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STRATIGRAPHY AND STRUCTURE OF THE YAKIMA INDIAN RESERVATION, WITH EMPHASIS ON THE COLUMBIA RIVER BASALT GROUP

by

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CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The Yakima Indian Reservation lies in the Columbia Plateau and adjacent part of the Cascade Range in south-central Washington (fig. 1). Most of the reservation is underlain by the rocks of the Columbia Plateau, principally flows of the Miocene Columbia River Basalt Group, with sedimentary interbeds of the Ellensburg Formation locally prominent between flows. The western part of the reservation is extensively covered by Pliocene olivine basalt and other volcanic rocks erupted from numerous cones in and adjacent to the Simcoe Mountains. The northwest corner of the reservation is underlain by older, altered volcanic rocks probably of the Oligocene Ohanapecosh Formation. Quaternary volcanic rocks and glacial deposits cover much of the area west of the Klickitat River. Quaternary sedimentary units flank some of the ridges and occupy most valleys and stream drainages; these deposits indicate a complex Quaternary history, recording effects of river aggradation and incision, landsliding, and the gigantic Spokane (sometimes called Missoula) floods.

The Yakima Indian Reservation is within the Yakima fold belt (Newcomb, 1970, Bentley, 1977a, Hammond, 1979). Three anticlinal uplifts (Horse Heaven-Simcoe, Toppenish, and Ahtanum) cross the reservation and are the dominant structural and topographic features (fig. 2). These anticlinal ridges are 3-5 km wide, trend east to northeast, and generally plunge east. The anticlines are characterized in many places by small thrust faults along their flanks.

The anticlinal ridges separate two 20-23 km-wide synclinal valleys, the Satus basin between the Horse Heaven-Simcoe and Toppenish Ridges and the Toppenish basin between Toppenish and Ahtanum Ridges. Several northwest-trending topographic lineaments cross the two valleys and are interpreted as right lateral strike-slip faults and fracture systems.

PREVIOUS WORK

The Yakima Indian Reservation has received relatively few detailed or comprehensive geologic studies. Russell (1893) was the first to study the region and outlined some major features. Smith (1901, 1903) mapped the area to the north and established much of the regional stratigraphy. Foxworthy's (1962) study of the Ahtanum Valley outlined the geology and groundwater resources along the northern margin of the reservation. Sheppard (1960, 1964, 1967a), mapped part of the Simcoe Mountains volcanic area in the southern part of the reservation. The Cascade Range on the western side of the reservation has recently been studied in reconnaissance (Hammond, 1980; Hammond and others, 1976, 1977). The Grande Ronde Basalt in the Tieton River area north of the reservation, including Darland Mountain at the northwest corner of the reservation, was studied in detail by Swanson (1967, 1978). Relations between the Columbia River Basalt Group and the Ellensburg Formation, and the stratigraphy of the youngest Columbia River basalt flows on the reservation, were outlined by Schmincke (1967a, b, c) and Bentley (1977b). Geologic structure and stratigraphy of the Yakima fold belt along the north margin of the reservation was reported by Bentley (1977a). The regional structural geology of the Yakima fold belt was studied by Newcomb (1971), Waters (1955), Kienle and Newcomb (1973), and Bentley (1977c). The Quaternary geology of the Yakima Valley has been studied by Campbell (1977, 1978). A summary of the geology of the reservation is given by MacLeod and Satkoski (1977). Recently, the geohydrology of parts of the reservation has been discussed by Gregg and Laird (1975), Cline (1976), Molenaar (1976), Mundorff and others (1977), and Pearson (1977).

PRESENT STUDY

This report is the result of approximately five man-months of field work conducted during the spring and summer of 1979. Map compilation and writing of the report were accomplished during the fall and winter of 1979-80. Areas of mapping responsibility are shown on plate 1. Toppenish Ridge between Satus Peak and Hembre Mountain was mapped in more detail (1:24,000) than adjacent areas by traversing most canyons and roads. The rest of the area was covered in reconnaissance by driving along all roads and making foot traverses where needed, supplemented by detailed study in some complex areas. Emphasis was placed on the Columbia River Basalt Group, for the mapping was part of a regional program supported by Interagency Agreement No. EW-78-1-06-1078 with the U.S. Department of Energy to study the feasibility of storing radioactive waste within the basalt beneath the Pasco Basin. Plate 1 is a larger scale version of part of a 1:250,000-scale map of the Columbia River Basalt Group in Washington and northern Idaho (Swanson and others, 1979b). Map units portrayed on plate 1 are briefly described in the appendix and in more detailed fashion in the following text; age relations among the units are shown schematically in figure 3.

Field identification of most units within the Columbia River Basalt Group was based on established physical and paleomagnetic techniques (Swanson and others, 1979a), with more than 200 major element chemical analyses made at Washington State University serving as checks on field identifications. Criteria for distinguishing units in the Columbia

River basalt and in the Quaternary deposits are discussed in the following section on stratigraphy and in separate reports (Swanson and others, 1979a) and Campbell (1977, 1978). The description and distribution of the rocks of the Simcoe Mountains volcanic area are adapted from Sheppard (1960, 1967a), with only brief field checks and limited modification of Sheppard's mapping along the margins of the volcanic area. Some of the geologic units near the western margin of the reservation are simplified and modified from Hammond (1980).

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STRATIGRAPHY

OLIGOCENE VOLCANIC ROCKS

The oldest rocks exposed on the reservation are zeolitized lava flows, tuffs, and volcanic breccias that crop out in the headwaters of the Klickitat River and along Diamond Fork. These rocks are particularly well exposed between Klickitat Meadow and Klickton Divide, along upper Coyote Creek, and along Diamond Fork below Sheep Point. Similar rocks probably underlie much of the unmapped northwestern part of the reservation, such as on Petross Sidehill, based on binocular observations. The exposed section is at least 520 m thick near Coyote Rocks and along Klickton Divide, with base not exposed.

The lava flows are dominantly basalt and andesite, with more silicic rocks present locally. These rock names are assigned on the basis of phenocryst assemblage and overall similarity to probably correlative rocks farther north, where studies are more detailed. Plagioclase, hypersthene, and augite are common phenocrysts, with a wide range in abundance among the flows. The volcanic breccias, most likely of mudflow origin, are composed of lithologies similar to those of the lava flows. The tuffs are fine grained and altered; some of them may be dacitic or rhyolitic, judging from their light colors.

No conclusive evidence regarding the age of these rocks was found. They unconformably underlie the Grande Ronde Basalt, with an age between about 16.5 and 14 m.y. (Swanson and others, 1979a), and are more highly altered than those of the Miocene Fifes Peak Formation in the Tieton River drainage north of the reservation (Swanson, 1966). They are similar in lithology and degree of alteration to rocks of Oligocene age in the Tieton River area (Swanson, 1978). Similar volcanic rocks also occur in the Goat Rocks Wilderness, adjacent to the northwest corner of the reservation, where they were assigned to the Ohanapecosh Formation by Ellingson (1972). Probably correlative rocks are found throughout the southern Cascade Range in Washington, where Hammond (1980) also refers them to the Ohanapecosh. On this basis we tentatively assign the oldest rocks on the reservation to the upper part of the Ohanapecosh Formation, which has been dated by fission-track methods at 31-35 m.y. (Vance and Naeser, 1977), early Oligocene in the time scale of Berggren (1972).

COLUMBIA RIVER BASALT GROUP

All of the Columbia River Basalt Group on the reservation is part of the Yakima Basalt Subgroup, and representatives of all three formations in the subgroup are present -- the Grande Ronde, Wanapum, and Saddle Mountains

Basalts in order of decreasing age (table 1). Swanson and others (1979a, b) provide a regional framework within which the units on the reservation can be understood.

Grande Ronde Basalt

The Grande Ronde Basalt, the oldest and thickest of the formations in the Yakima Basalt Subgroup, is a new name (Swanson and others, 1979a) for what was formerly called lower Yakima basalt (Wright and others, 1973). The Grande Ronde Basalt generally consists of fine grained, black to gray flows with dense interiors and vesicular to scoriaceous upper zones. Locally distinguishable plagioclase-phyric and coarser grained flows are noted below under individual unit descriptions.

The Grande Ronde rests with angular discordance on the Oligocene volcanic rocks in the Narrowneck Pass area. The thickness of the formation there is about 200 m, thinner than in most areas because the flows lap against a hill eroded in the older rocks. The maximum thickness of the Grande Ronde in the reservation is unknown, but extraprolation from surface and subsurface sections in adjacent areas suggests that its thickness does not exceed 1000 m. Thicknesses of 500 to 700 m are exposed in most sections along Toppenish Ridge. Measured sections at Toppenish Peak, Satus Peak, Pinegrass Ridge, and Grayback Mountain are 500 m, 600 m, 400 m, and 700 m respectively, with the base unexposed. Sections exposing the older part of the formation in adjacent areas suggest that the complete thickness is only a few hundred meters more at most. The thickness of the formation probably varies as much as 400 m owing to relief on the irregular erosion surface developed on the Oligocene volcanic rocks.

The Grande Ronde Basalt in the reservation is divided into three magnetostratigraphic units (table 1) on the basis of magnetic polarity, which was determined in the field using a portable fluxgate magnetometer. From oldest to youngest, the units are designated N_1, R_2, and N_2, where N denotes normal and R reversed polarity. These units correlate with similar magnetostratigraphic units mapped regionally by Swanson and others (1979a, b).

N_1 magnetostratigraphic unit--The N_1 unit is exposed in the reservation within the core of the Simcoe Mountains anticline at Grayback Mountain (sec. 24, T. 6 N., R. 13 E.). The unit consists of several flows collectively more than 85 m thick. The flows are fine to medium grained, dense, black basalt and are uniformly shattered and somewhat altered in contrast to overlying R_2 flows. Flows are iron-stained and have a pale green color in even the most recent exposures. Vesicles and fractures are commonly filled with chalcedony, opal, and zeolites. Representative major-element chemical analyses of this unit are given in table 2 (cols. 18-19)

R_2 magnetostratigraphic unit--The R_2 magnetostratigraphic unit is well exposed in the core of the Horse Heaven-Simcoe Ridge at Grayback Mountain, in the Pinegrass Ridge area, in the upper Klickitat River drainage, along the core of Toppenish Ridge at Satus Peak, and in the eastern part of Ahtanum basin. The R_2 unit consists of 3 to 6 basalt flows, each averaging 25 to 30 m thick. The flows are generally fine grained, but several are medium to coarse grained and some contain small plagioclase phenocrysts. Amygdules of chalcedony, opal, and zeolites are common. Most flows are weathered orange-brown and have subdued outcrops relative to the overlying more massive N_2 flows. Thick pillow and hyaloclastite complexes characterize parts of many flows. No lithologically distinctive flows occur in the unit on the reservation. Most flows have three tiers of columns with moderately well developed lower and upper colonnades. Representative chemical analyses are shown in table 2 (cols. 13-17).

N_2 magnetostratigraphic unit--The N_2 unit is the most widespread magnetostratigraphic unit of Grande Ronde Basalt on the reservation. It is well exposed along the core of anticlinal ridges, throughout most of the upper Toppenish basin, and in the upper Klickitat River area (pl. 1). The N_2 unit can be subdivided informally into two subunits on the basis of physical characteristics that appear to correlate with chemical differences (table 2, cols. 1-8 and 9-12). The older of these subunits contains flows of low MgO Grande Ronde chemical type; the younger, flows of high MgO Grande Ronde chemical type (table 2). This chemical division was first reported by Wright and others (1973) and recognized subsequently by Nathan and Fruchter (1974) and many others. In most areas of the Columbia Plateau, this chemical subdivision has no stratigraphic significance; flows of both types are interbedded in complex fashion with each other and with flows of intermediate M_gO compositions. However, in the southwestern part of the Columbia Plateau and farther west, flows of high MgO type systematically overlie flows of low MgO type (Nathan and Fruchter, 1974; Beeson and others, 1976; Anderson, 1978). This happenstance allows the chemistry to be used as a stratigraphic tool within the N_2 magnetostratigraphic unit on the reservation.

The lower subunit, designated $Tgn_2 1$ on plate 1, contains fine to medium grained, aphyric flows that commonly have thick, massive, hackly entablatures. These entablatures are very resistant to erosion and form prominent outcrops useful in distinguishing the low M_gO flows. The subunit varies in thickness from 100 to 250 m and consists of 3 to 5 flows. Several plagioclase-phyric flows at the top of the subunit in the lower Klickitat River and Satus Pass areas are collectively named the flows of Winter Water; they form a distinctive marker unit at the top of the subunit in the southwestern Columbia Plateau (Powell, 1978; R. D. Bentley, unpub data, 1979).

The upper subunit of N_2, designated Tgn_2h on plate 1, consists of fine- to coarse-grained, black to gray flows commonly containing small plagioclase phenocrysts. Flows in the subunit commonly weather orange or reddish-brown, in contrast to flows in underlying subunit Tgn_2l, which weather gray or tan. Most flows are three tiered, with well developed lower and upper colonnades and a commonly tiered entablature. The subunit contains 4 to 8 flows, some of which have ropy upper surfaces. The thickness of most individual flows is less than 30 m; the total thickness of the subunit varies from 200 to 300 m. The section becomes thinner toward the west, probably because of erosional stripping. Thick individual flows along the western margin have thick massive entablatures and can be confused with the underlying Tgn_2l flows. Several flows contain scattered distinctive broken plagioclase phenocrysts 3-10 mm long. These phyric flows characterize the Tgn_2h unit over most of the reservation and the southwestern Columbia Plateau, where they are informally called the basalt of Ortley (R. D. Bentley, unpub. data, 1979).

The N_2 magnetostratigraphic unit was not subdivided in the westernmost part of the reservation. Physical characteristics of the flows in this area are highly variable laterally and vertically, because of interaction of lava with water and sediment, producing pillow basalt and invasive flows. As a result, flows throughout the unit appear similar to one another and different from flows to the east. Thorough chemical sampling would presumably allow subdivision to be made and should be done in future more detailed studies.

Invasive flows--Invasive flows are common in all magnetostratigraphic units along the western margin of the Grande Ronde Basalt, where sedimentary interbeds of the Ellensburg Formation (see later description) are abundant. Invasive flows are lava flows that burrowed into and intruded unconsolidated sediments. Invasive contacts are best determined by relations along the top of an invasive flow. These contacts are characterized by: 1) thin or absent vesicular zones, 2) small dikelets of basalt projecting into the sediments, 3) glassy margins, and 4) irregularly shaped, bulbous, pillowlike bodies in some contact zones. A good example of an invasive flow and intruded sediments occurs at 840 m (2760 ft) elevation just west of Jungle Butte (SW 1/4 NW 1/4 sec. 35, T. 8 N., R. 12 E.). See Byerly and Swanson (1978) and Swanson and Wright (1978) for further discussion of invasive flows.

The Grande Ronde Basalt is overlain locally by the Vantage Member of the Ellensburg Formation or directly by the Frenchman Springs Member of the Wanapum Basalt.

Wanapum Basalt

The Wanapum Basalt conformably overlies the Grande Ronde Basalt and contains at least 9 flows of high TiO_2 chemistry. Wanapum Basalt is a new name (Swanson and others, 1979a) for what was formerly called the middle Yakima basalt (Wright and others, 1973). The formation in general is characterized by variable grain size, common presence of plagioclase and less common olivine phenocrysts, and reddish-brown to orange-brown weathering color. Flows generally show two tier columnar jointing, a lower colonnade with 1-1.5 m-diameter columns making up 60-90 percent of the thickness and a poorly developed entablature or upper colonnade comprising the rest. A sedimentary interbed of the Ellensburg Formation commonly separates the Grande Ronde and Wanapum Basalts, and similar interbeds occur in places between most members of the Wanapum.

The Wanapum Basalt on the reservation is divided into three members, from oldest to youngest the Frenchman Springs, Roza, and Priest Rapids Members. These members are distinguished on the basis of stratigraphic position, relative abundance of plagioclase phenocrysts, magnetic polarity, and chemistry. Flows of four different chemical compositions occur within the formation as follows: Frenchman Springs chemical type (in the Frenchman Springs Member); Roza chemical type (in the Roza Member); and Rosalia and Lolo chemical types (in the Priest Rapids Member) (table 3; Wright and others, 1973; Swanson and Wright, 1978). The Frenchman Springs and Roza chemical types are similar to one another, although averages of a large number of analyses show slight differences (Wright and others, 1973).

Frenchman Springs Member--The Frenchman Springs is the thickest and most widely distributed member of the Wanapum Basalt in the western Columbia Plateau. A maximum number of 6 flows is present at Union Gap, and three or four flows totalling 150-200 m in thickness occur across most of the reservation. The member gradually thins westward, and only two flows occur along the western outcrop margin.

Many of the flows in the member contain plagioclase phenocrysts and glomerocrysts. Formerly some geologists believed that all flows in the member were porphyritic, but recent work has uncovered several flows that contain few if any phenocrysts and hence are called aphyric or sparsely phyric. The phenocrysts are single crystals or, dominantly, glomerocrysts of labradorite in irregular clots up to 3 cm across, averaging 1-1.5 cm. Most are stained with hematite, giving the phenocrysts and glomerocrysts an orange or yellow-orange color. Their abundances range from less than 1 per 10 m^2 (aphyric and sparsely phyric) to more than 50 per m^2 (abundantly phyric).

The Frenchman Springs Member can be informally subdivided on the basis of phenocryst abundance and stratigraphic sequence into four subunits, from oldest to youngest, the flows of Ginkgo, the flow of Sand Hollow, the flow of Kelley Hollow, and the flows of Union Gap (table 1). This terminology is similar to that used in other reports dealing with the southwestern Columbia Plateau (Bentley, 1977a, b; Hammond and others, 1977), except that the Maryhill flow on the lower Columbia River (Hammond and others, 1977) is thought from our mapping to be equivalent to the Kelley Hollow flow in the Yakima area. Plate 1 presents the first attempt at systematic flow by flow mapping in the Frenchman Springs Member over a wide region and for the first time validates many of the regional correlations suggested by Holmgren (1969) and Hammond and others (1977). The subunits of the Frenchman Springs are distinguished by a regular stratigraphic succession consisting of abundantly phyric flows (Ginkgo), overlain by an aphyric flow (Sand Hollow), overlain by a flow having a highly variable abundance of phenocrysts (Kelley Hollow), overlain in turn by a nearly aphyric flow (Union Gap). The Sand Hollow occurs on the reservation only near Union Gap, but otherwise the sequence is continuous across much of the reservation.

This terminology is similar to that used by Mackin (1961) in the Vantage-Priest Rapids area, except that we use the term flows of Union Gap for his Sentinel Gap flow because of uncertainties regarding correlation of the Sentinel Gap flow with the flows of either Kelley Hollow or Union Gap.

We believe it most likely that the Sentinel Gap flow is one of the aphyric flows of Union Gap; if this correlation is eventually demonstrated, the name flows of Union Gap should be discontinued in favor of the prior name flows of Sentinel Gap.

The flows of Ginkgo generally consist of two lithologically similar flows. The unit is about 30 m thick and commonly occurs as a pillow and hyaloclastite complex. It may be confused with the flows of Kelley Hollow where the intervening flow of Sand Hollow is missing or not exposed. The Ginkgo, however, is consistently abundantly phyric, whereas the Kelley Hollow varies laterally and vertically from abundantly phyric to only sparsely phyric. The massive columns at the base of the flow of Kelley Hollow, together with an underlying sedimentary interbed, form a marker over much of the reservation. Two or three thin flows occur in the Union Gap near the type locality but are replaced by a single 65-70 m thick flow over most of the reservation. The thick Union Gap flow commonly is dense, fine to medium grained, dark basalt with a thick hackly entablature. It resembles some flows of the underlying Grande Ronde Basalt and the Elephant Mountain Member of the overlying Saddle Mountains Basalt; in areas of limited exposure and complex structure, chemistry is a welcome aid in distinguishing such flows (tables 2-4). The Union Gap flows are aphyric in most exposures but locally are sparsely phyric.

The thickness of the flows of Kelley Hollow (65 m) and Union Gap (65 m) is consistent over most of the Satus and Toppenish basins and adjacent ridges. These two flows are among the most conspicuous on the Yakima Indian Reservation and together with the overlying Roza Member form a key marker unit across the southwestern Columbia Plateau.

No completely exposed representative section of the Frenchman Springs Member occurs on the reservation, because the flows of Ginkgo are poorly exposed. The most nearly complete section is at Union Gap, where all flows are at least partly exposed. The upper part of this section is faulted, however, and the base of the lower Ginkgo flow is not exposed. The upper part of the section is well displayed in the Elbow of Dry Creek. The lower part is well exposed at Satus Peak but may not be complete, as only one Ginkgo flow is present.

All Frenchman Springs flows have normal magnetic polarity (Rietman, 1966; Farooqui and Heinrichs, 1976), but the flow of Kelley Hollow and upper flow of Ginkgo show a relatively shallow inclination to the south, representing a possible geomagnetic excursion (S. Sheriff and R. D. Bentley, unpub. data, 1978). The Frenchman Springs Member is conformably overlain by the Roza Member, with a thin sedimentary interbed of the Squaw Creek Member of the Ellensburg Formation locally present between the two basalts.

Roza Member--The Roza Member is characterized by abundant plagioclase phenocrysts and transitional magnetic polarity (Rietman, 1966). It is about 25-30 m thick over much of the reservation and generally consists of a single flow, although two flow lobes occur along Logy Creek in the west part of the Satus basin. The lower colonnade is commonly well developed, with columns averaging 1 m across. Pillows are common at the base of the Roza along its western margin, which follows a line from Yakima southwest to Simcoe Mountain. The member is irregularly distributed along Toppenish Ridge and is missing for about 6.5 km (4 mi) east of Toppenish Mountain (secs. 8, 9, 10, T. 9 N., R. 18 E.), suggesting the presence of one or more local topographic highs in this area at the time the Roza was erupted.

The Roza Member is readily distinguished in the field from all other flows on the reservation by its abundance of plagioclase phenocrysts, generally single crystals or small glomerophyric clots. The phenocrysts are more numerous and evenly distributed than in the flows of Ginkgo and Kelley Hollow, single crystals are more common, and glomerophyric clots are smaller, averaging less than 1 cm across. Locally the Ginkgo may be confused with the Roza, but experience and knowledge of the overlying and underlying flows allow confident identification.

The chemical composition of the Roza Member is similar to that of the Frenchman Springs (table 3), although averages of a large number of analyses show slight differences (Swanson and others, 1979a). The transitional magnetic polarity (Rietman, 1966) cannot be detected with reliability under field conditions; generally a weak to moderately strong pseudonormal polarity is obtained owing to the influence of the modern magnetic field. Laboratory measurements of the polarity direction are diagnostic, however.

The member conformably underlies the Priest Rapids Member, with a thin tuffaceous sandstone at the contact locally. Jasperoid pods up to 3 m thick are exposed along the contact on Toppenish Ridge in NE 1/4 sec. 10, T. 9 N., R. 19 E.

Priest Rapids Member--The Priest Rapids Member consists of two reversely magnetized flows across most of the reservation. The member is 50 to 70 m thick where both flows are preserved but less than 30 m near its distal margin, where only one flow is generally present. The western margin of the Priest Rapids approximately coincides with that of the Roza Member on the south side of Toppenish Ridge. The Priest Rapids extends farther north than the Roza, occurring from Ahtanum Ridge northward into the Yakima area.

The two flows in the member are difficult to distinguish from one another in the field. The older flow, of Rosalia chemical type (table 3, cols. 3-5), is generally coarse grained and contains rare plagioclase phenocrysts. The younger flow, of Lolo chemical type (table 3, cols. 1-2), is fine to coarse grained and contains scattered plagioclase phenocrysts 3-10 mm across and olivine phenocrysts 0.5-1 mm across. Phenocrysts are not distinct if the groundmass is coarse but stand out where the groundmass is medium or fine grained, as near the margin of the flow. Olivine phenocrysts are obvious only in fresh samples viewed with a hand lens. The presence of olivine phenocrysts is a guide for distinguishing the upper from the lower flow in areas where the lower flow contains more plagioclase phenocrysts than normal.

The Priest Rapids is distinguished from all other units in the Wanapum Basalt by its reversed magnetic polarity. It can locally be confused with the Pomona Member of the Saddle Mountains Basalt (see below), but careful observation and overall stratigraphic context generally permit firm identification. The chemical compositions within the Priest Rapids are likewise definitive; the Rosalia chemical type superficially resembles the Elephant Mountain chemical type (table 4, cols. 1-2) but contains significantly more P_2O_5.

The upper surface of the Priest Rapids Member is deeply weathered in many places and has jasperoid pods along it, suggesting that a relatively long time interval occurred before emplacement of the overlying Saddle Mountains Basalt. A sedimentary interbed is also commonly present along this contact and is described in the later section on the Ellensburg Formation.

Saddle Mountains Basalt

The Saddle Mountains Basalt is the youngest formation in the Columbia River Basalt Group. It contains ten members (Swanson and others, 1979a), only three of which, from oldest to youngest the Umatilla, Pomona and Elephant Mountain Members, occur on the Yakima Indian Reservation (table 1). Flows of the Saddle Mountains Basalt are chemically and isotopically diverse and were erupted over a long period of time, from about 14 to 6 million years ago during the prolonged final phase of volcanism that produced the group.

Umatilla Member--The Umatilla Member consists of a single normally magnetized flow of fine to rarely medium grain size and essentially aphyric nature. It is generally about 25-30 m thick but locally exceeds 40 m. The western margin of the Umatilla follows a line south from Yakima across Ahtanum Ridge just east of the Wiley City Road, beneath the Toppenish basin east of the Pumphouse Road, to just east of the area known as the Elbow on Dry Creek. From Dry Creek its margin trends south to just east of Satus Pass. The margin of the flow is only approximately located in this central part of plate 1; it may extend for 1 km or more west of the mapped pattern.

The Umatilla is distinguished in the field by its uniform grain size, giving a "smooth" or "even" texture to hand samples. This characteristic holds whether the flow is fine or medium grained. The Umatilla more commonly has a rubbly upper zone, presumably some sort of flow breccia, than do other flows. Nonetheless it is possible in places to confuse the Umatilla with other aphyric flows. For this reason, its distinctive chemical composition (table 4, cols. 5-6), rich in K_2O and P_2O_5 (and BaO, not shown in Table 4), is particularly useful for identification purposes.

The Umatilla is very complex along Logy Creek (Secs. 2-3, T. 9 N., R. 18 E.), where two or more flow lobes apparently fill an ancient valley or canyon eroded into the Priest Rapids Member before eruption of the Umatilla. Pillows are locally present in this area.

The Umatilla is between about 13.5 and 14 m.y. old, on the basis of unpublished K-Ar dates and stratigraphic relations with other dated flows. It is commonly overlain by a thin layer of tuffaceous sedimentary rocks of the Ellensburg Formation capped by the Pomona Member.

Pomona Member--The Pomona Member is a single porphyritic, reversely magnetized basalt flow about 12 m.y. old (McKee and others, 1977). Its thickness is about 50-60 m except near its western margin, where it is less than 30 m. The margin of the Pomona south of Toppenish Ridge lies slightly west of that for the Umatilla Member. North of Toppenish Ridge, the Pomona occurs far west of the Umatilla (pl. 1).

The Pomona displays a rather poorly defined colonnade, with columns about 1 m across, throughout most of the reservation. The entablature is commonly poorly developed, and the lower colonnade grades upward into a crude upper colonnade. Small fanning columns typical of the entablature in the Pomona Member in other areas (Schmincke, 1967a; Bentley, 1977a) are generally absent on the reservation.

The Pomona is fine- to medium grained and contains scattered plagioclase phenocrysts (several per hand sample), generally less than 5 mm across, and fewer small olivine and clinopyroxene phenocrysts. The plagioclase phenocrysts commonly have a sieve texture, containing small inclusions of clinopyroxene and glass that give a "motheaten" appearance to the phenocrysts when viewed with a hand lens. The plagioclase phenocrysts commonly have wedge or triangular shapes. These phenocryst characteristics alone usually suffice for identification, and with other criteria, such as its reversed magnetic polarity (Rietman, 1966; Choiniere and Swanson, 1979) and distinctive chemical composition (table 4, cols. 3-4), provide an unusually firm basis for correlation purposes.

In the Wiley City Pass area, the Pomona Member forms a thick complex flow interpreted as filling an ancient canyon of the Columbia River, which presumably crossed the Toppenish and Ahtanum Valleys at the time the Pomona was erupted. The member also occurs in a paleocanyon nearly 1 km wide and at least 120 m deep eroded into the Frenchman Springs Member on the north side of Grayback Mountain; the Pomona is at least 50 m thick at this locality.

A layer of fused tuff up to 20 cm thick (Schmincke, 1967b) commonly marks the contact of the Pomona with the underlying Selah Member of the Ellensburg Formation. This thin, black or gray glassy layer, formed by heating of the tuff by the Pomona, commonly overlies the reddish brown oxidized zone of the Umatilla Member. Together, this colorful doublet forms a distinctive marker unit over much of the western part of the reservation, and the lithologies are readily identified in the subsurface from well cuttings over much of the Toppenish and Satus basins and in the Horse Heaven Hills.

The Pomona Member is overlain by a thick sequence of tuffaceous sedimentary rocks assigned to the Rattlesnake Ridge Member of the Ellensburg Formation.

Elephant Mountain Member--The Elephant Mountain Member within the reservation consists of a single flow of fine-grained, nearly aphyric basalt generally less than 15 m thick. The member is the uppermost flow of the Columbia River Basalt Group in the area, capping most small mesas and buttes in Satus basin. Its western margin in Satus basin is along an approximately north-south line through Alkali Spring. The margin of the member extends northeast across the the Toppenish basin, based on subsurface information. The Elephant Mountain overlies a 20 m-thick interbed resting on the Pomona Member in a north-south-trending canyon of the ancestral Columbia River on the north side of Grayback Mountain.

The Elephant Mountain Member is characterized by a relatively short colonnade with many vesicle sheets. Plagioclase phenocrysts 2-3 mm long are rare. Its chemical composition is marked by high FeO and TiO_2 and is distinguished from the Rosalia chemical type by lower P_2O_5 (table 4, cols. 1-2). The Elephant Mountain is magnetized in a normal direction with a lower inclination than most other flows in the Columbia River Basalt Group (Rietman, 1966; Choiniere and Swanson, 1979).

ELLENSBURG FORMATION

The Ellensburg Formation as used in this report includes all sedimentary rocks conformably underlying, interbedded with, and conformably overlying the Columbia River Basalt Group in the western part of the Columbia Plateau. This usage is consistent with that of Bentley (1977a, b), Waitt (1979), and Swanson and others (1979a) and represents an extension of the Ellensburg as first used by Smith (1901). We informally subdivide the Ellensburg Formation into three units, the lower, middle, and upper parts of the Ellensburg, for convenience of discussion. None of the units is distinctive lithologically; all must be defined and further subdivided according to their relations to overlying and underlying units of the Columbia River Basalt Group.

Lower Part of the Ellensburg Formation

The lower part of the Ellensburg Formation includes all sedimentary units interlayered with and conformably underlying the Grande Ronde

Basalt. It is composed of thin volcaniclastic sandstone, siltstone, claystone and locally pumiceous volcanic breccia. The sandstone is composed of quartz, feldspar, and volcanic rock fragments with some muscovite, biotite, and hornblende. Grain size is 1-4 mm. Rounded pebbles of pumice 4-10 cm are common in some beds. Small pebbles of volcanic rocks up to 2 cm in diameter occur rarely in the coarse sandstones. Hyaloclastic units composed of palagonite and sideromelane fragments up to 2 cm in diameter are derived from basalt flows that entered water and were rapidly quenched. Torrential crossbedding is common in many of the coarse-grained sandstones and hyaloclastites.

The sedimentary rocks below and interbedded with the Grande Ronde Basalt were not mapped separately, because they form deposits that are too thin--generally less than 15 m -to show at the scale of plate 1. They occur at many stratigraphic levels in the Grande Ronde. Some of the best exposures of interbeds are along Satus Creek (SW 1/4 sec. 33, T. 7 N., R. 18 E.), Simcoe Creek (NW 1/4 sec. 12, T. 11 N., R. 15 E.), and at the 1055 m (3460 ft) elevation along the Howard Lake Road (sec. 9, T. 10 N., R. 13 E.). Interbeds separating the high and low MgO flows and the N_2-R_2 magnetostratigraphic units, and beds within the R_2 unit, may be extensive enough to be significant groundwater aquifers; more detailed mapping of these interbeds is therefore desirable. Sedimentary interbeds are more abundant near the western margin of the basalt and decrease in abundance and thickness to the east. Single interbeds are locally variable in thickness, laterally discontinuous, and unreliable as stratigraphic markers. Many invasive flows occur within and locally crosscut some of the interbeds. Landslides are common along contacts of basalt and underlying sedimentary interbeds.

Hyaloclastite units are most common in the Klickitat River basin and upper Toppenish Creek-Ahtanum Ridge areas. They are commonly associated with pillowed basalt flows. A particularly good example of hyaloclastite and pillows occurs at 2010 m (6600 ft) elevation east of Coyote Creek (east 1/2 sec. 28, T. 12 N., R. 13 E.).

Detritus in the lower part of the Ellensburg Formation has three recognizable sources, judging from our observations and heavy mineral studies by Schmincke (1967c) and Swanson (1967) in nearby areas. The volcaniclastic material is fresh and records contemporaneous volcanic activity in the Cascade Range. The mica, quartz, and many heavy minerals were derived from highlands far north of the reservation (near and north of Wenatchee) and carried into the area by a south-flowing ancestral Columbia River. The rest of the detritus was derived from erosion of older volcanic rocks, such as those in the Ohanapecosh Formation and older parts of the Grande Ronde Basalt.

Middle part of the Ellensburg Formation

The middle part of the Ellensburg Formation is used informally here for all sedimentary deposits interbedded with the Wanapum Basalt, including the previously named Vantage and Squaw Creek Members as well as unnamed units between the various Wanapum flows. These interbeds are similar lithologically and genetically to those of the lower part of the Ellensburg Formation, with coarse volcaniclastic sandstone, siltstone, and claystone being the dominant rock types. Thin layers of diatomite and conglomerate occur in the Vantage Member and interbeds between flows of the Frenchman Springs Member. None of these interbeds is thick or continuous across the reservation, and none is shown on plate 1.

The Vantage Member varies in thickness form 0 to 10 m and is probably the most extensive unit in the middle part of the Ellensburg on the reservation. It is best exposed along the Mount Adams Highway (sec. 31, T. 10 N., R. 17 E.) and is marked by a continuous spring line along Toppenish

Ridge.

Two unnamed sedimentary units similar lithologically to the Vantage Member occur below and above the flow of Kelley Hollow. These sedimentary layers vary in thickness from 0 to 4 m and are commonly exposed in canyons in upper Satus basin and along the north side of Toppenish Ridge.

The Squaw Creek Member is a thin (0-10 m) sedimentary layer between the Frenchman Springs and Roza Members. It forms the most prominent spring line in the southern part of Satus basin along Satus Creek. The unit occurs as a thick, coarse-grained volcanic sandstone in a roadcut on Cemetary Road (sec. 34, T. 8 N., R. 18 E.). Along Logy Creek (sec. 2, T. 8 N., R. 18 E.) a 7 m-thick basaltic conglomerate with cobbles ranging up to 15 cm in diameter is exposed below the Roza Member. The pebbles are composed of Grande Ronde Basalt and were deposited by an east-flowing stream, as shown by imbrication directions measured at three exposures.

Near Toppenish Ridge, pods of jasperoid up to 3 m thick occur below and locally above the Roza Member. These pods may represent an altered diatomite or bog layer that formed in a shallow lake into which the Roza advanced. The jasperoid is fine grained and contains numerous fragments of petrified wood. No definite evidence for invasion of the Roza into the sediment was found; the upper contact, however, lacks a vesicular zone.

A thin, buff or white, silicic tuff occurs locally between the Roza and Priest Rapids Members. It is well exposed in a gully in the Horse Heaven Hills in the extreme northeast corner of sec. 1, T. 7 N., R. 21 E, where it is about 30 cm thick. A thin diatomite layer is exposed along Logy Creek (sec. 3, T. 8 N., R 18 E.) at this level.

Sedimentary deposits between the two flows of the Priest Rapids Member are rare. A 30 cm-thick tuff is exposed in the same gully in the Horse Heaven Hills mentioned in the preceeding paragraph.

Upper part of the Ellensburg Formation

The upper part of the Ellensburg Formation includes all sedimentary rocks conformably interlayered with and overlying the Saddle Mountains Basalt. Sedimentary rocks between the Saddle Mountains and the youngest pre-Saddle Mountains flow are included in the upper part of the Ellensburg. The youngest pre-Saddle Mountains flow may belong to either the Wanapum or Grande Ronde Basalt. On the reservation, the youngest such flow is most commonly in the Priest Rapids Member, but in parts of Toppenish basin the upper part of the Ellensburg rests on the Frenchman Springs Member. In places the Saddle Mountains Basalt is missing and only sedimentary rocks occur above the older basalt; such deposits are also included in the upper part of the Ellensburg Formation.

The upper contact is arbitrarily defined as the top of the uppermost conformable deposit containing volcaniclastic detritus, chiefly pumice pebbles. The upper contact may be an angular unconformity near the anticlinal ridges, with basaltic pebble conglomerate the dominate rock type above the unconformity. Some of these basaltic conglomerates grade laterally into volcaniclastic rocks, however, and so are considered to be in the upper part of the Ellensburg Formation. The upper part of the Ellensburg in Toppenish basin probably contains such facies changes associated with local angular unconformities adjacent to Toppenish and Ahtanum Ridges.

The lithologic variety within the upper part of the Ellensburg is great, including andesitic, basaltic, and quartzitic conglomerate; non-sorted massive deposits interpreted as formed by lahars (volcanic mudflows); volcaniclastic sandstone and siltstone; water-laid tuff; and air fall tuff of silt to clay grain size. Most rocks are weakly consolidated, but caliche cementation locally forms resistant units. The laharic deposits are commonly more strongly indurated than the other rocks. Crossbedding, channels, imbricated gravel, and graded bedding are common. All directional structures indicate east- to southeast-flowing streams in the western part of the reservation and south- to southwest-flowing streams in the eastern part.

The upper part of the Ellensburg Formation crops out in two broad areas on the reservation. In Satus basin, the unit is interbedded with and overlies the Saddle Mountains Basalt. In Toppenish basin, most of the unit overlies the Pomona Member.

The upper part of the Ellensburg is subdivided into four informal units, from oldest to youngest the Mabton Bed, Selah Member, and Rattlesnake Ridge Member, all of Schmincke (1967a), and the conglomerate of Snipes Mountain. Those deposits that cannot be assigned to one of these units are placed in a lump unit, the upper part of the Ellensburg Formation undivided.

Mabton Bed of Schmincke (1967a)- The Mabton includes all sedimentary deposits between the Umatilla Member of the Saddle Mountains Basalt and the next older basalt flow. The Mabton is less than 1 m thick across much of the Satus and Toppenish basins but thickens eastward to a local maximum of 10 m in southeastern Satus basin and adjacent Horse Heaven Hills. The Mabton consists of coarse to fine volcaniclastic deposits and airfall tuff.

Selah Member of Schmincke (1967a)--The Selah contains all sedimentary deposits between the Pomona Member and the next underlying basalt flow. Over much of the reservation it includes sedimentary rocks between the Pomona Member and underlying Umatilla Member. Beyond the extent of the

Umatilla Member in the western Toppenish basin and adjacent Toppenish and Ahtanum Ridges, the Selah includes all sedimentary deposits between the Pomona and the underlying Priest Rapids or Frenchman Springs Members.

The Selah consists dominantly of an airfall vitric tuff over most of the area. The tuff is as much as 1 m thick, consists of nearly pure vitric ash, and contains scattered accretionary lapilli. In places, such as in sec. 2, T. 7 N., R. 20 E., as much as 2 m of coarse volcaniclastic sandstone and claystone underlie the tuff. The Selah likely contains lahars and volcanic conglomerate in the subsurface in the western part of the reservation. Quartzite pebble conglomerate 10-15 m thick occurs in the Selah just west of the Wiley City Road (sec. 25, T. 12 N., R. 18 E.); the conglomerate rests on the Priest Rapids Member and may be the age equivalent of either the Selah or the Mabton Bed.

Contact relations of the airfall tuff in the Selah with the Pomona Member are commonly complex. In many places, the tuff is fused to a gray or black glass at the base of the Pomona (Schmincke, 1967b). In some other places, the Pomona is mixed chaotically with the tuff, forming a peperite (Schmincke, 1967b). The peperite contains irregularly shaped fragments of basalt, generally with glassy rims and vesicular cores, mixed with pods of fused or non-fused tuff. Such peperites are as thick as 50 m and apparently formed in places where the tuff was thicker than several meters (Schmincke, 1967b).

Rattlesnake Ridge Member of Schmincke (1967a)--The Rattlesnake Ridge, shown separately in plate 1 as unit Tser, includes all sedimentary rocks between the Pomona and Elephant Mountain Members. It thickens from 20 m to 200 m northeastward across the Satus and Toppenish basins.

The unit is dominantly cream to buff colored tuffaceous siltstone and claystone. Thin layers of quartzite conglomerate are interlayered with the tuffaceous rocks in the eastern part of the reservation, and similar conglomerate occurs within a 20 m-thick sequence of micaceous and tuffaceous sandstone in a canyon of the ancestral Columbia River on the north side of Grayback Mountain.

The Rattlesnake Ridge loses its identity beyond the western margin of the Elephant Mountain Member, but we believe it likely that many of the older volcanic conglomerates, lahars, and coarse volcanic sandstones in the upper part of the Ellensburg Formation undivided are of equivalent age to the Rattlesnake Ridge. Many of these lithologies may intertongue with the tuff of the Rattlesnake Ridge in the subsurface of the Toppenish basin. These coarse units may represent deposits of the ancient Naches-Yakima River system, which probably crossed the northeast corner of the reservation at the time that the Rattlesnake Ridge was being deposited. The tuffs, siltstones, and claystones may represent floodplain deposits of the ancestral Columbia River, and the quartzite conglomerate the mainstream deposit.

Conglomerate of Snipes Mountain--This unit, shown as unit Tss on plate 1, includes the sedimentary deposits conformably overlying the Elephant Mountain Member. The top of the unit is bounded by an angular unconformity in many places near uplifted ridges, with Pliocene or Quaternary basaltic gravels overlying the steeply dipping Snipes Mountain. The thickness of the conglomerate of Snipes Mountain is irregular because of erosional stripping, ranging from thin lag deposits to as much as 200 m in the eastern part of Toppenish and Satus basins.

The conglomerate of Snipes Mountain is particularly well exposed in gravel pits along the Mabton Road in sec. 13, T. 8 N., R. 21 E. and sec. 18, T. 8 N., R. 22 E. The unit is characterized by yellow, buff, and reddish-tan quartzite pebble conglomerate interbedded with tan, cream, and buff colored tuff, siltstone, claystone, and fine grained sandstone. The conglomerates are commonly imbricated and contain lenses of crossbedded sandstone. Channel-fill deposits are common, and airfall tuff and rare laharic deposits occur locally. The conglomerate units are interpreted as mainstream deposits of an ancestral Columbia River, with the other rock types representing floodplain and tributary facies. The Snipes Mountain records evidence of the latest known course of the ancestral Columbia River across the reservation.

Upper part of the Ellensburg Formation undivided--This unit includes the upper part of the Ellensburg in those areas where the Saddle Mountains Basalt is missing. It overlies the Wanapum or Grande Ronde Basalts conformably and unconformably underlies Pliocene and Quaternary rocks. This unit is exposed in many scattered outcrops in the western Toppenish basin and along adjacent parts of Ahtanum and Toppenish Ridges; the best section is in sec. 34, T. 10 N., R. 18 E. The unit consists of volcaniclastic conglomerate, sandstone, laharic deposits, siltstone, and tuff. Basaltic conglomerate is interbedded in the upper part of the unit along Toppenish and Ahtanum Ridges. Airfall tuff occurs rarely in the upper part of the section. Almost all of this unit is thought to be younger than the Pomona Member, and most of it may be the age equivalent of the conglomerate of Snipes Mountain. Thicknesses of 200 to 400 m are suggested by subsurface data in the Toppenish basin.

The upper part of the Ellensburg Formation undivided is probably largely equivalent to the Naches section of the Ellensburg described in Smith (1903). It is the southern part of the main volcaniclastic wedge that covered much of the western Toppenish basin and Ahtanum and Selah-Wenas Valleys and intervening areas. As the ridges were uplifted during the late Miocene and Pliocene, local sidestream basaltic gravels interfingered with volcaniclastic debris deposited by the ancestral Naches-Yakima River system, which joined the ancestral Columbia in central Toppenish basin.

Most of map unit Tse (pl. 1) corresponds to the upper part of the Ellensburg Formation undivided.

OLIVINE BASALT AND ASSOCIATED ROCKS OF THE SIMCOE MOUNTAINS VOLCANIC AREA

Lava flows younger than the Columbia River Basalt Group and older than the Quaternary basalt and andesite of the Cascade Range were erupted from numerous vents, mostly east of the Klickitat River. Sheppard (1967a) called this area, which lies partly within the Yakima Indian Reservation and extends south to Goldendale, the Simcoe Mountains volcanic area. Rocks in this area have no formal name; terms such as Simcoe volcanics (Sheppard, 1960) and Simcoe lavas (Newcomb, 1967) have sometimes been used. Readers should see Sheppard's (1967a) map for the best available distribution and petrographic description of these units.

The Simcoe volcanics, shown as unit QTb in plate 1, are dominantly olivine basalt, with small volumes of andesite, dacite, and rhyolite (Sheppard, 1960, 1967a). Chemical analyses in table 5 are probably representative of the basalt; no analyses are available for the more silicic rocks.

The basalt flows are 1-12 m thick, poorly columnar, gray and commonly diktytaxitic. Olivine phenocrysts in many flows have rims and zones altered to iridescent iddingsite. A few flows (table 5, col. 6) are rather alkalic, as noted by Sheppard (1960).

The Simcoe volcanics was erupted from many vents, locations for some of which are shown in plate 1. Most of the vents are marked by cones as high as 100 m composed of cinder, agglutinate, and thin flows. Sheppard (1967a) noted that some vents south of the reservation are located along narrow, northwest-trending zones. Similar alignments may be reflected by the series of cones between Indian Rock and Simon Butte, Castle Rock and a cone in sec. 10, T. 8 N., R. 15 E., Hagerty Butte through Poland Butte onto the Lincoln Plateau (sec. 27, T. 10 N., R. 13 E.), and possibly others. These alignments suggest control by northwest-trending fracture or fault zones, such as those described in the section on structural geology. In addition, vents are markedly concentrated in a north-trending belt from Kaiser Butte to Simon Butte.

Andesite occurs in the unit at Signal Peak, a steep-sided cone composed of flows and tephra. The andesite is dark gray and locally flowbanded. A poorly exposed flow of dacite occurs near the site of Satus Ranger Station (sec. 2 and 3, T. 6 N., R. 16 E.). Rhyolite flows occur locally in the headwaters of Kusshi Creek and along the crest of the Simcoe Mountains east-northeast of Indian Rock.

Pumice lapilli tuff of dacitic or more silicic composition, possibly an ashflow or laharic deposit, is interbedded with olivine basalt along the Tomiith Road (SE 1/4 SW 1/4 sec. 4, T. 6 N. R. 18 E); similar material, together with crossbedded pumiceous tuff, crops out below an intracanyon flow of olivine basalt along Satus Creek in secs. 28 and 33, T. 7 N, R. 18 E.

A pink, columnar jointed, weakly to moderately welded ashflow tuff overlies olivine basalt along the Howard Lake Road east of McCreedy Creek (secs. 17-20, T. 10 N., R. 13 E.), and a similar tuff crops out along the Piscoe Road in the SE 1/4 sec. 2, T. 10 N., R. 13 E. Relations near McCreedy Creek suggest that the tuff is interbedded with the olivine basalt. The tuff contains numerous quartz and feldspar phenocrysts and is probably of dacitic or more silicic composition. No attempt was made to map the tuff separately, but future studies might find it to be a valuable marker unit.

Several olivine basalt flows north and west of the Simcoe volcanics proper are included in map unit QTb. A normally magnetized diktytaxitic flow caps the ridge north of Diamond Lake, and reversely magnetized olivine-phyric flows occur along Diamond Fork and upslope to the head of Cultus Hole. An eroded vent near Cultus Hole lies 40-50 m lower than the highest remnant of the flow it fed (table 5, col. 2), suggesting later tilting during uplift of the Sedge Ridge anticline.

The olivine basalt flow capping Fairview Ridge has reversed magnetic polarity. It overlies coarse river gravel resting on weathered and eroded rocks of the Ohanapecosh Formation at 1575 m (5160 ft) elevation due south of Butte Meadows in SE 1/4 NW 1/4 sec. 18, T. 11 N., R. 13 E. We speculate that this gravel occupies the former course of the Klickitat River during an early stage in the geomorphic history of the area.

A hornblende dacite(?) is exposed along the Mount Adams Lake Road between elevations of 1070 and 1100 m (3500-3600 ft) in sec. 34, T. 9 N., R. 12 E. and sec. 4, T. 8 N., R. 12 E. The dacite(?), in fault contact with the Grande Ronde Basalt, may be either an extrusive or intrusive body. It is included in unit QTb purely for convenience, for its age is unknown.

Three small patches of undated olivine basalt and andesite south of Quigley Buttte are assigned to unit QTb, following Sheppard (1964). They lie along an extension of the King Mountain fissure zone (Hammond and others, 1976) and may be related to it.

The age of the Simcoe volcanics is poorly defined. At least one flow of olivine basalt partly fills a canyon eroded through the Pomona and probably Elephant Mountain Members along presentday Satus Creek; this old canyon was at least 300 m (1000 ft) deep. Such incision suggests a prolonged period of time between eruption of the Saddle Mountains Basalt and the Simcoe volcanics. Basalt and andesite flows from Mount Adams occupy the Klickitat River canyon eroded into the Simcoe and are of Quaternary age (Hammond, 1980). Many of the Simcoe flows have reversed magnetic polarity, suggesting an age of more than 730,000 yrs (Mankinen and Dalrymple, 1979). Available K-Ar ages of the Simcoe volcanics range from about 900,000 yrs to 4.5 m.y. (Kienle and Newcomb, 1973). Thus the Simcoe is most likely of Pliocene and early Pleistocene age, using the time scale of Berggren and Van Couvering (1974).

OLDER GRAVEL DEPOSITS

Extensive deposits of basaltic gravel occur in the Medicine Valley area, along the north flanks of Toppenish and Ahtanum Ridges, and in old alluvial fans adjacent to the Horse Heaven Hills. The thickness of the gravel, shown as unit QTg on plate 1, is less than 200 m in most areas. The contact between the gravel and younger sedimentary deposits of unit Qs in Medicine Valley and on the north flank of Toppenish Ridge (pl. 1) is poorly defined and probably gradational. The gravel overlies the Ellensburg Formation and Columbia River Basalt Group. In most areas flanking the ridges, basaltic gravel rests with angular discordance on underlying rocks, but in the basins the gravel is generally conformable with the older rocks. The gravel consists predominately of subangular to well-rounded pebbles and cobbles derived from the Columbia River Basalt Group Silt with scattered sand-sized clasts fills interstices; coarse-grained crossbedded sandstone is commonly interlayered with the gravel. The lithology, layering, and sedimentary structures all indicate a fluvial origin, although some loess is mixed with the gravel in places.

With more detailed study, the basaltic gravel can possibly be divided into three units on the basis of geomorphic expression, degree of deformation, and thickness of weathering rinds on clasts, which vary from 1 mm to 2 cm. Clasts in the oldest unit, which dips at angles commonly greater than 10 degrees, apparently have thicker weathering rinds and generally are well rounded. The intermediate unit has clasts with weathering rinds up to 5 mm, commonly contains layers of subangular to subrounded pebbles, and dips at angles less than 10 degrees. The youngest unit is confined to floodplains of late Quaternary streams and contains a wide assortment of subangular to well-rounded pebbles; many of these pebbles were derived from the older gravel and retain thick weathering rinds, although most are less than 5 mm wide.

Basaltic gravel on the reservation is equivalent to the Cowiche gravel of Smith (1903; Foxworthy, 1962) and may in part be the age equivalent of the Thorp Gravel in Kittitas Valley (Waitt, 1979). The gravel contains caliche layers, dates from which suggest ages between 10 m.y. and 100,000 yrs old (N. P. Campbell, unpub. data, 1979). Further study of the gravel and its relation to older units is critical to unraveling the tectonic history of the reservation.

BASALT AND ANDESITE

Young flows of olivine basalt and olivine andesite cover much of the reservation west of the Klickitat River. These flows were erupted from vents on and near Mount Adams, including those in the King Mountain fissure zone extending through King Mountain southward to Quigley Butte (Hammond and others, 1976). Some of the flows entered and followed the old course of the Klickitat River; the river has subsequently eroded spectacular narrow gorges into and in places through this fill.

Both the basalt and andesite generally are gray and contain olivine phenocrysts; many flows carry plagioclase phenocrysts. Diktytaxitic texture is common. Flows of both basalt and andesite are generally thinner than 10 m and poorly columnar; canyon-filling flows are thicker, as much as 40-50 m, and commonly display complex columnar jointing. The basalt is generally coarser-grained than the andesite but otherwise is nearly indistinguishable without a chemical analysis (Sheppard, 1960, 1967b).

No attempt was made to subdivide the unit. Interested readers should consult the publications of Hammond and others (1976), Hammond (1980), and Sheppard (1960, 1964, 1967a, b) for such subdivisions.

All of the flows tested have normal magnetic polarity and hence are younger than about 730,000 yrs (Mankinen and Dalrymple, 1979). Many flows are younger than 100,000 yrs on the basis of radiocarbon dates and stratigraphic relations to dated glacial deposits (Hammond, 1980). Camas Prairie is underlain by a basalt flow, mostly covered by younger sediments, that is in the age range of 30,000 to 300,000 yrs as determined by analytically poor K-Ar dates (Kienle and Newcomb, 1973).

SLACK-WATER SEDIMENTS OF CATASTROPHIC FLOODS

Rhythmically bedded, vertically graded deposits of unconsolidated clay, silt, and sand occur below 335 m (1100 ft) elevation in Satus and Toppenish basins. The sediments belong to the Touchet beds of Flint (1938), which are interpreted to be deposits of catastrophic floods (Spokane or Missoula floods) that repeatedly innundated lower valleys of the area in late Quaternary time (Waitt, 1979; Campbell, 1977, 1978).

The sediments are chiefly light gray to white silt, with lenses of clay and sand. The deposits contain as many as several hundred beds with a total maximum thickness of 10 m. In Toppenish and Satus basins, the Touchet beds are well displayed up to 330 m (1,080 ft) but thin and indistinct between 330 m and 350 m (1,080 ft and 1,150 ft). The deposits are cut by many clastic dikes of silt and clay.

The Touchet contains numerous blocks of metamorphic and plutonic rocks carried into the area as ice-rafted erratics by the flood waters. These erratics commonly occur in mounds up to 5 m in diameter and a few meters high. Individual mounds contain as many as 20 angular clasts, which are rarely more than 1 m in maximum dimension. Erratics are abundant up to 350 m (1,150 ft) elevation and in a few areas occur up to 365 m (1,200 ft).

A doublet layer of Mount St. Helens tephra forms two thin beds up to a few centimeters thick in the upper 5 m of the Touchet deposits. The tephra, exposed at numerous localities in Toppenish basin (Campbell, 1978), is tentatively identified as that of set S (Crandell and Mullineaux, 1973), which has a radiometric age of about 13,000 yrs (Mullineaux and others, 1977). The age of the youngest Touchet beds is therefore somewhat less than 13,000 yrs. The lower part of the Touchet is not known but could be as old as 100,000 yrs, if the deposit records the passage of many floods (Waitt, 1979) rather than a single flood as previously believed (see article by Carson and others, 1978, for brief summary of the one-flood hypothesis).

The Touchet beds on the reservation are dissected by recent streams, overlain by less than 1 m of loess, and cut by ground ruptures along the lower flank of Toppenish Ridge (see later description of Toppenish uplift).

LOESS

Thin deposits of loess occur over much of the Yakima Indian Reservation. This unit was not mapped (pl. 1) except in Toppenish and lower Satus basin but is common in small patches less than 3 m thick in most of the area. It is the uppermost unit over much of the area and where thicker than 1 m may form tillable soils; it is missing only in the most recent flood plains and alluvial fans. In many deposits, it is interlayered with alluvium and colluvium. The loess locally contains lenses of tephra probably derived from eruptions of Mount St. Helens, Mount Mazama, and other Cascade volcanos in late Quaternary time. Most of the loess is unconsolidated, but some is weakly indurated where interlayered in older colluvial and alluvial deposits. The indurated loess is an older unit probably equivalent to the Palouse Formation in the central Columbia Plateau. Most of the loess is less than 100,000 years old, and much is less than 10,000 years old, based on a few ^{14}C ages and tentative identification of interlayered tephra units (N. P. Campbell, unpub. data, 1979).

LANDSLIDE DEPOSITS

Landslide deposits composed of chaotic, unstratified and unsorted material, occur locally along the flanks of ridges on the reservation. The material in most of the landslides is derived from the Columbia River Basalt Group, with minor components from the Ellensburg Formation and older gravel. Younger olivine basalt has contributed to slide deposits on Fairview Ridge and Borde Flat.

The landslides include both slumps and debris flows. The largest landslides occur on the north side of Toppenish Ridge and the Horse Heaven Hills. Many small slides occur along other ridges, where slopes are greater than 30 degrees. Plate 1 shows the extent of most larger slides, but many older and smaller slides were not mapped, especially on Ahtanum Ridge and in the western part of the Toppenish basin. Loess commonly mantles the deposits, and alluvium obscures some of the older slide deposits. Hummocky surfaces are common on the younger slides.

The landslides range in age from early Quaternary to historic.

Those slides near Olney Lake and Granger are probably less than 1,000 years old and may still be active. Large landslides along Toppenish Ridge may have been triggered or caused by Quaternary faulting; they occur on steep dip slopes, and the slip planes mostly follow steeply dipping preexisting faults along which sliding could have been facilitated by the presence of clay gouge or by actual tectonic movement of the fault itself. Slides in the Horse Heaven Hills are rooted in sedimentary interbeds and may record failure of these interbeds beneath the load of overlying basalt without direct influence of Quaternary tectonic events.

STREAM, COLLUVIAL, AND ALLUVIAL FAN DEPOSITS

Unconsolidated deposits of gravel, sand, silt, and clay along floodplains, alluvial fans, terraces, and valley bottoms comprise unit Qs. Tephra lenses of late Quaternary age (Mazama and Mount St. Helens tephras) are interbedded in places. In the Klickitat River Valley, glacial and glaciofluvial deposits, including outwash gravel and moraine debris, are included in the unit.

Two types of terrace gravel were mapped separately from the rest of the Quaternary sediments in the Toppenish basin and are shown as units Qst and Qsts on plate 1. These terrace gravels grade laterally into the deposits of unit Qs. The gravel of unit Qsts is composed of angular to rounded pebbles and cobbles mostly derived from the nearby Columbia River Basalt Group but in places including an admixture of older and younger rocks from west of the reservation. Such gravel is widespread throughout Toppenish basin. Unit Qst, found in the lower part of Toppenish basin, contains subrounded and rounded pebbles and cobbles of a variety of rock types, many of which were derived from the upper Yakima River basin upstream from Ellensburg. The gravel of unit Qst is interpreted as a mainstream deposit laid down by the ancestral Yakima River. The gravel of unit Qsts is considered the deposit of sidestreams, or tributaries, of the Yakima, such as ancestral Toppenish, Agency, and Medicine Creeks.

The sediments of unit Qs intertongue with landslide and loess deposits and with the Touchet beds. In the Klickitat River area, some of the glacial debris may be older than the youngest flow from Mount Adams. The terrace deposits, Qst and Qsts, are capped by the Touchet beds. Probably the sediments in units Qs, Qst, and Qsts formed mainly in the last 100,000 yrs.

STRUCTURAL GEOLOGY

The Yakima Indian Reservation is dominated by three narrow (3-5 km) east-west trending anticlinal ridges, which are separated by 20-25 km-wide synclinal basins. Rocks in the anticlines dip steeply and are complexly folded and faulted, whereas rocks in the basins are nearly flat-lying and are cut by only a few high angle faults. Major structures from south to north are: Horse Heaven-Simcoe uplift, Satus basin, Toppenish uplift, Toppenish basin, and Ahtanum uplift.

HORSE HEAVEN-SIMCOE UPLIFT

Horse Heaven-Simcoe uplift consists of three aligned ridges trending about N80°E along the southern edge of the Yakima Indian Reservation. The three ridges are, from east to west, Horse Heaven Hills, Bickleton Ridge, and Simcoe Mountains. This ridge system and associated structures extend more than 200 km westward from Pasco Basin to the foothills of the

Cascade Range. Maximum topographic relief of more than 400 m occurs 3 km west of Simcoe Mountain, where olivine basalt of the Simcoe Mountains volcanic area occurs at the ridge crest. Horse Heaven-Simcoe uplift is transected by the Klickitat River near Grayback Mountain, where a canyon more than 800 m deep has been cut into the Wanapum and Grande Ronde Basalts.

Structurally, Horse Heaven-Simcoe uplift consists principally of the Horse Heaven anticline and Simcoe Mountains anticline separated by the intervening Pine Creek Syncline. The Horse Heaven anticline extends from the reservation boundary near Mabton for approximately 30 km in a S70°W direction. The Simcoe Mountains anticline begins north of Bickleton and extends westward for more than 60 km along the southern boundary of the reservation before bending southwestward near Grayback Mountain to form the ridge along the southeast side of Camas Prairie. The two anticlines overlap each other over an interval of 10 km northwest of Bickleton, where they are separated by the Pine Creek syncline.

Horse Heaven anticline

The Horse Heaven anticline in the reservation is a relatively simple structure asymmetrically steep to the north. Monoclinal warps on the north flank cause abrupt changes in north dip from 45 degrees to less than 2 degrees. Just east of the reservation, a thrust fault juxtaposes the Priest Rapids Member over the Umatilla Member, but no other thrusts were found along the anticline. A steep, north-dipping normal fault with north-down displacement of less than 30 m follows the crestline of the anticline east of the Pine Springs Road, and a similar normal fault occurs along the crestline in R.21E. bringing the Roza and Umatilla Members in contact. The crestline is somewhat sinuous and even offset in places, although no faults have been recognized. The north base of the fold is a monocline that merges laterally into a normal fault of small, probably less than 20 m, displacement in R.20E. A shallow syncline lies just south of the fault but is poorly exposed.

Simcoe Mountains anticline

The Simcoe Mountains anticline is larger and more complex than the Horse Heaven anticline. The eastern part of the anticline is asymmetrically steep to the south, with dips as great as 30 degrees on the south limb. The symmetry changes 1 km west of Lone Pine Butte across a prominent northwest-trending right-lateral strike-slip fault, the northwest extension of the regional Arlington-Shutler Butte lineament of Kienle and Newcomb (1973). West of this fault the anticline is asymmetrically steep to the north, with a north dip as much as 45 degrees. Along Camas Prairie the anticline is asymmetrically steep to the northwest, with maximum dips of 25 degrees, and its northwest limb appears to be downfaulted.

Maximum structural and topographic relief along the entire uplift occurs within the western part of the Simcoe Mountains anticline. Culmination of the anticline is about 3 km west of Simcoe Mountain, where a flow of Ginkgo in the Frenchman Springs Member is exposed at more than 1700 m (5600 ft) elevation. The same flow is exposed at 1130 m (3700 ft) 10 km west and at 1300 m (4300 ft) 10 km east of the culmination along the crest of the anticline. Structural relief ranges from 300 to 450 m along most of the Horse Heaven-Simcoe uplift but is more than 775 m at Grayback Mountain near the Klickitat River. The culmination of the fold approximately coincides in location with a major part of the Simcoe Mountains volcanic area and may reflect broad regional uplift in addition to structural relief due to folding.

Fault systems

High and low angle faults parallel the Horse Heaven-Simcoe uplift over most of its length, forming complex splayed systems. The most extensive of these is the Milk Ranch fault system, which parallels the south side of the Simcoe Mountains anticline for more than 60 km. Segments of the system occur within the reservation south of Satus Pass and Grayback Mountain; the remainder of the system is displayed on the geologic map published by Swanson and others (1979b). The Satus Creek fault system is equally complex; it extends along the north limb of the Simcoe Mountains anticline from upper Shinando Canyon, near the west end of the Pine Creek syncline, to upper Satus Creek northeast of Simcoe Mountain. The Satus Creek system is considered to be laterally continuous with a similar fault system north of Grayback Mountain; unfaulted lava flows of the Simcoe Mountains volcanic area cover the intervening portion of the ridge, however, making it difficult to substantiate structural continuity between the two fault systems.

Milk Ranch fault system- East of Grayback Mountain, the Milk Ranch fault system consists of high angle faults trending parallel or sub-parallel to the south limb of the Simcoe Mountains anticline. The main Milk Ranch fault on the reservation has an offset of about 150 m down to the south. Numerous splays with smaller offsets extend into the upper part of the ridge. One such fault, downdropped to the north, obliquely crosses the anticline east of Lone Pine Butte along a N60-75°W trend and merges with the Satus Creek fault system near the mouth of Shinando Canyon. The throw on this fault increases from approximately 50 m near the summit of the anticline to greater than 300 m near U.S. Highway 97 north of Satus Pass.

The Milk Ranch fault system east of Grayback Mountain consists of at least one low angle thrust, whose fault plane dips less than 20 degrees north, at the base of the ridge; one or more high angle splays cut the upper part of the ridge. Vertical separation attributable to the main thrust is at least 250 m down to the south, and horizontal separation is at least 500 m. Offset on this fault decreases rapidly west of Klickitat River, and the fault plane appears to steepen.

Satus Creek fault system--East of Highway 97 the Satus Creek fault system consists of several high angle faults trending parallel or sub-parallel to the main anticline (N60°W to S85°W) and having a separation of approximately 350 m down to the north. These faults merge west of Highway 97 and become the Satus Creek thrust fault, whose main plane of movement shallows in dip to less than 30 degrees as revealed in exposures 50 m above Satus Creek. Flows above the fault plane dip greater than 35 degrees, and those below are nearly flat lying. At least two high angle faults parallel the thrust on the upper flank of the ridge. Net displacement across all of these faults is greater than 250 m down to the north.

A system of faults considered to be the western extension of the Satus Creek fault system cuts the north limb of the Simcoe Mountains anticline at Grayback Mountain. At least two of these faults are thrusts, including the lower Grayback Mountain thrust fault at the base of the ridge and the upper Grayback Mountain thrust fault more than 300 m higher. Fault planes of these two thrusts dip 40-50 degrees south and 10-15 degrees south, respectively, with a collective displacement of greater than 350 m. Flows above the basal thrust are overturned and dip 80 degrees southward, whereas flows below the thrust dip less than 5 degrees; this geometry is similar to that of the Satus Creek thrust fault and suggests that the folding and faulting are genetically related. The plane of the upper thrust fault appears to be folded where it intersects the crest line of the anticline.

Minimum horizontal separation on each of the two thrusts can be estimated on the basis of clearly defined fault plane inclinations and stratigraphic offsets. The upper thrust requires a horizontal separation of 350 m to produce the observed repetition of the Grande Ronde R_2-N_2 contact, and the lower thrust requires a horizontal separation of at least 250 m to account for juxtaposition of the normally magnetized low MgO Grande Ronde Basalt (map unit Tgn_2l) against the flow of Kelley Hollow in the Frenchman Springs Member.

Cross faults--Several cross faults transect the Horse Heaven-Simcoe uplift along a N15-45°W trend, forming noticeable lineaments on air photos and even topographic maps. The most prominent structures are, from east to west: the Bull Canyon fault near the west end of the Horse Heaven anticline; the northern extension of the Arlington-Shutler Butte lineament at Lone Pine Butte; the Luna Butte fault at the west flank of Simcoe Butte; the Goldendale fault east of Kaiser Butte; the Summit fault east of the Grayback Mountain lookout; and the Warwick and Laurel faults, as well as other unnamed faults, southeast of Camas Prairie. Southward continuations of these faults are shown on the regional geologic map by Swanson and others (1979b).

All of these faults are vertical or dip steeply and have extremely variable apparent normal displacements ranging from 0 to 300 m commonly in opposite senses along strike of the same fault. Cross faults having the greatest apparent normal displacement at the ridge crest are the Summit and

Luna Butte faults, which have offsets of 400 m and 180 m down to the west and east, respectively. All of the cross faults are believed to have right lateral strike-slip displacement on the basis of ubiquitous horizontal and subhorizontal slickensides and the offset of structures, drainages, and stratigraphic units. The Warwick, Laurel, and associated faults appear to offset and rotate in a right-lateral sense the crest line of the Simcoe Mountains anticline into a series of en echelon segments. The Arlington-Shutler Butte, Luna Butte, and possibly the Warwick and Laurel faults are regionally extensive and continue into Oregon as lineaments and possible faults. Other cross faults may also prove to be regionally significant.

Northeast-trending lineaments and faults, apparently conjugate with the northwest-trending structures, also cross the Horse Heaven-Simcoe uplift but are neither numerous nor prominent.

SATUS BASIN

The east-west trending Satus basin is a 25 km-wide syncline between the Horse Heaven-Simcoe uplift and the Toppenish uplift. A broad north south arch may cross the basin along the drainage divide between the Klickitat and Yakima Rivers and extend southward into the culmination of the Horse Heaven-Simcoe uplift 3 km west of Simcoe Mountain, dividing the basin into two parts. The western part of the basin is filled by Pliocene and Quaternary lava flows that obscure structural details. The eastern part slopes eastward, with greater than 1100 m of structural relief across the basin (Swanson and others, 1979c). Two broad synclines occur within the eastern part of basin. Dry Creek syncline is a structural low adjacent to the Toppenish uplift. Satus Creek syncline approximately follows the course of Satus Creek diagonally across the eastern basin. Elbow anticline separates the two synclines in the upper Dry Creek area (pl. 1).

More than ten topographic lineaments, interpreted as high angle faults and fracture systems, trend northwest across the basin. These lineaments can be shown in places (for example, in the SW 1/4 sec. 36, T. 9 N., R. 17 E. and along a road in the NE 1/4 NE 1/4 SE 1/4 sec. 22, T. 7 N., R. 17 E.) to be narrow, nearly vertical fracture systems generally less than 100 m wide. Most of the fracture systems contain several narrow zones of intense fracturing less than 1 m wide. Dip-slip separations along the systems are less than 20 m. These fractures are subtle, and many may have been missed during the reconnaissance mapping. The lineaments and fracture systems are interpreted as right lateral strike-slip faults on the basis of sub-horizontal slickensides, offset geologic contacts, and offset streams (for example, the offset of the South Fork of Kusshi Creek in NE 1/4 sec. 28, T. 7 N., R. 17 E.). They probably have strike-slip separations of a few meters to at most a few hundred meters. Some of these fracture systems are traceable from the Horse Heaven-Simcoe uplift across Satus basin into Toppenish uplift and Toppenish basin.

Mule Dry fracture system transects Satus basin in the vicinity of Mule Dry Creek and is typical of these fracture systems. No offsets could be found across the Mule Dry system within Satus basin, but topographic lineaments suggest throughgoing fractures. Displacements on these fractures, two of which are shown on plate 1, are probably small, a few tens of meters at most, across Satus basin; in the adjacent anticlines, however, several hundred meters of strike-slip displacement is possible. This fracture system may be wider than shown on plate 1, as several additional fractures may cross Satus basin east of Mule Dry Creek and connect with the numerous cross faults near Hembre Mountain on the east end of the Toppenish uplift (pl. 1). Mule Dry fracture system may cross the Toppenish basin and be continuous with faults across Ahtanum Ridge near

Union Gap. Late Quaternary ground breakage on Toppenish Ridge, described below, is limited to a segment of the ridge west of the Mule Dry fracture system.

Bull Canyon, Arlington-Shutler Butte, Luna Butte, and other northwest-trending lineaments and faults transect the Satus basin as narrow lineaments, probably steeply dipping fracture systems. Many of these lineaments are partly buried under Pliocene lava flows, but the Arlington-Shutler Butte, Luna Butte, and other nearby fracture systems may cut the young flows. Bull Canyon and adjacent Elbow fracture systems, mapped largely on the basis of photo lineaments, may be continuous with similar northwest-trending faults and fractures that transect Toppenish uplift, Toppenish basin, and Ahtanum uplift to the north. The Elbow fracture system is at the western limit of the late Quaternary ground breakage described below.

TOPPENISH UPLIFT

Toppenish uplift is a single, continuous structure that transects the reservation with a generally N80°E trend for 80 km between Granger and the Klickitat River. Topography of the ridge and structural relief of the uplift are directly related. The uplift is in general an anticline plunging eastward and westward from its culmination near Satus Peak. The westward plunge is less distinct, because much of the western segment is buried under Pliocene lava flows. The west end of the ridge appears to curve southwestward east of the Klickitat River, just as the Horse Heaven-Simcoe uplift does farther south.

Toppenish uplift consists of three segments with different geometries, from east to west the Hembre Mountain, Satus Peak, and Peavine anticlines. Each of the three anticlines changes geometry sharply in areas of northwest-trending cross faults.

Hembre Mountain anticline

Hembre Mountain anticline is the segment of the uplift east of the Mule Dry fracture system. The anticline is 15 km long, trends N70°E, and plunges eastward beneath alluvium in the Yakima Valley near Granger (pl. 1). It consists of about ten short segments bounded by north- to northwest-trending cross faults. Each segment is folded into a series of subsidiary warps that collectively form the larger Hembre Mountain anticline.

The south flank of the anticline is cut by low angle (10-15 degree) thrust faults with more than 100 m of horizontal separation. One fault juxtaposes the Umatilla Member over the conglomerate of Snipes Mountain near a secondary road in sec. 17, T. 9 N., R. 20 E. An eastward continuation of the Mill Creek thrust fault (see below) may extend along the north flank of the Hembre Mountain anticline, but Quaternary sediments obscure its presence. All of the deformation in the Hembre Mountain segment of the Toppenish uplift is pre-late Quaternary, except for a few ruptures in the westernmost segment near U.S. Highway 97.

The cross faults that divide the anticline into segments are part of the system of right lateral faults and fractures crossing Satus basin. The Mule Dry fracture system continues as two fractures from the basin into the westernmost segment of the anticline. The adjacent Hembre Mountain faults are subparallel to the Mule Dry system but have not been found in the adjacent basins. Individual Hembre Mountain faults dip steeply and are interpreted to be right-lateral strike-slip faults with less than 100 m of lateral displacement.

Satus Peak anticline

Satus Peak anticline, the middle segment of Toppenish uplift, extends for 30 km from the Mule Dry fracture system near U.S. Highway 97 west to the Bull Canyon and Elbow fracture systems near Satus Peak. The fold is fundamentally a single, east-plunging, asymmetric, box shaped anticline with angular hinge lines (pl. 1).

Faults occur along the crestline and within the upper hinge zones of the Satus Peak anticline. Most of these faults have less than 10 m of vertical separation; we have not shown them on plate 1 for scale reasons, as we wish to emphasize Quaternary ground ruptures in the same complex area. Some of these faults define graben and could be related to gravitationally induced ridge-top spreading; we feel, however, that they more likely are tectonic extension features formed at the same time as the major folding and thrusting. In this manner they are similar to the crestal faults along the Horse Heaven anticline described above.

The northern limb of the Satus Peak anticline is cut by the Mill Creek fault, probably a thrust fault with as much as 600 m of dip separation. This fault is mostly covered by Quaternary sediments but is exposed in sec. 6, T. 9 N., 4. 18 E. It can be located to within 50 m below the north side of Satus Peak, where reversely magnetized flows of Grande Ronde Basalt (R_2) are juxtaposed against normally magnetized flows near the top of the Grande Ronde (N_2). The dip of the fault is not known but probably low.

The Oak Spring fault cuts the south limb of the Satus Peak anticline. Dip separation on this fault near Oak Spring is more than 200 m but may decrease eastward to less than 100 m. The sinuous map pattern shows that the Oak Spring fault is a low angle (less than 15 degree) thrust along the eastern two thirds of the Satus Peak anticline, and it probably merges into the thrust faults on the south limb of the Hembre Mountain anticline (pl. 1). The Oak Spring thrust fault probably continues westward along Seattle Creek to the west end of the Satus Peak anticline and perhaps ends at the Elbow fracture system. No exposure of the fault plane is known. The Roza and Pomona Members are juxtaposed for several kilometers east and west of Oak Spring (secs. 7-8, T. 9 N., R. 18 E.), and the fault can be located within 10 m at several localities. The fault is probably a single surface or zone less than 2 m wide.

Late Quaternary deformation--A zone of late Quaternary ground breakage follows along the crest, north hinge, and north flank of the Satus Peak anticline from the Mule Dry fracture system near U.S. 97 west for 30 km to the Elbow fracture system. The zone of ground breakage, from 0.5 to 2.2 km wide, contains nearly 100 surface ruptures, shown in simplified form on plate 1; numerous smaller scarps are visible on large scale air photographs. The ruptures vary in length from 0.1 km to 9 km; most are less than 1 km long, but at least six exceed 3 km. As many as 12 ruptures, typically 6 to 8, occur in a profile across the zone. Nearly all of the ruptures in the crest and hinge area dip steeply, as seen along gully slopes and judged from straight map patterns, and have vertical separations of as much as 4 m. The northernmost surface rupture, on the north flank of the anticline near the probable location of the Mill Creek fault, has a sinuous trace and likely a gentle dip; horizontal and vertical separations of as much as 5 m and 2 m, respectively, are suggested by field observations. No strike-slip movement has been documented.

The total amount of vertical displacement (the summation of displacements on each rupture) in any one cross-sectional profile across the zone may exceed 25 m. This figure does not give the net displacement across the zone, however, because ruptures with south side down are nearly as numerous as those with north side down. The estimated net displacement across the zone is probably between 4 and 8 m, north down relative to south.

The surface ruptures can be divided into three sets: a summit set just north of and along the crest of the anticline, a north slope set along the north hinge area and on the steeply dipping north limb of the anticline, and an alluvial fan set near the probable location of the Mill Creek fault.

The summit set of surface ruptures cuts basalt as young as the Pomona Member and Quaternary loess and is associated with a ridge-top graben. Vertical displacement across the graben varies from 1 to 3 m. Disrupted drainage is common where southside-down faults cross north-draining gullies. Several sag ponds containing up to 1.5 m of silt occur along the interrupted drainage; augering in one sag pond (SW 1/4 SE 1/4 sec. 3, T. 9 N., R. 19 E.) recovered plant material from the lower part of the fill that yielded ^{14}C ages of 505 +/- 160 yr B.P. and 620 +/- 135 yr B.P. (N. P. Campbell, unpub. data, 1979).

The north slope set of surface ruptures cuts basalt as young as the Pomona Member, alluvial fan gravel of unit QTg, loess, and modern alluvium and landslide deposits. Ruptures in this set show vertical displacement as great as 2 m, commonly with south side down. One observed fault plane (SW 1/4 SW 1/4 SW 1/4 sec 32, T. 10 N., R. 19 E.) dips 81 degrees south. Drainage is disrupted across several of these ruptures. Younger slump blocks associated with landslides may have been localized by several of the ruptures.

The alluvial fan set of ruptures cuts gravel of units QTg and Qsts, alluvium, and the Touchet beds. This set follows the presumed trace of the Mill Creek fault; one exposure of the fault is located within 10 m of the northernmost surface rupture (sec. 6, T. 9 N., R. 18 E.), which cuts small alluvial fans resting on the Touchet beds. The surface ruptures follow the trace of a broad, minor uplift (horst or anticline) for at least 5 km.

On the basis of ^{14}C radiometric dates, most of the late Quaternary ground breakage is younger than about 13,000 yrs b.p., the age of the upper part of the Touchet beds, and older than about 600 yrs b.p., the age of the oldest silt in one of the sag ponds created by rupturing. The latest breakage in the north alluvial fan set is likely to be much younger than 13,000 yrs b.p., because ruptures in this set cut alluvium deposited by streams cutting the Touchet.

We interpret the ground ruptures as tectonic faults on the basis of their location and geometry. We consider an alternative explanation, that the ruptures are related to gravitational failure of the ridge ("ridge-top spreading") without direct involvement of tectonic forces, to be unlikely, because such an interpretation does not explain the abundance of south-side-down faults on the north slope of the ridge. Moreover, we know of no other ridge on the Columbia Plateau that displays such features despite topographic similarity to Toppenish Ridge.

If our interpretation is correct, the Quaternary thrust faulting and folding in the north alluvial fan set may record some of the latest north-south compressional deformation in the region. The summit and north slope sets of faults are in a position of extension along the crest and hinge of the Satus Peak anticline, consistent with north-south compression.

Peavine anticline

Peavine anticline, the western portion of the Toppenish uplift, extends from the Elbow fracture system near Satus Peak west for more than 50 km to the Klickitat River. Much of this structure lies along Peavine Ridge, where only the crestal portion of the anticline is exposed above the Simcoe volcanics. The anticline is asymmetrically steep to the north, with a gently dipping south limb. The overall trend of the anticline is nearly east-west; several changes in trend may be controlled by cross faults. Near the Klickitat River the anticline swings sharply and plunges moderately southwestward. Structural culmination of the entire Toppenish uplift occurs along the Peavine anticline between Satus Peak and Mill Creek Guard Station, where the elevation of the top of the Grande Ronde Basalt exceeds 1280 m (4200 ft).

The Mill Creek fault can be traced as far west as the eastern margin of the Simcoe volcanics. Its continuity farther west is conjectural. The fault zone is exposed 3 km west of Mill Creek Guard Station in the SE 1/4 SE 1/4 sec. 26, T. 9 N., R. 15 E., where vertical separation is about 650 m. Separation apparently decreases westward from here, but little is known owing to poor exposure.

A possible extension of the Mill Creek fault occurs near the Klickitat River. Field relations suggest that the fault is steeper here than farther east, and it is shown as a high angle, probably reverse, fault on plate 1. Another high angle fault follows the northern hinge line of the Peavine anticline where the fold bends southwestward. The two faults together may be considered as part of the Mill Creek fault zone, which decreases in displacement and increases in dip near the Jungle Butte fault.

Several abrupt changes in trend along the Peavine anticline may be controlled by northwest-trending faults. Two of these changes lie along projections of the Goldendale and Arlington-Shutler Butte faults, but poor exposures and lack of time precluded finding positive evidence for the faults across the anticline. The Jungle Butte fault cuts the western end of the anticline just east of the Klickitat River and may form part of a northwest-trending structure outlining the Klickitat basin. The Jungle

Butte fault projects northwestward across the Klickitat River, where it juxtaposes Grande Ronde Basalt and a hornblende dacite(?) included in unit QTb.

TOPPENISH BASIN

Toppenish basin is a 25 km-wide, east-trending, structural depression between Toppenish and Ahtanum uplifts. The eastern half of the basin is a poorly defined structural trough with a north to south structural relief in excess of 800 m (Robbins and others, 1975; Swanson and others, 1979c). The easternmost portion of the basin lies east of the reservation within the northwest-trending system of folds and faults along the Cle Elum-Wallula deformed belt (Bentley and others, 1978). A prominent N50^{o}W regional lineament, the Cleman-Snipes lineament (fig. 2), follows the Yakima River between Union Gap and Snipes Mountain and forms the southwest margin of the Cle Elum-Wallula deformed belt. The eastern part of Toppenish basin is probably cut by northwest-trending faults and folds obscured by alluvium and other late Quaternary deposits.

The western part of Toppenish basin is basically a broad east-plunging syncline in which the Grande Ronde and Wanapum Basalts are gently deformed except along narrow northwest-trending fracture zones. Most of the east to west structural relief in Toppenish basin, approximately 1800 m, occurs within the western part, which has a nearly uniform eastward gradient of 3-5 degrees probably related to regional upwarp of the Cascade Range.

Faults and fracture systems, largely interpreted from topographic and photo lineaments, cut the western part of the basin. Most of these structures trend N30-40^{o}W, but several have a more northerly orientation. These structures are interpreted as strike-slip faults and fracture zones similar to and in some cases extensions of those previously described. Most of the faults in the western part of the basin have less than 100 m of vertical displacement and probably no more than several hundred meters of lateral displacement.

Deer Butte anticline trends east-northeast across the middle of the basin. It plunges irregularly northeastward and may be segmented by the Bull Canyon-Elbow fracture system near Willy Dick Canyon. The anticline is asymmetrically steep to the south and has its maximum structural relief of about 200 m near Deer Butte. It apparently ends at or merges with a cross structure, possibly a fault, that crosses Ahtanum Ridge south of Wiley City, but the nature of this junction is obscured by young deposits and poor exposure. The Lost Horse syncline and several monoclinal flexures cross the basin subparallel to the regional trend of the Ahtanum uplift.

AHTANUM UPLIFT

Ahtanum uplift forms the northernmost continuous anticlinal ridge within the reservation. It is the western half of a narrow, 150 km long uplift extending from the Pasco Basin to the Cascade Range along the Rattlesnake Hills and Ahtanum Ridge. Ahtanum uplift is generally poorly exposed; loess and soil are thick and extensive at lower elevations, and dense forest mantles the higher western region. The uplift can be divided into eastern and western segments, the Tampico and Cowboy Parking Lot anticlines, respectively. Ahtanum uplift trends approximately east-west, but within the reservation the Tampico anticline is sinuous about N80°E and the Cowboy Parking Lot anticline trends N70°E.

Tampico anticline

The Tampico anticline extends from Union Gap east to the North Ahtanum Creek fault and is fundamentally an east-plunging box-shaped fold. Structural relief across the anticline is approximately 500 m, with locally 300-400 m of this relief concentrated across the hinge zones.

The northern hinge of the anticline is apparently cut by the Ahtanum Creek fault. The fault is not exposed but is inferred on the basis of stratigraphic relations and structural relief. It may be a thrust fault with perhaps a few hundred meters displacement. The fault may extend farther west than its limit shown in plate 1.

The southern hinge is cut by the low angle Union Gap fault, exposed discontinuously along the south side of the Tampico anticline. The fault juxtaposes the flow of Kelley Hollow (Frenchman Springs Member) over the Pomona Member, a maximum stratigraphic separation of about 150 m.

Cowboy Parking Lot anticline

Cowboy Parking Lot anticline extends from the North Ahtanum Creek fault west for 30 km to the Klickitat River. The anticline plunges approximately 1000 m from its west to east ends and has 300 m of structural relief across the hinge zones. Several minor folds parallel the western part of the anticline. Lost Horse syncline south of the anticline is poorly exposed and defined chiefly on the basis of topography.

Flows of unit QTb, interbedded with old colluvium and flow breccia, dip several degrees northward away from the crest of the Cowboy Parking Lot anticline along Diamond Fork, in sections 23 and 26, T. 11 N., R. 13 E. The dip of these flows may be primary, but post-eruption tilting related to uplift of the anticline cannot be excluded.

The Cowboy Parking Lot anticline is cut by four cross faults that offset the ridge and stratigraphy as much as 700 m. These cross faults are, from east to west, the Hog Creek, Rattlesnake Canyon, Soda Springs, and Kingfish Creek faults. They are on strike with regionally significant right-lateral faults and fractures of the Bull Canyon-Elbow fracture system.

SOUTH AHTANUM CREEK SYNCLINE AND SEDGE RIDGE ANTICLINE

South Ahtanum Creek syncline, north of the Ahtanum uplift, follows the boundary of the reservation from the headwaters of the creek to the Tampico area. The trough of the syncline coincides with the creek west of sec. 27, T. 12 N., R. 15 E. but is slightly north of the creek farther east. The geometry of the syncline also changes somewhat in sec. 27 along a projection of the Rattlesnake Canyon fault. West of sec. 27, the syncline is symmetric to slightly asymmetric (north limb steeper); east of sec. 27, the syncline has a relatively flat trough, with dips of only a few degrees, separated by hinges or monoclines from steeper limbs in the crestal regions of the bounding anticlines (pl. 1). The syncline abruptly changes trend at two localities, one at the intersection with the projected Rattlesnake Canyon fault, the other at the intersection with the Soda Springs fault. All segments plunge 2-3 degrees eastward.

Sedge Ridge anticline is north of the South Ahtanum Creek syncline, and its crestline follows the reservation boundary along the ridge crest northwest of Cultus Hole. The anticline plunges eastward 3-4 degrees and raises the Grande Ronde Basalt (N_2) to its highest elevation on the reservation, 2128 m (6981 ft) at Darland Mountain. A partial cross section of the anticline at Cultus Hole shows a broad structure with dips of 6-10 degrees. Elsewhere the anticline is poorly exposed but known to be segmented at or along the projection of the northwest-trending Soda

Springs and Rattlesnake Canyon faults and, north of the map area, along the North Ahtanum Creek fault (pl. 1; Swanson and others, 1979b). The R_2 and N_2 magnetostratigraphic units of the Grande Ronde Basalt are brought in contact by the Soda Springs fault, and vertical offset of at least 100 m, west side down, is probable.

Sedge Ridge anticline is part of a complex uplift in the Yakima fold belt, extending northeastward into Cowiche Mountain, which in turn merges eastward into Yakima Ridge. The west end of Sedge Ridge anticline probably has undergone some uplift and tilting in Pliocene or Pleistocene time, because the olivine basalt in unit QTb near Cultus Hole has apparently been tilted southward, as described in the section dealing with unit QTb.

SUMMARY OF GEOLOGIC HISTORY

The middle Miocene Cascade Range along the western margin of the reservation consisted of deformed and eroded lower Tertiary volcanic rocks (Ohanapecosh Formation) forming a highland locally surmounted by active volcanoes (Mackin and Cary, 1965; Swanson, 1966, 1967). Streams flowed eastward and southeastward from the highlands, carrying detritus eroded from the older rocks as well as that recently erupted from andesitic volcanoes. Presumably these streams were tributaries to a master river, the ancestral Columbia, which then drained a large area in northern Washington.

Little is known about the topography or rocks underlying the central and eastern parts of the reservation before eruption of the Columbia River Basalt Group. We surmise that the area was underlain by older volcanic deposits, such as those of the Ohanapecosh, Stevens Ridge, and Fifes Peak Formations (Fiske and others, 1963; Swanson, 1966).

Between 15 and 17 million years ago, huge eruptions of basalt from fissures in and east of the Pasco Basin produced flows that flooded south-central Washington. These eruptions formed the Grande Ronde Basalt. As the flows advanced westward, they gradually forced the course of the ancestral Columbia toward the west, and it was eventually established in the crease between the thickening basalt pile and the higher Cascades. A generally south-flowing master drainage system resulted, with tributaries from the Cascades contributing volcaniclastic detritus to other material, largely of plutonic and metamorphic derivation, carried by the Columbia. Periodically between eruptions, courses of the ancestral Columbia and its tributaries shifted eastward onto the flat basalt plain, and sediments were laid down in sheetlike deposits. The next basalt flow buried these sediments, which now form interbeds of the Ellensburg Formation, and again disrupted the drainage system. In this manner a complex assemblage of basalt flows and sedimentary interbeds was developed, with rapid lateral changes in lithology and thickness. Lakes often dotted the broad floodplains, and basalt flows became pillowed as they entered water (Moore, 1975). Flows commonly plowed into and mixed with loose sediment, forming invasive flows (Byerly and Swanson, 1978) and peperites (Schmincke, 1967b). Lahars frequently sped down valleys from active volcanoes and spread across the basalt plain. Volcanic ash fell into and mixed with other types of sediment. The streams seldom had sufficient energy to carry large boulders, except those of light, poorly resistant material such as pumice. The overall picture suggested by the evidence is one of sluggish, meandering streams flowing down a gentle southeast slope in shallow channels periodically overwhelmed by basalt flows.

The Cascades were being uplifted, at least in places, as early as late Grande Ronde time; when the uplift began is not known. Some of the folds now present on the reservation had probably also begun to form. This deformation produced changes in topography that affected the distribution of flows of Wanapum Basalt. In general, each successively younger member of the Wanapum was unable to advance as far west as its predecessor, owing to continued eastward tilting resulting from Cascade uplift and more local folding The ancestral Columbia likewise shifted eastward but still maintained a generally south-flowing course. As a result, sediments were laid down between flows farther east than previously, forming such deposits as the Vantage and Squaw Creek Members of the Ellensburg Formation. Conglomerates composed of basaltic clasts occur in places and attest to vigorous erosion of local uplifts.

Broad, structurally controlled basins had become noticeable at the onset of Saddle Mountains time, about 13-13.5 million years ago. The bounding anticlinal ridges were locally high enough to confine such flows as the Umatilla and Pomona Members, but the general distribution of these flows was still controlled more by the regional eastward slope than by the local uplifts. Thick sedimentary deposits, the Mabton, Selah, and Rattlesnake Ridge units, accumulated in subsiding basins as time between eruptions became longer and rate of deformation possibly accelerated. These deposits consist principally of volcaniclastic material derived from ongoing eruptions in the Cascade Range; basaltic detritus supplied by erosion of local uplifts is present but subordinate to the floods of dacitic Casacade debris. Material of upstream Columbia River derivation occurs but is most common in the central and eastern part of the area, reflecting gradual eastward migration of the river as regional tilting continued. The ancestral Columbia eroded canyons across growing uplifts in places; the deepest such canyon, on the north side of Grayback Mountain, contains both the Pomona and Elephant Mountain Members and was presumably first formed during late Wanapum or early Saddle Mountains time. These canyons were eventually filled by lava flows, and the river migrated eastward.

At some time after the Elephant Mountain Member was erupted, the ancestral Columbia established a southwest course across the reservation from Snipes Mountain to Satus Pass. This course, marked by the quartzite conglomerate of Snipes Mountain, is rather wide (pl. 1) probably reflecting shifting of the river in response to tectonic events. It is reasonable but not yet demonstrated that the Snipes Mountain becomes younger toward the east, as regional eastward tilting continued during deposition. Uplift of Umtanum Ridge near Priest Rapids Dam was likely responsible for cutting off the ancestral Columbia from its course across the reservation before the Simcoe volcanics formed.

Eruptions of basalt and related lava began in the Simcoe volcanic field probably during early Pliocene, about 4-5 million years ago. Much of the deformation of the area had been completed before these eruptions, although some flows appear to have been tilted by later folding. The eruptions, which may have taken place over a 2-4 million year period, produced a broad continuous basalt field dotted with cinder cones. The Klickitat River, whose early course may date from the time at which the ancestral Columbia flowed southward through this area, made its way along the western edge of the Simcoe field, eroding a deep canyon. Younger basalt flows erupted from vents in the Cascades, particularly in the Mount Adams area, poured down this canyon, forcing the river each time to recut narrow gorges such as now characterize the Klickitat. Such events have continued to the very recent geologic past, perhaps only a few hundred years ago. More such intracanyon flows can be expected in the future.

Meanwhile, continued erosion of anticlinal uplifts along the margins of broad basins led to deposition of thick sheets of basaltic gravel in alluvial fans and along stream drainages. Such deposits are particularly notable in Toppenish basin, where complex intertonguing relations with stream deposits and loess also are evident.

Glaciation in the Cascades during late Pleistocene time produced moraines and outwash gravel in the Klickitat River basin. Large floods loosed by failure of ice dams east of Spokane poured across the Columbia Plateau, backing up into Toppenish basin and depositing silt of the Touchet beds one or probably many times ending about 13,000 years ago.

Tectonic deformation, largely completed before the Simcoe volcanics formed, still continues in places, as attested by Holocene faults along Toppenish Ridge. Deformation may be part of a compressional wrench system affecting much of western North America as a result of interaction of laterally moving plates of the earth's crust (Bentley and Anderson, 1980). Such interactions are not apt to end suddenly, so deformation of the reservation as well as the entire northwestern United States is likely to continue for millions of years to come.

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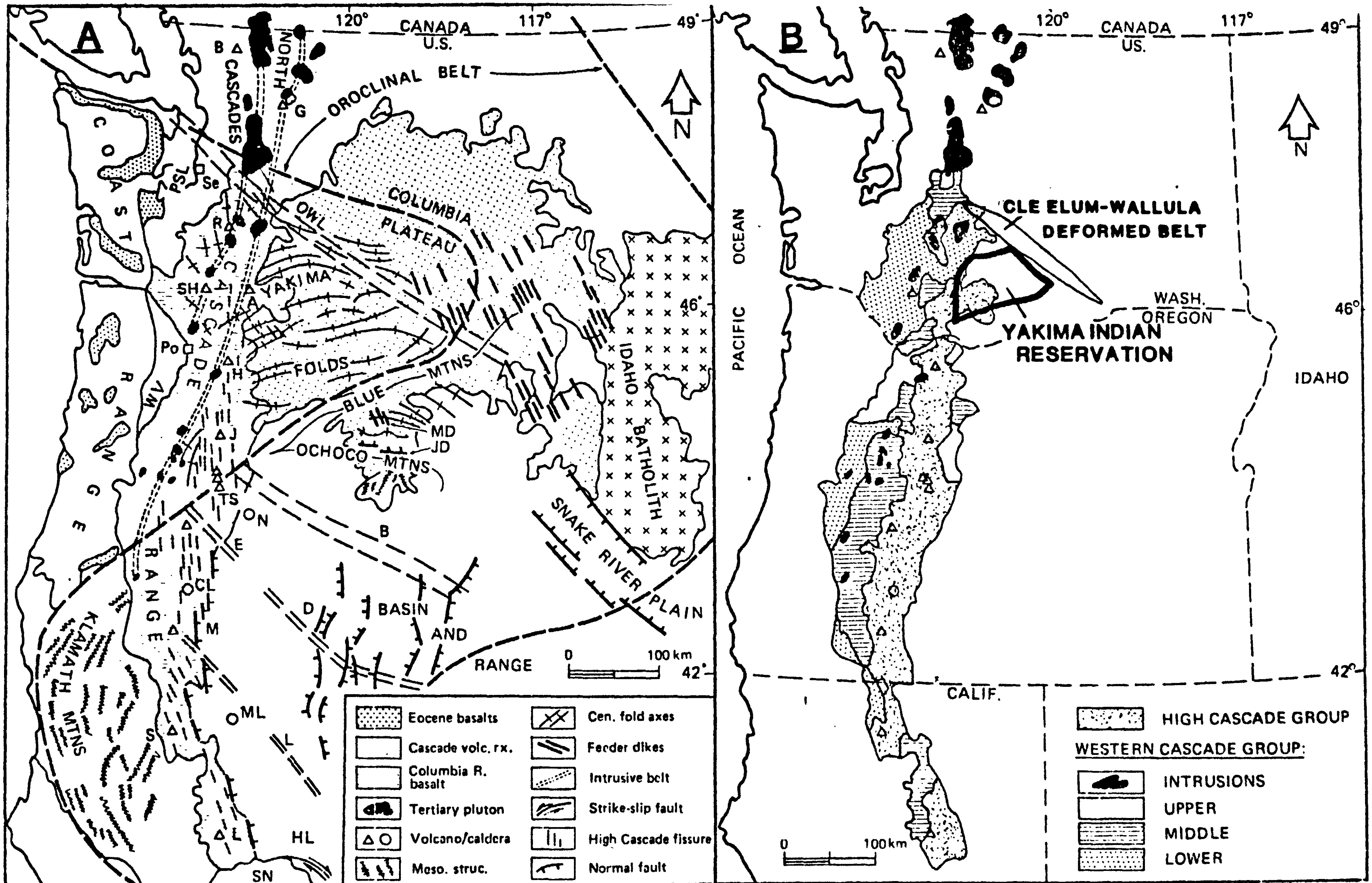

Figure 1. Generalized geologic and tectonic maps of the Pacific Northwest, slightly modified from Hammond (1979, figs. 1-2). A, Pacific Northwest regional map; B, map of volcanic part of Cascade Range. Abbreviations: Po, Portland; Se, Seattle; Md, Monument dike swarm; PSL, Puget Sound lowland; SN, northern end of Sierra Nevada; WV, Willamette Valley. Fault zones: B, Brothers, D, Denio; E, Eugene; HL, Honey Lake; JD, John Day; L, Likely. Volcanoes: A, Adams; B, Baker; CL, Crater Lake (Mazama); G, Glacier Peak; H, Hood; J, Jefferson; L, Lassen; M, Medicine Lake; N, Newbury; R, Rainier; S, Shasta; SH, St. Helens; TS, Three Sisters. Meso. struct., Mesozoic structural elements; Cen. fold axes, Cenozoic fold axes. The western Cascade Group of Hammond (1979) includes rocks from Eocene to early Pliocene in age; the High Cascade Group of Hammond (1979) includes rocks of Pliocene age.

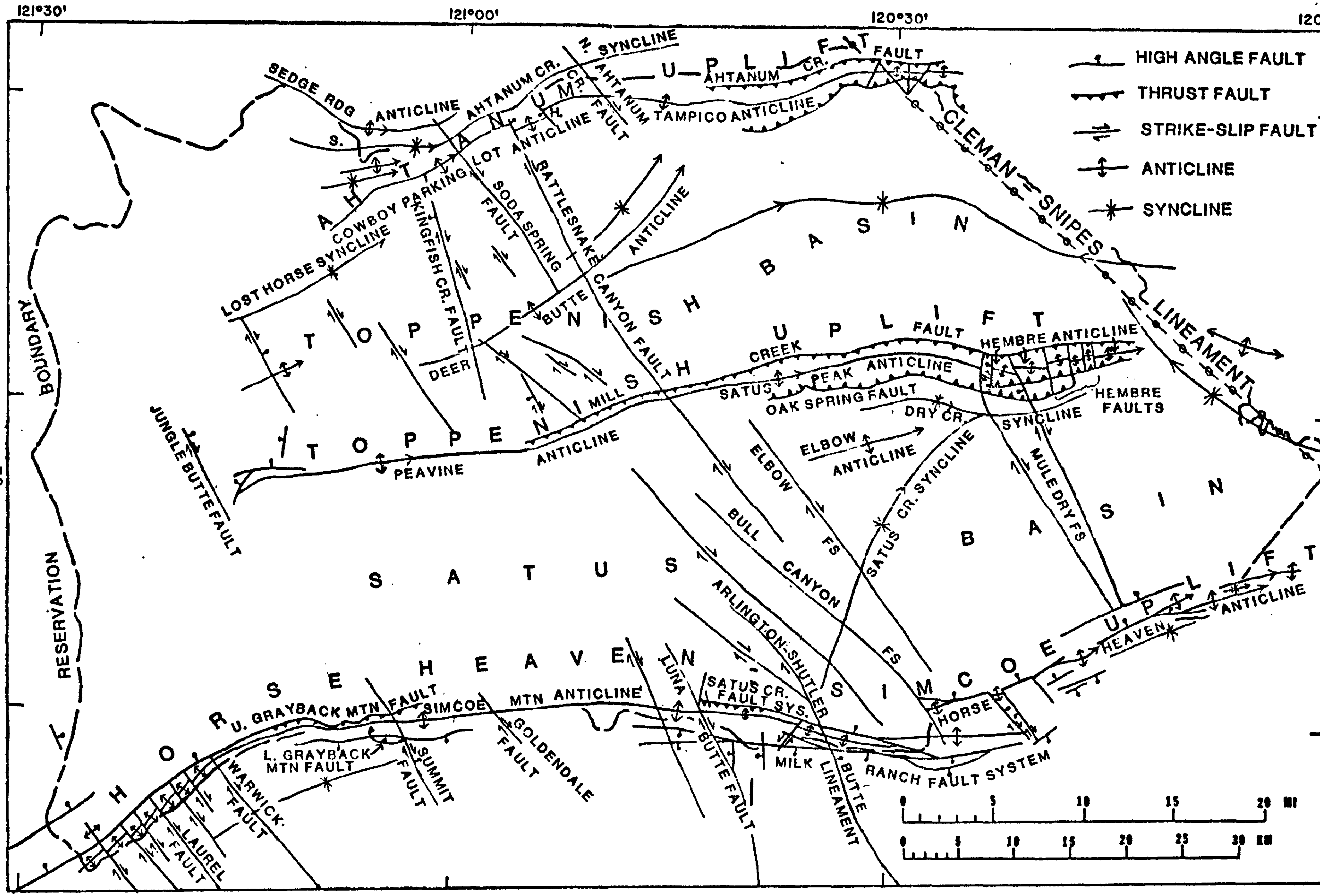

Figure 2. Map showing major tectonic features of the Yakima Indian Reservation. Generalized from plate 1. H, Hog Creek fault; FS, fracture system.

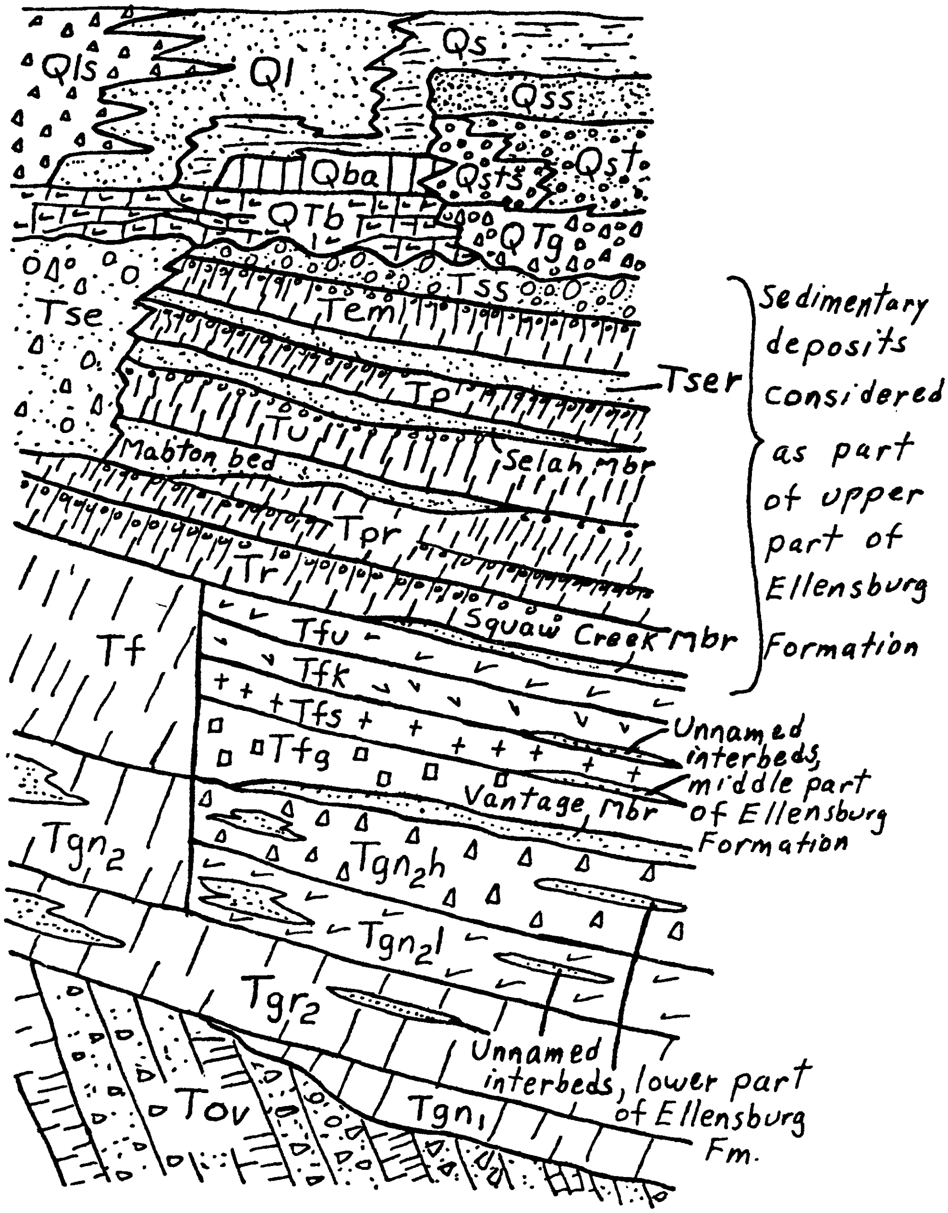

Figure 3. Sketch diagram showing age relations among stratigraphic units discussed in text. Explanation for symbols given in Appendix.

Table 1. Stratigraphic units of the Columbia River Basalt Group on the Yakima Indian Reservation. Symbols used on plate 1 shown in parentheses.

- Columbia River Basalt Group
    - Yakima Basalt Subgroup
        - Saddle Mountains Basalt
            - Elephant Mountain Member (Tem)
            - Pomona Member (Tp)
            - Umatilla Member (Tu)
        - Wanapum Basalt
            - Priest Rapids Member (Tpr)
            - Roza Member (Tr)
            - Frenchman Springs Member (Tf)
                - Flows of Union Gap (Tfu)
                - Flow of Kelley Hollow (Tfk)
                - Flow of Sand Hollow (Tfs)
                - Flows of Ginkgo (Tfg)
        - Grande Ronde Basalt
            - Magnetostratigraphic Unit N_2 (Tgn_2)
                - Upper flows (Tgn_2h)
                - Lower flows (Tgn_2l)
            - Magnetostratigraphic Unit R_2 (Tgr_2)
            - Magnetostratigraphic Unit N_1 (Tgn_1)

Table 2.—Representative chemical analyses of the Grande Ronde Basalt on the Yakima Indian Reservation, Washington. Analyses in weight percent. Samples analyzed by X-ray fluorescence techniques at Washington State University under the direction of P. R. Hooper. Value of Fe_2O_3 arbitrarily set at 2.00 wgt percent; for comparison with analyses giving total iron as FeO, as in Swanson and others (1979a), add 1.8 (i.e., 2.00 x .9) to value of FeO given below.

	Map unit Tgn_2h								Map unit Tgn_2l				Map unit Tgr_2					Map unit Tgn_1	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SiO_2	54.87	54.23	54.20	54.14	53.66	53.32	53.25	53.72	54.75	56.57	56.28	55.05	56.35	55.31	54.96	55.82	55.04	55.11	54.33
Al_2O_3	15.73	15.28	15.49	15.34	14.93	14.97	14.94	15.00	14.56	15.02	14.97	15.15	14.93	14.88	15.16	15.25	14.85	15.15	14.84
Fe_2O_3	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
FeO	8.45	9.63	8.75	9.19	10.22	10.09	10.16	10.50	11.12	8.95	9.40	9.40	9.92	9.97	9.75	10.08	10.46	9.83	10.68
MgO	4.46	4.52	4.85	4.72	4.81	4.98	4.65	4.48	3.49	3.31	3.61	3.78	3.23	3.63	4.22	3.36	3.67	3.73	3.61
CaO	8.72	8.42	9.01	8.81	8.76	8.85	8.70	8.28	7.31	6.91	7.30	7.74	6.69	7.38	7.71	6.78	7.39	7.61	7.25
Na_2O	2.17	2.42	2.23	2.19	2.24	2.41	2.64	2.23	2.30	2.62	2.33	2.35	2.66	2.27	2.36	2.59	2.28	2.69	2.40
K_2O	1.38	1.31	1.24	1.32	1.06	1.01	1.15	1.28	1.66	2.07	1.81	1.81	1.80	1.98	1.50	1.69	1.81	1.24	1.91
TiO_2	1.74	1.70	1.73	1.79	1.82	1.87	1.98	1.98	2.25	2.00	1.83	2.16	1.95	2.04	1.85	1.95	2.00	2.12	2.40
P_2O_5	0.29	0.29	0.29	0.30	0.29	0.28	0.31	0.31	0.35	0.33	0.30	0.35	0.30	0.33	0.29	0.30	0.31	0.33	0.37
MnO	0.20	0.20	0.22	0.20	0.21	0.21	0.21	0.22	0.21	0.20	0.19	0.21	0.17	0.21	0.19	0.20	0.19	0.18	0.21

Sample number and location

1-17. Satus Peak section, SE 1/4 sec. 13, T. 9 N., R. 16 E.
1. RDB9-137. Highest flow; 4065 ft. elev.
2. RDB9-138. Flow under RDB9-137, 4030 ft. elev.
3. RDB9-139. Flow under RDB9-138, 3990 ft. elev.
4. RDB9-140. Flow under RDB9-139, 3885 ft. elev.
5. RDB9-141. Flow under RDB9-140, 3790 ft. elev.
6. RDB9-142. Flow under RDB9-141, 3705 ft. elev.
7. RDB9-143. Flow under RDB9-142, 3625 ft. elev.
8. RDB9-144. Flow under RDB9-143. Lowest Tgn_2h flow. 3540 ft. elev.

9. RDB9-145. Flow under RDB9-144, 3330 ft. elev.
10. RDB9-146. Flow under RDB9-145, 3230 ft. elev.
11. RDB9-147. Flow under RDB9-146, 3060 ft. elev.
12. RDB9-148. Flow under RDB9-147. Lowest Tgn_2l flow.

13. RDB9-149. Flow under RDB9-148, 2760 ft. elev.
14. RDB9-150. Flow under RDB9-149, 2690 ft. elev.
15. RDB9-151. Flow under RDB9-150, 2600 ft. elev.
16. RDB9-152. Flow under RDB9-151, 2500 ft. elev.
17. RDB9-153. Flow under RDB9-152. Lowest flow exposed. 2460 ft. elev.

18. JA79-116. 1080 ft. elev., SE 1/4 NE 1/4 SE 1/4 sec. 24, T. 6 N. R. 16 E.
19. JA79-207. Road level, SE 1/4 SW 1/4 SW 1/4 sec. 24, T. 6 N., R. 13 E.

Table 3. Representative chemical analyses of the Wanapum Basalt on the Yakima Indian Reservation, Washington.
Analyses in weight percent. Samples analyzed by X-ray fluorescence techniques at Washington State University under the direction of P. R. Hooper. Value of Fe_2O_3 arbitrarily set at 2.00 wgt. percent; for comparison with analyses giving total iron as FeO, as in Swanson and others (1979a), add 1.8 (i.e., 2.00 x .9) to value of FeO given below.

	Priest Rapids Member					Frenchman Springs Member		
	1	2	3	4	5	6	7	8
SiO_2	49.99	50.16	49.63	49.67	49.69	51.02	51.12	50.68
Al_2O_3	14.12	14.14	13.66	13.71	13.68	14.00	14.13	13.87
Fe_2O_3	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
FeO	12.18	11.95	13.57	13.41	13.55	12.82	12.78	13.23
MgO	5.37	5.27	4.61	4.60	4.33	4.35	4.21	4.58
CaO	8.85	9.16	8.29	8.48	8.74	8.37	8.24	8.41
Na_2O	2.37	2.24	2.65	2.46	2.47	2.39	2.45	2.49
K_2O	1.10	1.01	1.23	1.33	1.05	1.30	1.25	1.11
TiO_2	3.13	3.15	3.50	3.45	3.58	2.95	3.04	2.92
P_2O_5	0.67	0.68	0.63	0.65	0.66	0.53	0.54	0.48
MnO	0.23	0.24	0.24	0.24	0.25	0.28	0.24	0.23

Sample number and location

Lolo chemical type
1. RDB9-117. 1580 ft. elev., center of NE 14 sec. 3, T. 8 N., R. 18 E.
2. RDB9-121. Roadcut at 2200 ft. elev., SE 1/4 NW 1/4 sec. 34, T. 8 N., R. 18 E.

Rosalia chemical type
3. JA79-093. 100 ft. above Satus Creek, SW 1/4 SW 1/4 NW 1/4 sec. 12, T. 6 N., R. 16 E.
4. RDB9-206. In canyon at 2660 ft. elev., NE 1/4 SE 1/4 sec. 13, T. 9 N., R. 17 E.
5. RDB9-120. Roadcut at 2180 ft. elev., SE 1/4 NW 1/4 sec. 34, T. 8 N., R. 18 E.

Flow of Union Gap
6. JA79-232. 1380 ft. elev., NW 1/4 NE 1/4 SW 1/4 sec. 14, T. 6 N., R. 13 E.

Flow of Kelley Hollow
7. JA79-118. 150 ft. above road, NE 1/4 SE 1/4 SW 1/4 sec. 14, T. 6 N., R. 13 E.

Flow of Ginkgo
8. JA 79-117. At road level below JA 79-118, NE 1/4 SE 1/4 SW 1/4 sec. 14, T. 6 N., R. 13 E.

Table 4. Representative chemical analyses of the Saddle Mountains Basalt on the Yakima Indian Reservation, Washington.

Analyses in weight percent. Samples analyzed by X-ray fluorescence techniques at Washington State University under the direction of P. R. Hooper. Value of Fe_2O_3 arbitrarily set at 2.00 wgt. percent; for comparison with analyses giving total iron as FeO, as in Swanson and others (1979a), add 1.8 (i.e., 2.00 x .9) to value of FeO given below.

	Elephant Mountain Member		Pomona Member		Umatilla Member	
	1	2	3	4	5	6
SiO_2	50.55	50.55	51.92	51.90	54.51	54.16
Al_2O_3	13.81	13.81	15.05	15.35	14.88	14.70
Fe_2O_3	2.00	2.00	2.00	2.00	2.00	2.00
FeO	13.19	13.51	8.65	9.06	9.84	11.02
MgO	3.81	3.92	6.50	6.66	2.71	2.90
CaO	8.93	8.48	10.79	10.47	6.46	6.05
Na_2O	2.28	2.34	2.35	2.04	2.84	2.60
K_2O	1.29	1.25	0.69	0.47	2.97	2.96
TiO_2	3.42	3.40	1.64	1.64	2.70	2.53
P_2O_5	0.49	0.50	0.23	0.24	0.85	0.86
MnO	0.24	0.24	0.18	0.17	0.22	0.22

Sample number and location

1. RDB9-89. Canyon floor, 1160 ft. elev., NE 1/4 SW 1/4 NW 1/4 sec. 2, T. 9 N., R. 19 E.
2. RDB9-156. 1100 ft. elev., SE 1/4 NW 1/4 sec. 17, T. 9 N., R. 20 E.
3. RDB9-216. Top of hill, 2770 ft. elev., SE 1/4 SE 1/4 NW 1/4 sec. 8, T. 9 N., R. 18 E.
4. DSTW79-14. Bluelight triangulation station, 2898 ft. elev., SW 1/4 SW 1/4 sec. 15, T. 7 N., R. 21 E.
5. RDB9-110. Top of nob, 2363 ft. elev., NE 1/4 SW 1/4 sec. 3, T. 9 N., R. 18 E.
6. DSTW79-13. Quarry just east of Mabton Road, 2790 ft. elev., SW 1/4 NW 1/4 sec. 21, T. 7 N., R. 21 E.

Table 5. Representative chemical analyses from Pliocene and lower Quaternary volcanic rocks of map unit QTb on the Yakima Indian Reservation, Washington. Analyses in weight percent. Samples analyzed by X-ray fluorescence techniques at Washington State University under the direction of P. R. Hooper. Value of Fe_2O_3 arbitrarily set at 2.00 wgt. percent.

	1	2	3	4	5	6	7	8
SiO_2	51.06	49.97	51.07	50.94	50.72	47.94	48.69	52.08
Al_2O_3	16.10	16.57	16.09	17.02	16.38	16.61	17.03	16.90
Fe_2O_3	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
FeO	9.26	9.51	8.97	8.46	9.11	12.37	10.86	10.68
MgO	8.77	7.98	7.00	6.43	6.30	5.25	5.56	3.07
CaO	8.33	8.57	9.28	10.19	10.19	7.04	7.69	5.24
Na_2O	2.06	2.67	2.84	2.65	2.52	3.06	3.13	3.73
K_2O	0.63	0.82	0.79	0.74	0.38	1.65	1.46	2.91
TiO_2	1.43	1.47	1.56	1.14	1.97	3.24	2.84	1.94
P_2O_5	0.20	0.26	0.23	0.19	0.28	0.62	0.54	1.19
MnO	0.17	0.18	0.18	0.23	0.15	0.22	0.19	0.24

Sample number and location

1. JA79-137. Roadcut, 1950 ft. elev., SE 1/4 SE 1/4 SE 1/4 sec. 36, T. 7 N., R. 13 E.
2. JA79-133. Erosionally overlies JA79-134. 1700 ft. elev., NE 1/4 SE 1/4 NW 1/4 sec. 14, T. 6 N., R. 13 E.
3. DSTW79-29. Head of Cultus Hole, 5940 ft. elev., NE 1/4 NW 1/4 sec. 1, T. 11 N., R. 13 E.,
4. DSTW79-24. Roadcut, 4060 ft. elev., SE 1/4 SW 1/4 sec. 23, T. 11 N., R. 13 E.
5. JA79-058. Base of cliff south of Satus Creek, NW 1/4 SE 1/4 sec. 11, T. 6 N., R. 17 E.
6. JA79-136. Roadcut, 2140 ft. elev., center of SE 1/4 NE 1/4 sec. 11, T. 6 N., R. 13 E.
7. JA79-150. Roadcut, 2200 ft. elev., SW 1/4 SW 1/4 SW 1/4 sec. 8, T. 6 N., R. 14 E.
8. JA79-097. Roadbed west of stream crossing, SE 1/4 SW 1/4 sec. 4, T. 6 N., R. 15 E.

APPENDIX

DESCRIPTION OF MAP UNITS IN PLATE 1

Qs

STREAM, COLLUVIUM, AND ALLUVIAL FAN DEPOSITS--Alluvium, primarily unconsolidated clay, silt, sand, and gravel of floodplains, terraces, and valley bottoms. Contains local lacustrine, paludal, and eolian deposits. Includes relatively undissected alluvial fans of Toppenish and Ahtanum Ridges. Most deposits exhibit little or no calcrete or other types of cementation. Includes talus formed by active and inactive rock fall and colluvium with primarily angular and subangular basaltic debris at base of steep slopes and cliffs. Includes morainal and glacial outwash debris in upper Klickitat River valley. In upland regions, unit mapped only where important bedrock relations are obscured

TERRACE DEPOSITS--Mostly sand and gravel with lenses of silt and clay in terrace remnants adjacent to Yakima River in Toppenish Valley. Unconsolidated with little or no caliche cap but may be mantled by loess and soil. Subdivided into two units:

Qst

Mainstream facies--Contains pebbles of basaltic andesite and other lithologies derived from headwaters of Yakima River off the Columbia Plateau

Qsts

Sidestream facies--Composed of well-rounded pebbles of basalt of local derivation. Unit Qs may contain similar terrace deposits in upper Toppenish and Medicine Creek Valleys

Ql — LOESS--Eolian silt with small amounts of fine sand. Includes lenses of volcanic ash and locally colluvium and alluvium. Commonly composed of reworked material of unit Qss. Mapped as separate unit only where thicker than 2 m in Toppenish Valley and adjacent lowlands. Unit not mapped separately but is extensive in Satus lowland between Toppenish Ridge and Horse Heaven Hills. May include deposits as old as Pliocene

Qss — SLACK-WATER SEDIMENTS OF CATASTROPHIC FLOODS--Touchet beds of Flint (1938) and related glaciofluvial deposits. Rhythmically bedded and graded silt, sand, and gravel deposited by low energy side channel slack waters of catastrophic Missoula (Spokane) floods. Generally light gray to white silt with lenses of fine clay and sand. Laminated layers show undulations. Commonly contains doublet layer of Mount St. Helens tephra (set S), about 12,000 yrs old, in upper five meters. Contains lenses and irregular deposits of ice-rafted erratics and coarse sand and gravel. Cut by clastic dikes and covered by loess and soil. Deposits are as much as 10 m thick up to 1,080 ft elevation, but are only a few meters thick and indistinct between 1,080 and 1,150 ft elevation. Absent above about 1,150 ft.

Qls — LANDSLIDE DEPOSITS--Poorly sorted, non-stratified, chaotic deposits formed by landslides, debris flows, and other types of mass movement. Locally includes talus, loess, alluvial fan, and young stream deposits. Surface of most deposits is hummocky, with large blocks of rotated and translated basalt downslope from amphitheater-shaped scars. Moats at head and margins of deposits are common

Qba BASALT AND ANDESITE--Flows and thin tuffs erupted from Mount Adams, the King Mountain fissure zone, and other volcanoes and fissures in Cascade Range. Generally olivine bearing and diktytaxitic. Plagioclase phenocrysts several millimeters long present in some flows. See Hamm (1980) for subdivision of unit

QTg GRAVEL--Older Pleistocene, Pliocene, and late Miocene(?) gravel and sand with lenses of silt, tephra, loess, and colluvium. Composed of rounded to subangular fragments of basalt. Commonly capped by calcrete 0.2 to 10 m thick and weakly cemented by iron oxides. Pebbles of basalt are weathered to different degrees depending on size, degree of cementation, and relative age. Some gravel may have been deposited in alluvial fans, and other gravel in sidestream facies of small streams. Undeformed except along north slope of Toppenish Ridge

QTb OLIVINE BASALT--Flows and tuffs, chiefly of high alumina olivine basalt but including small volumes of andesite, dacite, and rhyolite. Erupted from the Simcoe Mountains volcanic area (Sheppard, 1967) and other vents in western part of mapped area. May be age equivalent of some basalt and andesite of unit Qba. Includes thin silicic welded ash-flow tuff northeast of mouth of Piscoe Creek and above East Fork of McCreedy Creek. Potassium-argon ages of flows from Simcoe Mountains volcanic area range from 0.9 to 4.5 m.y. (Kienle and Newcomb, 1973)

ELLENSBURG FORMATION--Weakly lithified sedimentary rocks interbedded with and overlying Columbia River Basalt Group. Mapped only where thickness permits. Thin interbeds common between many flows of Wanapum and Grande Ronde Basalts but not distinguished in mapped area. Subdivided into three map units:

Tse Ellensburg Formation Undivided--Volcaniclastic deposits consisting of well to poorly sorted andesitic to rhyolitic debris erupted in Cascade Range and transported into area by streams, mudflows, and wind. Locally derived basaltic conglomerates and sandstones interbedded with volcaniclastic deposits in places. Contains rocks probably equivalent in age to both units Tser and Tss, but may include both older and younger deposits, perhaps correlative in part to gravel of unit QTg

Tss Conglomerate of Snipes Mountain--Weakly consolidated river gravel and sand containing abundant quartzite clasts. Contains rare laharic deposits and floodplain silts and sands in lower part of sequence. Interpreted as channel and overbank deposits of ancestral Columbia River

Tser Rattlesnake Ridge Member of Schmincke (1967a)--Volcaniclastic deposits composed of well to poorly sorted andesitic to rhyolitic debris erupted in Cascade Range and transported into mapped area by water, mudflows, and wind. Much of member is siltstone and claystone interpreted as floodplain deposit of ancestral Columbia or Yakima River.

YAKIMA BASALT SUBGROUP OF COLUMBIA RIVER BASALT GROUP

SADDLE MOUNTAINS BASALT

Tem Elephant Mountain Member--Nearly aphyric basalt flows of Elephant Mountain chemical type (Wright and others, 1973). Normal to transitional magnetic polarity (Rietman, 1966; Choiniere and Swanson, 1979). Potassium-argon age about 10.5 m.y. (McKee and others, 1977)

Tp Pomona Member--Slightly phyric basalt flow of Pomona chemical type (Wright and others, 1973). Contains small phenocrysts of plagioclase, clinopyroxene, and olivine. Reversed magnetic polarity (Rietman, 1966; Choiniere and Swanson, 1979). Potassium-argon age about 12 m.y. (McKee and others, 1977)

Tu Umatilla Member--Fine-grained basalt flow of Umatilla chemical type (Wright and others, 1973). Typified by very even grain size and near lack of phenocrysts. Normal magnetic polarity (Rietman, 1966)

WANAPUM BASALT

Tpr Priest Rapids Member--Fine- to coarse-grained basalt flows with reversed magnetic polarity (Rietman, 1966). Uncommon plagioclase phenocrysts 2-4 mm across. Includes flows of both Lolo (Wright and others, 1973) and older Rosalia (Swanson and others, 1979a) chemical types

Tr Roza Member--Basalt flow that consistently contains several per cent of single, rarely clotted, plagioclase phenocrysts averaging nearly 1 cm across and evenly distributed throughout flow. Roza chemical type (Wright and others, 1973). Transitional magnetic polarity Rietman, 1966) although generally overprinted by present normal magnetic field

Tf — Frenchman Springs Member--Highly plagioclase-phyric to aphyric basalt flows of Frenchman Springs chemical type (Wright and others, 1973). Normal magnetic polarity (Rietman, 1966). In places subdivided into four units:

Tfu — Flows of Union Gap--Very sparsely phyric, fine- to medium-grained basalt. One to three flows in Union Gap area, but one thick flow elsewhere. Probably equivalent to Sentinel Gap flow of Mackin (1961)

Tfk — Flow of Kelley Hollow--Moderately phyric flow with extremely variable abundance of plagioclase phenocrysts locally. One thick, coarse-grained flow over most of mapped area. Sedimentary interbed too thin to show on map commonly occurs above and below unit

Tfs — Flow of Sand Hollow (Mackin, 1961)--Aphyric fine-grained basalt. In mapped area, occurs only near Union Gap

Tfg — Flows of Ginkgo (Mackin, 1961)--Abundantly phyric flows in lower part of member. One or two coarse-grained flows over most of eastern part of outcrop area. Thin sedimentary interbed (Vantage Member of Ellensburg Formation) locally present at base of unit; too thin to show on map

GRANDE RONDE BASALT--Basalt flows, aphyric to very sparsely plagioclase phyric, generally fine-grained and petrographically nondistinctive. Upper flows in area commonly coarser-grained than lower flows. Chemical composition varies within broad field termed Grande Ronde chemical type (formerly called Yakima chemical type by Wright and others, 1973). Single flows from 5 to 60 m thick; generally about 20-30 m. Invasive flows (Byerly and Swanson, 1978) common in western part of area. Divided into three magnetostratigraphic units on basis of dominant magnetic polarity:

Tgn_2 — Upper flows of normal magnetic polarity--Magnetostratigraphic unit N_2 of Swanson and others (1979a). Subdivided in places into two units:

Tgn$_2$h Upper N_2 flows--Two to seven flows. Generally medium grained and commonly slightly plagioclase phyric, with phenocrysts 3-5 mm long. Many flows exhibit single tier of columnar joints and weather orange-red. Hackly flows rare. All flows analyzed are of high-MgO Grande Ronde chemical type. Sedimentary interbeds locally

Tgn$_2$l Lower N_2 flows--Two to four flows. Fine grained, dense, aphyric flows commonly having a thick hackly entablature above a thin colonnade. All flows analyzed are of low-MgO Grande Ronde chemical type. Fine-grained tuffaceous and subarkosic interbeds common above and below this unit, but invasive relations disrupt their continuity, and none was mapped. Distinction between units Tgn$_2$h and Tgn$_2$l was not made in western part of mapped area, where single flows have a wide range of grain size and jointing characteristics, apparently caused by interaction of flows with water and sediment during emplacement and cooling of the flows

Tgr$_2$ Flows of reversed magnetic polarity--Magnetostratigraphic unit R_2 of Swanson and others (1979a). Three to five flows of fine- to medium-grained aphyric basalt. Locally contains amygdules of chalcedony and other secondary minerals. Mostly of low-MgO Grande Ronde chemical type. High-Al_2O_3 flows of possible local origin occur in lower Klickitat River Valley. Commonly weathered more extensively than overlying flows. Contains several unmapped interbeds

Tgn$_1$ Lower flows of normal magnetic polarity--Magnetostratigraphic unit N_1 of Swanson and others (1979a). Low-MgO Grande Ronde chemical type

Tov OLIGOCENE VOLCANIC ROCKS--Flows, tuffs, and breccias, mostly basalt and andesite, in Ohanapecosh Formation(?). Generally zeolitized. May include lower Miocene volcanic rocks in places