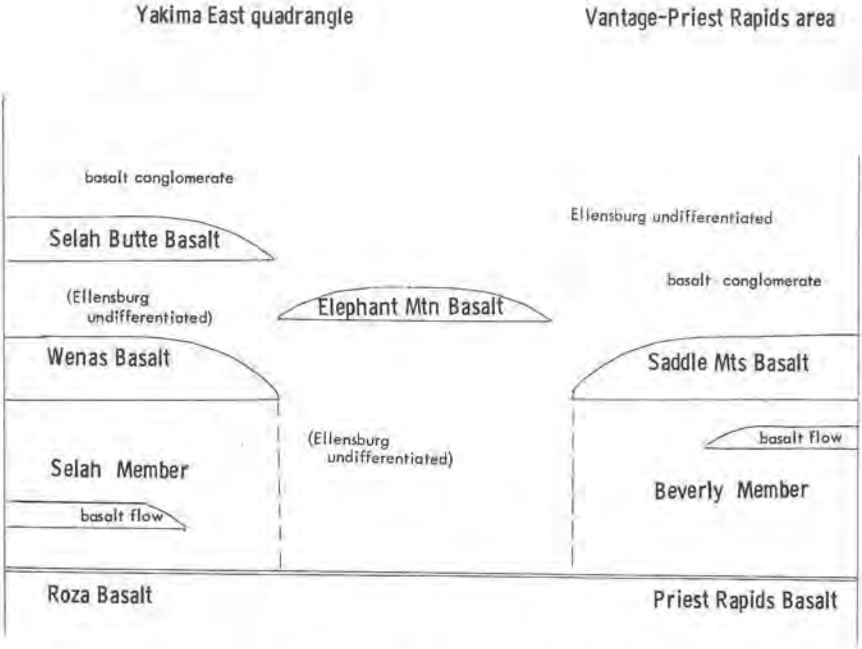

Figure 4.—Stratigraphic sequences in the lower part of the Ellensburg Formation.

Most of the conglomerate beds in the Selah Member at the type locality consist entirely of pebbles of volcanic rocks of Cascade origin, but some beds contain a small proportion of quartzite and plutonic rocks that mark the presence of the ancestral Columbia. The much smaller content of materials from the north than in the deposits of the ancestral Columbia at Sentinel Gap is thought to be due largely to dilution of the bed load of that river by exchange as it shifted about on an alluvial plain that was overspread from time to time by fans of Cascade volcanic detritus. As far as is now known on the basis of pebble counts, none of the fans from the Cascades extended east to the present position of the Columbia in this latitude in Selah time, and none of the shiftings of the Columbia took it west of the present position of the Yakima River between the towns of Ellensburg and Yakima.

Basalt conglomerate that occurs at several places in the post-Selah part of the Ellensburg in the Yakima East quadrangle rests unconformably on earlier sedimentary rocks and basalt, and has been further deformed by continued folding (Waters, 1955a, p. 674-675). The basalt conglomerate layers are interpreted by Waters as veneers on pediments analogous to those now forming on the flanks of the anticlinal ridges. As at Saddle Mountains and elsewhere, the basalt conglomerate affords clear-cut depositional evidence of the degree of advancement of the folding at the time the conglomerate was laid down.

Problems of Correlation

The Yakima East units are arranged in figure 4 on the basis of position above the top of the Yakima Basalt, shown as a horizontal line. Because the top of the Yakima was not horizontal; because the Ellensburg consists chiefly of fluvial sedimentary rocks and lava flows, both apt to vary markedly in thickness from place to place; and especially because of the likelihood of deformation and angular unconformities, the position of the units in the chart is not in any sense an indication of their relative age. The Elephant Mountain Basalt, for example, could be contemporaneous with either the Selah Butte Basalt, the Wenas Basalt, or the basalt flow in the sub-Wenas sediments, or with none of these.

Correlation between the Yakima East area and the Vantage-Priest Rapids area is of course much more uncertain than correlation within either area. Similarity in lithology suggests that a pumicite layer in the Selah Member at the type locality, and at about the same stratigraphic position in other places in the Yakima area (Carithers, 1946, p. 65-68), is the same as bed no. 1 in the Beverly Member, but until it is demonstrated that the layer is in some manner unique, or until it has been walked out between the two areas, the question of correlation must be left open. Although the Saddle Mountains Basalt Member of the Ellensburg Formation is perhaps approximately contemporaneous with the Wenas Basalt, any of the flows in either area may, as far as we now know, be the same as any or none of the flows in the other area. Indeed, though it is considered unlikely and is not taken into account in the nomenclature proposed in this paper, it is at least theoretically possible that one or more of the "Ellensburg" flows in the Yakima East quadrangle could be units of the Priest Rapids Basalt Member of the Yakima Basalt in the Priest Rapids-Vantage area.

The uncertainties make clear the advantage of assigning formal stratigraphic names to individual flows in the Ellensburg, as opposed to use of "Wenas" as a general term for all Ellensburg flows. There is no need for a locality name with this meaning, and continuation of the usage is certain to cause confusion as the physical stratigraphy is worked out in detail on a regional scale. Even though use of "Wenas" in the general sense is accompanied by a statement to the effect that it has no time-stratigraphic significance, one is apt to forget this disclaimer when he stops thinking about rocks and starts thinking about history.

The diagram (fig. 4) illustrates the flexibility of a nomenclature that includes (a) formally named sedimentary and igneous members and (b) members designated by numbers or lithologic terms or both, split off from the Ellensburg as the need arises. These are primarily cartographic units, and on most maps and sections they are necessarily separated from the undifferentiated Ellensburg and from each other, at least locally, by arbitrary cutoffs. They may or may not be time-stratigraphic units, such as a single flow or a pumicite bed formed during a single eruption. They may consist of or include sedimentary rocks of a single depositional type or provenance, as fluvial deposits of northern, Cascade, or local (anticlinal ridge) derivation, but more commonly the boundaries of these lithosomes cross the boundaries of the conventional stratigraphic units (Laval, 1956). These complexities, which are inherent in subaerial sedimentary and volcanic rocks generally, are further complicated in the Ellensburg Formation by contemporaneous deformation.

CHANGING PATTERNS OF SEDIMENTATION AND EROSION

Discussion of geologic history is beyond the scope of this report, but an interpretation of some of the stratigraphic relationships in the Vantage-Priest Rapids-Yakima-Ellensburg area may be useful by way of a summary, and may help to bring out their significance by viewing them in the regional setting. The concepts presented differ in some respects but are mainly extensions of those set forth in the Waters and Laval papers, in which the earlier literature is reviewed. The most important of a number of simplifying assumptions is that the Selah and Beverly Members are correlative.

The beginning of the present drainage is recorded by widespread gravel deposits, containing quartzite and northern plutonic rocks, at the base of the Ellensburg Formation. What may be called the Beverly-Selah alluvial plain of the ancestral Columbia (fig. 1) was the site of deposition of two principal lithosomes, northern and Cascade, both separable into channel deposits and overbank deposits, the latter including sediments formed in flood-plain lakes. This southward-sloping plain, controlled by the main stream, merged on the west with an eastward-sloping plain consisting of Cascade materials. From time to time basalt flows spread over parts of the composite plain as sheets or as fillings of river channels. The ancestral Columbia was locally and temporarily fixed in position in channels cut in low anticlinal ridges of basalt that rose above the plain in some places, but widespread distribution of the quartzite gravel indicates that the river continued to shift laterally during much of Beverly-Selah time, and therefore suggests that the ridges raised by folding were subordinate features, kept buried for the most part by the accumulating sediments.

This regime gave way to one in which growth of the anticlinal ridges so far outstripped the deposition of sediments that the ridges came to dominate the topography. Except for the transverse Columbia and Yakima Rivers, the drainage of the fold-mountain belt came to be consequent on the folding. Deposits of the main rivers are limited to synclinal segments of their valleys, and grade laterally into synclinal deposits consisting chiefly of basalt detritus derived from the neighboring anticlinal ridges. The thickness and rate of sedimentation in each syncline, and whether the deposits were entirely fluvial or partly lacustrine, presumably depended on the local rate of downfolding relative to the local base level determined by the transverse main stream.

Perhaps it is not coincidental that the present position of the Yakima River between Ellensburg and Yakima is the approximate western limit of quartzite and northern plutonic rocks in the Selah conglomerate; this north-south trending segment of the Yakima may have developed as a Yazoo-type consequent near the western margin of the alluvial plain of the ancestral Columbia (fig. 1). This hypothesis provides an explanation for a course that is otherwise anomalous, being at right angles to the generally eastward direction of flow of Cascade rivers of Ellensburg time. According to this hypothesis, the meanders that characterize this segment of the Yakima were inherited from an aggradational plain that existed before the folding, not from a wide valley floor "earned" by lateral cutting of the river after the folding. It does not conflict in any way with the Russell-Smith concept of antecedence; it explains the origin of the course that the river maintained as an antecedent when folds were raised across it.

It is evident from the distribution of the quartzite gravel, as shown by Warren (1941), that the ancestral Columbia flowed southwestward from the area under discussion across the site of the Horse Heaven (anticlinal) Plateau. Waters (1955a, p. 681), however, presents cogent reasons for rejecting the Warren view that the river maintained itself as an antecedent long enough to cut the Satus Pass wind gap in the Horse Heaven uplift, later to be diverted from it as a result of continued growth of the structure; he regards the gap as the result of local stream capture, and holds that the ancestral Columbia was in its present position in Wallula Gap during much or all of later (post-Selah) Ellensburg time. Whether the river was diverted from a more westerly course when the continuity of its Beverly-Selah alluvial plain was first interrupted by arching of the Horse Heaven fold; or whether it was forced eastward by a basalt flow that spread across the plain from the west, or by alluvial fans of Cascade volcanic detritus (Waters, 1955a, p. 680); or whether it merely chanced to be in the approximate position of Wallula Gap when this part of the Horse Heaven fold started up, is not now known. The same alternatives apply to the Yakima River, which for a time might have maintained an independent southwestward course in the western part of the alluvial plain of the ancestral Columbia before being diverted to its present position downstream from Yakima.

Erosional land forms contribute little to an understanding of these problems involving the early evolution of the drainage lines. As indicated above, gaps in anticlinal ridges are not necessarily evidence of the former position of a river unless they can be identified with that river by distinctive deposits. Pattern relationships are merely suggestive; it is likely that the sharp bend of the Columbia to the east around the plunging nose of the Umptanum anticline (fig. 1) represents the deflection of the river caused by the rise of that fold (Calkins, 1905, p. 41); all we can be sure of is that if the river formerly flowed straight south or southwest across the fold it was deflected before it cut a gap still recognizable as such. But a deposit of quartzite gravel at a given place proves that the ancestral Columbia was flowing over that place when the gravel was being deposited, provided, of course, that the gravel is in place, not reworked. Gravel consisting of Cascade volcanic rocks proves the presence of a Cascade river at that place; it shows, moreover, as noted by Waters (1955a, p. 680), that at the time of its deposition the ancestral Columbia could not have been athwart the supply line from the Cascades, but must have been farther east. Basalt gravel testifies to the presence of local streams, probably heading on anticlinal ridges; a lava flow signals the obliteration of all earlier drainage lines; and so on; in short, the evolution of drainage during the period of folding must be worked out primarily on the basis of the lithology of the deposits and the direction of spreading of lava flows.

Deposition of far-traveled as well as local detritus in deepening synclines in the belt of growing folds gave way, in turn, to the predominantly erosional regime of the present. In most of the synclines a dissected pediment suggests that there was a period of stability prior to the present epicycle of incision. The depth of incision varies from place to place, and it is possible that folding has continued to the present time. If so, its effects are superposed on the effects of an eastward regional tilting associated with uplift of the Cascade Range (see below). The record is complicated by the effects of Pleistocene glaciation.

The concept of three regimes: the first chiefly depositional on a broad alluvial plain on which the topographic effects of folding were minor; the second chiefly depositional in synclines of an actively growing fold belt; and the third chiefly erosional during a waning stage of the folding, is helpful in any attempt to grasp the stratigraphic problems of the area. This concept, however, should not be so interpreted as to beg the very questions it is intended to clarify. There are probably large areas in south-central Washington, including parts of the Horse Heaven Plateau, in which the folding began so early that there was no Beverly-Selah alluvial plain. It is likely that some high-standing synclines may have been undergoing erosion throughout the period of active folding; erosion in the eastern part of the Squaw Creek syncline, for example, may have been contemporaneous with deep sedimentation in the nearby Ellensburg synclinal basin. If deposition of the Pleistocene (?) Ringold Formation in the Pasco Basin was caused by uplift of the Horse Heaven axis, as thought by Warren (1941, p. 221) and Newcomb (1958, p. 339), synclinal deposition continued into the time of regional erosion. The suggestion by Brown and McConiga (1960) that Newcomb's lower Ringold is Ellensburg illustrates the sort of nomenclatural problem that is likely to arise as the stratigraphy is worked out.

DEFORMATION

The foregoing discussion emphasizes the effects of folding, and of the spreading of pyroclastic detritus from the west, on the localization of drainage lines and the erosional and depositional activities of the rivers in south-central Washington during the late Cenozoic. Folding, however, is only one of three types of deformation that occurred during that interval; the others are subsidence of the Columbia Plateau and arching of the Cascade Range. Because the Vantage-Priest Rapids-Yakima-Ellensburg area is on the east flank of the Cascades, the eastward plunge of a basalt fold at a given place may be a combined effect of (1) subsidence of the Plateau, (2) uplift of the Range, and (3) plunge genetically associated with the folding. It is not possible by routine study of rock attitudes to determine what fraction of the plunge of the fold should be credited to each of these causes. But it is evident that analysis of any one of the types of deformation depends first of all on a descriptive knowledge of its results, and this in turn requires that its effects be separated from those of the other two. The nature of the problem can be outlined by brief statements of the evidence bearing on the relative timing of the three types of deformation.

Subsidence of the Columbia Plateau

Late in Yakima time the Vantage-Priest Rapids-Yakima-Ellensburg area was the site of large lakes, dammed by the Frenchman Springs and Priest Rapids flows, both of which spread northwestward from a source somewhere to the southeast. The Squaw Creek and Quincy lakes were not at the margin of the lava field, in the normal position of Latah-type lakes dammed by flows advancing against the slope of the older terrane; these diatomite lakes were on the lava field, well back from its margin. Although much remains to be learned, the purity of the diatomite in the lake deposits indicates that conditions of sedimentation in these lakes were wholly different from those in the Latah-type lakes, which received supplies of mud from the area peripheral to the lava field. Moreover, if we may judge by the thickness of the diatomite, the Squaw Creek lake was wedge shaped in section, deepest in the southeast immediately adjacent to the front of the Sentinel Gap flow by which it was impounded. The diatomite rests directly on the unweathered ropy top of the next older Frenchman Springs flow, the surface of which initially must have sloped to the northwest, in the direction of flow. The same statements apply to the Quincy diatomite. The relations indicate that eruption of the Frenchman Springs flows and Priest Rapids flows was accompanied by southeastward tilting.

Sourceward tilting of the Yakima flows was recognized by Russell in 1901 (p. 54) as a distinctive habit of deformation in the Columbia Plateau. Because most of the flows spread radially outward toward the margins of the lava field, and because the center of the field is now several thousand feet below the margins, he suggested that the basining was in some manner genetically related to transfer of an estimated 50,000 to 60,000 cubic miles of basalt from great depth to the surface (see also Waters, in press).

Russell could not have gone much beyond this generalization, because his work was limited to rapid reconnaissance, which necessarily dealt with the basalt as a unit. Starting with the fundamental question of the timing of the deformation relative to emplacement of the flows, every step in the formulation and testing of working hypotheses for the cause of the basining depends on flow-by-flow stratigraphy. Evidently it is critical, for example, to distinguish flows that spread radially outward from the center of the lava field from those that were extruded from vents near the borders of the field (Waters, in press). The tendency of the late Yakima flows in the Vantage-Priest Rapids-Yakima-Ellensburg area to offlap, each being somewhat less extensive than the next earlier, is reasonably explained by contemporaneous basining. Variations of thickness in the individual flows, taken together with estimates of the initial slope of their surfaces, will provide measurements of the deformation that accompanied the eruptive activity. White's (1960) method of measuring the subsidence of the Keweenawan lava field, which depends on estimates of initial slopes of interbedded fluvial sedimentary units, is applicable in the Columbia Plateau, and can be supplemented in some places by use of such relatively sensitive slope indicators as the diatomite beds. Because of the excellence of exposures due to high relief and arid climate, and the absence of an unconformable cover over most of the Plateau, it may be possible to determine the rates and geometry of this particular type of crustal movement more precisely and more completely than in other areas of flood basalts, perhaps excepting Iceland.

Folding

Descriptions by Waters (1955a) and Laval (1956) of numerous examples of the unusual types of folds that characterize the Columbia Plateau bring out how completely the study of the form of these structures depends on flow-by-flow stratigraphy of the basalt.

Maintenance of thickness by interbeds and flows as young as Roza across anticlinal crests (Mackin, 1946) indicates that if any folding occurred during eruption of the Yakima flows it must have begun very late. Because the Priest Rapids flows have been removed by erosion from the axial parts of most of the folds mapped to date, it is not known whether the anticlines of the Vantage-Priest Rapids-Yakima-Ellensburg area started up during Priest Rapids time. Whenever the folding began, the structural and depositional record in the synclines indicates that folding was in progress during Selah time, but was so little advanced that the main rivers were free to shift widely over an alluvial plain that was only locally interrupted by basalt ridges. Basalt conglomerate indicative of high-standing anticlinal ridges first appears in the post-Selah Ellensburg sedimentary rocks of the synclines, and the transverse rivers became fixed in position at that time, maintaining antecedent courses across the actively growing folds. It is possible that the folding is still going on, but at a greatly reduced rate (Waters, in Gilluly, Waters, and Woodford, 1959, p. 119).

Arching of the Cascade Range

Uplift of the Cascade Range has raised the Yakima Basalt into a complex arch with a general north-south trend; the range continues northward through Washington and southward through Oregon far beyond the limits of the basalt, and is clearly a tectonic feature entirely independent of the basining of the lava field. But as indicated above, where the arching and the basining occur together it is not possible by ordinary methods of study of the structure to separate their effects nor to determine their relative dates.

An indirect approach is provided by the fossil floras. Chaney makes the point that the lower Ellensburg (Selah) flora is a humid assemblage, implying that the Cascade Range was so low at that time (late Miocene on the basis of the fossil plants) that it did not intercept the summer rains, whereas (early Pliocene ?) floras higher in the Ellensburg indicate a Cascade barrier high enough to bring a continental climate to eastern Washington (Chaney, 1959, p. 133-134).

It appears, therefore, that (1) folding of the basalt, as indicated by structures and deposits in the synclines, and (2) uplift of the Cascades, as indicated by a climatic change recorded by the floras, occurred at about the same time, and that both are later than all or most of the subsidence that accompanied the eruption of the Yakima Basalt. The testing of these loosely drawn conclusions, and refinement of them in quantitative terms both as regards the timing and magnitude of the movements, depend primarily on (1) the working out of the stratigraphy of the Yakima, Ellensburg, and Ringold Formations on a regional scale, and (2), especially in the late Pliocene and Pleistocene, on interpretation of erosional and depositional land forms.

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