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FOREWORD

Ever since our Reprint 9, "Mineral and Water Resources of Washington," went out of print a few years ago, we have needed a report to present an overview of the geology of Washington State. In recent years, the need has become so great that we decided to simply reprint the Geology section from Reprint 9 and publish it under a separate cover. When the geology section of the report was originally prepared, several U.S. Geological Survey geologists were given the responsibility of writing about the areas of the state where they had worked and with which they were familiar. As a consequence, the Geology section was prepared by a cadre of experts. Since this report was done originally in 1966 there has been much new work done in the state that would add more detail to the structure and stratigraphic nomenclature. In fact, there are some areas, such as the Olympic Mountains, where new age determinations have changed the stratigraphy drastically. Nevertheless, the lithologies and structures remain the same and only the determination of when and how they were formed has changed. In spite of this problem, Reprint 12 still probably represents the best short geologic overview of the state that exists.

Because this report is lifted in toto (except for the list of references) from Reprint 9 and much of the introductory material in Reprint 9 had no bearing on the geology, the extraneous material has been excluded. Because the excluded material amounted to several pages, this report starts with page 13. The list of references has been redone so that it contains only the references that were cited in the Geology section.

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GEOLOGY

INTRODUCTION

(By A. E. Weissenborn, U.S. Geological Survey, Spokane, Wash.)

Washington is familiarly known as the Evergreen State, but it might as aptly be termed the Land of Contrast. Within the State, rainfall varies from more than 200 inches annually in the Olympic Mountains to less than 10 inches in parts of eastern Washington. The lush forests of northern and western Washington contrast sharply with the barren, forbidding scablands of central Washington and the treeless wheat fields of the Palouse Hills; the towering, rugged Cascades contrast with the coulees and flat, basalt-covered mesas of central Washington and the level farmlands in the Puget Lowlands north of Seattle; the snow-capped volcanoes that crown the Cascades contrast with the magnificent beaches that stretch for miles along the Pacific Coast.

Washington's 68,192 square miles fall into seven distinct physiographic divisions. These are the Okanogan Highlands, the Columbia Basin, the Blue Mountains, the Cascade Mountains, the Puget Lowlands, the Olympic Mountains, and the Willapa Hills (fig. 1). Each of these areas differs from the others in climate, topography, and the natural resources that are available within it. These differences profoundly influence the economic life of the more than 2.8 million people who live within the boundaries of the State. These differences, in turn, are in very large part but a reflection of differences in the geology of each area. Natural resources and geology walk hand in hand. Therefore this volume, which discusses the mineral and water resources of Washington, begins with a summary of the geology of the State.

Our knowledge of the geology of Washington is derived from the findings of many geologists working over a period of many years, beginning back in the 1880's when Washington was still frontier country. Some of the early work of the U.S. Geological Survey was done in Washington, and geological mapping by this organization is still going on in many places in the State. The State of Washington Division of Mines and Geology—and its predecessor, the Washington Geological Survey—has actively been engaged in studying the geology and mineral resources of the State since the early 1900's and has produced a wealth of knowledge. Work done under the auspices of the University of Washington, Washington State University, and other universities has made important contributions to the knowledge of the geology, particularly in the Cascade Mountains.

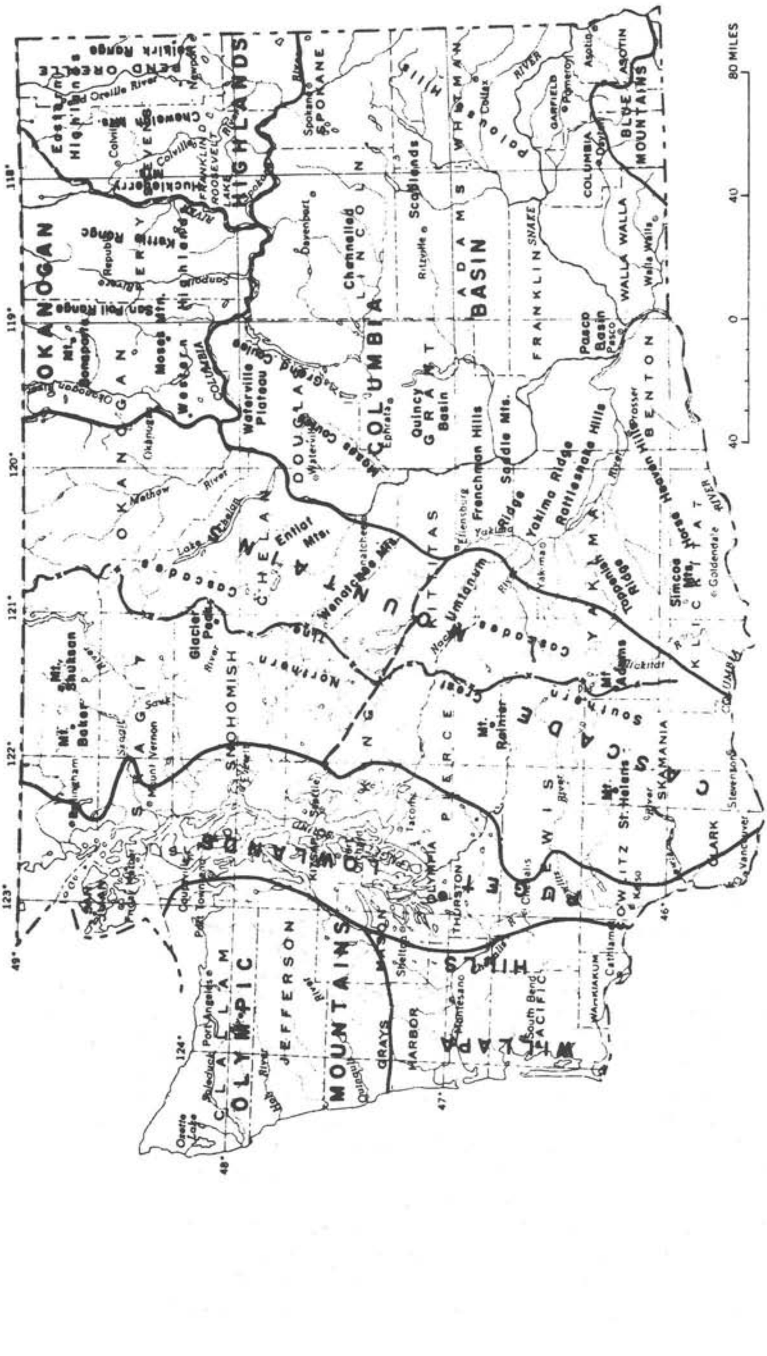


FIGURE 1.—Physiographic divisions of Washington.

Geologists from industry, searching for metallic and nonmetallic minerals as well as petroleum and natural gas, have likewise made many contributions to our knowledge of the geology of the State. Figure 2 shows the areas in the State covered by published geological maps from all sources. A number of other areas have been mapped geologically. Figure 2, however, includes only published geological mapping and does not include a considerable amount of work that has not yet been published.

Although there are a few critical areas where geological information is almost completely lacking, figure 2 indicates that the greater part of the State has been mapped geologically. However, published maps, on what by modern standards would be considered an adequate scale, are available only for the much smaller stippled areas of figure 2. Clearly, much remains to be done before it can be considered that the geology of the State is adequately known—or even as adequately known as that of its neighboring States.

Topographic maps are essential for many purposes such as recreational, industrial, and highway construction but are especially essential as bases on which to plot the geology and other data. Figure 3 shows the areas in the State which have been mapped topographically. Some critical areas from the standpoint of mineral and water resources still lack topographic maps, but because of intensive work during the past few years topographic map coverage for most parts of the State is well advanced—far ahead of the geologic mapping.

The following discussion of the geology of Washington is divided into four sections: northeastern Washington; the Columbia Basin, including the Blue Mountains; the Cascade Mountains; and western Washington. The geology of each of these sections is summarized with the intent of providing a background for the remainder of the report. As with other sections, bibliographic references are given for the benefit of those readers who wish more detailed information than can be included in these necessarily brief accounts. As an aid in following the geological discussion, the reader is referred to figure 4, a highly generalized map of the geology of Washington.

NORTHEASTERN WASHINGTON

(By R. G. Yates, U.S. Geological Survey, Menlo Park, Calif.)

Northeastern Washington, as defined here, includes Pend Oreille, Stevens, Ferry, eastern Okanogan, and northern Spokane Counties. It comprises less than 15 percent of the State's area, but from its mines comes over 90 percent of the State's metal production. It is, therefore, not surprising that the geologic setting of this part of the State is uniquely different from that of the remainder. Mountainous in character, it contrasts sharply with the smooth undulations of the Columbia Plateau to the south, but much less sharply with the higher and more rugged Cascade Mountains, which lie to the west. Likewise, its geology merges with the geology of the Cascades, but contrasts strongly with that of the Columbia Plateau.

This area, which lies east of the Okanogan River and north of the west-flowing stretch of the Columbia and its tributary, the Spokane,

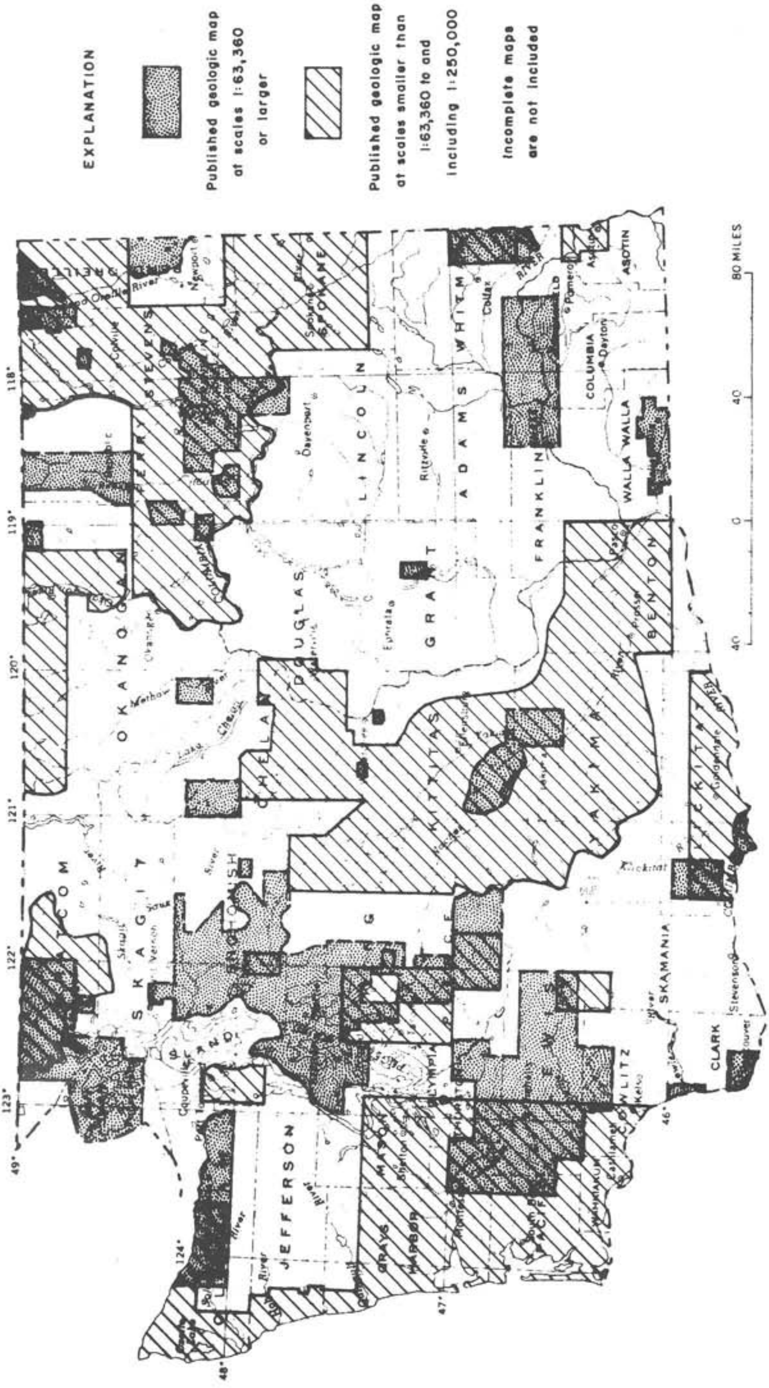


FIGURE 2.—Published geologic mapping in Washington.

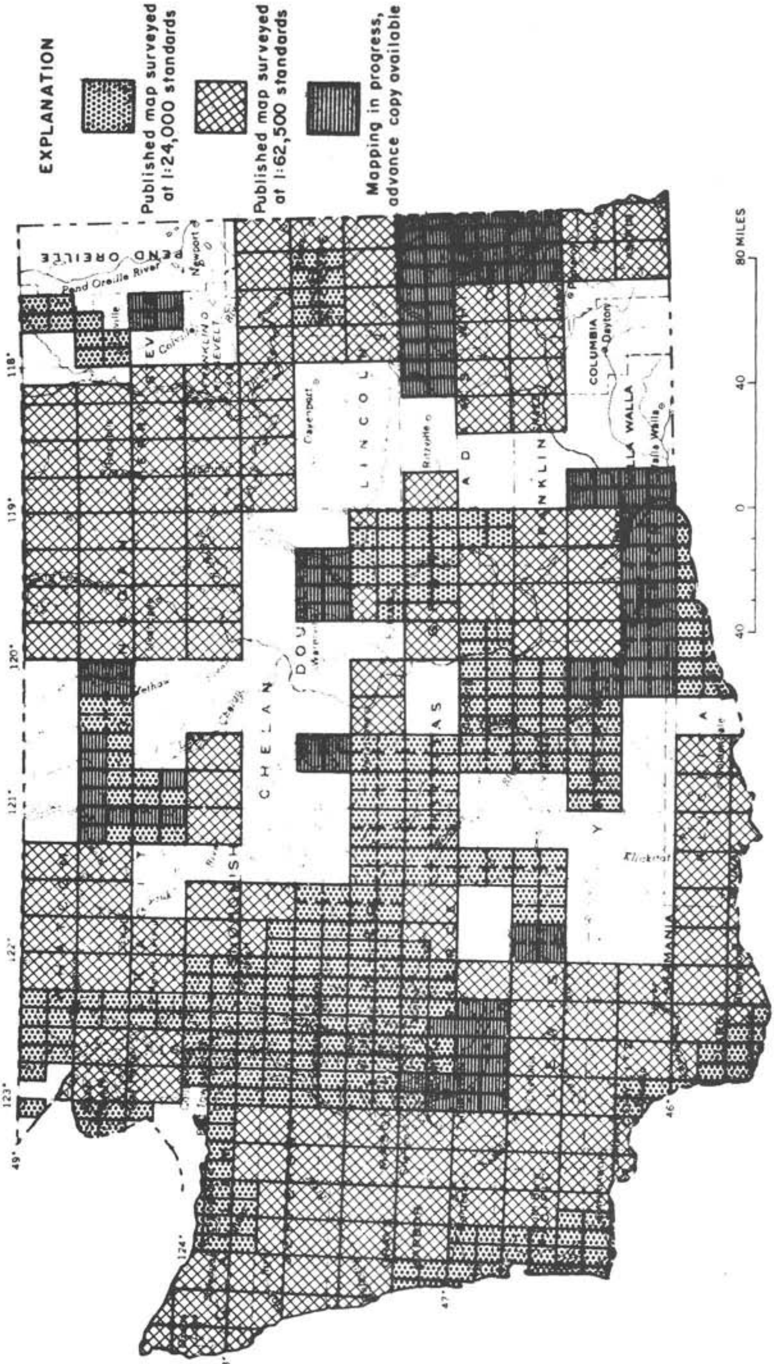


FIGURE 3.—Status of topographic mapping in Washington.

in places rises as much as 5,000 feet above the surface of the plateau. The area is commonly known as the Okanogan Highlands (fig. 1). In a general way, the Columbia River divides the Highlands into two geographic parts: east of the river are the Selkirk, Chewelah, and Huckleberry Mountains; west of the river are the Kettle, Sanpoil, and other ranges. The mountains, however, lack any orderly arrangement that would make it possible to separate them into a system of ranges and valleys. They appear to be crowded together, with little room for the narrow, south-trending valleys of the Columbia, Okanogan, Sanpoil, and Pend Oreille Rivers that drain northeastern Washington.

All the drainage from the area reaches the Pacific Ocean via the Columbia River, but some tributaries follow rather devious courses to reach the master stream. The Okanogan and Sanpoil Rivers behave as normal, orderly streams and flow directly south to join the Columbia in the shortest possible distance. But not so with the Pend Oreille and Kettle Rivers. The Pend Oreille swings northward in a wide arc to join the Columbia in British Columbia; the Kettle also selects a very circuitous route, as if it were making great—but futile—efforts to avoid a junction with the Columbia. Such irregularities reflect, in part, changes in the drainage pattern brought about by the great ice sheets that advanced southward during the Pleistocene epoch. The ice moved down the river valleys in great lobes that grew and coalesced to form a thick sheet that covered almost the entire area. As the climate warmed, the ice retreated northward, and lakes formed in the valleys of the Columbia and Pend Oreille Rivers and their tributaries. The melt waters of the swollen rivers, milky with suspended clay and fine silt, swept southward the sand and gravel that had been left by the ice, to deposit it and the suspended clay and silt in the slack waters of the lakes. Deposits of horizontal-layered silt, clay, and sand on the lower slopes of the valleys preserve the outlines of these ancient lakes. Near the International Boundary, terrace features indicate that the last high level of the lake in this valley was at an elevation of about 2,000 feet. The numerous steplike terraces along the valley walls of the Columbia River represent successive lower levels of the lake or lakelike river that succeeded the lake. The higher slopes and even the peaks near the Canadian border likewise were covered with the wastes of the glaciers; even today, deposits of gravel and sand, from a few to several hundred feet thick, and stray exotic boulders cover more than half the area of the mountain slopes. This extensive cover of ice-transported material greatly handicaps the interpretation of the bedrock geology, as well as increasing the difficulty of the discovery of mineral deposits.

Enough bedrock does extend through this mantle to demonstrate clearly that the sedimentary rocks in the eastern Okanogan Highlands record a different geologic history from those in the western Highlands.[1] The difference is not only in the age of the rocks, but in the conditions under which they accumulated. The oldest rocks in the State with well-established ages are east of the Columbia River. Most of these can be demonstrated to lie below the rocks that contain

[1] This division of two different groups of rocks, one in the eastern and the other in the western Okanogan Highlands, is only a broad generalization. The boundary between the two groups only approximates the course of the Columbia River. From the mouth of the Spokane River to Evans it is a few miles east of the river; from Evans to Northport it is west of the river; and from Northport to the International Boundary it is again east of the river.

fossils of Early Cambrian age. (The Cambrian is the earliest period of geologic time that can be identified by the kind of fossilized life preserved in the rocks.) These older rocks are of four categories: (1) Belt Series rocks, which are widespread in Idaho and Montana, (2) rocks similar to, but not identical with, the Belt Series, (3) rocks younger than the Belt Series, but older than Cambrian in age, and (4) gneisses of unknown Precambrian age. The Belt Series consists mainly of quartzite, argillite, and impure dolomite that were deposited in a slowly sinking basin whose western limit was probably somewhere in eastern Washington. They are not known to occur more than a few miles west of Pend Oreille County (Schroeder, 1952). Rocks that may be contemporaneous with the Belt Series occur in a south-southwest-trending belt near Chewelah and contain the famous magnesite deposits (Bennett, 1941; Campbell and Loofbourow, 1962; Campbell and Raup, 1964). The names of these formations are shown on figure 5. These are similar to Belt rocks in many respects but have more argillite and less quartzite; they may be representatives of an otherwise little-known part of the Belt depositional basin. Rocks of category 3 (Park and Cannon, 1943; Campbell and Raup, 1964), known in southern British Columbia as the Windermere Series, are a sequence of thick conglomerates and basaltic lavas that rest on the eroded edges of the older Precambrian rocks. Rocks of category 4 occur in the southeastern part of the area north of Spokane. Opinions differ on the age of these gneisses; some believe they are Belt rocks that were metamorphosed at depth under high temperature and pressure and have since been elevated to their present position by faulting; others believe they are very ancient rocks, much older than the Belt rocks, and form the basement upon which the Belt rocks were deposited.

In the eastern Highlands, all periods of the Paleozoic Era are represented by marine sedimentary rocks. The general sequence of Cambrian deposition began with sandstone (now quartzite), followed by shales (phyllites), limestones, and dolomites (Campbell and Raup, 1964; Campbell, 1947; Park and Cannon, 1943; Yates, 1964) (fig. 5). The Cambrian limestones and dolomites are hosts to the important lead-zinc deposits of Pend Oreille and Stevens Counties. By the beginning of the Ordovician Period, the carbonate deposition of the Cambrian had ended abruptly, and black muds, which were to become slates and argillites, were deposited over a wide area. The deposition of these black muds continued through the Ordovician, Silurian, and Devonian Periods, and very likely into the Mississippian (Dings and Whitebread, 1965). During Devonian time, conditions in the sea changed enough locally to permit the growth of reef-building organisms that resulted in the formation of lenses of limestone. These are found in northern Pend Oreille County in the Metaline area (fig. 5). Once again—probably during the Mississippian Period, and also in the Metaline area—the deposition of black muds was interrupted, and beds and lenses of coarse angular pebbles and cobbles were deposited. This change in sediments indicates a change in the character of the source area from which they were derived. In this case, a not-too-distant part of the sea floor was uplifted to a position where it could be eroded.

This is essentially the end of the record of Paleozoic deposition in the eastern Okanogan Highlands. For the record of the younger rocks

Republic area[1]		
Quaternary	Unconsolidated glaciofluvial deposits	
Miocene(?)	Klondike Mountain Formation	Basalt flows
		Volcanic conglomerate, breccia, and sandstone
Oligocene		Tom Thumb Member "lake beds"
Eocene	Sanpoil Volcanics	
	O'Brien Creek Formation--tuffs and conglomerate	
Permian	Greenstone, graywacke, argillite, and phyllite	
Pre-Permian	Phyllite, schist, and marble	

1/ Generalized after S. Muessig (1959).

2/ Modified after Park and Cannon (1943).

3/ Campbell and Raup (1964).

Northern Pend Oreille County (Metaline quadrangle)[2]	
Pleistocene	Glacial deposits
Tertiary	Tiger Formation (conglomerate and shale)
Devonian	Limestone and shale
Silurian	Slate
Ordovician	Ledbetter Slate
Cambrian	Metaline Limestone
	Maitlen Phyllite
	Gypsy Quartzite
	Monk Formation (phyllite)
?	
Precambrian	Leola Volcanics
	Shedroof Conglomerate
	Priest River Group (Belt Series?) (phyllite and quartzite)

Southern Stevens County (Hunters quadrangle)[3]	
Quaternary	Glacial deposits
Tertiary	Gerome Andesite
Farly Mesozoic(?)	Covada Group (greenstone and graywacke)
?	
Paleozoic	Slate and siltite
	Chert
?	
Ordovician	Limestone and slate
	Chert
Cambrian	Old Dominion Limestone
	Addy Quartzite
Precambrian	Huckleberry Formation (greenstone and conglomerate)
	Buffalo Hump Formation (argillite and quartzite)
	Stensgar Dolomite
	McHale Slate
	Edna Dolomite
	Togo Formation (argillite)

FIGURE 5.—Stratigraphic names in common use in northeastern Washington.

(Becraft, 1964; Campbell and Raup, 1964; Mills and Davis, 1962; Muessig, 1959; Parker and Calkins, 1965, Staatz, 1964; Waters and Krauskopf, 1941), we must go to the western Highlands, where fossils identify rocks that range in age from Mississippian to Cretaceous (fig. 5). The rocks in this section were also deposited in marine waters but under quite different conditions. They accumulated in an area of active volcanism, where the earth's crust was unstable and depth of water and shapes of the basins of deposition were constantly changing. Such an environment is known as eugeosynclinal and is identified by the distinctive group of rocks that accumulate within it. These rocks are graywackes (dark-colored "dirty" sandstones), lenses of thin-layered chert, beds of conglomerate, small pods and reeflike bodies of limestone, and lava flows and tuffs (fragmental volcanic material) of basaltic and andesitic composition.

The boundary between this eugeosynclinal assemblage of rocks and the older nonvolcanic Paleozoic rocks to the east appears to be everywhere a fault boundary; consequently, the depositional relations between these two groups of rocks have not yet been observed. It is probable, however, that the rocks west of the Columbia River are also underlain by older Paleozoic rocks that are very likely quite different from those exposed east of the river.

The interval of time between the middle of the Jurassic and the middle of the Cretaceous Periods, about 65 million years, is without a sedimentary record in northeastern Washington. During this time the rocks of Jurassic and earlier age were folded and faulted, and were also invaded, thousands of feet below the surface, by great masses of molten rock that slowly crystallized to form the granitic batholiths. After the batholiths had congealed into masses of coarsely crystalline rock, all of northeastern Washington was elevated, and as it was elevated it was eroded. Erosion was vigorous enough to expose the batholiths before the end of the Cretaceous Period.

This elevation or uplift of northeastern Washington was doubtless far from uniform. In early stages of the uplift, the earth's outer crust was cracked and broken into fault blocks. Some blocks were elevated more rapidly than others; these became mountains, and other blocks that were elevated less rapidly became temporary storage basins for the waste that was being shed from the "mountain blocks." Some of this waste is as old as the Late Cretaceous and is largely pebbles, cobbles, and boulders of the rock types no longer occurring in the area. The differential movement of the basin blocks was accompanied by the migration of molten rock, or magma, which, moving upward along the faults, reached the surface and spread out as lava flows that accumulated on the floors of the basins.

One of these "collecting basins" is the Republic graben (Staatz, 1960), an elongated downfaulted block that extends from Nespelem to Danville. This graben, which began to be filled early in the Eocene, has a well-preserved record of early Tertiary events. One of the later Tertiary events was the formation of the gold deposits of the Republic and Orient districts. The first material added to the graben was coarse gravel and boulders derived from the highlands on either side of the graben. These were buried by great thicknesses of lavas of intermediate composition, which in turn were covered by fine-grained sediments deposited in temporary lakes within the graben and then by still more lava flows and fragmental volcanic rocks. All in all, these lavas, tuffs, and lake sediments have a thickness in excess of 15,000 feet. Since it is extremely unlikely that these rocks accumulated in a gorge 15,000 feet deep, it can be confidently inferred that the graben floor subsided as they accumulated. Some magma, intruded during the late stages of graben growth, never reached the surface, but forced aside the early deposited lava flows and crystallized as granitic rock. The volcanic activity in the downdropped blocks appears to have ended before Miocene or late Pliocene times, when basalts of the Columbia Plateau lapped up on the south edge of the area.

The mountain-building and igneous activity that began in the Middle Jurassic and continued into the early Tertiary left a pattern firmly impressed in the rocks. In the eastern Okanogan Highlands, the layered rocks were tightly bent into folds whose axes trend northeasterly and extend into British Columbia, where they gradually change their trend to merge with the northwesterly continental trend. This belt of northeast-trending folds is called the Kootenay Arc. As these rocks were folded, they were also faulted along northwesterly directions as well as along the northeasterly trend of the folds. In the eastern part, the folding ceased before the Cretaceous granitic rocks were intruded, but farther west in the Okanogan Valley folding appears to have accompanied intrusion. By the end of the Cretaceous Period, the compressive stresses that produced the folds in northeastern Washington appear to have terminated, although they continued to the west in the Cascade Mountains. The folds in the western Okanogan Highlands are of northwesterly trends, conforming with those in the northern Cascades but contrasting with the northeasterly trends of the Kootenay Arc. Folds of both northeast and northwest trends, as well as intermediate north trends, occur in the valley of the Columbia River.

The information used in compiling this résumé of the geology of northeastern Washington was drawn largely from published reports on individual areas. The references cited are far from a complete bibliography, but were selected to give the interested reader an opportunity to expand his knowledge of the area from a fair sample of the more recent or more easily available published reports.

COLUMBIA BASIN

(By A. B. Griggs, U.S. Geological Survey, Menlo Park, Calif.)

In Washington the Columbia Basin occupies most of the area east of the Cascade Range to the Idaho border and south from the east-west course of the Columbia River and its tributary, the Spokane River, to the Oregon border. The Basin province encompasses all of this southeastern part of the State except for the southeast corner, where the Blue Mountains extend northeastward into Washington. Flows of basaltic lava flooded this entire area on a grand scale, forming a lava plain that has been modified by regional downwarping, so that it now has the general aspect of a structural basin centered in the Pasco area. On the west, north, and east the basin area is ringed by mountainous country; to the south it continues for many miles into Oregon. At the margins the top of the basalt lies between altitudes of 2,500 and 3,000 feet, except where arched into ridges, and from these margins the terrain slopes toward the Pasco Basin, where the low point is about 400 feet above sea level and the top of the buried basalt is about 200 feet below sea level. Much of the drainage is controlled by these centripetal slopes. Marked exceptions are the two major streams, the Columbia and Snake Rivers, upon whose courses the surface configuration has had little or no effect. The western side has been significantly modified by the arching of the flows into a series of west- to northwest-trending anticlinal ridges. These attain heights of more than 1,500 feet above the adjacent valleys and are as much as 100 miles long. The more prominent of these are the Horse Heaven Hills, Rattlesnake Hills, Saddle Mountains, and Frenchman Hills.

The Blue Mountains are part of a mountainous complex making up a separate geomorphic province that lies mostly within northeastern Oregon. Within Washington the Blue Mountains are a broad northeast-trending, basalt-covered, anticlinal arch which attains altitudes over 6,000 feet. These mountains are now mostly a region of deep, rugged canyons which in places have cut through the basalt to the underlying rocks. The canyons are separated by narrow, flat-topped basalt ridges and are in considerable contrast to the lower rolling hill surface of the plateau area to the north and west. Because they occupy only a small area of Washington, the Blue Mountains are discussed here with the Columbia Basin.

The absence in the Columbia Basin of any exposures of prebasalt rocks, except around the periphery, is indicative that the early flows spread out over a terrain of only moderate relief. The flows slowly covered larger and larger areas encroaching on the surrounding mountains, and as they built up, numerous drainage channels were dammed and lake and stream sediments accumulated in an interfingering relation with the flows. As the accumulation of basalt flows became thicker, general subsidence of the area began and continued intermittently, probably even to the present. After the basalt eruptions ceased, the group of anticlinal ridges of northwest to west trend formed along the western side of the basalt plain. Starting before, and continuing as the ridges developed, volcanic debris was washed down from the Cascade Range to blanket the western margin and then partially fill the low areas between the ridges (Waters, 1955). At the same time, warping at other places formed local basins and broad arches. By Pleistocene time, several of these basins had subsided sufficiently that sediments began to accumulate in them. Contemporaneously and continuing to the present, prevailing southwesterly and westerly winds picked up the fine sediments exposed at the surface in these basins, as well as material from other sources, and transported them eastward to form the loess deposits that mantle much of the Columbia Basin. Late in the Pleistocene glacial period, an ice lobe advanced down the Okanogan Valley and onto the Basin to the south. This dammed the Columbia River and caused its water to flow southward across the Basin, first forming one channel, then another—the greatest of which is Grand Coulee. Toward the end of this glacial epoch, tremendous floods of water swept west and south across the region from near Spokane, and cut a maze of anastomosing channels through the loess and into the basalt and dumped great loads of debris in low areas (Bretz, 1959).

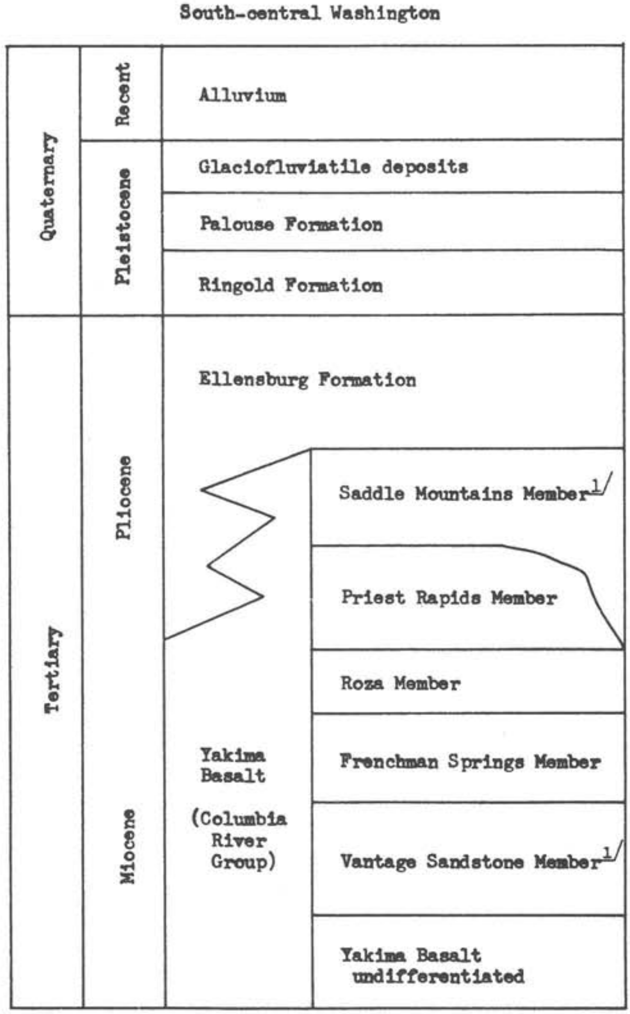
In the central part, the older rocks are completely covered; only around the periphery do they rise above the top of the lava surface as islands, or extend as partially buried ridges out from the edge of the mountains. These hills and ridges are most numerous in the northeast corner of the Basin and along the Washington-Idaho border. Those south and east of Spokane along the border are made up almost entirely of slightly metamorphosed sedimentary rocks of the Precambrian Belt Series, a group made up predominantly of argillite and quartzite. They are only the western outliers of this great series which forms the bedrock of much of northern Idaho and western Montana. Radiometric dating indicates an age of about 1,200 million years. Metamorphosed volcanic rocks, called greenstones, and some interlayered marine sedimentary rocks of Permian and Triassic age crop out within the Snake River canyon and in the canyon of the Tucannon River in the southeastern part of the State. Well-foliated gneiss and schist that are intruded by granitic rocks underlie the prominent ridges at the edge of the Columbia Basin east and north of Spokane. The gneiss and schist may be recrystallized parts of the Belt Series, or may be of even greater antiquity. Scattered low hills of prebasalt rock that rise above the basalt surface at intervals for almost 30 miles west from Spokane are made up mostly of Paleozoic sedimentary rocks. Granitic rocks that have intruded and metamorphosed the sedimentary group make up a smaller part of these hills. Westward beyond this, outliers of older rock are absent within the Basin, except within Grand Coulee. The basalt flows lap up on the north upon granite and a variety of metamorphic rocks on the west to the Cascade Range. Along most of the eastern border of the Cascade Range, the basalt flows lap over older volcanic rocks and continental sedimentary deposits.

The basalt under the Columbia Basin collectively is called the Columbia River Group. It is a dense, black, hard rock, which is dominantly crystalline but may contain as much as 50 percent glass. Individual flows are usually from 50 to 150 feet thick and are of great lateral extent, commonly having spread out over tens of miles or more. J. W. Bingham and M. J. Grolier (1966, in press) state that one of the most widespread flows in the central part underlies an area of over 20,000 square miles. Maximum thicknesses for the greatest accumulations of flows are around 5,000 feet; these have been found in deep canyons or have been determined from the records of wells. An exploration well in southwestern Lincoln County penetrated through the basalts at 4,465 feet and passed through more than 200 feet of unconsolidated sand and clay before bottoming in quartz latite (A. E. Weissenborn, 1965, written communication). Another well in the Rattlesnake Hills was stopped after penetrating 10,665 feet of volcanic rocks. It is not known whether the entire thickness represents basalts of the Columbia River Group or whether part belongs to an older volcanic sequence. At the peripheries only a flow or so may represent the group, and here pillow lavas (piles of discrete, bulbous masses of lava with glassy selvages) and fragmental tuffaceous aggregates are more common. These were formed where lava flowed into bodies of water. Swarms of basalt dikes, containing rock identical to the flows, have been found at several localities around the eroded margins of the Basin. These dikes (and probably others still concealed in the central part), rather than volcanoes, are considered to have been the conduits for the basalt. The total period of eruption spanned several million years, starting in the Miocene and continuing into the Pliocene Epoch. Fossil evidence, as well as numerous soil zones between flows, some of them very thick, point to this conclusion.

A division into two distinctive formations based upon stratigraphic position and chemical and mineralogic differences has been made of the Columbia River Group (Waters, 1961b). In Washington the older unit, the Picture Gorge Basalt, may underlie much of the Columbia Basin but is probably exposed only in the very southeast corner along the Grande Ronde or Snake Rivers; all the rest belongs to the younger sequence, the Yakima Basalt. Detailed maping at several localities has indicated the feasibility of delineating single flows or groups of flows, which can be traced over large areas (Mackin, 1961). Figure 6 shows the units delineated and mapped in the west-central part of the Basin in Washington.

Lake and stream deposits now consolidated to siltstone, sandstone, and conglomerate occur at many places around the margins. Most are interbedded with the basalt in layers usually from 10 to 50 feet thick, although locally they may be much thicker. They pinch out away from the margins in relatively short distances. In the vicinity of Spokane these rocks, which also accumulated to a thickness of many hundreds of feet beneath the basalt within the ancient Spokane River valley, are called the Latah Formation (Pardee and Bryan, 1926). At the western margin on the east-central flank of the Cascade Range, andesitic volcanic debris also accumulated on top of the basalt up to a maximum thickness of about 1,000 feet, and these rocks plus the interlayered sedimentary rocks are called the Ellensburg Formation (Smith, 1903b). Plant and animal fossils found in the Ellensburg and Latah Formations and other units of similar relations are from middle Miocene to Pliocene in age and bracket the span of time during which the basalts were extruded.

Beginning in the early part of the Pleistocene Epoch, gravel, sand, silt, and clay began to be deposited in lakes or by aggrading streams in the depressed basins. The largest of these, the Pasco Basin, had over 1,000 feet of material deposited on top of the basalt; most of this is sand and silt and is still relatively unconsolidated (Brown and McConiga, 1960). Other similar deposits accumulated west and north of Walla Walla; west of Lewiston, Idaho; in the Yakima Valley; and in the Quincy Basin (Lupher, 1944). Loess—wind-blown deposits of fine material, mostly silt—blankets much of the Columbia Basin; in places in the east-central part it is more than 200 feet thick. Overlapping, well-developed soil zones within the loess indicate that it has been accumulating through much of the Pleistocene Epoch (Washington State Univ., 1964). Glacial streams and the great floods denuded about a third of the northeastern part of the lava plain of its loess cover. The source of the floodwaters was glacial Lake Missoula, from which as much as 500 cubic miles of water was suddenly released with the failure of ice dams at the mouth of the Clark Fork Valley at Pend Oreille Lake (Pardee, 1942). These floodwaters are believed to have swept southwestward across the Columbia Basin in periods measured in days, denuding great tracts of their loess cover and cutting channels and rock basins in the basalt (Bretz, 1959). The floodwaters breached numerous divides, and the resulting



[1] Of Mackin, 1961.

FIGURE 6.—Stratigraphic column for Columbia Basin in south-central Washington (after Bingham and Grolier, 1966, in press)

denuded, anastomosing channel network is called the Channeled Scabland. (See fig. 7.) Constructional bars within the channels and accumulations of sand and gravel within the basins and at other places in the region were deposited by the floodwaters. These flood deposits have only a thin veneer of loess, which is indicative of their recentness.

The most valuable resource of the Columbia Basin is the loessial soils that make it one of the great grain-producing regions of the world. Clays, both residual and transported, which formed from the weathering of granitic rocks and basalt along the eastern margin of the State, are used for making refractory and common brick, and also

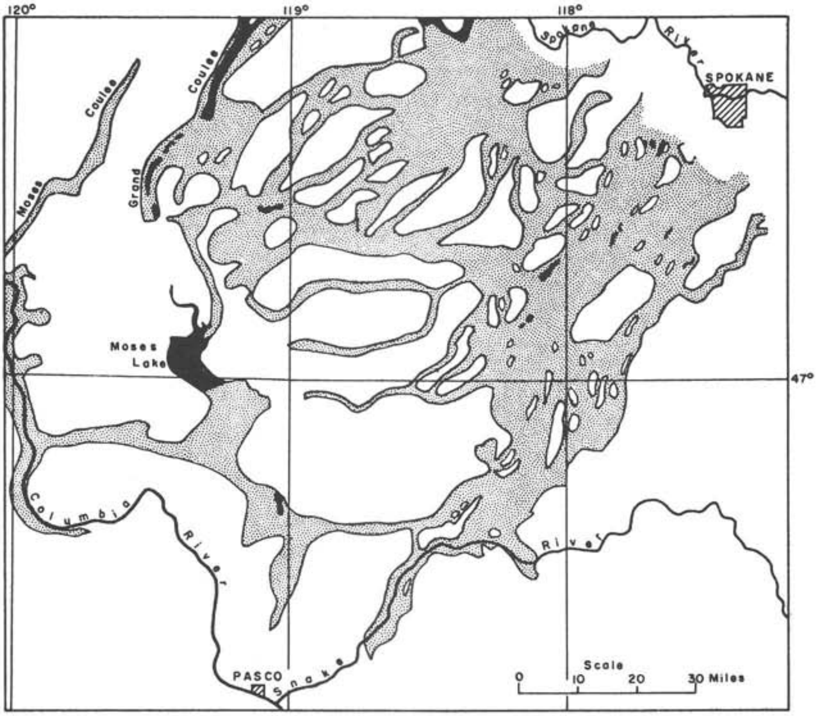


FIGURE 7.—Map of Channeled Scabland of eastern Washington (after Bretz 1959). Shaded areas are the channelways denuded down to or into the basalt, in which are scattered many deposits of gravel and sand. The islandlike areas between channels and to the east are loess mantled. Black areas are lakes.

are a potential source of alumina. The upper, more vesicular and fractured parts of some basalt flows, and some of the more sandy interbeds between flows, make good aquifers, which are the principal source of ground water in the Basin. With basalt outcrops only a short distance from any locality, good road metal is abundantly present all over the region, and sand and gravel deposits are scattered along many drainage channels. Diatomaceous earth occurs in thin deposits on top and interlayered with the basalt; a moderate production has come from some of these deposits.

THE CASCADE MOUNTAINS

(By A. E. Weissenborn, U.S. Geological Survey, Spokane, Wash., and F. W. Cater, U.S. Geological Survey, Denver, Colo.)

The Cascade Mountains of Washington are part of a vast mountain chain that extends nearly unbroken from Alaska through Canada and the United States to Mexico and beyond. In Washington, these mountains have profoundly affected the economic life of the State. Because of their ruggedness, the Cascades constitute a formidable barrier to east-west travel across the State. Only a few passes provide practicable routes across the mountains, and, except where the Columbia River breaks through the range, all are subject to heavy snows and dangerous snowslides during the winter months. The climate of the State is also profoundly affected by the mountains; rainfall is heavy on the western slopes, whereas much of eastern Washington is in the rain shadow of the Cascades and is arid or semiarid. Heavy precipitation in the mountains provides abundant resources of water and stimulates heavy forest growth at lower elevations. The crest of the range, however, is well above timber line.

Mineral deposits in the Cascades have been the source of a substantial part of the mineral wealth which the State has produced. The spectacular scenery is one of the great attractions of the State. The rugged Cascades form a recreational area of great variety and beauty, and tourism is an important factor in the economic life of the area.

Rock Units

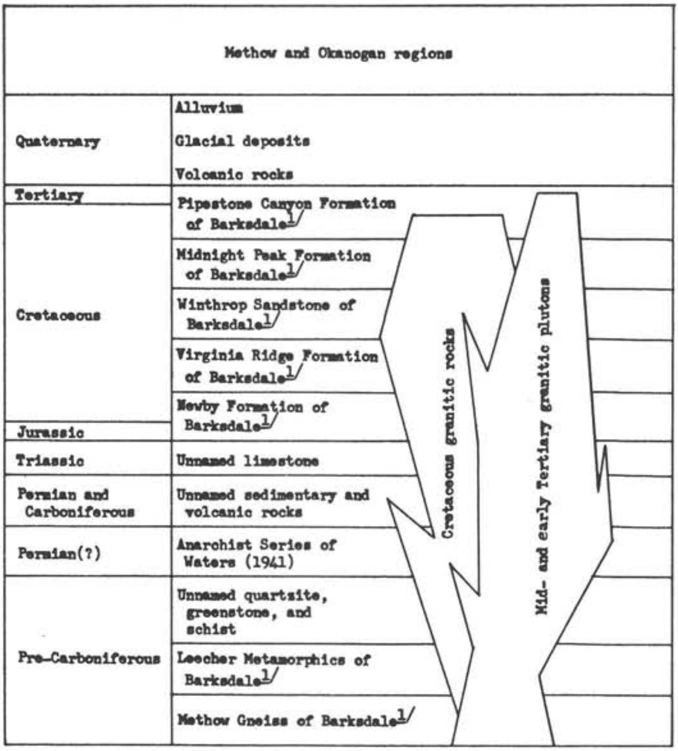
The Cascade Range in Washington consists of two geologically contrasting areas. South of Snoqualmie Pass, Tertiary volcanic rocks with relatively simple structures predominate. North of the pass, most of the exposed rocks are structurally complex pre-Tertiary igneous and metamorphic rocks. To some extent, the geologic differences are reflected in the topography, the area underlain by the pre-Tertiary rocks tending to greater ruggedness and topographic variety. Part of the ruggedness, however, is the result of Pleistocene and Recent glaciation, which has affected the northern part of the area more than the southern.

The northern part of the Cascade Mountains consists essentially of a core of crystalline rocks—mostly granitic rocks and metamorphosed ancient sedimentary and volcanic rocks—flanked by younger sedimentary and volcanic rocks. Superimposed on the rest of the range are five young volcanoes, which form the high peaks of Mount St. Helens, Mount Adams, Mount Rainier, Glacier Peak, and Mount Baker.

METAMORPHIC ROCKS

The oldest rocks in the Cascades are ancient sedimentary and volcanic rocks that have been intensely folded and metamorphosed into gneisses, schists, quartzites, and greenstones. These have been variously named, in different parts of the area, the Methow Gneiss, the Skagit Gneiss, the Swakane Gneiss, the Leecher Metamorphics, the Chilliwack Group, the Anarchist Series, and a host of other local names (fig. 8). Some are probably correlative, others are not.

The age of many of these rocks is not clear, but they represent a considerable interval of geologic time. Most are believed to be pre-Jurassic, but a few are younger. Various degrees of metamorphism are represented. In general, the less intensely metamorphosed rocks crop out along the west flank of the range, whereas moderately to strongly metamorphosed rocks occupy the core and the east flank. Course-grained gneisses underlie much of the more highly metamorphosed areas. Less abundant are biotite and hornblende schist, amphibolite, marble, and quartzite. In many places, these rocks are migmatized—that is, intricately mixed with or injected by granitic material, usually most intensely near pre-Tertiary intusive rocks.



1/ Huntting and others (1961); data source No. 2.

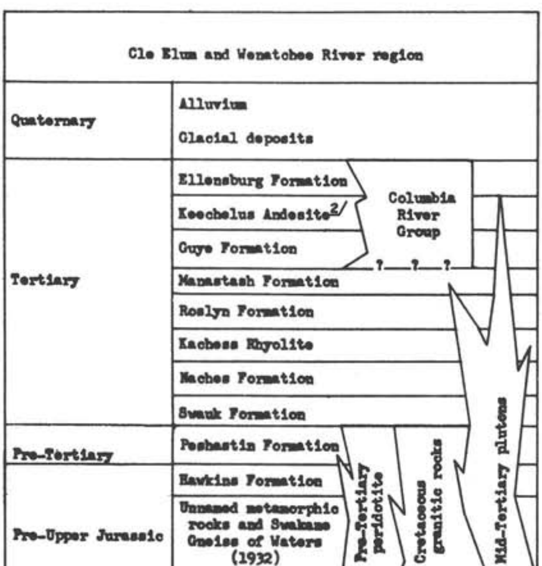


FIGURE 8.—Stratigraphic units commonly recognized in the Cascade Mountains of Washington.

Core of Northern Cascade Range (Lake Chelan, Glacier Peak, and Ross Lake region)		
Quaternary	Alluvium	
	Glacial deposits	
	Volcanic rocks of Glacier Peak	
Tertiary	Unnamed volcanic rocks	
	Swauk Formation	Mid- and early Tertiary granitic plutons
Permian and Carboniferous undivided	Unnamed sedimentary and volcanic rocks	Cretaceous granitic rocks; Mid- and early Tertiary granitic plutons
Pre-Upper Jurassic	Unnamed metamorphic rocks, Swakane Gneiss of Waters (1932), and Skagit Gneiss of Misch (1952)	Pre-Carboniferous granitic rocks; Cretaceous granitic rocks; Mid- and early Tertiary granitic plutons

West slope of Northern Cascades north of Snoqualmie River		
Quaternary	Alluvium	
	Glacial deposits	
	Mt. Baker volcanic rocks	
Tertiary	Unnamed volcanic rocks	Mid- and early Tertiary granitic plutons
	Fifes Peak Formation	
	Stevens Ridge Formation	
	Ohanapecosh Formation	
	Tejon Formation of Weaver (1916)	
	Puget Group	
	Swauk Formation	
Cretaceous	Chuckanut Formation of McLellan (1927)	
Jurassic	Nooksack Group of Misch 1/	
	Unnamed sedimentary and volcanic rocks	
Triassic	Unnamed sedimentary rocks	
Permian, Carboniferous, and Devonian	Chilliwack Group of Daly (1912) 2/	
Pre-Devonian	Unnamed metamorphic rocks	

1/ Nutting and others (1961), data source No. 70.

2/ Extended into Cascade area by Miller and Misch (1963).

FIGURE 8.—Stratigraphic units commonly recognized in the Cascade Mountains of Washington—Continued.

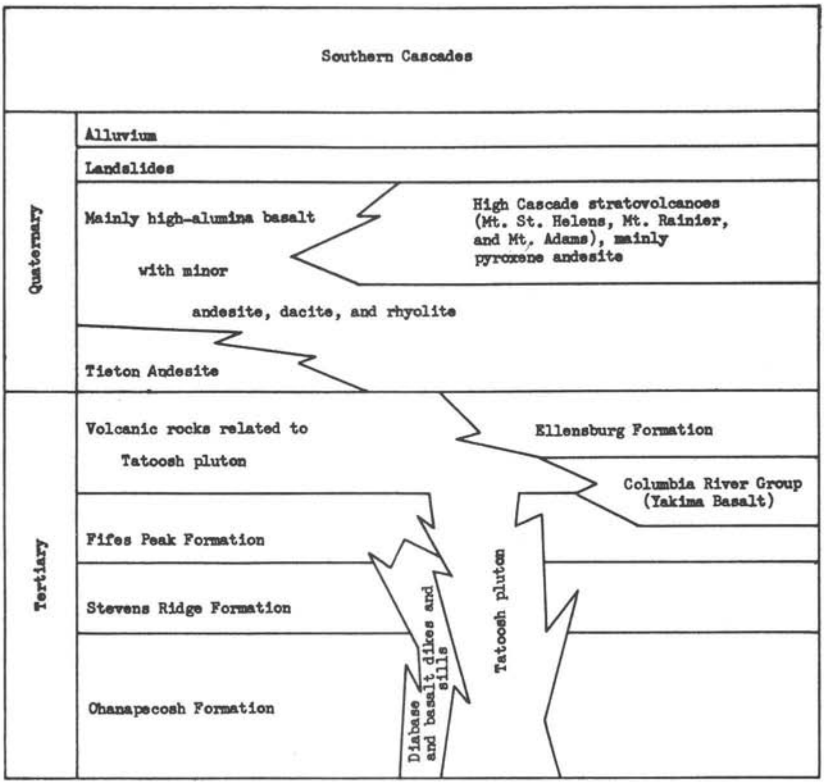


FIGURE 8.—Stratigraphic units commonly recognized in the Cascade Mountains of Washington—Continued.

Two units of biotite gneiss—the Skagit Gneiss as used by Misch (1952) that underlies much of the drainage basins of Lake Chelan and of the Skagit River in the Ross Dam-Newhalem area, and the Swakane Gneiss of Waters (1932) that crops out irregularly from the Columbia River above Wenatchee to the Suiattle River—are many thousands of feet thick. No positive stratigraphic correlation can be made between the two units because they are separated by masses of granitic rock and by structural complexities, but they are closely similar and may well be correlatives. Their composition suggests that they were formed from either acid volcanic rocks or from silicic sediments. Scattered limy and quartzitic layers in them are certainly of sedimentary origin.

Other units of the higher grade metamorphic rocks are thin but remarkably persistent along their strike. They serve as marker units in deciphering the geologic structures of the area. Remnants of conglomeratic textures and layers of marble and quartzite indicate that many of these rocks were derived from sedimentary rocks, but some of them may have been derived from volcanic rocks of basaltic composition.

Less metamorphosed rocks—slate, quartzite, marble, argillite, and metamorphosed volcanic rocks (greenstone)—crop out along the west flank of the range and in the upper Yakima River basin. Little is known concerning their ages; in all probability rocks of many ages are represented.

SEDIMENTARY ROCKS

Paleozoic sedimentary rocks.—Argillite, graywacke, sandstone, chert, limestone, and shale, all with interbedded volcanic rocks, crop out along the west flank of the Cascades. The sequence ranges in age from Devonian to Permian. Some units have been correlated by Misch (Miller and Misch, 1963) with the Chilliwack Group of Daly (1912); others are unnamed. Carboniferous and Permian rocks of much the same type are exposed on the shores of Ross Lake in the upper plate of a thrust fault. The Paleozoic sediments have been intricately and tightly folded but have not been greatly metamorphosed. Marine fossils are numerous in some of the rocks, and the probability is that most of these sediments are of marine origin.

Mesozoic sedimentary rocks.—Older Mesozoic rocks, mostly of Jurassic age, are exposed on both flanks of the Cascade ranges but are missing in the central part. They resemble the Paleozoic rocks but are less intricately folded and are still less metamorphosed.

Cretaceous beds crop out in a few scattered areas on the west slope of the mountains and extensively in down-faulted blocks in the drainage basins of the Pasayten and Methow Rivers. The rocks are mostly of marine origin and consist of shale, impure sandstone, graywacke, and conglomerate with only a few scattered lenses of limestone. The names by which they are known in the Methow-Pasayten area are shown in figure 8.

Continental sediments that span the time interval between the Cretaceous and the Tertiary are found in a great arc surrounding the Mount Stuart-Icicle Creek area, in the valleys of the Wenatchee, Swauk, and Cle Elum Rivers, and in scattered localities on the west side of the range. They consist of shale, shaly coal beds, arkosic sandstone, and coarse conglomerate derived from granitic and metamorphic rocks of local origin. In the Mount Stuart area, they include at the base laterite derived from underlying ultramafic rocks. The sequence was deposited on a surface of considerable relief. East of the mountains, and in the Mount Stuart area, these rocks are known as the Swauk Formation; west of the mountains they are assigned to the Chuckanut Formation of McLellan (1927). The two formations are probably correlatives (Miller and Misch, 1963, p. 170).

Tertiary sedimentary rocks.—Tertiary sedimentary rocks younger than the Swauk occur in an area near Cle Elum in the drainage basins of the Naches and Yakima Rivers. Like the Swauk, they are of continental origin and consist mostly of sandstones and shales interbedded with basalt. The formations into which they are divided are listed in figure 8. The Roslyn Formation contains workable beds of coal, and some coal beds are also known in the overlying Manatash Formation.

Quaternary deposits.—Glacial debris of various kinds is widely distributed throughout the Cascades. Thickest and covering the largest contiguous areas are the deposits along the lower parts of the western slope of the mountains. These deposits consist mostly of debris left by the ice lobe that occupied the Puget Sound area. The lower ends of many of the valleys were dammed by this debris, forming lakes in which fine-grained sediment accumulated. Similar debris deposited by a lobe of the continental ice sheet coming down the Okanogan Valley blocked some of the valleys on the east slope of the mountains.

Most of the mountain areas have been deeply sculptured by alpine glaciers; indeed the magnificent scenery of the Cascades is due largely to the effects of this glaciation. Debris left by these glaciers forms till and moraines in most of the valley.

VOLCANIC ROCKS

Older volcanic rocks.—Volcanic rocks of probably Carboniferous and Permian ages have been mapped by Peter Misch (Huntting and others, 1961, data source No. 70) in the Northern Cascades near Ross Lake and at a few places to the south. In the drainage basis of the Methow River, J. D. Barksdale (Huntting and others, 1961, data source No. 2) has mapped a few areas of volcanic rock (the Midnight Peak Formation) interlayered with the Cretaceous sediments (fig. 8).

Tertiary volcanic rocks.—South of Snoqualmie Pass, the Cascades are almost everywhere underlain by a sequence of volcanic rocks of Eocene, Oligocene, and Miocene ages (fig. 8). In the vicinity of Mount Rainier, Eocene and Oligocene volcanic rocks reach a thickness of more than 10,000 feet (Waters, 1961). The sequence consists of flows, mudflows, and water-laid pryoclastic rocks. Local patches are found elsewhere in the Cascades but are not volumetrically important. Most of these rocks are of andesitic composition, but basalt, rhyolite, and dacite flows and breccia are intercalated with the andesite. The older of these rocks have been more folded and faulted and more intensely altered than the younger ones. Lapping over the Eocene, Oligocene, and Miocene volcanic rocks are basalt flows of the Columbia River Group of middle Miocene through early Pliocene age. Restricted mostly to the Mount Rainier-Snoqualmie Pass area are small patches of Miocene dacite or rhyodacite flows that are related to the intrusion of granodiorite plutons. These are glassy and have been only slightly altered.

Quarternary volcanic rocks.—The great cones of Mount Baker, Glacier Peak, Mount Rainier, Mount Adams, and Mount St. Helens were formed in comparatively recent times. The last major eruption from Glacier Peak has been dated by Carbon–14 as 12,000 years ago (Fryxell, 1965). John C. Fremont reported Mount Baker and Mount St. Helens in eruption in 1843 (Fenneman, 1931, p. 425). There are also reports of later eruptions of Mount Baker. Ash alone was ejected; none of these eruptions included lava flows (Coombs, 1939).

INTRUSIVE ROCKS

Granitic intrusive rocks

Rocks of granitic composition underlie large areas of the Cascades. They were emplaced during several periods and over a long interval of time.

Older granitic intrusive rocks.—The oldest of these rocks are dioritic masses that crop out in two small areas near Marblemont. Their age is uncertain, but they are believed to be pre-Carboniferous. They are shown on figure 4, but they are not quantitatively important.

Cretaceous and early Tertiary granitic rocks.—The main period of igneous intrusion in the Cascades began in the late Mesozioc and continued into the early part of the Tertiary. Intrusive masses of batholithic dimensions consisting largely of quartz diorite and granodiorite were formed. The batholithic masses underlie much of the extreme northeastern part of the Cascades and also crop out north of Lake Chelan and in the adjacent lower drainage basin of the Entiat River, as well as in the vicinity of Mount Stuart. These masses are known respectively as the Similkameen, Chelan, and Mount Stuart batholiths. Small plutons are found at the headwaters of the White River, on Chiwaukum Ridge, and in several other places.

The granitic masses are discordant or cut across the enclosing rocks in some places and are concordant or intruded parallel to the enclosing rocks in others. Borders are mostly gradational into the enclosing schists and gneisses, and foliation has been developed within the intrusions, particularly near their margins. Replacement, assimilation, and granitization of the host (or enclosing) rocks indicate that these masses were emplaced at intermediate or great depths.

Field evidence points to at least two main periods of intrusion, but on figure 4 all the granitic rocks of Cretaceous and Cretaceous and Tertiary age have been grouped together.

Radiometric age determinations indicate that most of the Cretaceous granitic rocks are from 100 to 120 million years old, but some age determinations as young as 40 million years have been obtained. These determinations, however, need confirmation.

Tertiary granitic intrusive rocks.—Several batholiths and smaller stocks and plugs of Miocene age crop out in the Cascades of Washington. The best known of these are the Tatoosh pluton near Mount Rainier (Fiske and others, 1963, p. 40), the Snoqualmie batholith between Snoqualmie Pass and Monte Cristo, the Cloudy Pass batholith on the crest of the Cascades northeast of Glacier Peak, the Golden Horn batholith in the Methow River drainage on the eastern slope of the mountains, and the Chilliwack batholith east of Mount Baker. These rocks, therefore, are among the youngest exposed batholithic rocks known. Recent radioactive age dating suggests that the age of some of these are as young as 14 to 20 million years.

The Miocene intrusive rocks range in composition from granite to quartz diorite but consist mostly of granodiorite. Some of them have chilled margins of porphyritic rocks and phases gradational into extrusive rocks (Smith and Calkins, 1906; Cater, 1960; Waters, 1961a). The Miocene batholiths are only now in the process of being exposed by erosion, and it is at least possible that the exposed masses are only cupolas rising from a very much larger batholith. All the bodies have features characteristic of intrusives emplaced at shallow depths in the earth's crust.

In addition to these larger intrusions of granitoid rocks, numerous dikes and irregular bodies cut the older rocks. Some are satellitic to the batholiths; others served as feeders to lava flows or pyroclastic deposits. In a few localities, as, for example, along Phelps Ridge south of Lyman Glacier, intrusive breccias are found that must have risen from an underlying batholith. Some of these breccias are mineralized.

Small intrusive bodies of andesite porphyry and diorite are locally abundant in the Cascades south of Snoqualmie Pass. South of

Mount Stuart, a swarm of basalt dikes cut the Swauk Formation but are not shown on figure 4.

Ultramafic intrusive rocks

Peridotites now mostly altered to serpentinite form lenticular masses distributed along a northwest-trending belt extending from Sumas Mountain, northwest of Bellingham, to Cle Elum. The Twin Sisters Mountains mass, the largest of these bodies, is elliptical and about 10 miles by 4 miles in area. Much of the mass is the high-olivine variety of peridotite known as dunite. Chromite deposits are found in the dunitic parts (Thayer and others, 1943; Ragan, 1963). The Twin Sisters mass is remarkably fresh except where sheared and serpentinized along its margins and thus differs from most of the other ultramafic masses, which are thoroughly serpentinized throughout.

In places, lateritic deposits, which developed on some of the masses by weathering, now form the base of the Swauk Formation and Chuckanut Formation of McLellan (1927) of Tertiary age. These bodies must therefore be pre-Tertiary in age, and, by analogy with similar rocks in British Columbia, they may be as old as Jurassic or Late Triassic. However, Ragan (1963) states that the Twin Sisters mass is intrusive into Paleocene rocks, and therefore it and several nearby similar but smaller bodies must be Tertiary in age. On figure 4, all of the ultramafic rocks are shown by a single pattern.

Structure

The rocks of the Cascades have been folded, faulted, overthrust, uplifted, and downwarped. Most strongly deformed are the metamorphic rocks in the core of the range, which have been tightly and intricately folded along north-northwesterly trending axes. Paleozoic and Mesozoic rocks are also tightly folded in places but less so than the metamorphic rocks. The Paleozoic rocks in particular have been involved in overthrusting. In general, Tertiary rocks have not been tightly folded, but they have been repeatedly folded, faulted, downwarped, and uplifted. Especially pronounced among the younger structures are the large grabens or downdropped blocks so prominent in the drainages of the Pasayten, Methow, Wenatchee, and Chiwawa Rivers. These also follow the prevailing north-northwesterly trend.

The north-northwesterly structural grain of the region developed early, as is indicated by the direction of foliation and folding in the metamorphic rocks. Subsequent dislocations followed the same trend until Miocene time, when the Miocene batholiths were intruded along a north-south line, a line followed by the trend of the present Cascade Range.

Geologic History

The earliest geologic record of the Cascade Mountains is preserved in the tightly folded metamorphic rocks that crop out in the core of the northern part of the range. These rocks record periods of sedimentation, volcanic outbursts, metamorphism, and mountain-building. Deformation associated with the building of this oldest ancestral Cascade Ranges established northwesterly structural trends that controlled all later deformation until well along in Tertiary time.

These old mountains were eventually planed off, and by late Paleozoic time the region was again submerged and receiving sediments. The later deformation of these rocks and, of course, of the older underlying rocks was not accompanied by strong metamorphism. Older Mesozoic rocks record renewed depression and sedimentation. By late Mesozoic (Cretaceous) time the rocks of the region were invaded by vast amounts of igneous material that cooled to form the older batholiths that crop out so widely in the northern part of the Cascades. The Swauk and Chuckanut Formations of latest Cretaceous and early Tertiary age record rapid denudation of adjacent parts of the region that were being vigorously uplifted to form still another chain of mountains. Uplift and erosion continued until many thousands of feet of rock was removed from these mountains and their cores were exposed.

The most complete record of Tertiary events is preserved in rocks of the southern part of the Washington Cascades. Here the vast piles of Eocene, Oligocene, and Miocene volcanic rocks bear witness to the magnitude of eruptions that accompanied growth of the latest of the ancestrial Cascades (Mackin and Cary, 1965, p. 15). Related to these volcanic rocks are the Tertiary granitic intrusions that underlie large areas in the northern part of the present Cascades. Concomitant with growth of the range and volcanic activity some areas were relatively depressed and received sediments that formed the Roslyn, Manatash, and other formations.

In Miocene time, vast floods of basaltic lava of the Columbia River Group lapped over the older volcanic rocks. These flows were deposited in flat sheets that once extended unbroken nearly to the present coast line, although in Washington only isolated remnants remain west of the mountains. The Eocene, Oligocene, and older Miocene volcanic rocks to the south were in part inundated by the basalt flood and in part formed islands in the basalt sea. The sedimentary, metamorphic, and intrusive rocks in the northern portion for the most part stood above the basalt flood.

By Pliocene time the ancestral Cascades of Mackin and Cary (1965) had been reduced to a plain, called by them the "Weaver Plain." Beginning about the middle of the Pliocene, this plain was uplifted to form the "Cascade Plateau" of Russell (1900). This plateau was eroded and dissected to form the present Cascade range; in fact the most striking feature of the Cascadian landscape, as seen from a distance, is the uniform altitude of the peaks and ridges which are the remnants of the old plateau. Throughout most of the range, the summits that delineate the old plateau surface vary in elevation from 6,000 to 8,000 feet; summits are highest in the center of the range and lower along the sides. This bowing-up of the Weaver Plain to form the Cascade Plateau is clearly visible in the Columbia gorges where the Columbia River basalts are strikingly arched. The Weaver Plain was not uplifted evenly, but was broken up into a series of blocks trending northwesterly parallel to the ancient structural trends. Individual blocks rose different amounts, so that now the uniformity of summits outlining the former Cascade Plateau is disrupted in places.

The relatively even skyline is broken here and there by isolated mountains that rise thousands of feet above it. Some of these, of which Mount Stuart is an example, are monadnocks of granitic rocks, erosional remnants which, because they are formed of more resistant rock, rise above the general level of the dissected plateau. Others, such as Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams, are recent volcanic cones built on the platform of older rocks. These volcanic cones are independent structures not tectonically related to the uplifted surface on which they stand.

The rate of uplift was sufficiently slow so that the Columbia River maintained its course as the land rose. The rate of uplift was uneven, as shown by many Cascade valleys that consist of a broad "outer" valley into which a steep-walled, narrow "inner" valley has been incised, indicating a cessation of uplift followed by a renewal. This feature can be best seen on the slopes of the range and in the southern part; it has been destroyed by alpine glaciation in the higher mountains to the north. Some of these "inner" valleys have been cut in debris left by the continental ice sheets, indicating that uplift continued into the Pleistocene (Mackin and Cary, 1965, p. 23). Maximum uplift of the north-south trending range was about 8,500 feet.

The cones of the five Washington volcanoes are made of lava and volcanic ash, built up on a platform of the older rocks. They first appeared during the Pliocene, but volcanic activity has continued into very recent times; in fact, it may not yet have died out entirely.

The Cascade Range in Washington has been extensively glaciated, and nearly all the valleys have the typical U-shape of glaciated valleys. Glacial features, however, are more dominant in the northern part than they are in the southern part, where extreme glaciation was limited to the higher peaks. In the northern Cascades, cirques abound, and the details of the shapes of most of the peaks and ridges have been carved by glacial erosion. The rugged but spectacular and beautiful scenery of the northern Cascades is mostly the result of Pleistocene glaciation, which, in fact, is still going on. Several hundred active glaciers still remain clustered around the higher peaks.

WESTERN WASHINGTON

(By H. C. Wagner and P. D. Snavely, Jr., U.S. Geological Survey, Menlo Park, Calif.)

Western Washington includes an area of approximately 20,000 square miles, a region of exceedingly variable physiography and greatly divergent rock types. Physiographically, the area runs the gamut from picturesque seashores to rugged glacier-studded peaks; the bedrock includes mudstones and limestones deposited in the sea as well as conglomerate and coal-bearing sandstones laid down on land; volcanic rocks were erupted in both environments. The part of western Washington between the foothills of the Cascade Range and the Pacific Ocean may be conveniently subdivided into three physiographic regions. The Olympic Mountains compose the northwestern segment; the Willapa Hills, an extension of the Oregon Coast Range, form the southwestern segment; and the Puget Lowland separates these higher areas from the Cascade Range (fig. 9).

FIGURE 9.—Index map of western Washington, showing principal physiographic divisions and locations (circled numbers) of stratigraphic sections given in Figure 10.

The Olympic Mountains embrace an area of about 4,000 square miles and rise to heights of 7,965 feet at Mount Olympus. The Willapa Hills area includes the Black Hills, Doty Hills, and many lower hills in the southwestern part of the State. Approximately 3,000 square miles are encompassed in the Willapa Hills area, whose highest point, Boistfort Peak, reaches 3,110 feet above sea level. The broad downwarp of the Puget Lowland covers more than 6,000 square miles and contains most of the arable land in western Washington.

The lowland lies nearly at sea level, and much of the northern part is occupied by Puget Sound. The San Juan Islands separate the Puget Lowland from the Georgia Straits embayment of Canada, a small part of which extends into the United States. The foothills of the Cascade Range form a southern barrier in the vicinity of Longview, and separate the Puget Lowland from the northern extension of the Willamette Lowland of Oregon.

The foothills of the western Cascade Range, in particular those parts underlain by Tertiary rocks, are included in this description of western Washington geology.

The bedrock exposed in western Washington is chiefly of Tertiary age and is part of a eugeosynclinal [1] accumulation of sedimentary and volcanic rocks, predominantly of marine origin. Mesozoic marine sedimentary and volcanic rocks, although restricted in outcrop to the San Juan Islands and the northern foothills of the Cascade Range, may underlie most other parts of the area and represent deposition in a much more extensive eugeosyncline than that of Tertiary time. In this larger framework, the Tertiary eugeosyncline is a successor-basin whose axis of sedimentation migrated progressively westward as time passed and as the marine basin was reduced in size.

Pre-Tertiary Rocks

The bulk of the bedrock exposed in western Washington accumulated in Tertiary time, for in this area pre-Tertiary rocks are found only in the San Juan Islands, in the foothills of the northwestern part of the Cascade Range, and possibly in the core of the Olympic Mountains. The oldest rocks exposed in the San Juan Islands and the northwestern Cascades are a heterogeneous metamorphic and plutonic basement complex composed principally of gneissic amphibolites and quartz diorite (Danner, 1960a, 1960b; Misch, 1964). This complex is overlain by eugeosynclinal sedimentary and volcanic rocks that include conglomerate, graywacke, shale, chert, limestone, and basaltic lava flows, and such metamorphic rocks as quartzite, schistose graywacke, argillite, marble, phyllite, and greenstone. Poorly preserved fossil corals in the limestone indicate that rocks at least as old as Devonian are present (McLellan, 1927, p. 94; Miller and Misch, 1963, p. 166).

During late Paleozoic time (Mississippian, Pennsylvanian, and Permian Periods), a variety of predominantly marine sedimentary and volcanic material formed deposits of impure sandstone, shale, ribbon chert, limestone, submarine lava flows, and volcanic breccia. In Mesozoic time in the San Juan Islands, a thick unit composed of conglomerate, sandstone, shale, and silty limestone represents deposition near the strand line. Concurrently, in the northwestern Cascades marine shales and conglomeratic sandstones accumulated. In many parts of the San Juan Islands and the northwestern Cascades, metamorphism and associated deformation in Mesozoic time affected these pre-Tertiary rocks, and the shales were transformed locally into argillite and slate, sandstone into quartzite, limestone into marble, and volcanic rocks into greenstones. Accumulation of a thick sequence of marine siltstone and graywacke began in latest Mesozoic time

[1] A eugeosyncline is a linear downwarp of regional dimensions in which both sedimentary and volcanic rocks have accumulated to great thicknesses.

throughout much of western Washington, but these rocks are now exposed only in the core of the Olympic Mountains.

Tertiary Rocks

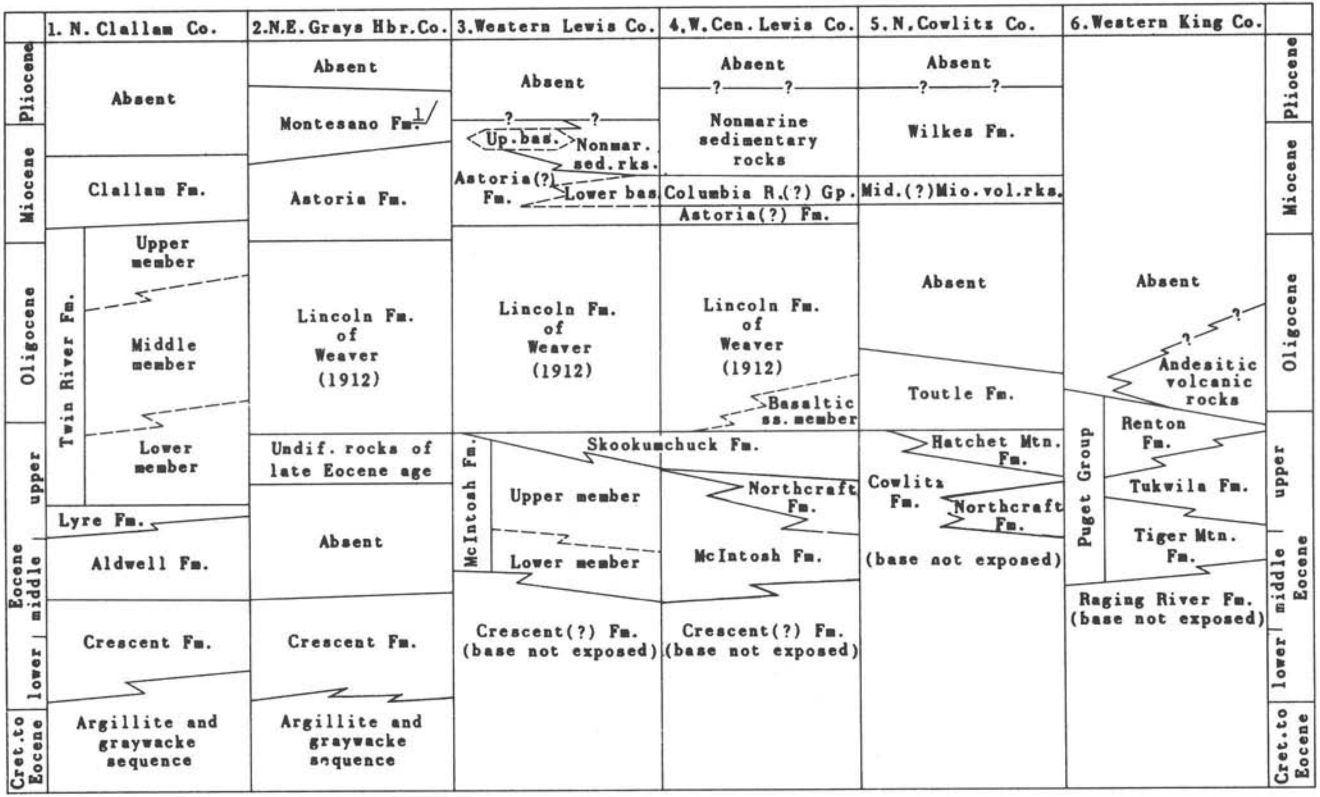
EOCENE DEPOSITS

At the beginning of Tertiary time, a north-trending depositional basin occupied the present area of the Olympic Mountains, the Willapa Hills, and the Puget Lowland in western Washington. The eastern margin of the basin is beneath the present site of the Cascade Range; the western margin was a submarine barrier or island chain and probably was some miles west of the present coast line. The depositional basin extended as a linear trough about 400 miles from Vancouver Island to the Klamath Mountains of Oregon (Snavely and Wagner, 1963, p. 1). This trough maintained its continuity throughout early and middle Eocene time, but regional uplift and folding in late Eocene time divided it into several separate basins of deposition.

The earliest Tertiary deposition in western Washington is a sequence of argillite and graywacke more than 30,000 feet thick that forms part of the core of the Olympic Mountains (fig. 10, cols. 1 and 2). Eocene fossils have been found about 15,000 feet below the top of the sequence, but the age of the lower part of these strata is unknown and may extend back to the Cretaceous.

The most widespread rock unit in western Washington is the Crescent Formation (fig. 10), a thick sequence of lower to middle Eocene volcanic rocks consisting of pillow lava flows, volcanic breccia, and water-laid fragmental debris that intertongues with thin units of tuffaceous marine sedimentary rocks. The lava in this predominantly volcanic sequence was erupted onto the sea floor, except in several places where the rate of extrusion exceeded the rate of downwarping of the basin, and islands were formed. Near centers of volcanism, thick prisms of basaltic flows and breccia accumulated to a thickness probably in excess of 20,000 feet; but only in the Olympic Mountains is the base of this volcanic sequence exposed. Away from volcanic centers, the basalt flows and breccia may exceed 10,000 feet in thickness; they form many of the structurally and topographically highest areas.

Along the northeast margin of the depositional basin, barrier-beach and coal-swamp conditions that had apparently persisted since Late Cretaceous time resulted in the accumulation of a thick series of sandstone and conglomerate beds with intercalated layers of concentrated plant debris that formed beds of coal (Weaver, 1937, p. 75–78). The coal-swamp conditions continued into middle Eocene time along the east margin of the basin where coal-bearing sandstones and carbonaceous siltstones are prominent in King and Pierce Counties (Tiger Mountain Formation of Puget Group, fig. 10). Westward these near-shore deposits intertongue with deeper-water siltstones in southwestern Washington (McIntosh Formation, fig. 10). Meanwhile in the Olympic Mountains, uplift in the Vancouver Island area resulted in a change from siltstone (Aldwell Formation, fig. 10) to sandstone and conglomerate (Lyre Formation, fig. 10) composed principally of metamorphic, granitic, and volcanic rock types. Locally, in extreme



[1] of Weaver, 1912.

FIGURE 10.—Correlation chart of Tertiary rocks in western Washington. (Data adapted from (1) Brown and others, 1960, and Gower, 1960; (2) W. W. Rau, unpublished data; (3) Pease and Hoover, 1957; (4) Snavely and others, 1958; (5) Roberts, 1958; (6) Vine, 1962, and Gower and Wanek, 1963.)

southwestern Washington, a middle Eocene sandstone-siltstone sequence was deposited by turbidity (density) currents that carried sand and silt, perhaps from the same Vancouver Island source, into the deeper parts of the basin.

In late Eocene time the depositional basin was divided by local uplift and volcanism (Northcraft Formation, fig. 10) into several separate basins of marine deposition. The northermost basin extended through the area of the present Juan de Fuca Strait and turned southward into the Puget basin; farther south a large embayment that projected into the present Grays Harbor area extended southeastward beyond Chehalis; the southernmost large basin occupied an area along the present lower part of the Columbia River. On the broad swampy coastal plains that bordered the late Eocene sea along the east margins of the embayments in the Puget and Grays Harbor basin areas, coal-forming plant debris accumulated into deposits of great lateral extent and uniform thickness. These deposits later became the economically important coal beds now found interbedded with arkosic sandstones and siltstones of late Eocene age in King, Pierce, Lewis, and Cowlitz Counties (Renton, Cowlitz, and Skookumchuck Formations, fig. 10). A locally thick sequence of basalt and andesite flows, breccia, and interbedded pebble conglomerates and sandstones (Hatchet Mountain Formation, fig. 10) in Cowlitz County locally intertongues with the coal-bearing nonmarine and near-shore marine sandstones and siltstones (Cowlitz Formation, fig. 10), and attests to the persistence of volcanic activity to latest Eocene time. Westward these near-shore coal-bearing deposits grade into deeper water marine tuffaceous (volcanic ash-bearing) sandstone and siltstone (upper member of McIntosh Formation, fig. 10). To the northeast in King and Pierce Counties, large quantities of andesitic volcanic sandstone, breccia, and conglomerate (Tukwila Formation, fig. 10) intertongue with and are overlain by thick nonmarine coal-bearing arkosic sandstone (Renton Formation, fig. 10) of late Eocene to possibly early Oligocene age, and indicate active subsidence of the land area adjacent to the Puget basin on the east.

In northwestern Washington, uplift in late Eocene time raised the area of the Olympic Mountains above sea level, and erosion locally cut through the middle to late Eocene siltstones, sandstones, and conglomerates (Aldwell and Lyre Formations, fig. 10) into the underlying volcanic rocks (Crescent Formation, fig. 10). Erosion of these uplifted volcanics furnished much basaltic debris to the marine strand and a thick sequence of lithic sandstone and siltstone with a few conglomerate lenses accumulated in the north coastal area of the Olympic Mountains (lower member of Twin River Formation, fig. 10).

OLIGOCENE DEPOSITS

In earliest Oligocene and latest Eocene time, very little detritus was furnished to the geosyncline from adjacent land areas, and basal Oligocene strata consist of basaltic sandstone and conglomerate (basaltic sandstone member of Lincoln Formation of Weaver (1912), and Toutle Formation, fig. 10) derived from erosion of islands composed of Eocene basalt. These deposits are widely distributed, are thickest near former volcanic centers or islands, and thin markedly or are absent in the central parts of the basins of deposition.

In early Oligocene time, regional subsidence took place, and most of western Washington was beneath the sea. Vigorous volcanism in the ancestral Cascade Range buried the coastal plain with andesitic debris and brought to an end the widespread coal-forming environment of late Eocene time. Debris-clogged streams carried great quantities of pyroclastic and detrital material to the near-shore marine environment where water-saturated volcanic detritus at steep delta fronts was periodically moved by submarine landsliding into the deeper parts of the basin. Meanwhile near the coast line, lagoonal swamps formed locally, and a thick deposit of basaltic conglomerate, sandstone, and pumice-rich lapilli tuff with local coal beds formed (Toutle Formation, fig. 10). The extensive accumulation of andesitic volcanic material along the Cascade Range blocked the streams that had carried arkosic detritus to the marine environment from northeastern Washington, and in most parts of the geosyncline ash, silt, and sand rapidly deposited throughout Oligocene time to form as much as 8,000 feet of marine tuffaceous siltstone and fine-grained sandstone with intercalated beds of pumiceous lapilli tuff (Lincoln Formation of Weaver, fig. 10). North of the ancestral Olympic Mountains, far removed from the volcanic vents of the Cascade Range, only a small amount of volcanic ash was furnished to a west-trending trough where more than 10,000 feet of siltstone and mudstone was deposited (middle and upper members of Twin River Formation, fig. 10). In late Oligocene time, continued subsidence resulted in burial of most of the Eocene volcanic highs, and in western Washington islands remained only in the area of the present Olympic Mountains.

MIOCENE DEPOSITS

In the deeper parts of the basin areas of western Washington, sedimentation continued uninterrupted from late Oligocene to early Miocene time. Volcanism in the low-lying ancestral Cascade Range waned and only silt-size material was supplied to the southwest-Washington part of the eugeosyncline. Late in early Miocene time, sand-size material from a northeastern Washington source was again transported by an ancestral Columbia River to the near-shore marine environment; and folding in southwestern Washington along generally northwest-trending structural axes developed many anticlinal and synclinal flexures that controlled in part the sites of deposition of Miocene marine and continental sedimentation. The maximum known eastward extent of the middle Miocene sea was near Centralia, where near-shore marine sandstones (Astoria Formation, fig. 10) overlie tuffaceous siltstones of Oligocene age. These near-shore sandstones grade eastward into continental basaltic sandstones and conglomerates derived from the western flank of the Cascade Range; westward they grade into fine-grained sediments deposited in the deeper parts of the Grays Harbor basin. Another broad embayment near the mouth of the Columbia River was the site of deposition of a thick sequence of fossiliferous sandstone and siltstone (Astoria Formation, fig. 10). Along the Strait of Juan de Fuca, an embayment may have extended as far as Puget Sound, but the only known middle Miocene rocks are the coal-bearing continental and near-shore marine strata exposed near Clallam Bay (Clallam Formation, fig. 10).

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Uplift in middle Miocene time shifted the strand line westward; and contemporaneously, a great volume of basalt was erupted from fissures east of the Cascade Range and supplied the basaltic lava that flowed down the Columbia River downwarp and spread northward into the Grays Harbor basin and westward to the sea ((Columbia River(?) Group and lower basalt of the Astoria Formation, fig. 10)). Where this lava reached the marine environment, thick accumulations of pillow basalt and breccia were interbedded with marine sandstones. Near the strand line in southwestern Washington, lava was extruded from local centers; in places, submarine and subaerial basalt flows and beds of basaltic fragmental debris from these vents are found intercalated with the micaceous fine- to coarse-grained sandstones of middle Miocene age.

In late Miocene time, additional uplift shifted the shore line westward nearly to Willapa Bay and subaerial basalt flows (upper basalt in Astoria Formation, fig. 10) were interbedded in coarse-grained sandstone in a nonmarine environment. In the Puget Lowland, large shallow lakes formed in local structural basins in late Miocene time. Sedimentation in these basins kept pace with downwarping, and as much as 1,000 feet of lacustrine clay, fluvial sand, and volcanic mudflow deposits accumulated (Wilkes Formation, fig. 10). These strata are in large part composed of pumice-rich pyroclastic debris derived from the venting of granodiorite plutons along the present site of the Washington Cascade Range.

Near the close of the Miocene, marked regional uplift of the Willapa Hills and intense deformation in the Olympic Mountains further reduced the area of marine deposition. The highlands thus formed furnished coarse debris to the near-shore environment, and a thick sequence of sandstones and conglomerates formed in the Grays Harbor basin near the present coast line (Montesano Formation of Weaver, 1912, fig. 10).

PLIOCENE DEPOSITS

Continued uplift shifted the shore line farther west in Pliocene time, and only the eastern fringe of marine deposits of Pliocene age is preserved near the present shore line. Sandy siltstones, sandstones, and pebble conglomerates (Montesano Formation of Weaver, 1912, fig. 10) as well as sandstones and siltstones of near-shore and deltaic origin (Quinault Formation, fig. 10) were deposited. Finer grained sediments undoubtedly accumulated offshore on the continental shelf. Downwarping and sedimentation that started in late Miocene time in the depression along the Puget Lowland continued into Pliocene time (Wilkes Formation, fig. 10), and in the southwestern part of the present Cascade Range remnants of andesitic lava of Pliocene and younger age are preserved in central Clark and western Skamania Counties. In westernmost Washington, the period of uplift that had started in late Miocene time continued, and the Willapa Hills and Olympic Mountains probably reached their maximum height by the end of the Pliocene Epoch.

Post-Tertiary Rocks

PLEISTOCENE AND RECENT DEPOSITS

During the Pleistocene Epoch the Puget Lowland and the flanks of the Olympic Mountains and Cascade Range underwent extensive and repeated glaciation, and many of the present land forms owe their origin to the ravages of ice scouring and the deposition of glacial debris. In the Puget Lowland are found the deposits of four major stages of glaciation (Crandell, 1963, p. 8); in the Olympic Mountains also are evidences of multiple glaciation (Brown and others, 1960: Crandell, 1964, pp. 135–138).

In early Pleistocene time a lobe of the great Cordilleran ice sheet of western Canada extended into the Puget Lowland to a point nearly 20 miles southwest of Olympia, and alpine glaciers and ice fields formed in the higher mountains of western Washington. Sheets of till formed by this lobe (Crandell, 1963, p. 13) are locally interbedded in thick deposits of glacial drift in the southern part of the Puget Lowland (Orting Drift, fig. 11). Piedmont alluvial fans of glaciofluvial origin were deposited along the western margin of the Cascade Range (Logan Hill Formation, fig. 11) and around the flanks of the Olympic Mountains (Taholah Formation of Glover, 1940 and Older drift, fig. 11). Debris derived mainly from the Cascade Range and the Olympic Mountains forms deeply weathered deposits preserved as broad benches that are as much as 1,200 feet above sea level in the western Cascade area (Logan Hill Formation, fig. 11) and nearly at sea level along the coast in the Grays Harbor area. When the climate ameliorated near the end of this cold period, the lobe retreated northward beyond the International Boundary, the climate became much as it is today, and northwestward-flowing streams, as well as mudflows formed of the products of contemporaneous volcanism, carried much debris from the Cascade Range into the Puget Lowland (Alderton Formation and lower part of Lily Creek Formation, fig. 11). At least twice more before the last period of extensive glaciation in the Puget Lowland the climate alternated between cold and warm for long periods of time, and Cordilleran glaciers invaded the area, leaving behind locally thick deposits of glacial drift and outwash gravels (Stuck Drift, Puyallup Formation, Salmon Springs Drift, Kitsap Formation, fig. 11). Concurrently, in the central Cascades, subaerial erosion, volcanism, and glaciation furnished large quantities of glacial drift and volcanic mudflow material to the western foothills (upper part of Lily Creek Formation, Wingate Hill Drift, and Evans Creek Drift, fig. 11). In the northern part of the Olympic Mountains, drift from alpine glaciers was deposited in many of the large valleys (Alpine Drift, fig. 11). Concurrently, and also later in Pleistocene time, broad piedmont ice lobes extended beyond the mountain front in the southwestern part of the Olympics and spread out upon the bordering lowland (Crandell, 1964, p. 137).

<table>
<tr><th rowspan="2"></th><th colspan="2">OLYMPIC MOUNTAINS</th><th colspan="2">PUGET LOWLAND</th></tr>
<tr><th>Western</th><th>Northern</th><th>Central</th><th>Eastern edge</th></tr>
<tr><td rowspan="3">Middle(?) and late Pleistocene</td><td>Queets Beds of Glover (1940)</td><td>Vashon Drift</td><td>Vashon Drift</td><td>Vashon Drift</td></tr>
<tr><td rowspan="5"></td><td>?—?</td><td>Kitsap Fm.</td><td>Evans Creek Drift</td></tr>
<tr><td>Alpine drift
?—?</td><td>Salmon Springs Drift</td><td>Wingate Hill Drift</td></tr>
<tr><td rowspan="3">Early(?) and middle Pleistocene</td><td rowspan="3"></td><td>Puyallup Fm.</td><td rowspan="3">Lily Creek Fm.: upper part / lower part</td></tr>
<tr><td>Stuck Drift</td></tr>
<tr><td>Alderton Fm.</td></tr>
<tr><td></td><td>Taholah Fm. of Glover (1940)</td><td>Older drift(?)</td><td>Orting Drift</td><td>Logan Hill Fm.</td></tr>
</table>

FIGURE 11.—Pleistocene stratigraphy of western Washington.

In late Pleistocene time, ice lobes from the Canadian ice sheet again extended southward beyond Olympia in the Puget Lowland and westward through the Juan de Fuca Strait to the Pacific Ocean. Streams flowing out of the mountains were dammed by these thick lobes, lakes formed, and lacustrine sediments many hundreds of feet thick accumulated before the climate again changed and the Ice Age came to a close. As the ice lobes retreated, thick deposits of glaciofluvial outwash and till remained in their wake along the north coastal area of the Olympic Mountains and in the Puget Lowland (Vashon Drift, fig. 11). Simultaneously, glaciofluvial deposits accumulated locally west of the Olympic Mountains (Queets Beds of Glover, 1940, fig. 11).

Marine sediments at Seattle provide evidence that, as Pleistocene time ended and the Recent Epoch began, waters from the Pacific Ocean flooded part of the Puget Lowland. The climate became somewhat warmer than at present (Crandell, 1963, p. 9), streams with headwaters in the higher mountains carried much silt and sand to the adjacent lowlands, and great mudflows swept masses of volcanic boulders and ashy silt into the southern part of the Puget Lowland. Worldwide melting of the continental ice sheets, and resultant rise in sea level, brought marine waters to their present position in the glacier-cut troughs of Puget Sound.

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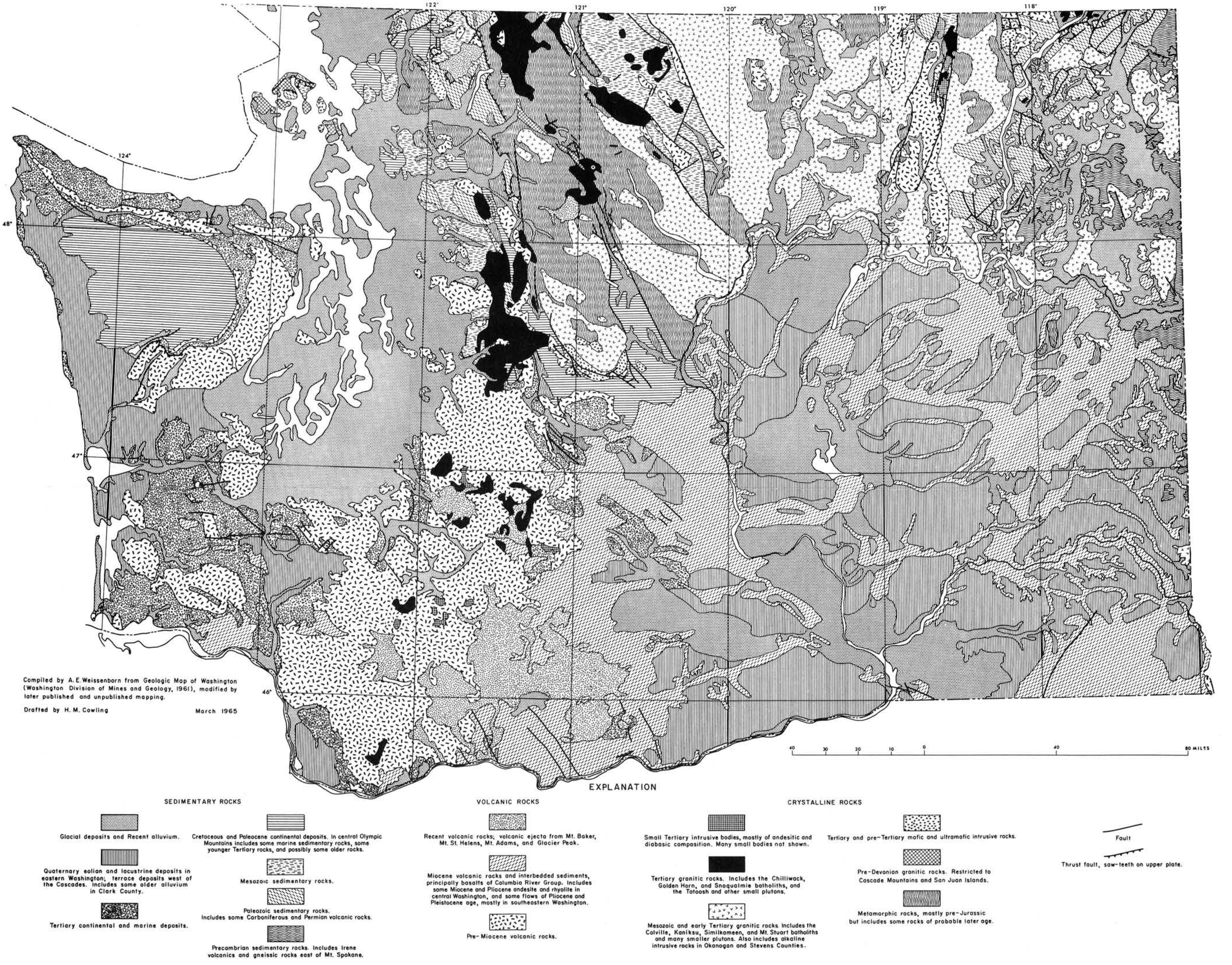

FIGURE 4.—Geologic map of Washington.