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Introduction to WASHINGTON GEOLOGY AND RESOURCES

By
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FOREWORD

In 1953, when the Washington State Division of Mines and Geology published Information Circular No. 22, Mr. Sheldon L. Glover, then Supervisor of the Division, wrote in the foreword:

> The Centennial Edition of Research Studies of the State College of Washington, vol. XXI, no. 2, published in June 1953, contains a section, pages 114 to 154, entitled "Washington Geology and Resources," by Dr. Charles D. Campbell, Chairman, Department of Geology. In preparing this account, Dr. Campbell has filled a marked need for a popular, nontechnical introduction to the more obvious and outstanding features of the geologic makeup of the State and to the land forms and resources that are dependent on these geologic forces and processes.
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> The State Division of Mines and Geology wishes to express its appreciation of the cooperation of the State College of Washington, of Dr. Howard C. Payne, Editor, Research Studies of the State College of Washington, and particularly of the courtesy of Dr. Campbell in making it possible for the Division to publish and distribute this account as No. 22 of its Information Circulars.

Because of the heavy demand for this report the original edition was completely exhausted within a few years. Continuing requests for a brief account of the geology of Washington have emphasized the need for reissuing the report. In this reprinting the author has corrected a few printing errors and has made a few minor revisions. Because of the limitations imposed by the method of printing, it was not practical to make other major revisions suggested by the author in order to update the report to include some knowledge acquired subsequent to 1953. However, we believe that Information Circular No. 22R will satisfactorily answer many general questions about the geology and mineral resources of Washington.

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WASHINGTON GEOLOGY AND RESOURCES

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INTRODUCTION

The western states have highly diverse scenery, and Washington is no exception. Within its borders are some of the highest and steepest mountains of the United States; some of the flattest land; some of the wettest forest; and some of the dryest sagebrush semi-desert. These features are the results of geologic processes, believed to have taken place within the most recent 1 per cent of geologic time: perhaps 20 to 30 million years would cover the geologic activities that have modeled the land to its present form. Nearly all the other 99 per cent of the geologic record in this part of the earth must be deciphered from the appearance and composition of such rocks as happen to be exposed to view.

Being located on the Pacific coast, Washington is in what has been called the "Pacific ring of fire," in reference to the interrupted chain of volcanoes and broad lava fields, active or recently extinct, that girdle the ocean. The five great volcanic peaks of St. Helens, Adams, Rainier, Glacier Peak, and Baker are Washington's share of the family that includes Katmai in Alaska, Kluchevskaya in Siberia, Fuji in Japan, Mayon in the Philippines, Krakatau in Indonesia, Erebus in Antarctica, Aconcagua on the Chile-Argentine border, Cotopaxi in Ecuador, Popocatepetl near Mexico City, and the Cascade peaks south of the Columbia River from Mt. Hood to Mt. Lassen. Earthquakes are another feature of the "Pacific ring of fire"; but as Washington suffers only occasionally from them, and the volcanoes are quiescent, this area is one of the less active segments of the ring.

In describing the geology and resources of Washington, and their effect upon the life of man here, it is most convenient to subdivide the state into seven natural provinces, whose boundaries only locally and approximately coincide with county and state lines. Each natural province has its distinctive type of scenery, which generally is the result of large-scale movements in the earth or of widespread activities of glaciers; most provinces consist of rocks that are different, on the whole, from those in the adjoining provinces.

The provinces are described in order from west to east. Each description includes the principal scenic and climatic features and their origin, and the effects of these upon travel routes, irrigation projects, and so forth; the most important rock types and their ages; the major mineral resources; and other resources such as timber if the distribution of these is dependent upon the geology.

An outline map of Washington, showing the locations of places referred to, is included with the photographs near the center of this article.

For occasional reference, there are at the end of the article a geologic time chart and a glossary of such few rock and mineral names as are necessary. Those who wish to read in greater detail about Washington geology will also find a short listing of useful publications. For a nearly complete and very convenient listing, good up to 1950, the reader should purchase for 35 cents the *Geologic Map Index of Washington,* obtainable from the Distribution Section, U.S. Geological Survey, Denver Federal Center; and topographic maps may be selected from the *Index to Topographic Mapping in Washington,* obtainable free from the same place. It will frequently be convenient to consult W. A. G. Bennett's *Bibliography and Index of Geology and Mineral Resources of Washington, 1814-1936,* Washington Div. Geology Bull. 35, and its successor for 1937-1956 by W. H. Reichert, which is Bull. 46.

OLYMPIC MOUNTAINS PROVINCE

The Olympic Mountains province forms the northwestern part of the state and comprises the whole Olympic Peninsula. The Olympic Mountains make up the whole central part of the Peninsula. They are extremely rugged, comprising a complex system of valleys and canyons with intervening ridges and peaks that commonly attain altitudes of 6,000 feet. Mount Olympus, the highest peak, has an elevation of 7,954 feet. Relatively narrow hilly lowlands border the mountains on the north, west, and south, but the descent on the east, to Hood Canal, is abrupt. Precipitation is heavy, particularly on the west and south, and the mean annual rainfall ranges from 141 inches at Wynoochee, Grays Harbor County, to 17 inches at Sequim, Clallam County. Streams abound, and many are large and swift; the largest have their sources in the many glaciers or permanent snow fields of Mount Olympus and other major peaks. Except at high altitudes, snowfall is not heavy and soon melts.

The glaciers of the Mount Olympus region aggregate about 20 square miles in area at present but are shrinking, because of generally warmer weather since 1900. At their maximum, which was at least twice during the Pleistocene (see time chart, end), each of the valleys of the Olympic Mountains was shaped by its local glacier. A typical U-shaped valley profile resulting from this glacial erosion may be seen in the Dosewallips valley as viewed from the Seabeck-Brinnon ferry across Hood Canal. At the foot of each local glacier was formed a terminal moraine—a ridge-like deposit of sediment dropped from the melting ice. Some of these have escaped later destruction, like the one which forms a dam for Lake Quinault, in northern Grays Harbor County. The heads of these valleys, back in the high central part of the Olympics, were the gathering-grounds for the local glaciers, which froze to the rocks and then pulled away downhill, leaving vertical rock faces behind and adding thereby to an already fantastically rugged terrain.

There is no granite in the bedrock of the Olympic Range; yet abundant boulders of granite and other "foreign" rock types lie on the ground, up to elevations of 3000 feet across the north face of the mountains. These can be explained when we add what we know of glaciation in the Puget Sound lowland and elsewhere. A very thick tongue of ice oozed south from the Georgia Strait (between Vancouver Island and the British Columbia mainland) and piled up high upon the Olympics, which divided the glacier into two lobes. One lobe continued south beyond the site of Olympia, and the other turned west to the ocean, through the Strait of Juan de Fuca. The boulders that had become frozen into the ice back in British Columbia now melted out again in the Olympics, and most of them have probably remained where they fell.

Glacial ice is plastic; and blunt extensions of the Puget Sound ice lobe pushed up into the valleys of the Olympics for some distance, leaving what might be called terminal moraines also. One of these moraines of the Puget ice forms the dam for Lake Cushman, in Mason County.

Exposed in sea cliffs along the Olympic coast are two series of gravelly sediments, deposited in different parts of Pleistocene time—the lower series locally crumpled and offset, but the upper series undisturbed. These formations have been named the Taholah (the older) and the Queets. Both contain "foreign" rock types as pebbles, showing that they were derived in part from material melted out of the Juan de Fuca lobe of the northern ice sheet. The Taholah is in many places so deeply weathered as to be quite soft. From this fact one may suppose either that it is an early Pleistocene deposit that had much time to weather in place, or that the pebbles that came to it in streams were half-weathered already. The Taholah beds are not so widespread as the Queets. For example, the offshore islands are capped with Queets gravels resting directly upon formations older than Pleistocene. (If one lines up the Queets beds on the main shore with those capping the islands, one must conclude that the ocean shore of Queets times lay miles west of the present shore.) One peculiarity of the Queets beds is that in places they include layers of peat and branches. These seem to be remains of a line of swamps that paralleled the mountain front and were kept from draining seaward by a scarcely perceptible ridge.

Softer rocks from Grays Harbor south have resulted in the rapid accumulation of sand along the coast. The waves and the wind have been distributing this sediment into long bars, making good beach resort areas. Where bars and dunes block the mouths of small bays, oceanside lakes have formed; and streams that enter the ocean in this stretch have been so slowed up that they have silted in and now flood easily.

The mountains are composed of bedded rocks only. In the highest part, except for Mount Constance, are the oldest rocks: a series of slates, argillites, sandstones, and even schists (see rock chart, end), all marine sediments originally. These rocks have been elaborately crumpled and twisted so that the wrinkles stand vertical in some areas. Such extreme deformation has until now baffled our efforts to work out the original succession of the beds and to determine just what has happened to them. Their age is in doubt: it is greater than Eocene (see time chart), but perhaps not much greater.

Wrapped around this core, and open to the west, is a thick sheath of basalt flows and tuffs, erupted under water and now more or less altered to greenstone, with which are interbedded sandstones and argillites that are mixtures of all kinds of grains, and thick beds of peculiar gray and maroon limestone of marine origin. The age of the basaltic series is middle Eocene, according to C. H. Clapp, who first described them on Vancouver Island, and C. E. Weaver and others, who studied the Olympic Peninsula series. Although the Eocene basaltic series is generally at lower elevations around the margins of the Peninsula, it includes also Mount Constance on the northeast.

Almost entirely surrounding the Peninsula is a broad border of unaltered but, in places, intricately folded and faulted marine Tertiary shales, sandstones, and conglomerates. Among these, rocks as young as Oligocene are involved in thrust faulting, described below, which brings them into contact with the Eocene basalts and the older rocks of the central highland.

In the southern part of the Peninsula the younger rocks lie in folds that trend southeast, parallel to those in the Willapa Hills to the south; and to this extent the south part of the Peninsula might be termed a northern extension of the Willapa Hills province, detached from it by the valley of the Chehalis River and its broad deep covering of outwash from the Puget Sound ice lobe.

In a general way, therefore, the distribution of younger rocks around older ones suggests that the structure of the rocks of the Olympic Peninsula is a huge dome open to the west—a dome whose core is crumpled and twisted, whose top has been faulted and buckled, and whose east side, as indicated below, has been telescoped. All of this has occurred since Oligocene time, and some of it during the Pleistocene.

These facts have been difficult to collect. The areas above timber line—about 5000 feet—are well exposed, and the jagged, chaotic peaks resulting from differential weathering of up-ended hard and softer beds, are difficult to traverse but still more difficult to interpret. The real trouble begins below timber line, where the solid forest cover is broken only by river-beds and roadcuts. Fortunately the rivers in general radiate outward from the center of the Peninsula and thus cut transversely across the concentrically-disposed rocks, providing exposures along which the thicknesses of the formations can be measured. The most surprising of these is described below.

Several years ago, C. F. Park, of the U.S. Geological Survey, measured a section from the mouth of the Dosewallips River west to Mount Claywood, across an apparently unbroken succession of 120,000 feet of beds (almost 25 miles), which is the world's record if it really is continuous. But as the thicknesses elsewhere on the Peninsula aggregate less than a quarter of this, and because belts of younger rocks had been found enclosed in older ones, Park believed that the excessive thickness was due to duplication of beds by thrust faulting: that is, the harder beds, which predominate, had been telescoped together into overlapping slices and the softer ones crumpled to thicknesses greater than they originally had. Such thrust faulting, since it involves beds of Oligocene age, along with older ones, must have taken place almost within that most recent 1 per cent of geologic time during which, as already stated, most of Washington's scenic features were formed.

The region as a whole is very sparsely mineralized, though it has one outstanding resource in its manganese deposits. These are confined to the Eocene volcanic series and its interbedded sedimentary rocks and, except where these occur as down-faulted remnants among the older rocks of the central area, are found only in the marginal belt covered by them. The manganese mineral hausmannite (Mn_3O_4) was mined here in the Crescent property just west of Crescent Lake, during two different periods, and some 45,000 tons in all were produced. Some additional hausmannite occurs in various claims in the same area, but the general manganese mineralization throughout the region is in the form of bementite and neotocite, which are silicates that would require special treatment to give them marketable value. A little native copper has also been found with these deposits.

In recent years there has been a considerable amount of activity by major petroleum companies and independents in the marginal area of Tertiary rocks; but it is too early to say from their results what the future of oil and gas production on the Peninsula will be.

WILLAPA HILLS PROVINCE

The Willapa Hills province, in the southwestern part of the state, extends from Grays Harbor and the lower Chehalis River to the Columbia River. It fronts on the Pacific Ocean and extends east to an indefinite boundary that separates it from the southern extension of the Puget Sound basin. The Willapa Hills—they would be termed mountains in many parts of the United States—trend southward through the region and, although only of moderate elevation, characterize the area. The highest altitude reached is 3,111 feet at Baw Faw Peak, 6½ miles northwest of Wildwood, Lewis County. Most of the region is under 2,000 feet in altitude. The descent to the Columbia River, on the south, is rather precipitous, but elsewhere the hills merge gradually into the surrounding lowlands.

The rainfall is relatively heavy, ranging between 55 and 85 inches; as a result, there are many large streams. The countless tributaries have developed a very complex drainage network that intricately dissects the area into a maze of forested hills. Winter snow is not heavy and soon melts.

The bedrock comprises a series of moderately folded Tertiary formations: volcanic and sedimentary rocks of Eocene age; sedimentary rocks of Oligocene and Miocene age, the latter intercalated with basalt flows that are the westernmost representatives of the great mass of Columbia River basalts; and a minor amount of late Miocene and Pliocene sedimentary rocks. Concealing these formations in parts of the area, as along the western border, are thick deposits of unconsolidated Pleistocene sediments, some of which, though exposed well above present ocean level, contain shells of oysters. Latest of the sediments are the beach sands, which are a southward extension of those described in the Grays Harbor area.

No metallic minerals of possible economic importance have ever been found in the Willapa Hills province except titaniferous magnetite in deposits of "black sand"—one at McGowan, near the mouth of the Columbia River, and one near Grays Harbor. Such material is sparingly distributed in the Eocene and Miocene basalts of western Washington and has been weathered out from them and concentrated by running water.

Some limestone, in small isolated bodies, crops out at two or three places, but even the common industrial minerals are scarce. As is true for the Olympic Peninsula, however, the results of recent work by oil companies may prove the existence of oil and gas reserves in the Willapa Hills province.

PUGET SOUND PROVINCE

The Puget Sound province lies between the Olympic Mountains-Willapa Hills area to the west and the Cascade range to the east. It consists of a depressed area, mostly below 1,000 feet in altitude, that reaches across the state from Canada into Oregon, where the Willamette Valley is its geological continuation. The northern half is partly occupied by the intricate reaches of Puget Sound, Admiralty Inlet, and the Rosario, Haro, and Georgia Straits. Rainfall is moderate, varying from about 28 to 55 inches annually in the areas of greatest population. There are many streams, but virtually all the large rivers have their sources in the Cascade Range, one major exception being the Chehalis River that heads in the Willapa Hills.

The outstanding feature of the Puget Sound area is the complexity of its coastline, with many irregular islands and embayments appearing from the map to form a typical drowned river valley. But if the land were raised today well above sea level, much of it would still hold undrained lakes: for there are many parts of the bottom 100 fathoms deep and one, off Point Jefferson near Seattle, reaches nearly 160 fathoms; whereas the outlet past Port Townsend is only about 40 fathoms deep. Clearly the Sound is no simple preglacial river valley, developed when the ocean was down and then flooded when it rose. J H. Bretz, following the pioneers in this study, I. C. Russell and Bailey Willis, showed that whatever may have been the preglacial topography, it can now scarcely be guessed at except in the north, because it was completely buried under deposits of the first glaciers to pour down from British Columbia. Instead, the present pattern of embayments is that of the rivers that formed during the long Puyallup interglacial stage on this outwashed sediment of the earlier Admiralty glaciation. The river system must have developed a perfectly good drainage without hollows in the valleys; but the returning ice (Vashon glaciation) plowed up parts of these valleys and, in retreating at last, left an uneven mantle of debris to blur, but not destroy the old outlines.

One might ask this question: Why is the present valley under water? We do not know the truth; but of all the possibilities, the most probable reason is that the land under Puget Sound has actually sunk about 1,000 feet since the river of the Puyallup interglacial cut its maze of valleys into the Admiralty outwash.

Where the larger present-day rivers flow into the Sound, they have silted up their estuaries to form rich farm lands and—in intermediate stages—marshes. Thus, for example, the Skykomish and Snoqualmie Rivers have built up long fills that converge at Monroe, Snohomish County, whence they continue as the Snohomish River to Puget Sound at Everett, forming a broad valley flat. During this filling process, one of the incidents which occurred, probably not long ago and perhaps during a single very rainy season, was the shifting of the Skykomish River from its old course direct between Monroe and Snohomish, to its present one southwest to its confluence with the Snoqualmie. Similarly, the Stillaguamish River filled in its estuary, first south from Arlington to Marysville, probably in pre-Vashon time, and now west from Arlington to the Sound.

A considerable number of rivers entering the Puget Sound area from the Cascade Mountains were, in fact, dammed, diverted, or otherwise disturbed as a result of the latest glaciation; for the great Vashon ice lobe spread up the Cascade valleys as it did in the valleys of the Olympic Mountains. The valleys were thus dammed, forming lakes whose finely-bedded sands and silts can be seen for considerable distances along, for example, Snoqualmie River. In places the lake silts overlie glacial till that contains rock types found only in that valley, indicating that the valley glaciers had grown and extended far down their valleys before the arrival of the Vashon glacier from Canada. Above the silts also is glacial till, but containing rock types from northern localities; this indicates that the Vashon glacier continued to spread up the valleys after the lakes had formed and silted up. One well-known example will serve to illustrate this late-Pleistocene sequence and its effect on an engineering project.

J. H. Mackin, A. S. Cary, and S. L. Glover have at various times shown how Cedar River, which was once a tributary of the Snoqualmie River, was dammed by the Vashon glacier and its terminal moraine, and diverted southward from the Snoqualmie across a rocky divide, where it flowed long enough to cut a permanent course. Cedar Lake formed just upstream from the new rocky channel. In 1914 the city of Seattle, against geologic advice, built a dam across the Cedar River in its rocky defile, in order to raise the lake level and make it a city reservoir. Within a year water was rapidly leaking out of the newly flooded area and passing through more than a mile of gravels that plugged the former Cedar River channel; and in

1918 a torrent of water burst out this way, creating a massive landslide, which buried a stretch of railroad and formed a dam behind which a settlement was drowned. At present the lake is held at a level only slightly higher than it was before the dam was built, so that several yards of unused dam project above the water. The old lake bottom does not leak because its pores were long since sealed with mud; and this suggests a means of restoring the full capacity of the reservoir.

The south part of the Puget Sound province, from Olympia to the Columbia River near Portland, Oregon, lies above sea level and contains no estuaries except the river itself. Much of this 100-mile stretch is covered by gravel, sand, and finer sediment that was sluiced out toward the south by the melting Vashon glacier; but south of Toledo the sedimentary and volcanic rocks of early to middle Tertiary age rise from beneath the outwash. The "prairies" of this area are flat gravelly portions of the Vashon outwash, which drain so promptly after rains that only deeper-rooted trees, such as oaks, flourish on them.

An interesting and much debated feature of the prairies is the Mima mounds (named from their type occurrence on Mima Prairie), a few miles west of Tenino, Thurston County. These occur here and on neighboring prairies in great profusion, and airplane photographs show them to be in closely spaced and discontinuous rows, though an observer on foot can see no regularity in their distribution. Each mound is a low dome, or heap, of any size up to seven feet high and 70 feet wide, composed of mingled gravel and silt but locally containing isolated (ice-rafted?) boulders. Many people believe the mounds to be the work of prehistoric gophers, but the examination by geologists, during the last 20 years or so, of the frozen ground of Alaska has provided a better answer. R. C. Newcomb, of the U.S. Geological Survey, and A. M. Ritchie, of the Washington Department of Highways, have recently presented the case for a permafrost, or frozen ground, origin of the Mima mounds at a time when the Vashon glacier still filled the Puget Sound area to the north. These workers consider the mounds to be the stripped (Ritchie) or collapsed (Newcomb) remains of buckled polygonal blocks of frozen ground, such as can be observed over wide areas of Alaska today.

Throughout the Puget Sound province the bedrock consists largely of Tertiary sedimentary formations and associated lavas. In the northern half of the region, however, erosion has cut through these formations, exposing here and there the Paleozoic and Mesozoic metamorphic rocks beneath. The San Juan Islands are outstanding examples of exposed older formations, and western Skagit and Whatcom Counties contain similar extensive outcrops as outliers of the northern Cascades rocks.

This province is a region principally of industrial minerals; but some metal mines have operated in areas where pre-Tertiary formations are exposed. Most important, economically, is the bituminous and subbituminous coal of the Eocene Puget group, a correlative of the Swauk, in the Cascades, and the Chuckanut formation. These coal measures occur rather extensively within the eastern part of the province for almost its full length. In fact, of the eight major coal fields of the state, all but one are in this general area.

The deposits of glacial sediments that are so abundant here supply excellent sands and gravels for structural purposes and also clays for common brick, partition tile, and other red-fired wares. Higher grade clays and shales, some of which are suitable for refractory and semirefractory ceramic wares, are found in the coal measures and have been mined—sometimes with coal—since the early days of statehood. The flora of the coal swamps included palms of a tropical character, showing the climate of the Eocene in western Washington. Eastern Oregon had the same climate at that time, and it seems that the Cascade Range did not exist then. The refractory clays, mentioned above, are the soil in which the tropical swamp flora grew.

High-quality limestone used in the manufacture of lime and in demand for a great variety of chemical and industrial purposes occurs in the San Juan Islands, and other extensive bodies are found in the eastern part of the region and where the Puget Sound province merges into the northern part of the Cascade Mountain province. Three large portland cement plants in this area and one in the province to the east all obtain their limestone and clay from local sources.

Exploration for oil and gas is continuing along the east side of the Puget Sound province, and also to the southwest.

CASCADE MOUNTAINS PROVINCE

The state is naturally divided into a western and somewhat larger eastern part by the Cascade range, which parallels the Puget Sound province, extending southward from Canada, across the state, and far beyond through Oregon. This range, characterizing the Cascade Mountains province, has a width in its northern half of about 100 miles, and in its southern half of some 50 to 70 miles. It reaches a general elevation on the higher ridges of 8,000 feet above sea level at the north end and 4,000 feet at the south, but five volcanic peaks rise far above the rather uniform summit levels of the range. The altitudes of these extinct cones are: Mount St. Helens, 9,671; Mt. Adams, 12,307; Mt. Rainier, 14,408; Glacier Peak, 10,436; and Mt. Baker, 10,750.

Precipitation, particularly on the west slope of the range, is of course high, averaging from 144 inches annually at Snoqualmie Pass to 86 inches at Wind River, on the Columbia. The rainfall is much less on the eastern slope and there decreases rapidly as altitudes decline. As much of the precipitation is in the form of snow, permanent snow fields cover many of the places of higher elevation. Glaciers are common in favorable situations, such as the north slopes of many high ridges, on the higher peaks, and on all the major volcanic cones, where snowfall is heavy, even on the lower slopes. The annual average snowfall at Mt. Baker Lodge is 41 feet, and at Paradise Inn, on Mt. Rainier, nearly 50 feet. Mt. Rainier, with 27 named glaciers, has the most extensive glacier system of any peak in the United States outside of Alaska.

The many large rivers and their innumerable tributaries have dissected the mountainous area into deep valleys, canyons, and ravines. The intervening ridges are commonly steep-sided, high, and where above timberline, intricately serrated; and the region, with its snow fields and its luxuriant forests, is one of spectacular grandeur.

The five volcanoes are the best known and most striking features of the Cascade Range. Most of them required intermittent activity throughout Pleistocene and Recent times to attain their great height, but Mount St. Helens appears to be wholly postglacial. All were initiated on a topography that was already very rough and mountainous, and Mt. Rainier was built on the top of an area whose ridges are at least 1,000 feet higher than those to north or south. Glaciated valleys extending far down from the present glaciers indicate that Mt. Rainier, Glacier Peak, and Mt. Baker, at least, had grown practically to full size by the end of the Pleistocene, even though they have not been inactive since then. Of interest in this connection are the curious volcanoes of Garibaldi Park, north and east of Vancouver, B. C., which extend the volcanic chain north of Mt. Baker. Mt. Garibaldi erupted through and onto the main ice sheet, which we have called the Vashon ice in the Puget Sound area, so that when the ice melted, great masses of the volcanoes washed away rapidly. The same might well have happened to the Washington volcanoes if the major ice sheets had been in contact with them.

The latest volcanic activity has been in historic times. There are reliable reports of a heavy ash fall in 1842 and eruption of a basalt flow in 1854 from Mount St. Helens, and late gases have deposited free sulphur at the summit of Mt. Adams. Mt. Baker also strewed the country with ashes in the same year as did Mount St. Helens.

In 1883 the geologists Hague and Iddings observed that volcanoes of the Oregon and California Cascades erupted lavas of diverse compositions, whereas the Washington volcanoes were nearly homogeneous. Their observation is still good, even though we cannot explain it. The peaks from Mt. Rainier north are composed of black and gray lavas (where fresh and unaltered) of a fairly uniform composition, which straddles the line that geologists have arbitrarily and perversely drawn between andesite and basalt. Farther south, so little study has been made of Mt. Adams that its composition is not known in detail. Mount St. Helens is basalt and pumice, of apparently the last 1,000 years, built upon the soil-covered debris of "Old Mount St. Helens," dated at 2,000 years old, which consisted of a reddish lava of quite a different composition, and so it begins to fit the pattern of diversity for the southern extensions of the Cascades.

Glacial features of the Cascades include the examples already mentioned of the Cedar Lake-Snoqualmie River area and the filled estuaries along Puget Sound. Such examples could be multiplied for the west Cascade slope. On the east slope, Lake Chelan occupies 60 miles of a narrow U-shaped valley trending southeast from the northern Cascades. The glacier that occupied this valley was the longest on the east slope and reached almost to the outlet into the Columbia River. It was so active that it deepened the valley floor in one place so that the lake is now 1,500 feet deep and the bottom 400 feet below sea level. A major tributary, Railroad Creek, approaches Chelan valley from the west in a valley of similar U-shape, but the floor of Railroad Creek lies several hundred feet higher than Lake Chelan, not to mention the bottom of the lake, and is therefore one of the many "hanging valleys" that characterize glaciated mountain valley. The lesser glacier in Railroad Creek had less eroding power than the one in Chelan valley; therefore, although the tops of the glaciers probably joined in a continuous surface, their floors did not.

Near the outlet of Lake Chelan is another feature due to glaciation acting as it did in the Cedar Lake situation, except that the Chelan drainage was not permanently diverted. The highway leading south out of the Chelan valley toward Wenatchee climbs about 550 feet to pass through a dry rocky channel, Knapp Coulee, which is cut across the ridge separating Chelan valley from the Columbia River. Knapp Coulee is thought by A. C. Waters and earlier workers to have been cut by a stream which flowed from a high-level lake trapped between two glaciers in Chelan valley—the valley glacier itself, and an offshoot of the larger glacier that came down from Canada via the Okanogan River and pushed up Chelan valley a short distance.

While in this area, one cannot miss the "Great Terrace" of the Columbia River. From its abrupt termination near Chelan outlet, northward far up the Okanogan River into Canada, it is a nearly flat-surfaced sheet of loose sediment into which the Columbia is entrenched several hundred feet. Early geologists thought it to be the delta of the Columbia, formed where it entered "Lake Lewis," a presumed vast lake that flooded most of central Washington during maximum glaciation farther north. The slanted bedding exposed in some of the road cuts would suggest this to be correct; but many complications have since been found to disrupt this simple picture, and one must now accept the work of Waters and R. F. Flint showing that the "Great Terrace" is a complex of stream and lake deposits, whose original, unevenly coalesced surface was swept smooth and plane by a final flood of glacial meltwater, released when the ice dam across the Columbia River near Grand Coulee broke.

Such a flood, with icebergs tossing on its surface, is thought by

Waters to have left its record at the north end of Alta Coulee, a few miles north of Chelan. The highway passes through Alta Coulee, a deep notch cut into granite by the Methow River as it tried to reach the Columbia by flowing along the edge of the glacier. When the glacier melted back, and everything seemed to have quieted down, the ice dam upstream broke, and the huge bergs formed an ice jam in Alta Coulee, settling deep into the sediment and becoming covered over with more sediment. Finally the buried ice blocks melted so that the smooth terrace surface became pitted with deep hollows such as the highway passes today. As the rush of water subsided, the Columbia first stopped depositing sediment and then gradually began to cut a channel into the terrace as it is doing now.

Farther north, the Okanogan River and its tributary from the west, the Similkameen, both of them flowing down from Canada, early attracted the attention of geologists by their erratic courses. As one of his early assignments with the new U.S. Geological Survey, Bailey Willis reported in 1887 on drainage changes due to glaciation in this part of Washington Territory, showing how before glaciation the Similkameen flowed south to Loomis before turning east to join the Okanogan (Okinakane at that time) at Tonasket; how the ice filled the valley so that some of the meltwater flowed on south past Conconully before joining the Okanogan; and how in the meantime an ice-edge stream found and deepened a low divide east of Nighthawk so that this became the permanent course of the Similkameen. The original course, from Loomis to Tonasket, is full of sand and gravel and contains two lakes but no stream. The temporary course past Conconully shows few signs of its former occupant besides the rocky notch type of dry channel.

Moraine-dammed lakes are plentiful. Just southeast of the Cascade summit, the Snoqualmie Pass highway runs along Keechelus Lake. The glacier that flowed down the upper part of the Yakima River valley stood long enough in one place—that is, the ice melted just as fast as it flowed downhill—for a considerable embankment of debris to accumulate at the toe of the glacier, where the melting of the ice liberated all of the rocks and dirt that had been carried there, frozen in the ice. Upon retreat of the glacier, this embankment, or terminal moraine, acted as a dam to the river, and Keechelus Lake came into being. Kachess Lake and Cle Elum Lake, in tributaries to the upper Yakima nearby, were formed in the same way.

Figure 1. Mount St. Helens, a Cascade volcano built since Pleistocene time. (Courtesy of Washington State Advertising Commission)

Figure 2. Sea cliffs of Eocene basalt near Cape Disappointment, just north of the mouth of the Columbia River. (Courtesy of Washington State Advertising Commission)

Figure 3. The "Great Terrace" of the Columbia River. View north from basalt rim opposite Chelan. The shadowed slot left of center is Alta Coulee. (Photo by Eliot Blackwelder)

Figure 4. Upper Grand Coulee, viewed from the north, above Coulee Dam. Feeder canal, center, equalizing reservoir (floor of Grand Coulee, background). The floor of the Coulee and the foundation of the dam are granite; the walls of the Coulee are of Columbia River basalt.

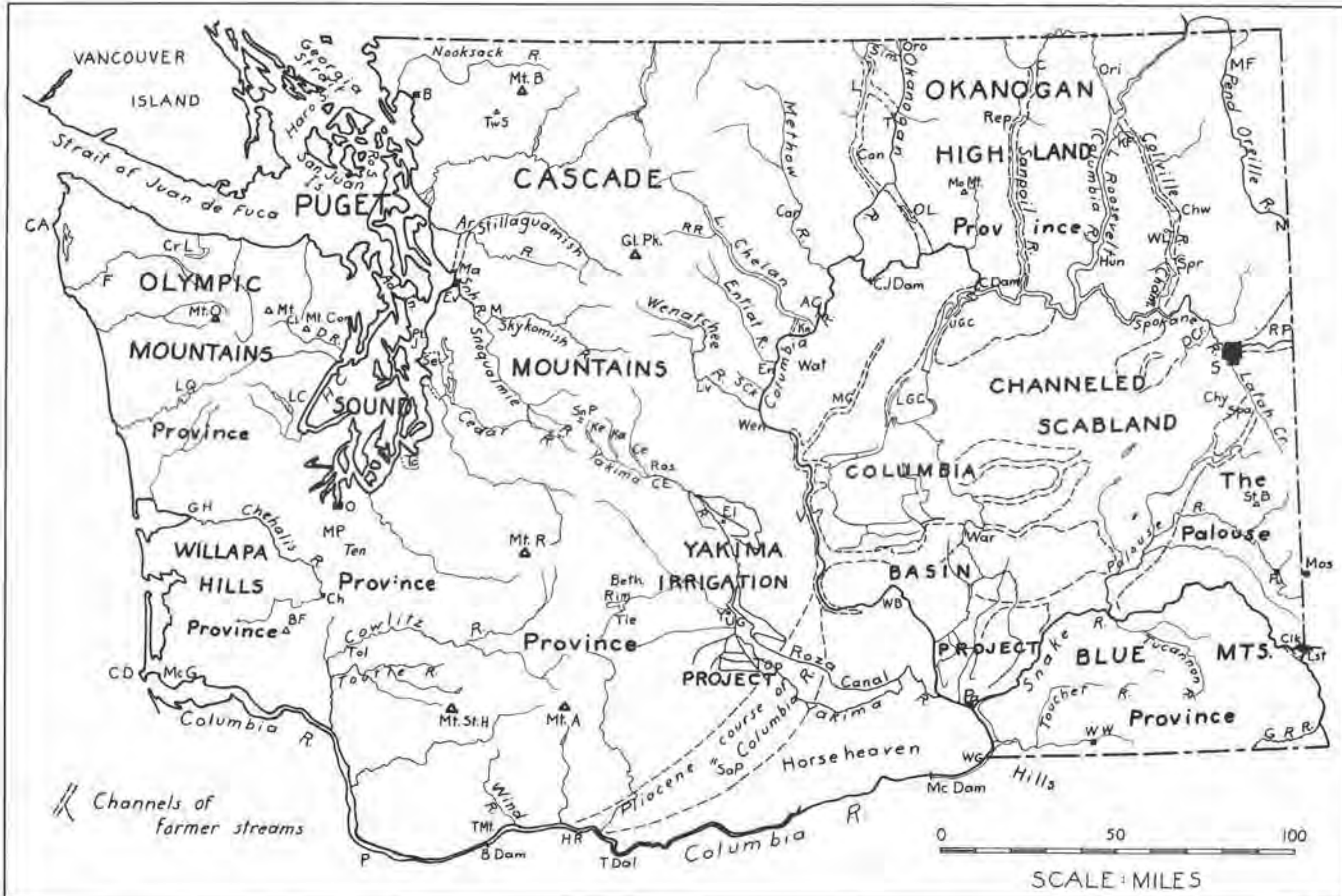

Figure 5. Outline map of Washington, showing locations of places mentioned in the article.

Key to abbreviated names:

AC	Alta Coulee	Ev	Everett	Mt.A	Mount Adams	Sim	Similkameen River
Ad In.	Admiralty Inlet	F	Forks	Mt.B	Mount Baker	SnhR	Snohomish River
Ar	Arlington	GH	Grays Harbor	Mt.Cl	Mount Claywood	SnP	Snoqualmie Pass
B	Bellingham	Gl Pk	Glacier Peak	Mt.Con	Mount Constance	Spa	Spangle
BDam	Bonneville Dam	GRR	Grande Ronde River	Mt.O	Mount Olympus	Spr	Springdale
Beth	Bethel Ridge	HC	Hood Canal	Mt.R	Mount Rainier	StB	Steptoe Butte
BF	Baw Faw Peak	HR	Hood River, Oregon	Mt.St.H	Mount St. Helens	T	Tonasket
C	Curlew	Hun	Hunters	N	Newport	Tc	Tacoma
CA	Cape Alava	Ka	Kachess Lake	O	Olympia	TDal	The Dalles, Oregon
Car	Carlton	Ke	Keechelus Lake	OL	Omak Lake	Ten	Tenino
CD	Cape Disappointment	KF	Kettle Falls	Orl	Orient	Tie	Tieton Basin
CDam	Coulee Dam	Kn	Knapp Coulee	Oro	Oroville	TMt	Table Mountain
Ce	Cle Elum Lake	L	Loomis	P	Portland, Oregon	Tol	Toledo
CE	Cle Elum	LC	Lake Cushman	Pa	Pasco	Top	Toppenish
Ch	Chehalis	LGC	Lower Grand Coulee	PtJ	Point Jefferson	TwS	Twin Sisters Mt.
Cham	Chamokane Creek	LG	Lake Quinault	Pu	Pullman	UG	Union Gap
Chw	Chewelah	Lst	Lewiston, Idaho	Rep	Republic	UGC	Upper Grand Coulee
Chy	Cheney	Lv	Leavenworth	Rim	Rimrock Lake	V	Vantage
CJDam	Chief Joseph Dam	M	Monroe	Ros	Roslyn	War	Warden
Clk	Clarkston	Ma	Marysville	RoS	Rosario Strait	Wat	Waterville
Con	Conconully	MC	Moses Coulee	RP	Rathdrum Prairie	WB	White Bluffs
CrL	Crescent Lake	McG	McGowan	RR	Railroad Creek	WG	Wallula Gap
DCr.	Deep Creek	MF	Metaline Falls	S	Spokane	WL	Waits Lake
DR	Dosewallips River	MoMt	Moses Mountain	SaP	Satus Pass	Y	Yakima
El	Ellensburg	Mos	Moscow, Idaho	SCk	Swakane Creek		
En	Entiat	MP	Mima Prairie	Se	Seattle		

Many other lakes were similarly formed, but some have since been drained by overflowing and cutting down their outlets; for these are among the most ephemeral kinds of lakes. Such breached terminal moraines can be seen about 20 miles up the Entiat River from the Columbia, near Leavenworth on the Wenatchee River, and near Carlton on the Methow River.

Quite different, and much more enduring, are the small rock-bound lakes among the steep cliffs at the heads of the valleys. Many of these cirque lakes, which are dotted all over the high Cascades, are still fed from the shrinking glaciers, which, at their maximum, utilized these huge vertical-walled amphitheaters as gathering grounds for snow and ice, whence they slowly flowed down-valley.

Not all the drainage changes have been due to glaciation: the much-harried Columbia River has left a record of its wanderings in Yakima and Kittitas Counties. Its course during the first half of Tertiary time is buried several thousand feet deep somewhere underneath the Columbia River basalt flows. When these basalts poured out, flow after flow, they pushed the Columbia westward against the front of the early Cascades. Outwash from the Yakima and other rivers was repeatedly buried under fresh lava flows; but when the flows ceased, the volcanic detritus from the Yakima River built up a huge fan on the top of the lava plain. This alluvial fan (the Ellensburg fan), whose pale-gray crumbling beds remain on many hillsides northwest of Yakima, reached a thickness of 1,500 feet and extended eastward to an arc passing from Vantage Ferry to Toppenish.

Being unable to remove the toe of this fan as fast as it formed, the Columbia skirted it and flowed on southwest to Hood River, where it encountered another large fan (The Dalles fan) built out from the Oregon Cascades. The river flowed for a long time along this early Pliocene course and ranged widely, strewing sand, pebbles, and cobbles of rock types from Canada and northeastern Washington, as well as from the Cascade lavas. The resulting gravels, now cemented and weather-stained, were buried beneath abundant olivine basalts in the Satus Pass region, and to the north they were buried under the Ellensburg fan.

During several million years thereafter—from Middle Miocene to the end of the Pliocene or so—the Cascade Mountains must have worn down, and the country to the east sagged under the weight of lava and sediment aggregating perhaps 5,000 to 10,000 pounds per square inch; and the resultant eastward shift of the Columbia has not yet been satisfactorily separated from that due to a renewed rise of the mountains at the end of the Pliocene. The present pattern of southeast-trending ridges then appeared, with results that may be both imagined and verified in the field. The hard, solid basalt slowly buckled up into ridges lying directly athwart the Columbia and Yakima Rivers; and once the soft beds of the Ellensburg fan had been washed away from the high spots, the basalt ridges formed a series of dams. Lakes formed on the north sides of these and rose until they overflowed, around the southeast ends of the folds, but across low saddles also. As the ridges grew, the Columbia and its chain of the lakes shifted eastward, disrupted even further by new basalt flows of limited extent. We can be confident about this because an ash fall from the Cascades conveniently blanketed the country during these proceedings, furnishing us with a reference bed that is everywhere of exactly the same age.

By this time the Pleistocene glaciers had arrived in the north, and all the rivers of eastern Washington were pouring floods of sediment-laden water into a growing inland lake (a smaller version of the "Lake Lewis" referred to earlier), filling in the lake with sediment as it rose intermittently behind the basaltic arch of the Horseheaven Hills. Overflowing the arch first at a low saddle near Wallula, the sluggish Columbia, approaching from across its gravelly plain, sawed its way down only indifferently well through the hard rock and cascaded down the south side, very likely forming a waterfall.

The sediments deposited by the Columbia back of the Horseheaven Hills blockade are called the Ringold formation, and their best exposure forms the White Bluffs of the Hanford Reservation of the Atomic Energy Commission. They contain bones of various large animals, and the bones in the upper beds indicate that the Horseheaven dam was still formidably high in late Pleistocene time. It has therefore been a relatively short time since the blockade was removed, Wallula Gap formed, and most of the accumulated gravels of the Ringold beds washed on down the Columbia. The most probable explanation for this "sudden" lowering of the outlet is that a waterfall really did form, and that it retreated upstream by caving-in of the brink until it removed even the last vertical septum of basalt that held back the accumulated water-soaked Ringold sediments and allowed the river to begin sluicing them down the new Wallula Gap, until only scattered remnants remained.

Other watergaps were forming during and prior to this time, upstream where the Columbia and Yakima Rivers were meeting the same problem with other ridges. Union Gap, just south of Yakima, is such a watergap. Another one, widely illustrated in texts on geomorphology (the science of landforms), is the course of the Yakima River from Ellensburg to Yakima, where the river valley is a steep narrow gorge whose wide loops are an inheritance from a time when the river flowed slowly back and forth over a flat plain—the lava plain. When the Cascades rose, so also did the two closely parallel ridges—Manastash and Umptanum Ridges—athwart the Yakima River south of Ellensburg. Apparently the land rose up under the river so slowly that the river was able to cut down into it at an equal rate, entrenching itself in the meandering course it had before the uplift. It is not difficult to imagine what a different pattern of cities, railroads, and highways would exist if any of the watergaps had failed to open up.

Among more recent geological events, which concern the engineer, are landslides, of which many large ones are known in the Cascades. The best-known and largest slide area is the North Bonneville, which extends along the Columbia River for 15 miles in Skamania County west of Wind River. The Oregon geologists, Ira A. Williams in 1916 and E. T. Hodge in 1938, described the succession of massive, generally slow-moving slides from the north, into and even across the Columbia. The sixth and latest major slide is probably the Bridge of the Gods of Indian accounts, recently summarized by Ella E. Clark. The blocking of the river, so that it rose and drowned forests upstream, was ended, according to best estimates, around 1770. It has been suggested that Table Mountain will be the next to go. The cause of the landslides is the dead weight of hundreds of feet of the Columbia River basalt overlying the soft, wet beds of the Eagle Creek formation, sloping south from the center of a large volcano that once rose some miles north of the Columbia. So long as the later basalts covered these soft beds completely, nothing moved; but when the Columbia River eroded its gorge down to the Eagle Creek formation, things began to move briskly, and it is a possibility that this is only the beginning of the rapid enlargement of a valley northward that will finally exhume the old Eagle Creek volcano, which has been buried under basalt these 25,000,000 years.

The rocks in the northern half of the Cascade Mountains province are chiefly Paleozoic and Mesozoic sedimentary and metamorphic types, and granitic rocks; and in the southern half are younger sedimentary rocks and volcanics: presumably the northern area has been raised more than the southern.

In the northern Cascades, thousands of cubic miles of granitic rocks, with their satellite ore deposits, were formed at some considerable depth among the older compressed rocks, and then raised up into a mountain range high enough that their cover was eroded away. Pebbles and grains of these granites are among the most abundant constituents of the great masses of sandstone and conglomerate, of early Eocene age, which are the solidified form now assumed by the extensive sedimentary detritus washed out upon the plains along the southeast foot of the new range, from Wenatchee to Bellingham. The types of fossils found in these deposits indicate that there were fresh-water lakes and streams, and that the climate was tropical enough to support fan palms and extensive coal-forming coastal swamps. In their present condition, the moderately folded tan and gray sandstones, shales, and conglomerates form bulky outcrops, prominent along the Wenatchee Valley and in places on the Blewett Pass road, where the main part of them is called the Swauk formation. At the other end of the belt, Chuckanut Drive passes through outcrops here called the Chuckanut formation. This belt of sedimentary rocks actually extends at least as far south as Mount Adams and west to the old ocean floor around Centralia, but most of it has been buried under later lava flows. Geologists at the 1951 combined summer field camp of the State College of Washington and University of Washington measured a thickness of 10,000 feet of Swauk beds north of Leavenworth, a thickness only possible if the ground sagged while they accumulated, just as the ocean floor sagged while the Paleozoic and Mesozoic sediments accumulated earlier, which later became the Eocene mountain range.

From the time when these Eocene sediments were deposited, up to the present time, the geologic history of the Cascades is a picture of volcanoes and earth movements, recorded in the southern half of the range. (Prior to Eocene time, this part of the Pacific Ring of Fire had been flooded with basalts during the Permian, and huge volumes of granitic rocks had been formed at the end of the Cretaceous.) There seems to be a certain rhythm in the sequence of events beginning in the Eocene, as follows:

1. Eocene: quiet flows of basalt, gushing out of many deep cracks.
2. Late Oligocene to early Miocene: alternately quiet flows and explosive eruptions of andesite and basalt at certain centers, forming large volcanic peaks.
3. Middle Miocene: same as (1), but on a vast scale.
4. Late Pliocene and Pleistocene: same as (2), forming the present peaks.

To accentuate this rhythm, add that there was a lesser uplift of the Cascades just before event (2), and a major one just before event (4).

To see examples of the basalt of event (1), drive over Blewett Pass, where scores or even hundreds of parallel dikes—lava-filled cracks—slice up through the Swauk formation mentioned above. The flows that came out of these cracks lie in an area of modest size in the vicinity of Cle Elum and Easton, and they are called the Teanaway basalt.

It is somewhat conjectural whether or not the extensive lavas and tuffs of the second event formed volcanic peaks. The present attitudes of the volcanics in some places suggest it, but the lavas are so extensively buried, or eroded away, or broken up by faulting in other places, that it is too early to be sure of their original forms. To see their remains, any of several places is worth a visit. In the Bonneville area along the Columbia River, the Eagle Creek volcano has already been described as being half exhumed by the Columbia, aided by landslides, from underneath a basalt cover. On the north side of the Tieton Basin, in Yakima County, the slopes of Bethel Ridge display an impressive and colorful section through the east-dipping tuffs and flows, which, projected westward, appear to have risen to a high volcanic peak somewhere around the present site of Mt. Rainier, and to be thus about 60 miles north of the Eagle Creek volcano. In Mount Rainier National Park, the "Keechelus" is two series of volcanics, the younger one being fresher and less disturbed than the older. W. C. Warren found the same situation in the Tieton area, where he called the younger lavas the Fifes Peak andesite. Therefore the picture of the Keechelus volcano belongs only to the older part of the volcanics originally called Keechelus.

The third episode of the Tertiary volcanic history of the Cascades was the eruption of the Columbia River basalts. The Cascades province received only a minor fraction of the flood of 35,000 cubic miles of basaltic lava, of remarkably uniform composition, which buried all of the Columbia Basin province of southeastern Washington; extended south in Oregon almost to California; and covered parts of western Idaho. The Columbia River basalts, like the earlier Teanaway basalts, were erupted through cracks, quietly and without much explosive activity except at the beginning in a few places. Since the individual flows keep a uniform thickness over several miles, it is supposed that the lava was thin and free-flowing, as are similar basalts erupted from time to time in Hawaii and elsewhere. A more explicit description of these lavas will be given in the section on the Columbia Basin province, where they are the dominant feature.

In the Cascade Mountains province, the Columbia River basalts cover wide areas from the Columbia River, where they are exposed in a thickness of 730 feet above the Eagle Creek formation, northward over a wide area in varying thicknesses. The west margin of the basalt-covered area extends down the east side of the Cascades from Lake Chelan to Wenatchee; thence the limit runs southwest to the Chehalis area. Most of the lava has been eroded from the narrow belt south of Lake Chelan, re-exposing the rolling surface, of Miocene age, upon which it was erupted. The more recent Entiat River and tributaries have cut deep into this surface, leaving only flat interstream divides at elevations upward of 2,000 feet, some of them stripped clean of basalt, some sprinkled with huge residual boulders, and some still basalt-covered, like Ribbon Mesa, just north of Entiat. A person driving along the Wenatchee-Chelan highway can look east across the Columbia River and see the extension of this stripped surface as an undulating line beneath the basalts that cap the canyon: east-trending ridges 1,500 feet high were completely flooded by the basalt, and then the Columbia River cut its way down through them transversely, exposing the whole section like a diagram.

The fourth and latest volcanic episode, following the Columbia River basalt floods, was the building up of the present volcanic peaks, already described. The Cascade mountain mass rose to its present height in the interim; for its valleys are cut into the basalt but are themselves flooded by the peak-building lavas. The uplift must have been gradual, probably chiefly during the Pliocene epoch.

The Cascade Mountains province, particularly in the northern half, is very well mineralized. One of the largest mines in the state was situated here in Chelan County, on Railroad Creek, which was described as tributary to Lake Chelan. This is the Holden mine of the Howe Sound Company and produced some 2,000 tons per day of copper-zinc ore containing also gold and silver. The ore deposits are in a zone of highly altered sedimentary rocks, now quartz-soaked schist, within a broad streak of granitic rocks that extends unbroken from Swakane Creek, north of Wenatchee, to the headwaters of the Nooksack River and into Canada.

The black chromium mineral, chromite, forms layers and lenses in the rocks of Twin Sisters Mountain, just southwest of Mt. Baker. Except for the chromite, this rock is composed almost entirely of the mineral olivine, which is hard, heavy, glassy-green, and usable itself in the making of highly refractory furnace-brick. The Twin Sisters mass, one of the largest of its kind, is about eight by twelve miles in size; and nobody has yet satisfactorily explained its origin. Serpentine, which is also a magnesium silicate but hydrous and quite soft, is found in many rather small masses scattered around the margins of the large granitic areas; but little chromite has been found in them, although serpentines contain most of the chromite deposits in Oregon and California, and elsewhere around the Pacific Ring of Fire.

The coal fields of Washington are almost entirely in lower Eocene beds and are the fossilized remains of the tropical coastal swamps of that time, described above. The principal fields are of subbituminous and bituminous coal, and occur on the lower west slopes of the Cascades and in the upper part of the Yakima valley near Roslyn. Small fields of anthracite, northwest of Mt. Baker and southeast of Mt. Rainier, are in places where the ordinary coal was so intensely deformed that most of the volatile components were driven off, leaving nearly pure carbon.

OKANOGAN HIGHLANDS PROVINCE

The Okanogan Highlands occupy the northeastern part of the state, from the Cascade Range east to Idaho and from the Columbia and Spokane Rivers north into Canada. Much of the region is more than 4,000 feet above sea level, and a few mountain tops reach altitudes above 8,000 feet. Although there are cliffs and slotted valleys locally, moderate slopes and broad, rounded summits are the rule; and the area, in general, lacks the ruggedness that characterizes the northern Cascades.

Precipitation is moderate, ranging from 15 inches or less in the low altitude areas of the western and southern parts of the province, to 25 inches near the Idaho line. This is sufficient to support a cover of timber that is open, in the drier parts, to dense in the northeast. The rather broad north-south valleys (in succession from the west) of the Okanogan, Sanpoil, Kettle-Columbia, Colville, and Pend Oreille (Clark Fork) Rivers divide the province into a series of individual uplands.

The combined valleys of the Spokane and Columbia Rivers mark definitely the south limit of the province, whose south-trending ridges disappear there under the deep cover of the Columbia River basalt, as do those described in the area south of Lake Chelan. The course of the Columbia, from the Spokane to the Wenatchee Rivers, is clearly a consequence of the eruption of the basalts, which here flowed outward toward the mountains, damming the various streams and forcing them to skirt the lava field westward to the Cascades and then south. Necessarily this new-formed master stream, the Columbia River, had to cut directly across all of the ridges of the older landscape, because the wall of lava overrode even the ridgetops.

As in the Cascades, former glaciers have disrupted the drainage, filling wide valleys with sediment and forcing large streams into notches too small for them. The province was almost entirely buried under ice from Canada more than once during the Pleistocene, but, from Moses Mountain east, the higher peaks and ridges projected and show that the ice was about a mile thick in the valleys.

As the glaciers melted, small lakes formed along their edges in the higher parts of the side-valleys; and the sediments, which settled in these lakes, can be seen clearly now as small terraces high up in the valleys. Their flat tops are a great boon to roadbuilders and they furnish many pleasant camp sites (the huckleberries are wonderful), though their gravelly flanks present problems in road maintenance. These ice-edge terraces form a sort of staircase down any particular valley, recording the ice wastage, and the elevations of their "treads" do not necessarily accord with those of "treads" in neighboring valleys. It is only in the main valleys, at lower elevations, that terraces matched in elevation can be found; and these have a different history, being the remains of the blanket of sediment washed out over the valley floor during the final ice retreat.

The most remarkable of these broader matched terraces, as might be expected, is the one common to the whole province. It has been called the Nespelem terrace. Much of it has been washed away as the Columbia and its tributaries subsided; and the progressive shrinking of the rivers is recorded in the progressively lower flats that they have eroded into its flanks, down to the flood plains of the present day. But broad, undissected areas of the Nespelem terrace still remain, and road cuts in it reveal how it was built up, year by year; each year of its growth shows a definite pattern, or cycle, of sedimentation. A thin sheet, perhaps a fraction of an inch thick, of coarser sediment for the melting season, passing upward into a sheet of fine sediment for the freezing-up. In some roadcuts, hundreds of these cycles record hundreds of years of growth of the terrace, but they have not been assembled into a connected chronology as have similar sediments in the Connecticut Valley and in Scandinavia. Some road cuts show groups of layers contorted into sharp folds, as though the glacier readvanced briefly and rumpled the surface of its recent deposits.

The top surface of the Nespelem terrace is the site of most of the agriculture of the province. Its thicker beds of sand and gravel are quarried and screened for use; some of its soapy-fine, pale-gray clay layers have been used for ceramic ware. And its long, gently sloping surface has made easy the construction of highways and railroads, though the unsurfaced roads are either too dusty or too sandy in the summer.

Two major stream diversions, the result of glaciation, may be mentioned for the Okanogan Highlands province. The Columbia River now forms the boundary between Stevens and Ferry Counties. But for a time at least it turned east at Kettle Falls and followed south along the valley of what is now the north-flowing Colville River and, below Springdale, the south-flowing Chamokane Creek.

The Pend Oreille River (Clark Fork), before the latest glaciation, flowed from Pend Oreille Lake direct to Spokane, and thence west. One could call it the ancestor of the Spokane River. But its valley was then filled by a particularly large and gravelly glacier which, when it melted, flushed huge volumes of gravel and sand southward into the valley, forming Rathdrum Prairie. The small tributary streams were blocked off by this wall of sediment and formed lakes, such as Coeur d'Alene Lake whose level rose until its outlet—the present Spokane River—found a way west. Meanwhile the Pend Oreille was diverted to its present course north through Pend Oreille County and west to the Columbia. A veritable underground river still flows through the gravels underneath Rathdrum Prairie, however, from which Spokane and the East Valley pump their water supplies.

The rocks of the Okanogan Highlands are similar in their diversity and ages to those in the northern Cascades, but are in general older toward the east, where a variety of pre-Cambrian sedimentary rocks and greenstones form the hills of southwestern Stevens County and eastern Pend Oreille County. They are western outliers of the famous Belt series, in which are found the rich ore deposits of the Coeur d'Alene district of northern Idaho; and, in both of the Washington areas mentioned, their thickness is about 30,000 feet. Lying above these, in progressively lesser thicknesses, are rocks of the Cambrian (notably the ore-bearing Metaline limestone), Ordovician, Devonian, and Mississippian systems. In the northwest part of the province is a great thickness of Permian greenstone, originally basalt. As in the Cascades, the wealth of geologic history recorded in all of these rocks has not yet been deciphered in more than rough outline.

As in the northern Cascades, granitic rocks are the most abundant kind in northeastern Washington. Most of them are streaky and might be older sedimentary rocks "granitized" by hot alkaline solutions at the close of the Mesozoic Era. Other smaller masses are clearly younger and may, as A. L. Anderson has indicated for Idaho, be the most important ore bringers.

Apart from the smaller granite masses just mentioned, the Tertiary record is one of deposition in rivers and lakes, and of lavas erupted upon the surface and into the sediments. A considerable part even of this recent a record has been removed by erosion, but some trends are apparent. The sediments are bedded as though by rivers, and their remains are found near the present Okanogan, Sanpoil, Columbia, and Pend Oreille Rivers, in aggregate thicknesses generally under 1,000 feet but reaching 2,000 feet just west of Oroville, Okanogan County. This seems to indicate that something like the present river pattern had established itself before and during the time these sediments formed. The poorly preserved plant remains —oak, elm, pine, spruce—tell that this was the Tertiary, most likely the Miocene epoch, with a climate rather like the present. A diligent search six or seven miles south of Metaline Falls, Pend Oreille County, in the blackish shales along the highway, may uncover leaf prints. Other such fossils may be found near the dam on the Similkameen River a few miles west of Oroville, in the 2,000-foot section, which includes massive conglomerates and sandstones as well.

Along the same north-south valleys were then erupted andesite and similar lavas. These flows piled up 2,000 feet thick in the Okanogan valley, 1,200 feet in the Sanpoil, 700 near the mouth of the Spokane, and 1,100 in the Pend Oreille valley northwest of Newport. It is not difficult to find them. They filled the Sanpoil valley and were then gullied out by the new stream, so that the valley walls expose them clearly in gray rocky slopes most of the way up to the Kettle River at Curlew. All around the confluence of the Spokane and Columbia Rivers are the remains of a volcano described by C. E. Weaver as buried under the Columbia River basalts to the south, but which includes a dome-shaped mass overlooking the Columbia just west of Hunters, in Stevens County.

One must again here, as in the discussion of the Cascade rocks, defer an account of the eruption of the Columbia River basalts, leaving this to the next section where they are most widely developed. The Columbia River, as mentioned, forms their north boundary in most places, but the flows poured north, up what is now the middle of Stevens County, as far as Waits Lake; and they sent an extension into the area between Omak Lake and the Okanogan River. (The preglacial Columbia River went around the north end of this extension, instead of through the middle of it.) The basalts can be recognized anywhere by their somber vertically-fluted cliffs.

The ore deposits of the Okanogan Highlands province are about as diverse as possible. Much of the lead-zinc ore of the famous Metaline district of northern Pend Oreille County is volume-for-volume replacement of parts of the Metaline limestone, far from any granitic rock such as is presumed to be the source of the ore metals. For many decades Republic, Ferry County, has been a mining center utilizing gold-silver ore formed in early to middle Tertiary lavas and related rocks at shallow depth. One kind of

Republic gold ore contains the unusual element selenium, and its closest known relative is in Sumatra, Indonesia.

Stevens County alone has a great variety of ore deposits. Magnesite, quarried from a bed in the top of the pre-Cambrian series, west of Chewelah, is dead-burned and shipped east as a basic refractory used in the steel industry. Lead-zinc-silver ores are mined from limestones in the northeast part of the county; gold from veins extending down from the Rossland district, B.C., as far as Orient; copper from veins northeast of Chewelah; dolomite marble as an ore of magnesium metal has been quarried a few miles southwest of Northport; and in the same vicinity are quarries in limestone and shale for portland cement. Ferry and Okanogan Counties too have a variety of mineral deposits, including a deposit of magnetite (magnetic iron oxide) in northeastern Okanogan County, which was used during World War II by the Kaiser shipyards near Portland as ballast.

COLUMBIA BASIN PROVINCE

The Columbia Basin province, which includes approximately two-thirds of eastern Washington, is one of the most distinctive physiographic parts of the state. It extends south from the Okanogan Highlands and continues far into Oregon, though restricted on the east by the Blue Mountains. On the west it merges into the Cascade Mountains; and on the east, into the outliers of the Idaho mountains at about the state line. The province may be thought of as a saucer-like area whose rim is about 2,500 feet above sea level on the west, north, and east, but missing at the south border of the state. In a few places, the interior is elevated into hills over 2,500 feet above sea level; but most of the province is gently undulating to moderately hilly and between 1,000 and 2,000 feet in altitude, declining under 1,000 feet in much of the southern area.

Most of the province has an annual precipitation of less than 10 inches and is semi-arid and treeless; in fact, the lowest annual precipitation for the state (6.46 inches over a 20-year period) was recorded in Benton County. This is the immediate effect of the Cascade Mountains, whose rise in relatively recent times dried up the eastern part of the state by trapping most of the moisture from winds coming in off the Pacific. As would be expected, streams heading within the province are few, small, and commonly intermittent. The Columbia, Spokane, and Snake Rivers, which border or flow through the province, have their sources far outside of its boundaries; and it is the fortuitous combination of the large, cool Columbia River and an arid and therefore little-inhabited area, which made an ideal location for the Hanford Works of the Atomic Energy Commission. The dryness of a million acres of otherwise fertile ground in the Columbia Basin is also the result of the rain-shadow from the Cascades; but the presence of the ample Columbia River, to the north, made possible an irrigation project as extensive as that which the U. S. Bureau of Reclamation is bringing toward completion.

The principal rock of the province is the Columbia River basalt, a part of the immense series of lava flows, mostly middle Miocene in age, that cover some 100,000 square miles in Washington, Oregon, and Idaho. The maximum thickness of this series is probably over 11,000 feet; nearly that thickness of flows was cut in a hole drilled into the Horseheaven Hills in Washington. The thickness at Union Gap, near Yakima, is over 4,000 feet. In the Columbia River Gorge through the Cascades, the thickness of basalts above the Eagle Creek formation reaches 730 feet.

The entire lava plain is built up of innumerable overlapping flows, each relatively small. The individual flows average about 100 feet thick in the Gorge and about 80 feet thick along the Snake River, in Whitman County. The length of individual flows is generally measured in miles, but little is known of their shape in plan view. It is reasonable to suppose that, since each flow must follow a low crease between earlier flows, it is elliptical in plan.

Around the margins of the basalt area, high hills were surrounded but not submerged by the lavas. Steptoe Butte, in Whitman County, is the type example of a "steptoe"—an island in an ocean of lava—but there are many others along the east boundary of the state.

There is an infinity of interesting detail that can be seen in the flows, but only a small sampling can be noted here. Their most prominent but least understood feature is their jointing, or pattern of cracks. The vertical columns, of polygonal cross section, are probably the result of solidification of the lava after it had ceased flowing but was still largely liquid. Similar cracks develop in any film that shrinks as it cools or dries out, as will a muddy surface. Larger columns—some of them are over five feet in diameter and can be sawed and ground into broad slabs used in checking the flatness of precision-machined surfaces—are the result of very slow cooling without movement. Some short but fairly thick columns line the highway (US 10) to Cheney from Spokane, just south of the Seattle junction. But what about the many examples of thick flows in which the columns are slender and clustered into radiated units called rosettes? Most of these are not explained, though some have been shown to be the result of later lavas filling tubes or surface channels in early flows; and one idea envisions a moving lava flow, of the right viscosity, engulfing air and spreading it into films within the sticky mass, and then coming to a halt, so that the polygonal columns begin to form at right angles to the curved air-film surfaces. Many flows lack distinct columns, but are broken up by close-set curving, shell-like joints or by a sort of cubical, blocky joint pattern. At some distance, these flows present rounded surface forms, instead of the vertical lines of columnar jointing. Such flows may have kept moving while crystallizing, or were somehow racked after they had become brittle.

Pillow lavas is the name given to basalt flows composed of separate or joined ellipsoidal masses whose glassy black borders indicate quick cooling. In some flows the pillows are embedded in yellow-tan clay full of basalt-glass particles, and their curious form appears to have resulted from the lava having flowed over a damp, or muddy surface that generated steam. Some of these are exposed in low cuts beside the highway about two miles north of Rosalia, just into Spokane County. The next logical step—where basalt lava ran into open water—seems to have resulted in complete granulation of the flow into coarse glassy sand, much of it altered to the yellow clay. Though some such deposits are an unbedded mass, dropped when the water stopped boiling, some display the same sort of steeply slanted bedding as characterizes river deltas, where the newly dumped sand slants away from the current. Such "foreset beds" can be seen in a water-quenched basalt flow near the top of the cliff north of the highway, a short distance toward Quincy from the mouth of Moses Coulee. Here the flows moved a little west of north.

Lastly, almost all flows have porous tops, which serve as markers between flows studied in the field. The holes (vesicles) are the memorials to the gas bubbles that were too late in leaving the cooling lava; and in many places they have subsequently been filled with the silica minerals opal and chalcedony, some of it of gem quality.

Whence comes 35,000 cubic miles of free-flowing basalt of almost uniform chemical composition? This is definitely exceptional, though there are a few other such areas of basalt in the world. The best guess is that a multitude of deep narrow cracks—perhaps 30 to 50 miles deep—split the earth's crust in this area, allowing great quantities of the world-wide subcrustal basalt to rise rapidly to the surface and come out as flows. Thus the Columbia River basalts are an uncontaminated sampling of the earth 30 miles down.

The disruption of the Columbia River drainage by the lava advance has been described in earlier sections. Where the flows moved eastward into the Idaho mountains, they dammed the streams, forming broad lakes in which hundreds of feet of fine-grained sediment accumulated. These "Latah beds" of the Spokane area contain good imprints of fossil leaves (maple, birch, cypress, and many others), and even stumps and flattened branches are exposed in the Latah beds at water level along Deep Creek, close to the Spokane River. These fossils indicate a Miocene climate like that of today.

In addition to the Latah beds of the Spokane area, lake beds with excellent leaf fossils occur below the basalt at the extreme north end of Grand Coulee; and the City water wells of Moscow, Idaho, penetrate several hundred feet of water-bearing beds under the basalt. Thus it would seem that the Latah lakes were extensive around the margins of the lava field.

Lake beds with plant remains occur in many places within the basalt series itself. The best known of these is an extensive petrified forest exposed along the Columbia River north and south of Vantage. The Ginkgo Petrified Forest State Park is a part of this, named from the remains of this odd tree, which is now native only to China. Dr. George Beck of Ellensburg has identified many species of temperate-climate trees from their silicified woody parts.

The basalt series lies flat, or nearly so, throughout most of its area; but locally, and especially southwest of the Columbia River, it has been bent into surprisingly sharp folds for so brittle a rock. These folds were so recently made (early Pleistocene) that their form is generally closely reproduced by the shape of the resultant hills and ridges, modified by erosion increasingly with proximity to the high land of the Cascades. The series of west and northwest trending ridges, which have previously been described as dams to the Columbia, extend in succession from the Entiat-Badger Mountain uplift near Waterville, down to the Horseheaven Hills 120 miles to the south, which forms a connection between the Cascades and the Blue Mountains.

The timing of these uplifts has been shown, in the section on the Cascade Mountains province, to be early to late Pleistocene, from the testimony of the Ringold beds of the blockaded Columbia; and geologists assume that the warping of the basalts in southeastern Washington took place at the same time. The west-trending "Lewiston monocline" is like a gigantic, 2,000-foot step whose top tread is the 2,500-foot plateau on which are situated Colton and Uniontown, and whose lower tread begins at Lewiston and Clarkston, elevation around 750 feet, and slopes gradually upward into the Blue Mountains to the south. In the "riser" of this step, the basalt flows dip as much as 60 degrees, a few miles west of Clarkston, but everywhere there are faults that complicate and even reverse the dips, as a sharp-eyed driver can see for himself on the Lewiston grade.

Two interesting bits of recent geological activity can easily be seen in the Lewiston-Clarkston area and record two abortive attempts of the Snake and Clearwater Rivers to cut permanent channels before they finally succeeded. The first effort resulted in the two rivers meeting about a mile east of Asotin, or about six miles south of their present confluence. These channels were then filled by two or three late basalt flows, whose remains are landmarks locally: Swallow Rock and the bluffs west of the golf course and at the north end of the Clearwater bridge. The floors of the lava-filled Snake River channel rise considerably, both upstream (south) and downstream (northwest) from this area, showing that the channel was already there before the last of the sagging movements ceased in the Lewiston Basin. Next, the rivers cut new channels alongside and across the lava-filled ones; but again they were ousted, this time by an excessive influx of sediment related to the glacial episode that formed Grand Coulee, described below. One section of gravel-filled channel follows beside a lava-filled one directly northwest from Asotin, across the back side of Clarkston. Since that time, the rivers have been able to cut their present channels unmolested.

The history just related is true also, with local variations, of other parts of eastern Washington. Spokane, for example, has its late basalt, exposed widely in the downtown area, which filled a valley cut in the Miocene Columbia River basalts and Latah beds; and this late basalt is overlain by hundreds of feet of glacial outwash, best seen in the slopes that rise east of Latah Creek at the south city limits.

The history of glaciation in the Columbia Basin province is of peculiar interest, not only for the diversity of its effects, but also for the manner in which the glacial features have been utilized by man.

Barring an obscure and debatable relic of early glaciation in one place, the oldest glacial feature is the Palouse loess, a layer of tan, silty sediment 150 feet or more thick, which covers an elliptical area 100 miles long in southeasternmost Washington, with fingers into adjoining Idaho valleys. This loess was probably brought in by wind (as implicit in the name), but much of it is evidently water-bedded, probably by ephemeral streams and lakes of the time. A few elephant, bison, and camel bones show its Pleistocene age. The loess forms smoothly rolling hills of great fertility, the dry farming of which produces large harvests of wheat, peas, and other crops.

The Palouse hills are steepest (30 to 35 degrees) on their northeast slopes: a fact that has led some people to consider them as wind-drifted dunes. This they are, but only in the sense that the southwesterly winds of recent centuries have brought in and deposited dust that has accumulated thickest on the lee brows of the hills that were already there. Recent study by soil scientists at the State College of Washington have shown that this new material contains minerals whose most obvious source is the volcanoes of the Cascade Mountains, as would be expected from the wind pattern. But underneath this recent blanket, which is a few inches thick on the south slopes and a few feet thick on the north, the bulk of the hills contains no such minerals. Since there is no reason to think that the Cascade volcanoes ceased to erupt during the time when the Palouse loess was accumulating, it seems as though the main part of the dust came from a different direction; *i.e.*, that the wind pattern was different. We should have no idea what other direction this might be, were it not that studies on Greenland and Antarctica have shown that large ice caps have their own outward-blowing winds, which generate great dust clouds around their margins; and because we are confident that a very large ice cap once stood with its margin a few miles south of the Spokane and Columbia Rivers, we might suppose that the wind, which brought the Palouse loess, blew southward. This is only a good possibility, not proven; but if true it indicates that the main loess was deposited at the time of a glacial maximum.

To the northwest and west, a large part of the Palouse loess has been washed away by floods of water, leaving dry, rocky "scabland channels" that interweave and trend southwest, and today contain no rivers, but only marshy spots, reedy ponds, and small brooks. The channels are not accessible to any large river and must be the work of glacial meltwater, either from the same glacier that provided dust and wind for the Palouse loess, or from a later one. The two largest channels of this family are Moses Coulee and Grand Coulee. The story of the formation of the Grand Coulee has been told vividly by the University of Chicago geologist, J Harlen Bretz, whose work around Puget Sound has been mentioned: but it can only be summarized here, especially as low-cost booklets by Otis W. Freeman and Joseph G. McMacken are widely available to tell the same story.

We start with an ice block across the Columbia from Grand Coulee to the Okanogan. (What happened downstream in Alta Coulee when this ice dam gave way has been described in the section on the Cascade Mountains province.) The river backed up to form a lake nearly deep enough to overflow south across the loess-covered plain. Then it received from upstream a huge surge of water—the "Spokane flood"—enough to cause it to spill over in many places at once and not just the lowest place, where Grand Coulee was later excavated. As the excess water subsided a little, most of the scabland channels dried up, leaving the main current to continue along the low channel that became Grand Coulee. Such an outsized flood seemed for many years most improbable, despite the evidence for its passage, but some features found northwest of Missoula, Montana, indicate the collapse of an ice dam there that held back a glacial lake large enough to supply a mass of water of the dimensions needed.

The sediment washed southward at this time blanketed the country down to the Pasco Basin, and the churning flood even moved up the Snake River as far as Lewiston, forming there a delta whose bedding, clearly visible across the highway from the Lewis and Clark Hotel, shows an east-directed current. Minor features too numerous to mention—lesser channels, gravel bars, terraces, and such—have been described by Bretz in support of his hypothesis; but it should be made clear that there are strenuous and well-considered objections and more reasonable-sounding alternatives, which, however, lack the mass of evidence that Bretz has continued to accumulate.

The latest extensive deposits of the Columbia Basin are of well-sorted sand, with minor amounts of gravel and silt, called the Touchet beds from their exposures along the Touchet River west of Walla Walla. The bedding of these sediments suggests that they were deposited in temporary lakes and on flood plains of large rivers. In many places, sheets of silt or sand pass at an angle through the bedded sediments. They are called clastic dikes, and geologists are not agreed on how they formed. Such clastic dikes have been found in Alaska, where hard-frozen sand beds have cracked in mass, allowing the more plastic silt and clay underneath to squeeze up through the cracks. If this is how the clastic dikes in the Touchet beds formed, then these beds must have accumulated during or before the latest glacial stage. Very possibly they are north and east extensions of the Ringold beds of the Columbia River, so that we may visualize the latest glacier melting along its terminus, and large sediment-laden rivers flowing southwest and south to join the Columbia during the time before the Wallula Gap was cut.

The Touchet beds near Warden, Grant County, contain man-made flints and include thin black layers that appear to be hearthsites, either in place or washed along the edge of a river of that time. If the climate was glacial, as suggested above, then early man must have arrived in Washington no later than the end of the latest glacial stage, 10,000 or more years ago.

The dryness of an otherwise rich and diverse soil, over a million acres of the Columbia Basin, has led irrigation engineers for many years to weigh the possibilities of bringing water to it from the Columbia or the Spokane, which flow in valleys hundreds of feet below and scores of miles to the north. The best of the several schemes was the present one, which utilizes the low-level connecting channel of Upper Grand Coulee, between the Columbia River Valley and the head of the irrigated area, as an equalizing reservoir 27 miles long, held in by long low dams across both ends. The construction of a sufficiently high (550 feet) Coulee Dam across the Columbia not only brought the waters of the lake within 300 feet below the long reservoir in Upper Grand Coulee, but provided a head of water for generating the power needed to hoist it, with a good deal left over for export. From the south end of the Upper Grand Coulee equalizing reservoir, the impounded water is led by gravity across the face of the irrigated land, as a last phase of the project.

In the paragraphs above, some confidence has been expressed that there actually were one or more times when large glaciers came south across the Columbia, and perhaps the evidence should be cited. Across the Waterville plateau is a winding line of low hills upon which, and north of which, perch enormous blocks of basalt as big as a house, called locally "haystack rocks," which most probably were torn off the south rim of the Columbia Valley, a few miles to the north of the line of hills, frozen into a glacier, then melted out at their present sites. Finding in the same area, in and north of the hills, blocks of rock identical in character to rock types outcropping far up the Okanogan Valley, we are strengthened in the belief that glaciers, not water, did the work. South-trending grooves in the rocks north of the line of hills suggest ice action also; and the line of hills itself, marking the south limit of the ice, is a terminal moraine. On the plateau north of Spangle, Spokane County, the distinct moraine is missing, but the other features are there; and the absence of the Palouse loess north of the line is emphasized by a growth of open pine forest.

The mineral deposits of the Columbia Basin province are largely stone, sand, and gravel. The Latah beds are quarried for clay, used in brick and tile. As yet undeveloped are zones of clay that apparently formed on a widespread swampy surface of weathering that developed during a long interval in the eruption of the Columbia River basalts. Some of this residual clay contains a usable percentage of titanium. Increasingly, however, the wealth of this province will come from agriculture.

Deposits of snowy-white diatomite, very fine grained and almost as light as cork, form lenses and more extensive beds between basalt flows. The material is actually opal (glassy hydrous silica), but in the form of minute, lacy shells of diatoms (primitive plants) that lived at that time suspended in the lakes. There are many diatomite deposits in eastern Washington, the two largest being northeast of Yakima and north of Vantage. The fineness of its pores makes diatomite a good filter and decolorizer for liquids, but it has many lesser uses.

BLUE MOUNTAINS PROVINCE

As a physiographic feature, the Blue Mountains have their main development farther south, in Oregon. The many streams have deeply incised the region into gorges and canyons, but the intervening areas—in some places sharp ridges and in others broad-topped tablelands—rise gradually from the general levels of the Columbia Basin to altitudes as much as 8,000 feet.

Precipitation—probably in excess of 30 inches in the higher mountains—is sufficient throughout much of the province to support a good stand of timber and smaller vegetation.

The Blue Mountains, like the Cascades in southern Washington, were formed by an arching of the earth's surface where the predominant rock is the Columbia River basalt. The many superimposed flows of lava reach thicknesses in excess of 3,000 feet in the canyon of the Grande Ronde, at the extreme southeast corner of the state. However, the Tucannon River and probably a few others, besides the Snake River itself, have channeled through the lava, in places, to expose various rocks, which once were high spots in the pre-lava topography. These older rocks include Triassic greenstones south of Lewiston, and Mesozoic granite at Granite Point about 20 miles northwest of Lewiston.

No metallic minerals are known to occur in the Blue Mountain region, and the nonmetallic resources are mostly limited to common stone and Pleistocene terrace sand and gravel. Limestone belonging to the Triassic series, is locally quarried at Hatwai, in Idaho just east of Lewiston, and is available though less accessible on the Snake River south of Lewiston.

The sands of the Snake River contain sparse amounts of gold, platinum, and monazite, a tan phosphate of the valuable elements cerium and thorium, all of them washed in from central Idaho.

CONCLUSION

Unintentionally, the writer has made the point, in the foregoing pages, that geologic processes are still actively at work, and will no doubt continue so. The only certain thing is change. The earthquakes at Mount Si and west of Olympia, in recent years, and the minor volcanic activity at Mt. Baker and Mount St. Helens a century ago are only the more newsworthy evidences. So perhaps are the floods that occur from time to time; but the rivers work around the clock, dust is swept away and settles elsewhere, soil particles creep downhill, and few people are the wiser. These processes move slowly, but they are inexorable; and some understanding of them is certain to increase one's enjoyment of the scenery, sharpen his imagination, and give him a greater insight into the many ways in which his life has been influenced by the recent and even remote geologic past.

CHART SHOWING INTERRELATIONS OF SOME OF THE ROCK TYPES

Sedimentary Rocks		Metamorphic Rocks			(Debatable area)
Loose form	*Cemented form*	*Recrystallized*	*Same, plus steam from below*		*Same, plus alkalies*
			(coarser grain)		
Gravel & larger	Conglomerate				
Sand	Sandstone	Quartzite	Quartzite	? →	Gneisses & Granitic rocks
Silt	Shale	Argillite			
Clay		Slate	Schist		Serpentines & Olivine rocks
Lime mud	Limestone	Marble	Marble		
	Dolomite	Dolomite marble			

Plant remains

Peat, lignite, subbituminous, bituminous, anthracite (coals)

Extra Notes:

Loess is a wind-deposited mixture of silt and clay, plus some fine sand.

Glacial till (also called boulder clay) is an ice-deposited mixture of all sizes of sediment, from huge boulders to finest clay.

Pumicite is a loess whose particles are entirely of volcanic glass.

Rocks formed from magma:

("Magma": Temperature 600° to 1,200° Centigrade; Viscosity pasty to thin-oily; Texture smooth to lumpy; Composition complex silicate solution)

1. *Cooled underground* (coarse grain):
Granitic rocks
Serpentine & olivine rocks

2. *Erupted* (fine grained to glassy):
Basalt and andesite (dark colored lavas). Metamorphosed to *Greenstone*
Pumice (light colored glass froth)

GEOLOGIC TIME SCALE

Cenozoic Era (the latest)
Quaternary
Recent — Since 10,000 B. C.
Pleistocene

Tertiary — 1 million years ago
Pliocene
Miocene
Oligocene
Eocene
63 million years ago

Mesozoic Era
Cretaceous
Jurassic
Triassic
230 million years ago

Paleozoic Era
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
600 million years ago

Pre-Cambrian
4,500 million years ago?

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