THE GEOLOGY OF MOUNT RAINIER NATIONAL PARK

BY HOWARD A. COOMBS

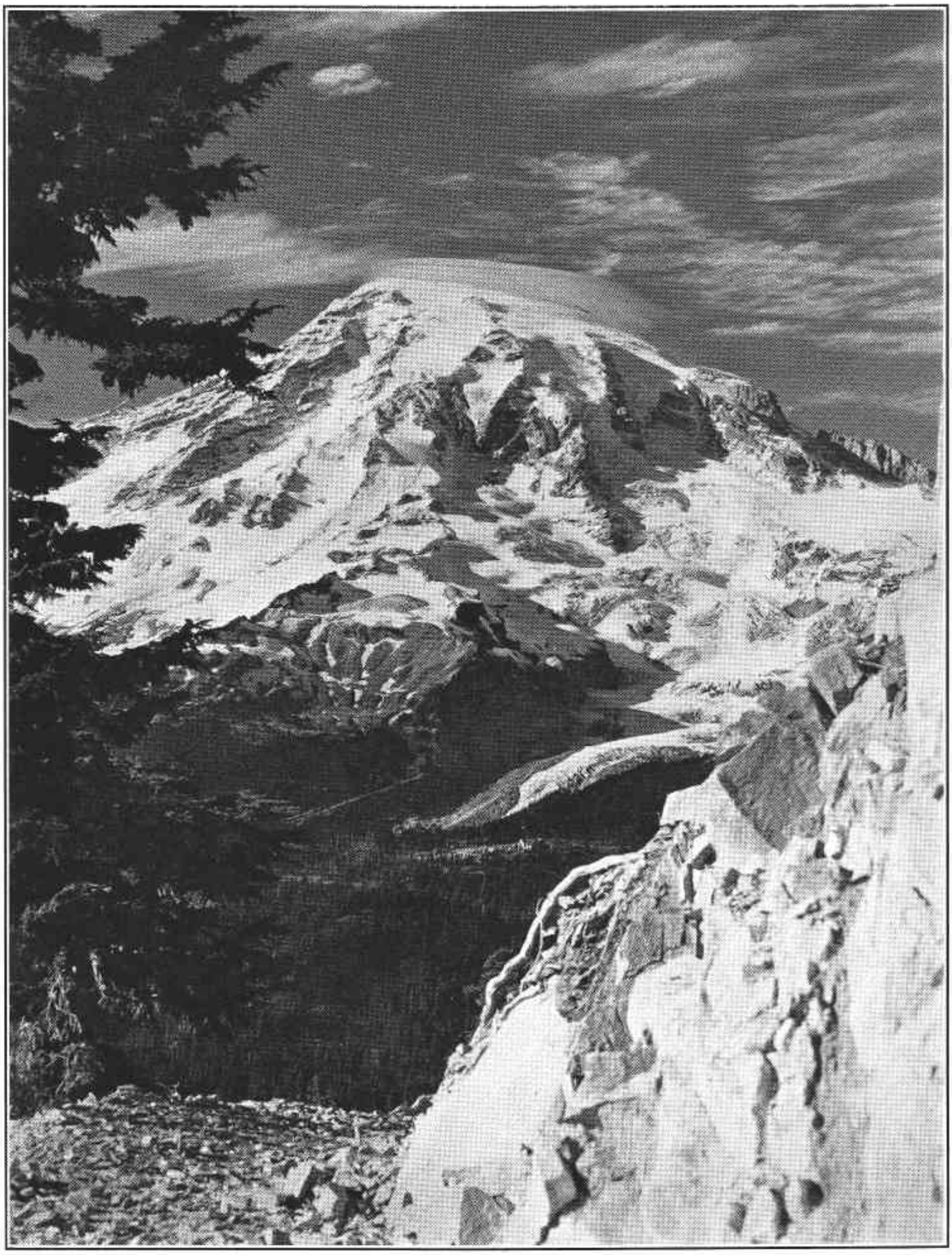

FIG. 1. Mount Rainier from the west side of Pinnacle Peak.

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INTRODUCTION

LOCATION

No landmark is more familiar to the people of western Washington than the volcanic cone of Mount Rainier. Rising to a height of 14,408 feet it is the highest volcano in the United States, exclusive of Alaska, and towers 9,000 feet above its immediate base. The base, in this case, is the mile high Cascade Range which trends in a north-south direction dividing the State of Washington into two distinct units.

To the east is the Columbia plateau consisting of a tremendous series of basaltic flows collectively known as the Columbia River lavas. These also extend into eastern Oregon and southern Idaho and cover a total area of approximately 200,000 square miles. Continuing northward from the Columbia plateau are the Okanogan highlands composed of older plutonic and metamorphic rocks.

To the west of the Cascades is the Puget Sound depression which also trends in a north-south direction. The rocks in this trough are marine and brackish water sediments and intercalated volcanics, all of Tertiary age. Much of this area is covered with glacial deposits which locally may attain thicknesses of 1,000 feet. Farther to the west rise the northward extension of the Coast ranges in the prominent Olympic Mountains.

Mount Rainier is located on the top of the central Cascades, approximately 150 miles south of the Canadian border and 80 miles north of the Columbia River, the southern boundary of the State. To the north this range also bears the volcanic cones of Mount Baker and Glacier Peak; to the south are Mount St. Helens, Mount Adams, Mount Hood, and numerous others, extending down to Mount Shasta and Lassen Peak in northern California. In this chain, Lassen Peak, Crater Lake, and Mount Rainier are the only peaks which have been awarded National Park distinction.

ROUTES OF APPROACH

Mount Rainier National Park is readily reached in a single day's journey, by auto, from the principal cities of the northwest. Routes of approach extend to all four corners of the Park. The Nisqually entrance, in the southwest corner, is joined to Tacoma and the Pacific Highway, some 56 miles to the northwest, by an excellent paved road. The Carbon River entrance and the Mowich entrance are located in the northwest corner and may be reached from Tacoma, 46 miles distant, or from Seattle, which lies 76 miles to the northwest. The Puget Sound approach to the White River entrance, or northeast corner, is made through Enumclaw, where paved roads leading from Tacoma, Seattle, and other Pacific Highway points converge. The eastern Washington approach to the White River entrance is made through the city of Yakima over the Naches Pass highway which crosses over the summit of the

Cascades. In the southeast corner, the Ohanepecosh entrance is reached from Tacoma or from Mary's Corner on the Pacific Highway; the road then follows the Cowlitz River up to the Park.

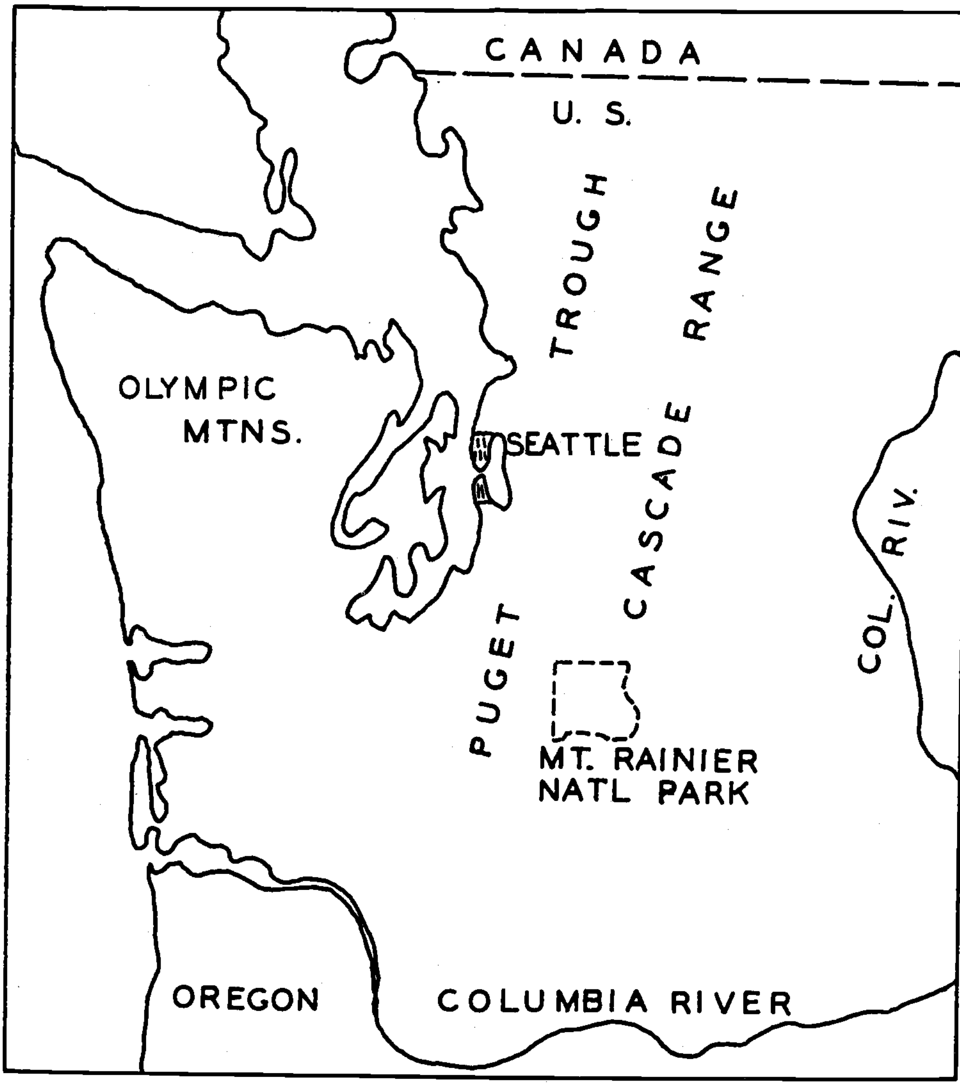


FIG. 2. Index Map Showing the Location of Mount Rainier National Park.

FIELD WORK

While engaged as a ranger and ranger-naturalist in the National Park Service from the years 1929 to 1933 inclusive, the writer became interested in many of the geological problems in the Park. Actual field work was carried on during the months of September from 1930 to 1933 inclusive and again in 1935 a few weeks were spent in the field.

ACKNOWLEDGMENTS

The writer wishes to express a sincere debt of gratitude to Professor G. E. Goodspeed of the University of Washington for his interest and aid in this work and for his many valuable suggestions.

It is a pleasure to acknowledge the many kindnesses shown by members of the National Park Service and especially Supt. O. A. Tomlinson, Chief Ranger John Davis and Park Naturalist C. F. Brockman.

Mr. Keith Whiting has aided the writer considerably in the field.

HISTORY

Spanish explorers entered what is now known as Puget Sound in 1790 and must have been familiar with Mount Rainier as seen from a distance, but so far as records go, they did not give a name to the mountain. (27)

Later, in 1792, Capt. George Vancouver explored and mapped a portion of Puget Sound and named many prominent features of the Sound and the adjacent territory. Mounts Baker, Hood, and Rainier were named at this time in honor of the officers of the British Admiralty. When Vancouver anchored near what is now Port Townsend, he (45) noted that,

> A very remarkable, high, round mountain, covered with snow, apparently at the southern extremity of the distant range of snowy mountains (Cascades) before noticed, bore south 45° east.

When further south in Puget Sound, he (45) recorded:

> The weather was serene and pleasant and the country continued to exhibit between us and the eastern snowy range the same luxuriant appearance. The round, snowy mountain now forming its southern extremity, and which, after my friend, Rear Admiral Rainier, I distinguish by the name of Mount Rainier, bore N. 42° east.

Probably the most vivid narrative in the history of Mount Rainier is the story of the first ascent, in 1870, by General Hazard Stevens, (35) who was accompanied by P. B. Van Trump. Their superstitious Indian guide, Sluiskin, led them as far as Paradise Valley and pleaded with them to go no further. Unheeding, the two men made the ascent by the Gibraltar route which, even today, is the most popular approach to the summit. After being forced to spend the night in the crater, they descended the following day by the same route. Sluiskin had given up all hope of these men ever returning and, as he was preparing to leave, Stevens and Van Trump walked into camp.

As the stories of these early visitors to Rainier began to spread, several mountaineering and scientific organizations became interested in the region and took active measures to encourage its adoption into the National Park System. Such men as John Muir of the Sierra Club, T. W. Powell of the American Association for the Advancement of Science, Bailey Willis of the United States Geological Survey, and G. G. Hubbard of the National Geographic Society, were extremely influential in having this area set aside as a National Park by an Act of Congress in 1892. The area of the Park, as originally defined, was 378 square miles, but 53 square miles were added when the eastern boundary was extended to the summit of the Cascades by an Act of Congress in 1931.

REVIEW OF LITERATURE

The earlier geological work in the vicinity of Rainier was practically confined to reconnaissance explorations carried on by the United States Geological Survey during the latter part of the nineteenth century. Emmons and Wilson of the 40th Parallel Corps, under Clarence King, made an ascent (8) of the mountain in August, 1870, and gathered geological data and specimens, but unfortunately, the records of their work are limited to a very brief publication, dealing chiefly with the glaciers.

Iddings, in 1833, made use of the data and the specimens collected by Emmons and collaborated with Hague (15) in preparing a paper on Mounts Hood, Shasta, Lassen, and Rainier. With the aid of chemical analyses and petrographic descriptions, they came to the conclusion that the lavas of these four cones were very similar and stated: "Mount Rainier is composed almost wholly of hypersthene andesite." In the same year, and under almost identical circumstances, Oebbeke (23) examined a specimen from Mount Rainier which had been collected by Professor Von Zittel. Oebbeke was particularly intrigued by the hypersthene and tried to isolate enough of the mineral for chemical analysis; this failing, he gave a fairly complete list of its optical properties.

In 1896, Russell (27) published a paper describing in detail each of the major glaciers and many of the smaller ones. His narrative includes a graphic account of a trip to the top of the mountain and an excellent description of the summit area. He also makes frequent statements concerning the general geology. A few of these are quoted on the following pages.

> Mount Rainier is a typical example of a lofty volcanic cone built largely of projectiles, but containing also many lava streams. It belongs with the class of volcanic mountains known as composite cones. At one time the mountain was more lofty than it now is, its reduction in height being due to an explosive eruption which blew away the upper 2,000 feet of the original cone, leaving a great crater in the truncated remnant. After the loss of the summit, the mountain was not symmetrical; the rim of its great summit crater was the highest on the west, and lowest and probably breached on the eastern side. At a more recent date, two small craters were formed by mild explosive eruptions within the great crater and nearly filled it. The building of these secondary craters partially restored the symmetrical outline of the top of the mountain but gave to it a dome shape instead of a conical summit.

Smith (30) made a reconnaissance trip to the north and east sides of the mountain during the field seasons of 1895-96 and published an excellent eight-page summary of the various rocks encountered. He states:

> Two classes of rock are to be discussed as occurring on Mt. Rainier; the lavas and pyroclastics, which compose the volcanic cone, and the granite rocks, forming the platform on which the volcano was built up.

These two papers by Russell and Smith are the most comprehensive works on the geology of the Rainier area.

In 1900, Smith (29) published a rather popular account of the geology of the Park in *Mazama*, a mountaineering journal of the northwest. In this he says: "The date of the uplift of the Cascades was not earlier than the close of Tertiary time." He also describes the building up of the cone and emphasizes the destructive power of the past and present glacial systems.

In 1905, Landes (19) published some "Field Notes on Mount Rainier," in which he describes the pre-Rainier topography and mentions a few localities where this surface was deeply eroded. Landes also calls attention to the composite nature of the cone and the effects of the glaciation. For the last 30 years practically no work of a geological nature has been done within the Park, with the exception of Matthes' masterly description of the glaciers. (21)

TOPOGRAPHY

The cone of Mount Rainier, rising 14,408 feet above sea level, is so dominating a feature that the lesser portions of the topography seldom receive their due share of attention. For a better understanding of the Park as a whole, it seems wise to consider, first, the features of the Cascade Range independently of Mount Rainier.

The Park is located on the western side of the Cascades, extending from the main divide almost to the western margin of the range. This area can scarcely be regarded as a slope, as the peaks in the general upland surface maintain a remarkably constant elevation—approximating 6,000 feet— regardless of their position in the Park.

The sculpturing of the Cascades in this vicinity has been described as follows: (22)

> To one standing on the flanks of Mount Rainier, the surrounding crests and ridges appear like the waves of a turbulent sea. Although infinitely diverse in sculpture, none conspicuously outtops its fellows and, at a distance, all seem to merge into one vast mountain platform.

This mountain platform has a very inconspicuous divide. On the eastern side, the rivers are roughly parallel and trend in a general southeasterly direction, finally emptying into the Columbia River. On the western side of the range, practically all the major rivers flow in a westerly direction and emerge upon the plains of Puget Sound.

These rivers, augmented by local glaciation near their sources, have bitten well over 3,000 feet into the Cascade upland. The valleys are noteworthy because of the low, flat bottoms, the remarkably steep sides, and the extremely low gradient they possess up to within a few miles of the main divide. Adding to this decided relief the upland surface is a maze of pinnacles, spires, knobs, and knife-like ridges which have been sharpened by small alpine glaciers. It is upon these rugged westward trending ridges and valleys that the cone of Mount Rainier is superimposed. Although the Cascades are more than a mile in height and have been deeply dissected, they dwindle to a rather indefinite base when compared to this volcano which towers 9,000 feet above them. This height is even more impressive when the mountain is viewed from any of the neighboring towns which are practically at sea level.

Although two peaks in the United States are higher, Mount Whitney, in California, and Mount Elbert, in Colorado, which top Rainier by 93 feet and 12 feet respectively, they rise but a few thousand feet from their immediate surroundings. On Rainier, the elevation changes from 2,000 feet to more than 14,000 feet within the short distance of 10 miles.

The volcano itself does not enjoy the dainty symmetry of Fujiyama but is, rather, a huge, broad-shouldered cone of somewhat irregular shape, being elongated, both at its summit and at its base in a northwest-southeast direction. Its rather bulky shape is perhaps more easily understood when one realizes that the flows from this 9,000-foot cone seldom spread more than 6 miles from the central vent.

Covering the top and streaming down the sides of the cone is the largest single peak glacial system in the United States, exclusive of Alaska. These tongues of ice, averaging between 4 and 6 miles in length, have carved out tremendous cirques and canyons in a radial fashion about the summit. The loosely consolidated rocks of the upper reaches of Rainier have allowed the glaciers to entrench themselves with comparative ease. However, the ice-scoured canyons are not limited to the slopes of the mountain but extend beyond and continue down into the older lavas and granodiorite below. The extreme ruggedness and scenic beauty of towering ridges and glacial canyons was undoubtedly the greatest factor in having this area preserved as a National Park.

Between the glaciers are lofty, vertical-walled slivers of rock which have been fashioned by ice into unusual shapes. Most picturesque are the triangular areas resembling the prow of a battleship cutting the swells, and, on the map, these forms are labelled "prows," "wedges," or "cleavers." For a vivid word picture and a complete description of all the glaciers, the reader is referred to the writings of Matthes and Russell. (21) (27)

DRAINAGE

A noteworthy feature of the topography is the superposition of the radial drainage pattern of Rainier upon a previous pattern in which the main rivers were essentially parallel and drained to the westward. Although the actual volcano of Mount Rainier occupies only one-fourth the area of the Park, the drainage pattern inherited from this mass completely dominates the entire Park and also influences the drainage for a considerable distance outside. However, as the cone is located on the western side of the range, all the major rivers are finally turned westward and reach the Pacific Ocean either through Puget Sound or, as in the case of the Cowlitz, through the Columbia River.

The Nisqually, Puyallup, Carbon, White, and Cowlitz rivers originate on the higher slopes as glaciers. At an elevation of approximately 4,000 feet, the glaciers terminate and the melting ice and snow above give rise to full-fledged streams which emerge from below the glaciers. The milky appearance of these streams is due to the particles of pulverized rock or "rock flour" suspended in the water.

Falling and cascading down deep canyons, the rivers lose their elevation rapidly and soon spread out, in a very leisurely fashion, on rather wide valleys which are but slightly elevated above sea level. The remainder of their westward course is over the softer sediments and glacial drift of Puget Sound. Occasionally interbedded flows or intrusives have provided more resistance to the cutting power of the rivers, and, in such cases, narrow canyons and gorges are formed locally. Examples are to be seen near the Carbon River bridge and in the La Grande Canyon of the Nisqually River; both are located outside and to the westward of the Park.

In a region of such high altitude, the melting snows contribute generously to the rivers, which during the spring months are enlarged to torrents. Most tables

(16) show the discharge to reach its maximum during the month of June. All during the summer months the melting effect is very obvious. This is especially impressed on hikers going around the mountain on the famous Wonderland Trail. These people are obliged to cross all the radiating rivers at various times of the day. In the early morning, the streams and rivers are mere trickles to what they will be later in the day when the warm sun has had its effect on the glaciers and snow fields above. During the early evening the clunking of large boulders is a familiar noise as they are pushed along by the swollen streams.

Many factors exert a steadying influence on the rate of the run-off. The precipitation is not extremely variable although 90 per cent falls from October to May. This would diminish the run-off during the summer months, were it not for the aid given by melting snow.

The soils within the Park are almost strictly volcanic in origin, and, being quite porous, provide a good moisture retainer. This is aided by grass and flower growths which mat the ground at elevations between 4,000 and 5,000 feet. Below this level and down to 2,000 feet, the soil is a spongy mat of volcanic and vegetable debris which is highly absorbent. Held in place and aided by the thick underbrush and a dense forest growth, the conditions for water retention are ideal. Consequently, water and power sites are numerous. Already many of the larger cities of the Puget Sound region receive their power and water from this supply, but a great number of potential sites remain untouched.

CLIMATE

The western side of the Cascades is well-watered by the moisture-laden winds coming in from the Pacific Ocean. This cooling mountain barrier causes the clouds to rise and expand with the resultant effect of precipitation.

In the Puget Sound depression the rainfall averages from 40 to 50 inches annually but, as one goes higher up the flanks of the Cascades, the increased cooling effects cause a gradual increase in the amount of precipitation. Snoqualmie Pass is one of the lowest points on the summit of the range and here the average total precipitation is 144 inches annually. As this location is 3,000 feet in elevation, a good portion of this falls as snow. Within the boundaries of the Park, the United States Weather Bureau (9) gives the following data: The Carbon River entrance at an elevation of 1,760 feet has a total precipitation of 91 inches annually; while at Longmire, which is 2,760 feet above the sea, it is 113 inches. At Paradise, a mile in elevation, no figures are given for the total precipitation, but the total snowfall is well over 500 inches annually. This corresponds closely to the total for the Snoqualmie Pass region.

Few places exist within the Park boundaries where the precipitation does not fall as snow at some time during the winter. This is in contrast to the very mild climate enjoyed in the Puget Sound area where snow, at any time during the year, is uncommon. Because the snow conditions are so ideal on the slopes of Rainier, this area has enjoyed widespread popularity as a site for skiing and allied winter sports. Thousands are attracted weekly during the winter and spring months to participate in these sports. At the settlement of Paradise, the first snows usually fall in October, and all during the winter and early spring months the ground is covered to a depth of 10 to 15 feet. The drifts linger well into July. However, at Longmire, the time and amount of snowfall is most irregular and, no matter how severe the winter has been, with the coming of May, all the snow is melted.

During the relatively short summer season the climatic conditions are nearly perfect. The crispness of the mountain air, the warm sunshine, and cool, clear nights unite with the scenery to attract hundreds of thousands of people annually to this national playground.

FAUNA AND FLORA

In a region with such a wide range of altitude, the environmental conditions for plant and animal life are extremely varied. As a result, Taylor and Shaw (36) have been able to divide the Park into zones corresponding to those established by Dr. H. C. Merriam. Each of these zones is based largely on latitude but, as a change in altitude on a high mountain has a very similar effect to a change in latitude, many zones can be represented on a single peak. In a general way, the contour lines define the zones but these are often obscured by the powerful influence of moisture. The four zones—the Arctic Alpine, the Hudsonian, the Canadian, and the Transition—are represented within the Park. Of all the zones in the United States only the Sonoran is missing.

The Transition zone, between the Sonoran and Canadian, is the smallest and least important in the Park. It is characterized by the grand or white fir, salal, Oregon grape, vine maple, devil's club, and salmonberry. Typical animals include the California quail, Seattle wren, Oregon ruffled grouse and chickadee, as well as the mink and racoon.

The Canadian zone, from 4,500-5,000 feet in elevation, is a heavily-timbered area containing Douglas fir and western hemlock of huge diameter and height. Other members of the flora include lovely fir, noble fir, lodgepole pine, mountain ash, forest anemone, and alpine beauty. Among the fauna are the Cooper chipmunk, snowshoe rabbit, Stellar jay, and the western pileated woodpecker.

Between the elevations of 4,500-6,500 feet, or in the Hudsonian zone, are the flowers for which the Park is famous. The rather dense woods in the lower portion of this zone gradually dwindle until they meet the open grassy parks or the jagged glaciated peaks. Alpine fir, mountain hemlock and Alaska cedar are the dominant trees. The heathers (Phyllodoce and Cassiope), avalanche lily, gentian, huckleberry, squaw grass, and lupine are only a few of the hundreds of species of flowers found in these natural garden spots. The chipmunk, mantled ground squirrel, cony, and marmot are all familiar sights to the Park visitor.

Above the 6,500-foot contour, 80 square miles of the mountain belong to the Arctic-Alpine zone. Sharing this region with the glaciers are the mountain goat, ptarmigan, Hepburn rosy finch, and the pallid horned lark. Such flowers as the golden aster, Indian paint brush, yellow heather, Tolmie saxifrage, and pigeon-billed lousewort exist on these high slopes. No mention of the fauna should exclude black bear, that trouble-making clown of all the animals, who ranges from the lower Park boundaries to timberline.

The Department of the Interior has issued a series of pamphlets on glaciers, (21) birds and mammals, (36) forests, (1) and flora (10) of the Park which contain detailed and specific information on these subjects.

GEOLOGY

DISTRIBUTION AND RELATIVE AGES OF THE ROCKS

Within the Park the type of rocks exposed are almost endless in variety. Although volcanic and plutonic rocks predominate, the lesser types include sediments and metamorphics. For the purpose of mapping, all these types have been placed into four, more or less distinct, formations. For two of these formations, the writer has followed the groupings suggested by Smith and Calkins. (34) The other two are somewhat individual and they will be defined later.

The oldest and smallest formation in the Park is an extremely small outcrop of carbonaceous sediments located near the snout of the Carbon Glacier. The base of these sediments has been replaced by the invasion of a granodioritic batholith and the top is covered by a concordant series of siliceous rocks resembling felsitic tuffs. Tentatively the carbonaceous sediments have been referred to the Puget Series.

The second group, known as the Keechelus andesitic series, occurs above the first formation and, in places, overlies it with an angular unconformity. The rock types consist of altered and indurated massive tuffs and breccias with subordinate amounts of flows, porphyries, hornfels, sediments, and many other heterogeneous varieties. This group extends in an almost complete circle around Mount Rainier and forms the most important areal unit inside the Park boundaries.

The third formation is granodioritic in character and has been correlated with the Snoqualmie granodiorite. Because of its invasion into both of the above mentioned groups it may be regarded as the basement rock in this vicinity. The outcrops are limited to regions where glacial action has been effective in removing the older rocks above. Exposures are found near the termini of the larger glaciers, such as the Emmons, Winthrop, and Nisqually, as well as at the base of the Tatoosh Range.

A considerable erosion interval followed the invasion of the granodiorite and, as a result, a distinct unconformity separates these three older groups from the youngest, and fourth group, the lavas and pyroclastics of Mount Rainier.

THE PUGET GROUP

The oldest rocks are black argillites which have been so well indurated that it is difficult to scratch them with a knife. These are well exposed on the west bank of the Carbon River near the mouth of Cataract Creek. Individual beds vary in thickness from an inch to more than a foot and alternate with layers of a peculiar light-colored rock which closely resembles small porphyry sills or possibly silicified pyroclastics. This alternation of light and dark colored layers produces a most striking outcrop. A more detailed study of the rocks in this exposure is now being made by Professor G. E. Goodspeed of the University of Washington and the writer, and the results will be published in a subsequent paper.

In the Puget Sound region, immediately to the northwest of the Park, is a two-mile thick sequence of sandstones, shales and arkoses, with a considerable amount of carbonaceous matter and intercalated volcanics. To these beds, White (40) gave the name, Puget Group, and assigned to them a lower Tertiary age. Within 10 miles of the Carbon River locality, at Fairfax, coal has been mined from this sequence. Sediments definitely referable to the Puget Group are exposed 8 miles due west of the Carbon River locality. The carbonaceous argillites of the Carbon River region within the Park boundaries are tentatively assigned to the Puget Group because of their proximity to large, known masses of Puget rock, because of the carbonaceous content which is common to both and because the structural trend of the Carbon River outcrop parallels the general trend of the Puget beds. During the Miocene, the sediments and volcanics of the Puget Group were thrown into a series of folds trending, generally, in a northwest-southeast direction.

KEECHELUS ANDESITIC SERIES

The Keechelus andesitic series is a large mass of rocks covering hundreds, and possibly thousands, of square miles of the Cascades and averaging more than one-half mile in thickness within the Park. The dominant types are a series of massive tuffs, breccias and porphyries of andesitic composition which have been altered and indurated. The subordinate types include andesite flows, felsites, basalts, hornfels and sediments.

The name, Keechelus andesitic series, was applied originally to similar rocks occurring in the Snoqualmie quadrangle which adjoins the Mount Rainier National Park sheet immediately to the north and east. The Keechelus rocks of the Snoqualmie region can be traced with continuity directly across into the Mount Rainier region. Smith and Calkins (34) predicted that: "The Keechelus series is probably the most voluminous assemblage of rocks in the Cascade Range for some distance to the south and west," and, later work has proved their prediction. Fuller (11) found Keechelus in the northern part of the Cedar Lake quadrangle, which lies west of the Snoqualmie and immediately north of Mount Rainier. (4) Observations made by the writer during brief visits to the southern half of the Cedar Lake region indicate that Keechelus rocks occupy a major portion of that quadrangle. This same material has been traced into the Mount Aix quadrangle, lying to the east of Mount Rainier. To the south, the extent is unknown. To the west, the sediments of Puget Sound come almost up to the Park boundary and thus limit the extension of the Keechelus in that direction. Within the Mount Rainier sheet this series outcrops almost continuously along all four of the Park boundaries and extends inward, finally disappearing under the lavas of Mount Rainier.

Regarding the distribution of rock types, the Keechelus formation may be divided into areas which are relatively homogeneous and those which present the extreme in variability. In practically every case, the former are far removed from intrusive bodies; while the latter are adjacent to known exposures of granodiorite. Homogeneity prevails in the Ohanepecosh district in the southeastern corner, where the only rocks exposed are altered and indurated porphyries and breccias of intermediate composition. The same is true in the southwestern corner, in the neighborhood of Mount Wow. The 3,000-foot cliff on the east side of this mountain is an excellent place to observe the massive character of these porphyries and breccias.

Elsewhere, considerable more variety is shown. This is notably true in the northeast corner, along the White River, where granodiorite invades the Keechelus with many interesting effects. The rocks vary from massive porphyries 30 meters thick, to thinly-bedded pyroclastics displaying marked changes almost every centimeter. The colors may be chocolate-brown, purple, tan, and black, but the inevitable greens and grays, so typical of the Keechelus, prevail. The rocks in this

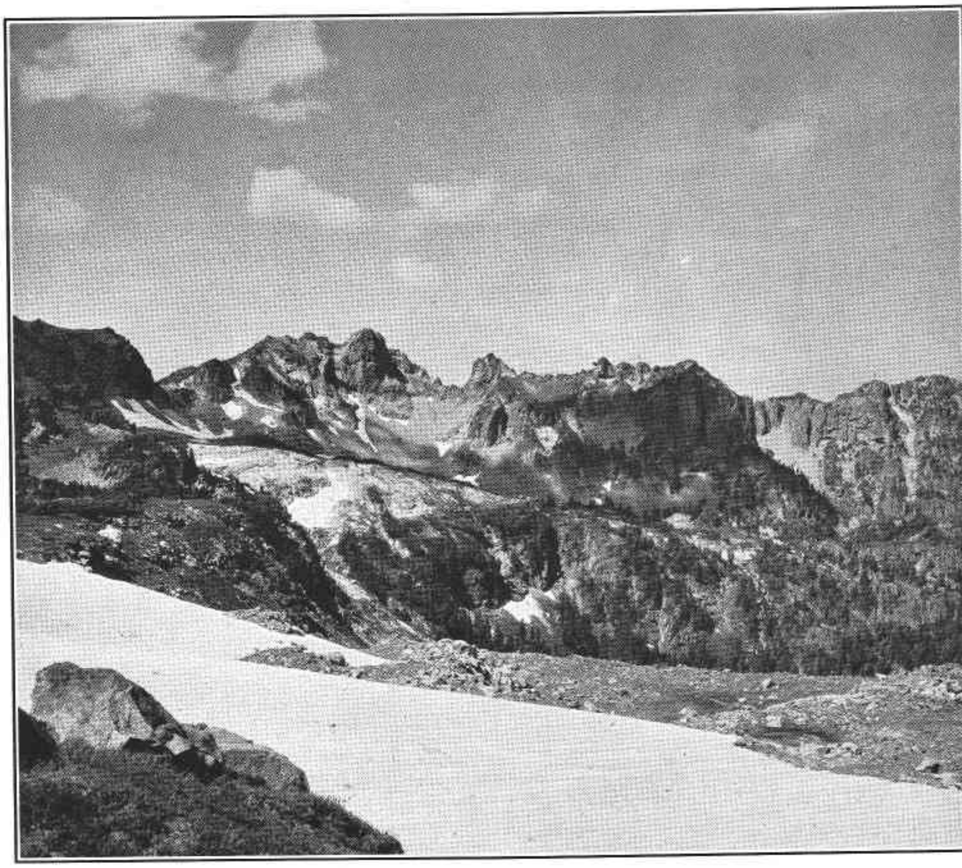


Fig. 3. Mother Mountain from Seattle Park, looking northward. (This entire mountain is composed of Keechelus andesite. The upper portion of Mother Mountain is a series of almost flat-lying flows; the lower portion is largely massive and altered breccias and porphyries.)

vicinity are about as fresh as any to be found in the formation and all have partaken in a gentle dip to the northward. The Mather Memorial Parkway has provided almost continuous exposures for miles in a long, diagonal section across this region, extending from the granodiorite below, across the xenolith swarms of the contact, and up into the Keechelus. Numerous intrusives of small dikes and sills, as well as irregular tabular masses, have contributed several new types to this already hetrogeneous group of rocks.

Another locality noteworthy for its variety is the Tatoosh Range, paralleling the southern border of the Park. Here the Keechelus is the capping, while the granodiorite forms the base of the range. The intrusive contact is well exposed on the northern face. This area is worthy of more detailed study than the writer could possibly allow at present and will receive further attention.

Before going deeper into the discussion of the Keechelus, a few of the rock types will be described. It is impossible to obtain an adequate representation of this formation from a suite of specimens. There is not only great diversity in the rocks, but infinite gradations that exist between the end types. However, a number of specimens have been selected for petrographic description in the hope that they will convey a general impression of the material in this formation.

Mineral Mountain Andesite Porphyry

At Mineral Mountain, near Mystic Lake, a porphyry occurs as an irregularly shaped mass, several hundred meters in width. Although definitely invading the lower portion of the Keechelus in this vicinity, it continues upward and forms an integral part of this series above. The specimens from Mineral Mountain represent a type of porphyry commonly found in the Keechelus and are good examples of the younger portions of this formation.

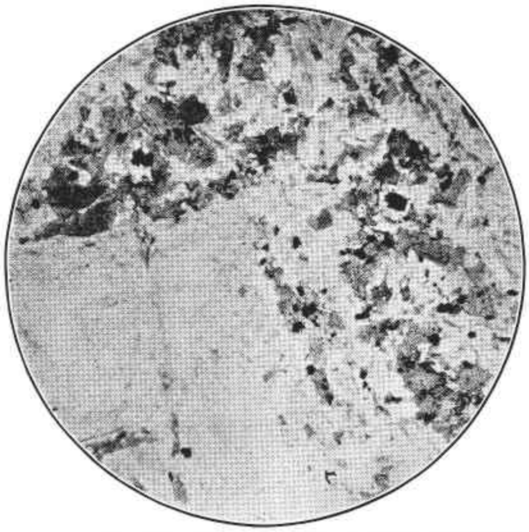
The rock is medium-gray in color with numerous stringers of hornblende 1 mm. in width traversing the mass in every direction. Phenocrysts of feldspar occur frequently and attain an average length of 4 mm. The groundmass is fine grained, with the individual crystals averaging about 1 mm. or less in diameter.

Microscopical Petrography. The porphyry consists of euhedral plagioclase crystals imbedded in felt of plagioclase, hornblende, biotite, and quartz. The phenocrysts exhibit a very intense oscillatory zoning and have lines of inclusions consisting of flakes of biotite, hornblende, and magnetite dust parallel to the euhedral borders. Intermediate andesine, with a composition of $Ab_{62}An_{38}$, is most prevalent. However, a few of the phenocrysts are rather ragged and these contain clear patches with the composition of labradorite $Ab_{44}An_{56}$.

The ragged and rather moth-eaten appearance is characteristic of the smaller phenocrysts but it reaches its greatest development in the feldspars of the fine-grained groundmass. It is due to innumerable particles of included mafic minerals. With higher magnification, the particles are easily distinguished as being identical to those found outside the feldspars and which make up so large a portion of this rock.

The hornblende is usually deeply-colored with X, a pale yellow; Y, a dark, brownish-green; and Z, a dark green. The refractive index reaches a maximum of 1.660. Some of the crystals contain abundant subrectangular magnetite grains and, in such cases, the hornblende is noticeably paler in color. The magnetite is always intimately associated with the hornblende and occurs in grains up to 1 mm. in length.

The biotite is of the siderophyllite variety with X a clear yellow and Y and Z both a deep reddish-brown. Quartz occurs both interstitially and as a mosaic associated with the more idiomorphic hornblende crystals. The percentage of each is approximately as follows: feldspar phenocrysts, 15 per cent; feldspar in the fine-grained groundmass, 30 per cent; hornblende, 25 per cent; magnetite, 10 per cent; quartz, 12 per cent; and, biotite, 8 per cent.



A. x25, plane light. (Large L-shaped plagioclase phenocryst in a matrix of hornblende, plagioclase, biotite and quartz.)

B. Same view as above, under crossed nicols.

FIG. 4. Mineral Mountain andesite porphyry.

Sheepskull Gap Tuffs

A rather typical Keechelus tuff outcrops in the vicinity of Sheepskull Gap. Here the fragmental rocks are well-bedded to massive; all are essentially flat-lying, and have associated with them a small amount of igneous material in the form of minor injected bodies.

In the specimen chosen from Sheepskull Gap, the color is predominantly gray, but, on closer inspection, the individual fragments may be seen to be light gray, dark gray, green or even purple. Because of this variation in color, the fragments range in size from 50 mm. or more down to particles too small to be seen with the unaided eye. The average is close to 3 or 4 mm. in diameter. As a result of induration, the rock is now so hard and compact that it can scarcely be scratched with a knife.

Microscopical Petrography. Under the microscope, the fragments can be identified as chips of andesite and angular pieces of feldspar crystals. Both are embedded in a dusty, almost opaque matrix of extremely fine ash.

The andesitic chips usually exhibit a distinct felted texture but they may be porphyritic or even cryptocrystalline. In any case, cloudy feldspars are the dominant mineral. A few clearer crystals indicate the composition to be andesine (Ab_{63}-An_{37}). The only other distinguishable minerals in these chips are quartz, in amygdules, chlorite, with properties very similar to clinochlore, and magnetite, occurring as small specks disseminated throughout the rock. The percentage of matrix between the fragments is relatively small. It contains numerous patches of clear, green clinochlore, stringers and angular pieces of calcite, gray dusty ash, and small flakes of andesite and feldspar.

The approximate content of the tuff is: andesite chips, 35 per cent; feldspar chips, 30 per cent; ash matrix, 18 per cent; chlorite, 10 per cent; quartz, 3 per cent; calcite and magnetite, 2 per cent each.

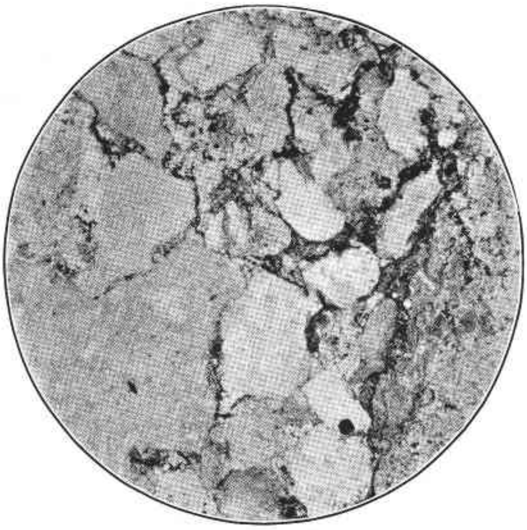


Fig. 5. Sheepskull Gap tuffs, x25, plane light. (The rock is composed of angular chips of several andesitic types. A few cloudy plagioclase fragments are also embedded in the fine ash matrix.)

SOURDOUGH MOUTAIN BRECCIAS

The breccias exposed along the northern face of the Sourdough Mountains near Yakima Park are quite different from the distinctly fragmental tuffs of the Sheepskull Gap area. At first sight, the breccias appear to be black porphyritic lavas but, on closer examination, the lighter phenocrysts are abundant in some patches and wholly lacking in others. In the field, the so-called patches have no distinct boundaries but grade from a lighter to darker colored, or from a porphyritic to a non-porphyritic type. Some of the larger patches average over 1 meter in diameter but the more ordinary ones range from 30 to 40 mm. in length. This patchy texture is one of the most characteristic features of the Keechelus formation and usually is very obvious because of the differences in color of the various components. In the case of the Sourdough Mountain breccias, the colors are limited to a very dark grey and black and, hence, the general texture is more obscure. The lighter grey color is caused by swarms of plagioclase phenocrysts, approximately 3 mm. in length; while in the darker patches, the phenocrysts are either lacking or are very sparse in the dull, dense groundmass.

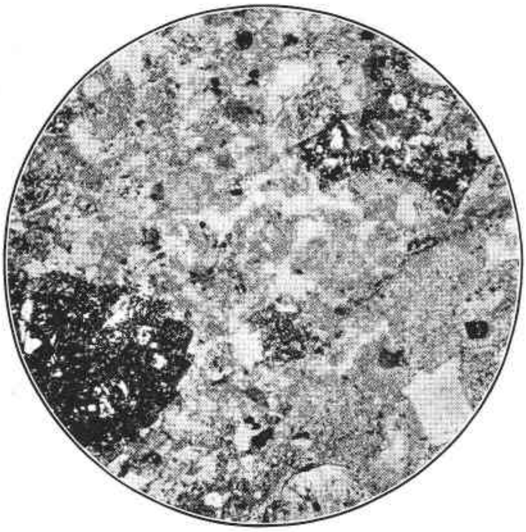
Microscopical Petrography. Several kinds of phenocrysts are visible. The larger ones so readily recognized in the hand specimen are, in reality, merely glomerophyritic groups of plagioclase phenocrysts which average less than .4 mm. in length. These range in composition from acidic to basic andesine but, generally, are close to Ab_{55}-An_{45}. Some show pronounced zoning, while others are twinned according to the Carlsbad law. All are charged with quantities of magnetite dust, or antigorite flakes, or both. The arrangement of the inclusions is either in zones, parallel to the periphery of the crystal, or confined almost exclusively to the center and surrounded by a clear, and slightly more acidic, rim.

The pyroxene (?) phenocrysts were of the same size as the feldspars, but since have been uralitized and completely replaced by a fibrous antigorite with smaller amounts of biotite, magnetite and quartz.

The groundmass is so heavily charged with a dense magnetite dust that it is almost opaque. However, minute flakes of feldspar and antigorite are scattered throughout the groundmass, and under high magnification, the alternating transparent and opaque minerals give it a salt and pepper effect.

Cutting across the rock are thin stringers of clear, green antigorite and titanite. These clearly indicate the type of solutions which permeated the mass and contributed so much to its present condition. The composition is as follows: plagioclase, 35 per cent; antigorite, 20 per cent; groundmass (including magnetite), 35 per cent, biotite, 7 per cent; and, quartz, 5 per cent.

A. Section view. (The larger and more irregular phenocrysts of plagioclase are charged with magnetite dust and flakes of antigorite. A small veinlet of antigorite and titanite may be seen cutting across the rock.)



B. Section view. (The fragmental nature of the rock is not always apparent. This section shows the darker fragments—heavily charged with magnetite dust—in a much lighter colored matrix.)

FIG. 6. Sourdough Mountain breccias, x25, plane light.

Chinook Pass Diorite Porphyry

A diorite porphyry outcrops 1 mile below the summit of Chinook pass as a tabular mass approximately 25 meters in thickness. It is separated from the country rock, an andesitic breccia, by a narrow border noticeably finer in grain than the central portion of the porphyry. Following the general color scheme of the Keechelus, this rock is dark greenish-gray and contains swarms of lighter gray feldspar phenocrysts.

Microscopical Petrography. The plagioclases form a definitely seriated fabric with the size of the euhedral crystals ranging from .5 mm. up to 4 mm. in length. The larger crystals represent the "phenocrysts" identified in the hand specimens. The remaining minerals occur interstitially as roughly triangular patches filling up what little space is left by the abundant feldspar. All the minerals have participated in a widespread alteration in the form of saussitierization and uralitization. This may be attributed to paulopost action or, as an alternative, to mild regional metamorphism.

The plagioclase is traversed by numerous stringers of phrenite, chlorite, epidote, and more acid plagioclase. Labradorite, with a composition of $Ab_{40}An_{60}$ is general, but more acid rims reach $Ab_{50}An_{50}$. Water-clear plagioclase with a markedly lower refractive index occurs irregularly throughout the feldspars. The twinning is not entirely obscured by the alteration and follows the Carlsbad and Albite laws, the latter displaying relatively wide lamellae. About 50 per cent of the feldspars contain included particles of chlorite that are independent of the stringers and which choose to align themselves either parallel or at right angles to the twinning lamellae.

The pyroxenes have not fared so well as the feldspars. Few remnants of the original augite remain and these are enclosed by wide borders of chlorite and actinolite. Large octahedra and cubes of magnetite are always associated with the altered pyroxenes. Quartz, showing undulatory extinction, and most of the other minerals listed below, occur interstitially. The mineral percentage is roughly as follows: plagioclase, 50 per cent; quartz, 10 per cent; actinolite, 7 per cent; phrenite, 5 per cent; augite, 4 per cent; epidote, 4 per cent; and, clinozoisite, 3 per cent.

Longmire Acid Breccias

At the settlement of Longmire, on the Nisqually River, are a series of almost white breccias. These are exposed to the best advantage in the low, rounded knobs behind the government houses and along the road leading across the suspension bridge to the auto camp grounds. Being so massive and light-colored, it is difficult, from a distance, to distinguish these breccias from the granodiorite exposed in the Paradise River valley nearby. In the hand specimen, the true texture of the rock is revealed as the fragments display a wide assortment of colors, ranging from a purplish-gray to white. The larger ones average 30 mm. or more in diameter, but the smaller ones, ranging from 5 to 10 mm., are much more plentiful. Little regularity exists in regard to the size, shape, and color of the rock particles. A noticeable feature in the hand specimen is the clear lustrous quartz grains embedded in a dense, dull matrix.

A. x25, plane light. (The plagioclase forms a definitely seriated fabric of roughly euhedral crystals. Altered pyroxenes and chlorite occur interstitially between the blocky feldspars.)

B. Under crossed nicols. (A portion of one of the larger plagioclase crystals can be seen in the upper right hand side.)

FIG. 7. Chinook Pass diorite porphyry.

Microscopical Petrography. In thin section, the fragmental texture is not so pronounced as the megascopic examination would lead one to expect. All the fragments are turbid and altered and none differ markedly from the others in texture, color, and amount of alteration. The only relief from the cloudiness are the clear, fresh grains of quartz. These have a general subangular shape with beautifully resorbed and sinuous borders. Occasionally small embayments will protrude one-third the diameter of the crystal. Some of the fragments show a dense pilotaxitic texture wherein the small feldspar laths may be determined only under the highest magnification as intermediate andesine. The fragments may display either a microcrystalline mosaic of quartz and feldspar, or may consist of actinolite, chlorite, clinozoisite, and feldspar, with accessory magnetite. A few display an amygdaloidal structure; the vesicles being filled with quartz, chlorite, and titanite. Rare patches of intensely pleochroic brown biotite and clear quartz occur as a mosaic within these fragments.

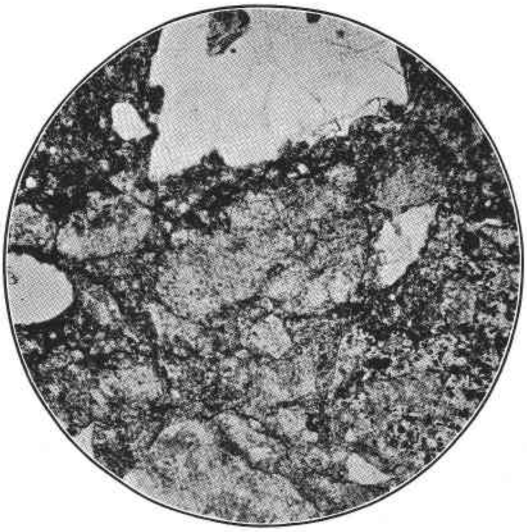


FIG. 8. Longmire acid breccias, x25, plane light. (The clear quartz crystals show resorbed boundaries and embayments. The andesitic fragments are so altered and turbid that it is often difficult to determine their constituents and outlines.)

The remaining portion of the rock is made up of cryptocrystalline fragments and a microfelsitic base containing scattered crystals of plagioclase. The feldspars are subhedral in shape, cloudy with kaolin and filled with inclusions, and the determinable ones have a composition ranging from andesine (Ab_{53}-An_{47}) to oligoclase (Ab_{78}-An_{22}). It is impossible to estimate with any degree of accuracy the percentage composition of a rock of this kind.

Starbo Altered Tuffs

In Glacier Basin, between the Emmons and Winthrop glaciers, the Keechelus tuffs and porphyries have been invaded by granodiorite. The old Starbo mining camp has its tunnels immediately above the contact where an attempt was made to mine the sulphide seams in the narrow joints of the tuffs and porphyries. This massive, indurated, and altered series continues upward to the base of Mount Ruth where it is overlain unconformably by the lavas of Mount Rainier. The texture varies from porphyritic to a porphyry with inclusions and, finally, results in a mass so charged with chips of rock and minerals, averaging between 1 and 4 mm. in length, as to make it a tuff. Yet the physical properties of the rock, such as its extreme hardness, the even, dark gray to black color, and general compactness, certainly do not suggest a fragmental origin. The true texture is well brought out under the microscope.

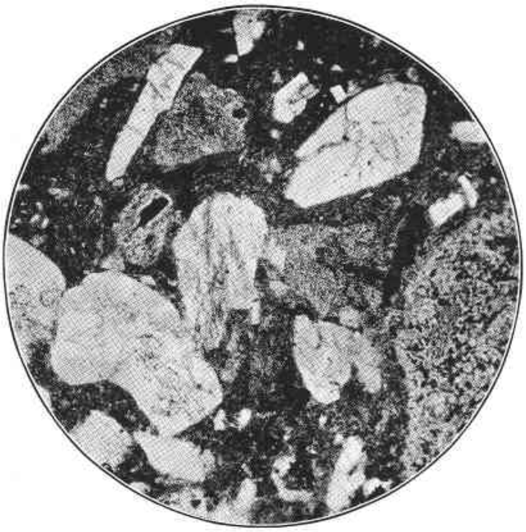


Fig. 9. Starbo altered tuff, x25, plane light. (The plagioclase is represented by the lighter, partially-rounded crystals. The groundmass is crypto- to microcrystalline material and contains angular andesite chips identified by their felted texture.)

Microscopical Petrography. The rock may be divided into three roughly equal parts; the chips of rock, the phenocrysts and fragments of feldspar, and the micro- to cryptocrystalline matrix. Most of the rock chips have a fine pilotaxitic felt of slender plagioclase laths and abundant interstitial magnetite with a little actinolite. The feldspars are very cloudy but both the low refractive index and the small extinction angle suggest a composition close to intermediate oligoclase. Certain chips are charged so completely with magnetite dust that they are almost opaque. Other of the rock fragments display a felsitic texture of quartz and feldspar with abundant magnetite and occasionally a cloudy feldspar phenocryst.

The widely distributed chips and angular fragments of feldspar present many features. They may be either clear or very cloudy, euhedral or anhedral, twinned or untwinned, or range in size from 2 to .4 mm. or less. The composition lies between Ab_{13} and Ab_{30}. The untwinned ones are often remarkably clear and show wavy extinction, due to zoning. These strongly resemble the quartz found in other Keechelus tuffs but the negative biaxial sign discloses their character. The majority of the feldspars are twinned in some fashion or else show oscillatory zoning.

The micro- to cryptocrystalline matrix contains magnetite specks, and minute flakes of actinolite and feldspar, in addition to much unidentifiable material, and serves, more or less. as a base for the rock and mineral fragments.

Cayuse Pass Acid Hornfels

At Cayuse Pass on the Mather Memorial Parkway, the road is blasted out of an acid hornfels overlain, conformably by andesitic tuffs, all partaking in a gentle northward dip.

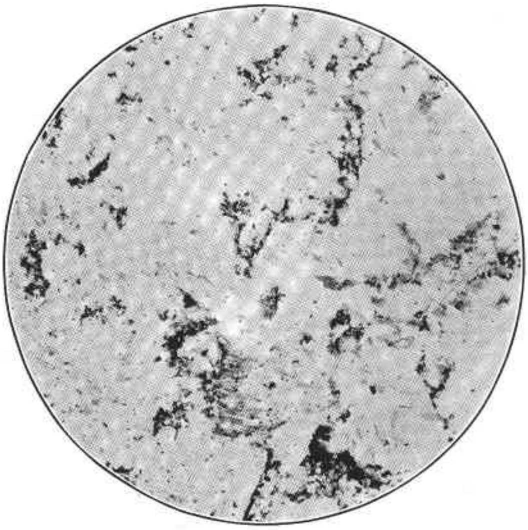
The rocks are generally buff colored with all gradations from a pale cream color to a deep rusty brown. Individual beds vary from a centimeter to many meters in width with each layer distinguished by a noticeable change in color and grain size. The examination of the hand specimen shows small spots of buff colored material, alternating with dense particles of a white substance—all having a dull appearance. Nevertheless, the rock is extremely hard and cannot be scratched with a knife blade.

Microscopical Petrography. The rock exhibits a palimsest structure indicative of psammitic sediments, now partially hornfelsed with the production of feldspar, sericite and biotite. Added to this is an abundance of quartz with a smaller amount of limonite, which is partially responsible for the buff color. Lesser quantities of calcite occur interstitially.

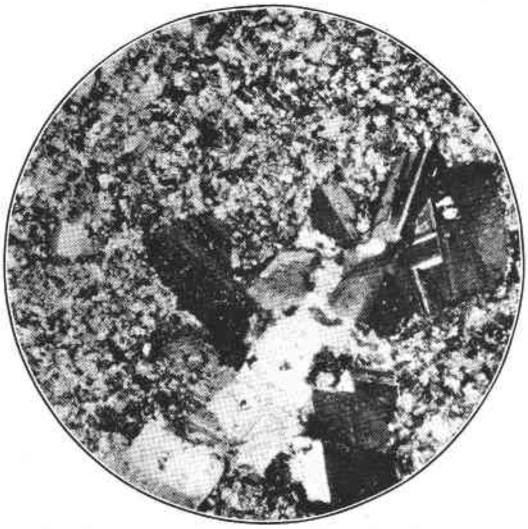
Haphazardly distributed throughout the rock are groups of feldspar porphyroblasts with as many as ten individual crystals occurring in one of these clusters. The turbid appearance of the plagioclase is not due to alteration but rather to the presence of many inclusions, of the same type and size, as are found elsewhere in the groundmass. So perfect is the continuation of the groundmass materials through the porphyroblasts that it is practically impossible to locate the larger crystals in plane light. The porphyroblasts attain lengths up to one mm. and vary in shape from idioblastic to hypidioblastic. They may be twinned according to either the Carlsbad or Albite laws or both, or may show a very complex twinning. The composition is albite (Ab_{92}-An_8).

The groundmass contains quartz and feldspar as the essential minerals. The quartz is typically xenoblastic and averages .2 mm. in length. The feldspars contain inclusions of a type and number comparable to the porphyroblasts but they do not display the prominent twinning of the larger feldspars. Judging from the low refractive index the smaller laths of plagioclase have the composition of albite and are, undoubtedly, similar to the porphyroblasts in the percentage of Ab to An.

The biotite flakes range around .02 mm. in size, but they are usually in clusters that attain an overall length of .1 mm. or more. The sericite and limonite occur



A. x25, plane light. (A microcrystalline matrix of quartz and feldspar containing plagioclase porphyroblasts. Note that it is almost impossible to detect the presence of the larger feldspars in this photomicrograph.)



B. Under crossed nicols. (This view is the same as above; note the cluster of feldspar porphyroblasts.)

FIG. 10. Cayuse Pass acid hornfels.

around the quartz and feldspar grains and have dimensions similar to the biotite specks. The calcite, on the other hand, has entered the rock in small veinlets, replacing other minerals, notably the feldspar phenocrysts, and often has clear quartz as an associate.

The percentage composition is approximately as follows: phenocrysts (plagioclase), 10 per cent; plagioclase (groundmass), 40 per cent; quartz, 30 per cent; biotite, 8 per cent; sericite, 5 per cent; limonite, 4 per cent; and, calcite, 3 per cent.

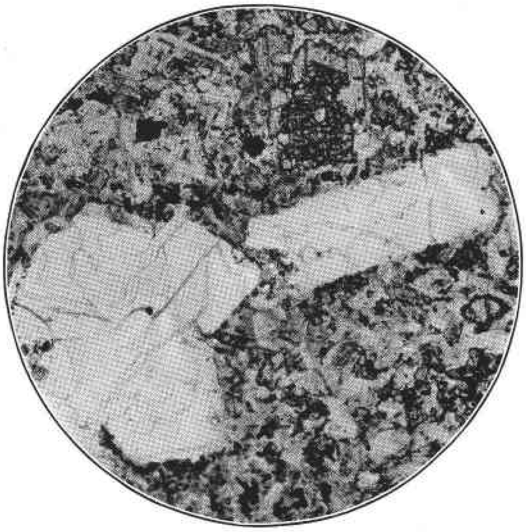
Mowich Hypersthene Basalt

Breccias and porphyries make up by far the greater portion of the Keechelus, but to emphasize the wide divergence of rock types encountered in this one formation, a felsite and a basalt are also included in this description. Some of the freshest basaltic flows in the entire formation are exposed between Mowich and Eunice lakes in the northwestern corner of the Park. Vertical cliffs in these thick, horizontal sheets often display well-defined columns, reaching a height of 30 meters or more. The rock is a coarsely porphyritic, black basalt. The feldspar phenocrysts are but slightly lighter than the groundmass in color but their presence is betrayed by their clear, glassy lustre and the light reflected from the cleavage planes. The phenocrysts average 3 mm. in length and are set in a rich, black, aphanitic groundmass.

Microscopical Petrography. The phenocrysts of feldspar, pyroxenes and olivine are crowded in a holocrystalline groundmass, displaying a granulitic texture. The larger feldspars invariably show strong oscillatory zoning and they may be filled with concentric or scattered inclusions or be water-clear. Albite twinning, with wide lamellae, is common; Carlsbad, less so. The composition varies from very basic andesine through labradorite with the percentage ranging from Ab_{47}-An_{53} to Ab_{35}-An_{65}.

The mafic phenocrysts include augite, olivine, and hypersthene. The fresh augite crystals occur as euhedral, stubby prisms exhibiting lamellar twinning on 100. The faint pleochrosim and reddish tinge suggest a titaniferous variety. The rounded olivine grains are traversed with widened cracks filled with lamellar, greenish-yellow antigorite. The centers are remarkably clear and fresh. Hypersthene is especially abundant, both as euhedral phenocrysts and as smaller grains in the groundmass. In each case the mineral is noticeably pleochroic and has suffered a slight amount of serpentinization but to a lesser extent than the olivine.

The groundmass contains small laths of feldspar, grains of hypersthene, augite, and olivine, all averaging .06 mm. or less in diameter. Magnetite cubes and octahedra, twice the size of the other grains, are scattered through the groundmass. A striking feature of the feldspathic base is the presence of fine acicular apatite, often penetrating through several plagioclase crystals and attaining a length of .3 mm. or more. These are so numerous that even under the limited area of high magnification no portion of the groundmass has failed to show crowds of these fine needles. The base also contains considerable alteration products in the form of antigorite, chlorite, and cloudy material. The composition is approximately as follows: feldspar, 48 per cent; hypersthene, 19 per cent; augite, 13 per cent; antigorite and other alteration products, 12 per cent; olivine, 4 per cent; and, magnetite, 3 per cent.



A. x25, plane light. (Glomeroporphyritic plagioclase with concentric lines of inclusions near the periphery. Note alteration of the hypersthene along the cleavage cracks and in the center; magnetite often fills these cracks, producing a Schiller effect.)

B. Under crossed nicols.

FIG. 11. Mowich hypersthene basalt.

Summary

After examining several hundred thin sections of Keechelus rocks, the writer was impressed by three characteristics that were almost unfailingly present.

One of the most constant characters is a porphyritic texture. This is seen is best advantage in the numerous bodies of andesite and diorite porphyries, but it to also prevalent in the various flows and serves as a modifying texture in the fragmental rocks. The average size of the phenocrysts for all the specimens examined is 1.5 mm. Exceptions to this texture are confined to a very few dense pyroclastic layers and to small dikes and sills (less than .5 meter in width) intruding the younger portions of this formation.

Another distinguishing trait is the presence of abundant opaque minerals. In the vast majority of cases, magnetite may be seen as dust, small granules, or moderately sized grains—the size being roughly proportional to the dimensions of the other minerals in the groundmass. In the dense flows, the magnetite is usually in the form of dust but, in the porphyries, the octahedral grains often attain a size sufficiently large to be distinguished megascopically. The only exception noted in regard to the opaques was one specimen of felsite and it contained limonite in place of the magnetite. Less plentiful opaques include ilmenite, leucoxene, and pyrite.

The green color of so many of the Keechelus rocks is undoubtedly related to the presence of chlorites, serpentines, actinolite, and, to a smaller extent, to the pyroxenes. Such minerals as antigorite clinochlore, actinolite, and bowlingite are especially plentiful and one or more may be found in most any of the Keechelus rocks, with the exception of the felsites.

Other traits are not so constant. However, certain strong tendencies are thought to be worthy of mention. The feldspars are zoned more often than not and usually contain inclusions of material identical to that in the groundmass. There is a distinct inclination toward a glomeroporphyritic texture in many of the rocks. The pyroxenes are almost totally lacking in the lower, and older, part of the formation and are but slightly more abundant in the younger. The chlorites and serpentines are far more prevalent and continue down to the actual contact of the granodiorite.

The jointing of the formation is rather distinctive in that the blocks are huge and roughly rectangular—simulating those of granite. The joint planes are remarkably flat and continuous. This type of jointing is not confined to the massive porphyries but is seen in the younger tuffs as well. The columnar structure of the topmost flows is a notable exception.

Relations and Age

The Keechelus series can scarcely be regarded as a unit. From a lithologic standpoint, the formation is largely composed of andesitic porphyries and breccias in various stages of alteration but a great wealth of other types are likewise included in sufficient amount to make it impossible to consider as a formation. Reference has been made in the previous pages to the older and younger portions of this series. Such a division was recognized by Smith and Calkins (34) while mapping the Snoqualmie quadrangle. This grouping is evident to field workers in the Keechelus, yet innumerable difficulties arise when an attempt is made to represent the component parts on a map. The reason is well summed up by Smith and Calkins in the following paragraph:

> In short, the criteria, while sufficient to establish the presence of two distinct groups of these volcanics, fail, except locally, to serve as a basis for the determination of the boundaries between them. On the average, the later andesite is much fresher, less tilted and less dissected than the earlier, but, in contiguous areas, certain phases of the two are so similar that they cannot be discriminated with certainty, and the endeavor to map them separately was, therefore, abandoned.

The lower and altered portion is extremely massive and indurated and, where the attitude may be distinguished, displays a gentle folding. Rocks of this character average 2,000 feet in thickness within the Park.

The age relationships of both the older and younger parts of the Keechelus leave much to be desired. In the northern half of the Snoqualmie quadrangle, the lower part of the Keechelus was found to overlie, unconformably, the Swauk, Teanaway, and Guye formations. The youngest of these Tertiary formations is the Guye; its age being determined as Miocene on the basis of fossil leaves. In the southern half of the quadrangle, the Keechelus lavas are overlain by beds of the Ellensburg formation, which has been assigned to the late Miocene in age on paleobotanical evidence. Hence, the Miocene age of the Keechelus formation, seemingly, is well established.

The exposures of the Guye are known, only, in the northwest corner of the Snoqualmie quadrangle. Concerning it, Smith states:

> The Guye consists of detrital rocks with some chert and limestone and interbedded basalts and rhyolites. The base of the formation is nowhere exposed; the top has been removed by erosion so that its limits and thickness are unknown. The formation is much-folded; its structure cannot be worked out in detail, nor can any general section of it be compiled.

Obviously, great care should be exercised in using this formation as a basis for correlation for so large and important a series as the Keechelus. Before wholly accepting the evidence limiting the Keechelus between two Miocene formations, caution should be taken for the following reasons:

1. It is doubtful if the Keechelus overlies that portion of the Guye wherein the leaves have been found. If that be true, it is not known whether the younger or older Keechelus covers the leaves.
2. On a lithologic basis, the limestone strata in the Guye have no counterpart in any known Tertiary formations, either to the east or west of the Cascades. Limestone is, however, found in the older rocks.
3. A considerable time interval must have elapsed between the two Miocene formations, the Guye and the Ellensburg, for the Guye is overlain unconformably by thousands of feet of Keechelus material and this, in turn, is overlain by the Ellensburg.
4. Smith and Calkins remark:

   > The stratigraphic relations to the overlying rocks, added to the lithologic resemblance of the Guye to the Eocene formations, would have lead to its reference to the Eocene were it not for the paleobotanical evidence.

5. The entire age determination was based on two fossil leaves referred to the Miocene and one to the Fort Union (Eocene or Cret.).

The younger Keechelus may be separated from the older on lithologic, structural, and possibly topographic evidence.

Lithologically, the younger fragmental rocks are characterized by a well-developed bedding. The flows have a freshness that makes them exceedingly difficult to distinguish from the lavas of Mount Rainier. The older rocks, on the other hand, are more massive, dull and altered looking.

Structurally, the younger flows and pyroclastics still retain a horizontal position, or, locally, they may be slightly warped. The older rocks have been tilted and folded and suffered minor fracturing.

Topographically, the attitude of the younger lavas is still expressed in some of the flat-topped park areas. The older part is deeply dissected, and, being so massive, exerts little influence on the drainage pattern. A possible exception would be a tendency toward a subsequent drainage following the general northwest-southeast structural trend of these older rocks.

The exact upper age limit of the Keechelus is unknown. The only materials definitely overlying the younger capping flows in the vicinity of the park are the Rainier volcanics. Elsewhere, volcanic activity in the Keechelus may have extended well into the Pliocene, and judging from the freshness of the flows, they may be equivalent to the Rainier lavas in age.

SNOQUALMIE GRANODIORITE

The presence of granular igneous rocks at the base of Mount Rainier was first mentioned by Lieutenant Kautz in 1857 and again, in 1870 Emmons (7) observed ". . . a beautiful white syenitic granite rising above the foot of the Nisqually Glacier." Since then, numerous other masses of similar rocks have been encountered in the Cascade Range. Most of these, however, differ in age and are in no way related to the granodiorite in the Park. An exception is believed to have been found in the Snoqualmie granodiorite, first described in the quadrangle bearing the same name. The Snoqualmie granodiorite invades the Keechelus series in a manner identical to the plutonic masses surrounding Mount Rainier. Both are essentially granodiorite, a term described by Lindgren (20) thirty years after Emmons' visit to the mountain.

Areal Extent

The outcrops in the Park are to be explained by the effectiveness of the glaciers in cutting through the overlying Keechelus and bringing to light portions of the granodiorite below. An irregular F-shaped exposure occurs along the northern face of the Tatoosh Range with prongs extending up the Paradise and Nisqually rivers. This mass is well-exposed along the tortuous highway leading from Longmire to Paradise and on the Reflection Lake branch.

The longest expanse of granodiorite in the Park roughly follows the White and Klickitat rivers, extending from their sources to approximately 1 mile north of the old White River entrance. Beautiful exposures of this mass are to be seen along the Chinook Pass Highway and the Yakima Park road.

Other smaller patches of granodiorite occur at the following localities:

1. White River Park near Hidden and Clover lakes.
2. Below St. Elmos Pass on the Winthrop side.
3. Garda Falls on Granite Creek at the terminus of the Winthrop Glacier.
4. Goat Island rock and adjacent territory on either side of the Carbon Glacier.
5. Chenuis Falls at the junction of the Carbon River and the north boundary.
6. The foot of Ranger Creek across the Carbon River from Chenuis Falls.
7. Below Sylvia Falls.

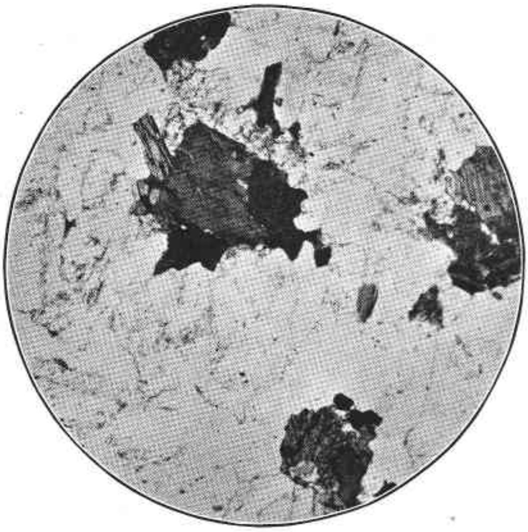
Many other and smaller patches of granular igneous rocks are to be found in the Park. Because of their limited extent, hybrid nature, and intimate association with the Keechelus, these rocks have been included in the latter formation, following the precedent set in the Snoqualmie folio.

Petrography

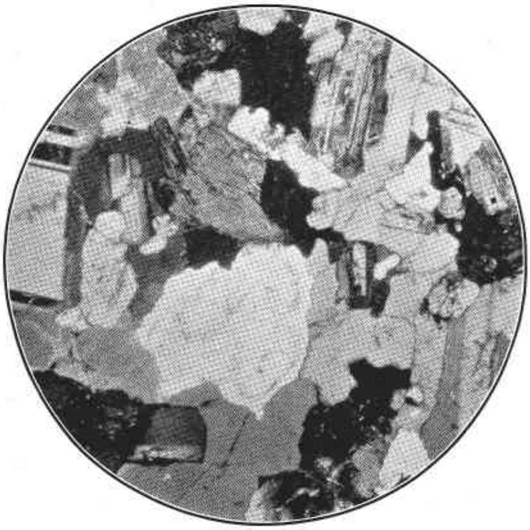
As the glaciers have merely scratched the surface of this batholith, few localities exhibit a clear-cut and homogeneous granodiorite. Rather, the types so often met with are immediately below the contact with the Keechelus and contain swarms of xenoliths and other, more diffused, material. This tends to impart a darker color and a more hybrid appearance than is usually characteristic of the deeper portions of the granodiorite. At the White River and the Nisqually localities, the rock is relatively homogeneous, except for a few small aplitic and hornblendic dikes. Here, the grandiorite is a medium-grained aggregate of milky-white feldspars; colorless, glassy quartz; lustrous black biotite and hornblende—all easily distinguishable megascopically. The strong contrast between the white feldspars and the black mafics gives the rock a very pleasing appearance when cut and polished.

Microscopical Petrography. The rock has a hypidiomorphic granular texture. In addition to the minerals listed above, magnetite, titanite, and apatite are present, as well as a small amount of sericite and calcite in minute cracks in the feldspars. As a whole, the minerals are clear and fresh. The idiomorphism of the soda-lime feldspars, so common in the Cascade batholiths, is well displayed in this granodiorite. Without exception, the plagioclases show strong oscillatory zoning with relatively more acid rims. The composition varies from andesine (Ab_{65}-An_{35}) in the cores, to oligoclase (Ab_{80}-An_{20}) in the rims. The biotite is of the siderophyllite variety with Ng and Nm$=$1.650 and a 2V of less than 2°. Pleochroism is marked with X yellow, Y, and Z greenish-brown to opaque. A clear, green rim of a chlorite surrounds the biotite as an alteration product. The hornblende is decidedly greener than the biotite and varies from pale yellow (X) to green (Y) to dark green (Z).

The orthoclase is exceedingly fresh and, especially when the section is cut parallel to 010, it becomes increasingly difficult to distinguish from the quartz. The



A. x25, plane light. (The blackest mineral is biotite; the larger pieces of somewhat lighter shade are hornblende, and, the almost colorless minerals are feldspar and quartz.)



B. Under crossed nicols. (The plagioclase is, for the most part, idiomorphic, while the quartz is interstitial. The oscillatory zoning of the feldspar is very common.)

FIG. 12. Snoqualmie granodiorite.

optical character of each had to be checked while estimating the percentage composition. Both orthoclase and quartz are anhedral and their interstitial position and inclusions indicate they were the last minerals to crystallize. The accessories are limited to titanite, magnetite and apatite. The magnetite forms grains 0.3 mm. in diameter and, together with the smaller wedges of titanite, are always associated with the hornblende and biotite. While the euhedral prisms of apatite have not been so selective in choosing their host, they seem to favor the feldspar and quartz. The composition, based on 15 specimens from the Nisqually and White River localities, is as follows: plagioclase, 54 per cent; quartz, 18 per cent; orthoclase, 10 per cent; biotite, 8 per cent; hornblende, 5 per cent; magnetite, 2 per cent; chlorite, 1 per cent; apatite, 1 per cent; and, sericite, calcite, and titanite make up the remaining 1 per cent. Although the more basic phases of this mass grade into diorite and quartz diorite, the composition as given above, of this homogeneous facies, falls well into the granodiorite class as defined by Lindgren.

Relations and Age

The granodiorite invades both the Keechelus and the Guye formation; the relation being abundantly proved by a great number of contacts seen in the Rainier district, the Snoqualmie quadrangle, and the northern portion of the Mount Aix quadrangle. In the northeastern corner of the Park, the contact is characterized by a xenolith zone some hundreds of feet in thickness. Well-exposed along the road leading from the White River bridge to the old Starbo camp, and also at Hidden Lake, for the hurried Park visitor this interesting contact may be seen to best advantage on the Chinook Pass Highway between the junction of the Yakima Park road and Ghost Lake. The writer (14) has examined the granodiorite-Guye contact several times in the Snoqualmie quadrangle, and there is no doubt as to the relative ages of the two formations—the granodiorite is definitely younger. Since the age of the Guye has already been established (?) as Miocene, then the lower age limit of the granodiorite must be post- or late Miocene.

The uppermost limit must be set as pre-Pleistocene as the granodiorite is overlain, unconformably, by the Pleistocene, or perhaps Pliocene, lavas of Mount Rainier. The best example of this uncomformity is seen at the snout of the Nisqually Glacier on the southeast side of the river. This would confine the invasion of the batholith either to late Miocene or Pliocene time. In view of the fact that considerable erosion has taken place since the emplacement of the batholith, it seems more plausible to establish the time of the emplacement to as old a date as possible. From present data, this is necessarily limited to late Miocene.

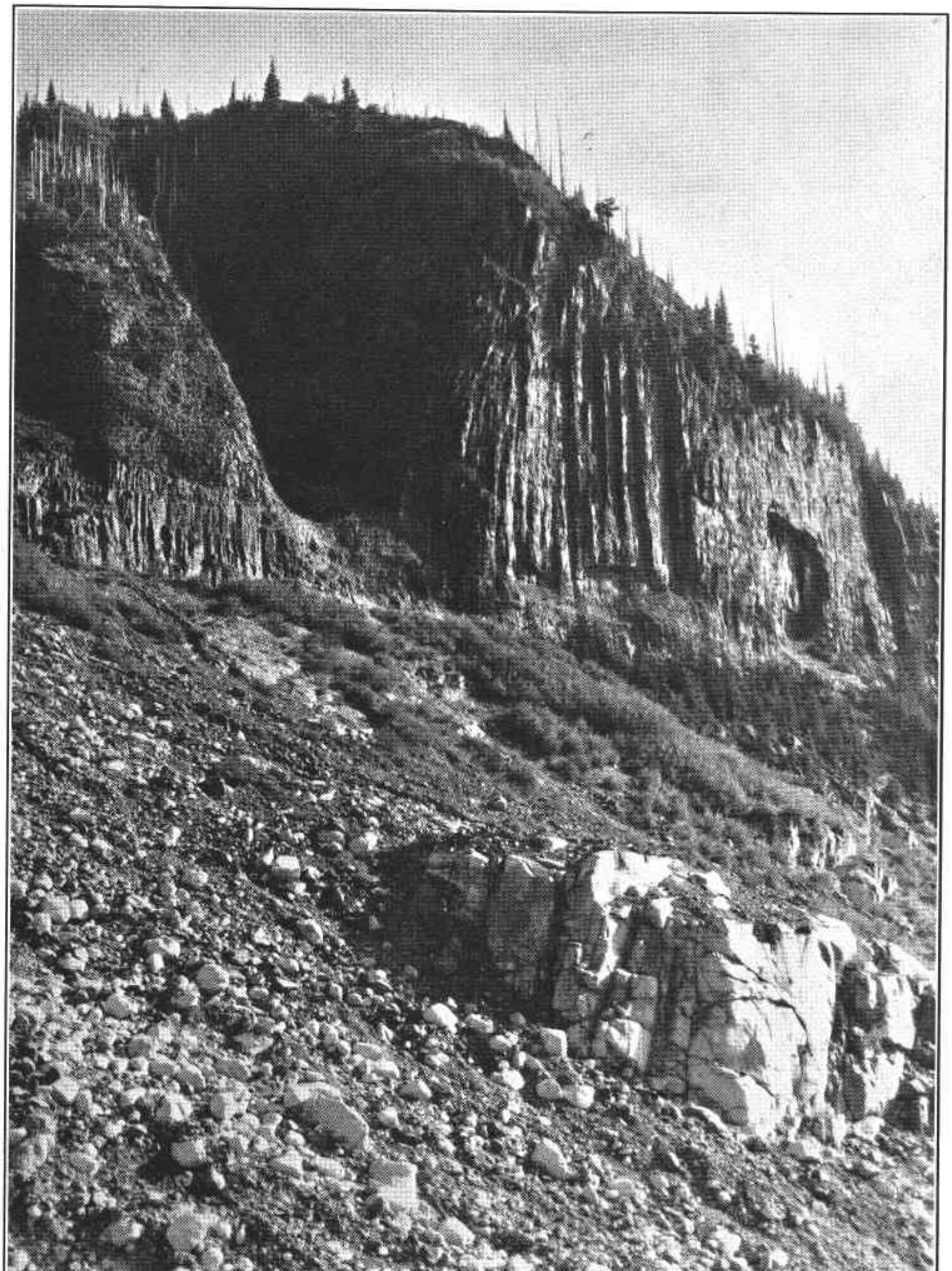


FIG. 13. Unconformity between the eroded surface of the Snoqualmie granodiorite and the lower flows of Mount Rainier. (View looking southeast across the Nisqually Canyon near the snout of the Nisqually Glacier.)

THE MOUNT RAINIER VOLCANICS

Mount Rainier is a typical strato-volcano comparable, in many respects, to the other andesitic cones scattered along the Cascade Range from Lassen in California to Baker near the Canadian border. Spread out in a very irregular fashion, the Rainier lavas occupy approximately 100 square miles in areal extent. Of this amount, 45 square miles, or nearly half, are covered by perennial snow and ice. Vertically, the lavas range from the upland surface of the Cascades, at an elevation of 6,000 feet, to the crater, which towers 14,408 feet above sea level. Thus the actual volcano is well over 8,000 feet high.

Although exhibiting much less diversity than Mount Shasta and Mount Lassen, in general form and composition, Mount Rainier has suffered intense glaciation and the original symmetry of the cone is now destroyed. An erosional remnant worthy of mention is Little Tahoma. Because of its 11,117-foot elevation, shape, and position, it has been mistaken countless times for a parasitic cone. When viewed from Seattle or any of the neighboring towns, this lesser peak rather closely resembles Shastina, a parasitic cone on Mount Shasta. However, on closer inspection, the alternating flows and beds of pyroclastics all partake in a common dip to the southeast, away from the crater of Rainier and pass under the summit of Little Tahoma without interruption. The peak is only one of the many wedge and cleaver remnants of the original cone.

The Rainier volcanics may be roughly divided into two groups; the loose and crumbly pyroclastics, and the compact flows. On the higher slopes of the mountain, the pyroclastics are abundant. The material presents a wide assortment of sizes and includes dust, ash, tuff, tuff-breccias, breccias, volcanic conglomerates, and small mud flows. The volcanic conglomerates and mud flows extend down toward the base of the mountain, while the greater portion of the true ejectamenta (with the exception of the widely-scattered small pumicious lapilli and ash) are confined above the 9,000-foot elevation.* Vertical sections, exposed on the sides of the various wedges and cleavers, show the unconsolidated nature of the tuffs and ash to be in strong contrast with the intercalated flows. The pyroclastics are especially annoying to climbers who attempt to scale the higher peaks. These rocks allow no secure hand or foot holds and they present the added difficulty of continuously falling from above. In color, the fragmental rocks vary from a light to dirty-brown, through all shades of red and pink, to maroon and black. The red tuff-breccia and pumice beds along Gibraltar are easily seen from Paradise. Others, even more completely exposed, outcrop along the sides of Little Tahoma and the Cathedral rocks. These probably have a counterpart in the Red banks near the summit of Mount Shasta. (43)

The observed fragmental beds generally dip away from the central vent with angles between 7° and 30°, the steeper dips being nearer the summit. Dips up to 25° have been observed as low as 9,000 feet in the coarse, loose breccia of Steamboat Prow.

*Since there has been such a wide diversity of opinion regarding the terminology of the pyroclastic rocks, the writer has used the definitions set forth by the National Research Council in describing these pyroclastics. Cf. Wentworth and Williams. (39)

Not all of the pyroclastics have been dropped on the slopes of Mount Rainier. Ash and pumice fields, undoubtedly derived from this cone, are scattered over much of the contiguous area. These vary from a few centimeters to a few meters in thickness and contain fragments ranging from dust to lapilli size. Similar fields, but of much larger extent, have been described by Williams (41) in the vicinity of Crater Lake and Mount Theilson.

The lava flows of Mount Rainier attain their greatest development in the basal portions of the mountain but, as mentioned previously, this material may also occur on the higher slopes intercalated with the pyroclastics. The earlier flows were comparatively fluid and spread out as tongues, partially filling previously formed valleys. A high degree of fluidity is not to be inferred, however, for lavas extending more than 6 miles from the central vent are exceptional. Individual flows up to 40 meters in thickness are not uncommon, but the average would be closer to 25 meters.

Quantitatively, a very small amount of flow material has been added through fissures located at St. Elmos Pass on the Interglacier side of the divide, and also on the west side of the mountain below Emerald Ridge adjoining the South Tahoma Glacier, and possibly near Yakima Creek, although here the relations are obscured by talus and slope wash.

The great majority of flows are fresh in appearance and compact. Scoriaceous and vesicular facies are of minor importance. A platy jointing is very typical with examples exposed at Ricksecker Point, below the inn at Paradise, and on Burroughs Mountain. At the higher elevations, vigorous frost action, together with wide diurnal temperature changes, have been effective in wedging the plates apart and, as a result, the peaks are covered with loose slabs of andesite.

Columnar structure is well shown at a number of localities. At the terminus of the Nisqually Glacier, the flows resting on the granodiorite have vertical columns 25 meters or more in height. At Basaltic Falls, on the east side of the Cowlitz Glacier, and at Pearl Falls, on Pyramid Creek, the columns are larger and even more perfectly developed. On the Yakima Park road, near Yakima Creek, perfect horizontal columns are piled one on the other like cord-wood. These are modified by a secondary parting at right angles to the long axis of the columns and on the north end of the outcrop a platy parting is developed parallel to the long axis.

In color, the lavas are chiefly shades of gray. The lighter shades are restricted to the earlier flows, while the darker grays to blacks may be encountered anywhere on the mountain from the first flows overlying the granodiorite to the crater rim. Other colors include red, pink, purple, bluish-gray, and brown. The red color, as in the case of the fragmental rocks, is prevalent near the summit. As will be shown later, the color is largely dependent on the condition and amount of glass in the groundmass.

In the literature there is a slight disagreement concerning the proportion of pyroclastics as compared to flow material. Russell (27) states:

> The main mass of Mount Rainier is composed of andesite and basalt, which were ejected to a considerable extent in a fragmental condition as scoria, pumice, lapilli, bombs, etc. Lava flows were not abundant during the latter stages of eruption. The mountain ranks as a composite cone but so far as its structure is revealed in the canyons. . . it was built largely by the material thrown out by explosions from a summit crater.

On the other hand, Smith (30) declares: "The breccias, agglomerates, and tuffs, although of striking appearance, are, perhaps, less important elements in the construction of the composite cone."

This difference in opinion may be explained by the districts visited by each man, or, as an alternative, to their interpretation of the areal extent of the Rainier lavas. Russell evidently spent much of his time on the glaciers and higher slopes where the fragmental rocks are dominant. Smith, however, visited many of the lower, as well as the higher reaches, and encountered large quantities of flows. The writer concurs with Smith in estimating the bulk of the mountain to be composed of flows.

It is interesting to note that on the limited excursions taken by the average Park visitor, no pyroclastics are encountered; with the possible exception of the small and surficial beds of ash. The majority of trails lead over the marginal tongues of the Rainier lavas and the Keechelus andesites.

The exact time of issuance of the Rainier lavas is unknown, but it is thought that the greater portion of the volcano was formed during Pleistocene time. Paleobotanical evidence (46) indicates post-Pliocene eruptions, as leaves have been found intercalated with some of the Rainier pyroclastics. Witnesses (18) have observed eruptions in the form of a series of brown, billowy clouds in 1879 and again in 1882.

Composition

After examining the first specimens ever gathered from the mountain, Hague and Iddings (15) came to the conclusion that "Mount Rainier is formed almost wholly of hypersthene andesite." Later work on the mountain has not only failed to alter, but has forcibly emphasized this statement. In comparing the volcanoes of the United States Pacific coast, these men stated further:

> While the rocks from the volcanoes, in general, present the closest resemblances, there is a wider range and a greater variety of structure in the more acid types from Lassens peak and Mount Shasta. On the other hand, judging from the collections, the range in the character of the extrusions is most restricted at Mount Rainier.

Smith attempted a more detailed classification of types and mentioned:

> Four rock types are represented; hypersthene andesite, pyroxene andesite, augite andesite, and basalt—any of which may carry small amounts of hornblende. A rigid separation of these rock types, however, is impossible since insensible gradations connect the most acid with the most basic. In the same flow, hypersthene andesite may occur in one portion while in close proximity the lava is an augite andesite.

Even in the classification suggested by Smith, the majority of rocks from Mount Rainier are hypersthene andesites. Pyroxene andesites, in which both hypersthene and augite are essential, would be a close second. The augite andesites and basalts are of minor importance.

A wide diversion of opinion exists among petrographers as to just what constitutes a basalt and how it may be separated consistently from similar rocks, as, for example, andesites. If the distinction between basalts and andesites is based on the nature of the feldspars, andesine characterizing andesites and the more basic varieties the basalts, then the lavas from Rainier contain approximately 7 per cent basalts. Following the other school which regards the abundance of olivine and the preponderance of mafic over felsic minerals as criteria for basalts, then less than 1 per cent of the Rainier rocks are basalts.

In the chemical analyses which follow, No. 1 is from the crater. This, undoubtedly, is one of the darker and more glassy types so abundant along the crater rim. The analysis shows it to be a rather acid andesite.

Unfortunately the locality for No. 2 is unknown. Smith (30) mentions that it was collected from the "northern slope of the mountain." Because of the close similarity between the Rainier and the Keechelus lavas, and this is especially true on the northern slope, it is not improbable that this analysis might be of a Keechelus rock. The low alumina and magnesia and the high soda, potash and lime are unusual for the andesites of the Cascade volcanoes.

	No. 1 (23)	No. 2 (15)
SiO_2	61.62	54.86
Al_2O_3	16.86	15.04
Fe_2O_3	....	4.92
FeO	6.61	3.11
MgO	2.17	1.88
CaO	6.57	9.19
Na_2O	3.93	....
		11.30
K_2O	1.66	....
P_2O_5	....	.46
	99.42	100.76

Microscopical Petrography

The rocks of Mount Rainier are extremely monotonous in their mineral content, but, happily more varied in their textural characteristics. In the pages to follow, the minerals occurring as phenocrysts will be described in the order of their importance. Added to this is a brief description of some of the textures encountered. The data is compiled from the examination of several hundred thin sections, and, while lacking in detail, should provide a general acquaintance with the Rainier volcanics.

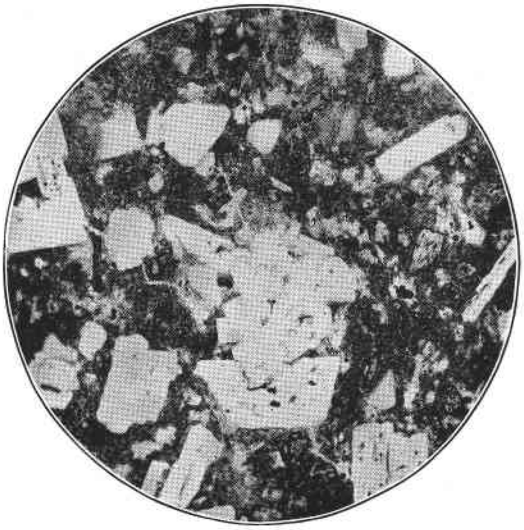
The dominant phenocrysts are plagioclase, hypersthene, and augite. Such minerals as hornblende and olivine may be present but are quantitatively so subordinate as to require little attention.

Plagioclase. It occurs in two, and possibly three, more or less distinct generations. Generally the difference in size will serve as a criteria to distinguish the various sets of feldspar. However, this characteristic is not always dependable as in

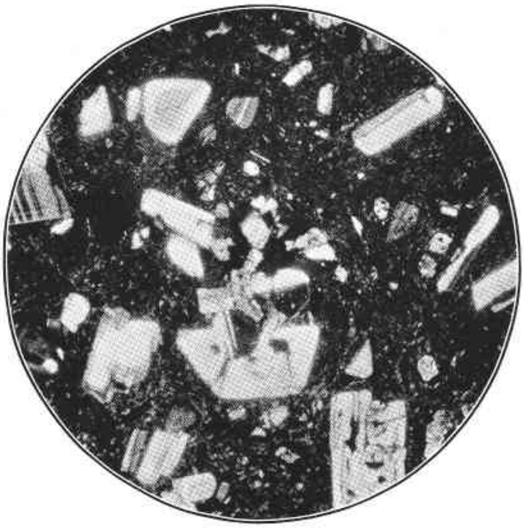
A. x25, plane light. (A blotchy, plagioclase crystal.)

B. Under crossed nicols. (The component parts of the plagioclase phenocryst are, for the most part, arranged in a parallel fashion; however, one side is formed by individual crystals oriented in different directions, indicating a glomeroporphyritic mechanism.)

FIG. 14. Andesite from north side of the South Puyallup Glacier.



A. x62, plane light. (The light-colored area in the center of the photomicrograph is a cluster of plagioclase crystals.)



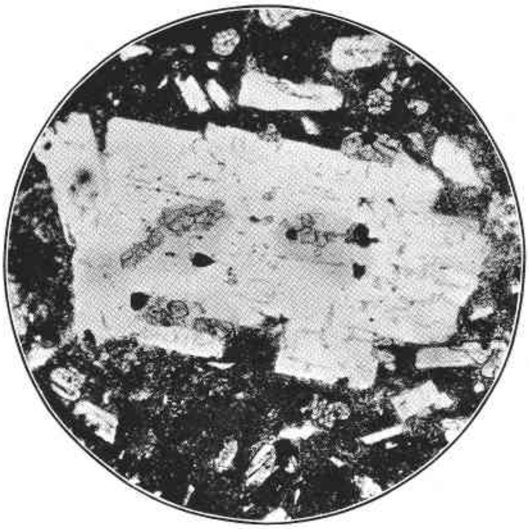
B. Under crossed nicols. (The orientation of the various crystals in the glomeroporphyry can be seen in this photomicrograph.)

Fig. 15. Hypersthene andesite from Saint Elmo Pass.

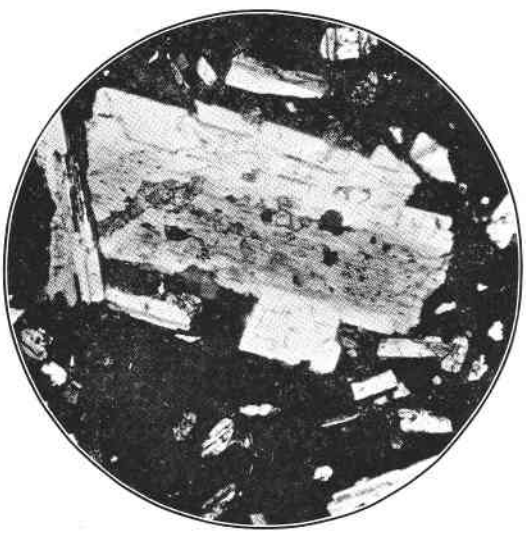
several of the flows all gradations in size are to be found from the smallest to the largest. In such cases, other features, to be described below, will serve to separate the various generations.

The largest phenocrysts are unique in several ways. In plane polarized light they display a chunky, blocky outline, seemingly made up of several smaller crystals having a common orientation. Under crossed nicols many of these blocky phenocrysts are composed of smaller crystals, each twinned on the Carlsbad plan with the composition planes usually parallel to each other. A zoning is invariably present and is superimposed on the Carlsbad twins. Pericline twinning is rare. The feldspars are normally crowded with inclusions, the chief constituent being a brownish-glass, subordinately, mafic minerals or portions of the groundmass may be included. Frequently, smaller feldspar crystals are attached to the larger ones with a marked difference in orientation. The effect of the attached crystals is obviously a glomeroporphyritic tendency and this, together with a cumulophyric texture, is very typical of the Rainier lavas. In some of the larger clusters, the individuals are welded together so perfectly that it is impossible to distinguish the component parts in ordinary light. Under polarized light, the sets of Carlsbad twins can often be distinguished, but sometimes even this is lacking and the resulting phenocrysts are strongly zoned, complexly twinned, and full of cuneiform-shaped inclusions. The fact that all steps exist, even in the same section, between the larger phenocrysts and the glomeroporphyritic clusters, strongly suggests the phenocrysts were formed by the accretion and welding together of smaller feldspars of an earlier generation. This would also account for their oversize dimensions (averaging close to 2 mm. in length) when compared to the second generation feldspars, which average only .3 mm. in length. This explanation would offer a plausible reason for the complex twinning; the abrupt and angular lamellae and composition planes being inherited from the arrangement of the former individuals and not obliterated by later cohesion effects. The chunky shape, with blocks protruding from the margin and also outlined within the phenocryst by continuous lines of brown glass, fits well into this explanation. The tendency toward a glomeroporphyritic texture is not only abundantly displayed in the Mount Rainier lavas but also in many other of the Cascade andesitic volcanoes. (42)

Patton (24) has figured a feldspar phenocryst from Crater Lake which fits the above description perfectly. He attributes the formation of the crystal to "secondary enlargement," and his figure indicates a thin rim of clear material added to the inclusion-filled core. Thin rims are also found on the plagioclase in the Rainier lavas and they may be either clear, as compared to the cores, or full of inclusions with relatively clear cores. In either case, while the rim has added to the dimension of the crystal, it is, nevertheless, quite thin and not of sufficient magnitude to account for the great difference in size between the first and second generation feldspars. The secondary enlargement idea fails to account for the blocky shape of the feldspars as the rims would be merely added, in a constant thickness, to the previously formed crystal. Then, too, by secondary enlargement the only difference in the twinning should be encountered in the rims as compared to the cores. This, however, is not the case. The complex twinning extends through rims and core alike and roughly divides the crystal into wedges and blocks.



A. x25, plane light. (Note the blocky character of the plagioclase; perhaps indicating a glomeroporphyritic mechanism in the formation of these crystals.)



B. Under crossed nicols.

Fig. 16. Andesite from near the snout of the Nisqually Glacier.

The large phenocrysts have other features worthy of mention. In the majority of rocks with a holocrystalline or hypocrystalline groundmass, the feldspars are whole and show little evidence of cleavage. In the more glassy flows and, especially, in the pyroclastics, as for example, the Muir pumice, the feldspars are a maze of cracks. Quick chilling and violence of ejection probably are responsible for much of the fracturing. Glass inclusions are also more numerous in rocks with a glassy groundmass. So many of the plagioclases have interesting peripheries. In a few of the flows, near the terminus of the Nisqually Glacier, the phenocrysts have ill-defined margins which seem to grade insensibly into the groundmass. On further examination, most all of the feldspars showed this effect; an amount out of all proportion to the percentage expected by tapering wedges. Williams (42) has figured a similar effect from the Mount Harkness lavas. Many of the feldspars of both the first and second generation have moderately-rounded corners, due to resorption.

In composition, the largest phenocrysts range from acidic to basic andesine and into acidic labradorite (Ab_{63} to Ab_{48}). The majority are basic andesine.

The second generation of plagioclases must be considered as phenocrysts for they are distinctly larger than any minerals in the groundmass. Although they range considerably in size, most of them fall fairly close to the average of 0.3 mm. in length. The crystals are, for the most part, clear and fresh and present crisp, euhedral outlines to the groundmass. The shape is characteristically tabular to stubby rectangles with square cross-sections. Polysynthetic twinning is not always distinguishable, but a mild, oscillatory zoning is common. Carlsbad twinning is almost universally present, dividing the crystal into two equal halves. The composition varies from acidic andesine to intermediate labradorite (Ab_{30} to Ab_{61}). The second generation plagioclases differ from the first in many respects. In size they are from one-tenth to one-fifth as large as the first. The outlines are euhedral, regular, and sharp; while the older phenocrysts are blocky and jagged. The twinning is most often confined to simple Carlsbad halves which are combined with a mild zoning; in the larger crystals, the twinning is very complex and the zoning is more pronounced. The smaller feldspars are relatively free from inclusions as compared to the larger ones.

The third generation of plagioclase must be considered as a part of the groundmass. They can often be detected in the glassy rocks as microlites but reach their greatest perfection in the more holocrystalline types. In size, the crystals of the third generation vary between microlites and 0.07 mm. in length, with the average falling close to 0.04 mm. The shape is typically elongated, microlithic laths often displaying castellated terminations. In spite of their incomplete terminations, they strongly resemble the feldspars of the second generation and, in addition, correspond almost identically to them in composition, in so far as the composition can be determined.

Hypersthene. As early as 1883, Oebbeke was fascinated by the hypersthene in a rock brought back to Germany from Mount Rainier by Professor Zittel. Due to

Fig. 17. Hypersthene andesite from Spray Park. (x62, plane light. This shows a hypersthene crystal surrounded by a jacket of augite. The groundmass is a deep red glass.)

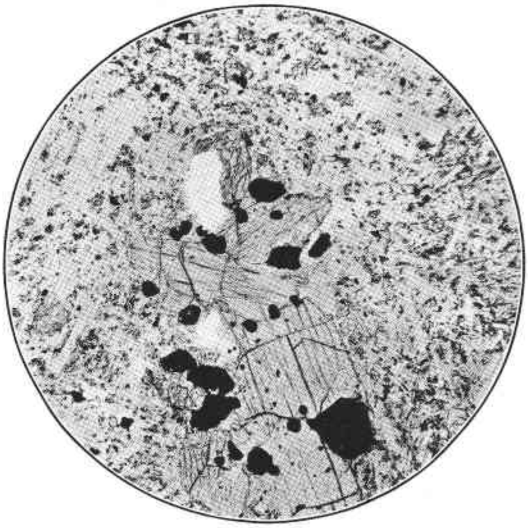


Fig. 18. Hypersthene andesite from Faraway Rock. (x62, plane light. This association of hypersthene and magnetite is exceedingly common. The small, lighter colored crystals also in the hypersthene cluster are apatite. This type of pilitic groundmass is quite common.)

his failure to isolate enough of the mineral for chemical analysis, Oebbeke (23) gave a rather complete description of its optical properties. A portion of the description follows:

> Leider gelang es nicht, den pleochroitischen Pyroxen zu isoliren, um ihn einer chemischen Prüfung zu unterziehen. Es blieb daher nichts übrig, als sich auf die microscopische Untersuchung zu beschränken.
>
> Die Schnitte senkrecht zur Längsrichtung ziegen ausser der prismatischen noch eine pinakoidal Spaltbarkeit; in den Längsschnitten, besonders in denjenigen der kleineren Krystalle, ist die Spaltbarkeit nicht immer deutlich, häufig beobachtet man in ihnen enie zur Längsrichtung senkrecht verlaufende Querabsonderung. An Einschlüssen sind die erwähnten Krystalle arm. Ausser glas, Magnetit und Apatit wurden keine Einschlüsse gefunden.
>
> Der pleochroismus der Längsschnitten ist der Richtung der C Axe grünlich (hellgrünlichblaulichgrün), senkrecht dazu gelblichgrün, hellbräunlich odor rötlichbraun.
>
> Die Schnitte senkrecht zur Längrichtung ziegen parallel der pinakoidalen Spaltbarkeit hellbraune bis rötlichbraune, senkrecht dazu grünlich gelbe bis hellbraunliche Farben.
>
> Wurden diese Schnitte im convergenten polarisitiren Licht untersucht, so sah man eine optische Axe austreten; die Ebene der optischen Axen geht der pinakoidalen Spaltbarkeit parallel.
>
> Die Längschnitte in gleicher Weise untersucht liessen bald den Austritt einer optischen Axe zeimlich am Rande des Gesichtsfeldes erkennen, bald konnte deutlich wahrgenommen werden, dass eine Mittellinie senkrecht zu ihnen stehen und dass der Axenwinkel ein ziemlich grösser sein müsse.

Rarely can a rock be found on the slopes of Rainier which does not contain at least a few crystals of hypersthene. It normally presents euhedral to subhedral outlines and forms short to long rectangular crystals with rather abrupt terminations. When pyramids and domes occur, they are remarkably flat and quite often have slightly-rounded corners. The prismatic cleavage is well shown and the 010 parting, while not so regular, is usually present. The phenocrysts average 0.5 mm. in length, but may be either much larger or smaller than this mean. In the more holocrystalline varieties, hypersthene may occur in the groundmass as small stubby crystals or displaying a lath like habit and averaging .05 mm. in length.

The pleochrosim is one of the most outstanding characteristics of the mineral and, while varying in intensity among the different flows, it is always pronounced. Generally X is an orange color, Y a yellowish brown, and Z a green. The optic angle changes considerably depending, in part, on the amount of magnetite included within the different crystals. In those heavily charged with magnetite the 2 V drops as low as (−) 60 degrees, but in the clearer crystals, and these are far more common, the 2 V averages (−) 70 degrees. In a few cases an optic angle of 90 degrees was obtained. The determination of refringence based on immersion oils was Np = 1.765 to 1.680 and Ng = 1.700 to 1.705.

Following the example set by the feldspars the hypersthene has a tendency to form glomerophyritic clusters or to associate with the augite, plagioclase and magnetite in cumulophyric groups. Among the inclusions found in hypersthene, large grains of magnetite and rounded blebs of glass are equally important with clear stubby apatite prisms being slightly less common.

An interesting association is that of hypersthene and augite. Occasionally the augite will crystallize in jackets around the partially resorbed hypersthene so that both pyroxenes will have their C axes and their prismatic cleavages parallel to each other. A similar structure was observed by Williams (42) in the Red Mountain basalts. In one instance, in a brillant red flow from Spray Park the augite jacket

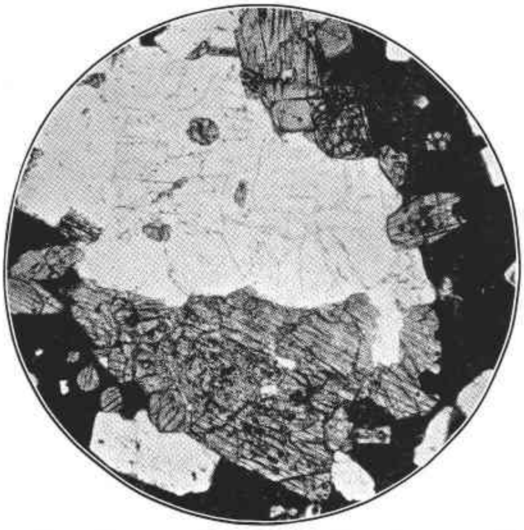


FIG. 19. Andesite from McClure Rock. (x25, plane light. A cumulophyric group of plagioclase, augite, and hypersthene in a glassy groundmass charged with magnetite.)

FIG. 20. Andesite from Register Rock at the summit of the mountain. (x25, plane light. It is quite usual for the rocks near the summit to display a well-developed fluxion structure.)

showed a lamellar twinning (001) which occurred in a direct line on each side of the jacket but was interrupted by hypersthene in the center. It is difficult to determine whether the jackets continue over the end of the hypersthene or not. In most of the sections containing the jackets the hypersthene ends are free. At times the augite completely encircles the rhombic pyroxenes but, in these, the section is not cut exactly parallel to the C axis.

Monoclinic Hypersthene

A noteworthy feature of the rocks of Mt. Rainier is the clino-hypersthene encountered in the lavas. Scarcely a section examined failed to show the presence of at least one crystal of hypersthene with a definitely inclined extinction. These angles range from 1° up to a maximum of 15° although by far the greater percentage of this particular type of hypersthene usually had maximum angles of 8°. Occasionally zoned crystals were observed in which the extinction angle varied from center to periphery by as much as 3°. The remaining optical properties for the clino-hypersthene are very similar for those given for the rhombic varieties. The sign was universally negative, the 2 V and pleochroism were approximately identical and the refringence was only slightly higher in the inclined types.

Clino-hypersthene has been described by Winchell (47) as having indices of $Ng=1.73$, $Nm=1.715$ and $Np=1.713$ and by graphic solution he found the (+) 2 V to be 30° and $Z \wedge C$ of 46°. From this description it is readily seen that Winchell's clino-hypersthene has little in common with that from Mount Rainier.

Recently J. Verhoogen (48) found clino-hypersthene in the lavas from Mount St. Helens and has since been studying pyroxenes in lavas from Lassen Peak, Mount Shasta and Mount Theilson. The results of his work will be published in a forthcoming paper. An exchange of material and information on these pyroxenes indicates that the clino-hypersthenes from the various Cascade volcanoes are practically identical although similar material has never been described elsewhere.

Augite. Hypersthene and augite go hand-in-hand as the typical mafic minerals of the Rainier volcanics. Seldom is one present without the other and, to have both absent is, indeed, a rarity. The monoclinic pyroxenes closely approach the hypersthene from a quantitative standpoint but only in a limited number of cases can they be considered the dominant mineral. Usually in the Cascade volcanoes the augite is not so persistently idiomorphic as the hypersthene and the Rainier pyroxenes are no exception to this generalization.

Subhedral crystals commonly assume either an elongated tabular form or stubby prisms modified by pyramidal terminations. Most prominently displayed are the phenocrysts, similar in dimensions to the hypersthene (0.5 mm.), but small grains of augite as a groundmass constituent are very abundant. These rounded grains or microlithic laths average 0.02 mm. in length. A good many crystals show a greenish color and some exhibit a weak pleochroism with X and Z greenish and Y brownish. $Ng=1.700 \pm .001$. The maximum extinction angle ($Z \wedge C$) reaches 49°. Inclusions in the augite are identical to those in the hypersthene with brownish glass and magnetite being prevalent.

The augite does not cluster with its own kind as do the feldspars and the hypersthene but it is included in the cumulophyric groups. Both of the pyroxenes are exceedingly fresh. In a few instances, slight leaching by iron-rich solutions has resulted in the deposition of hematite, limonite and possibly göthite along the cleavage cracks. Although the pyroxenes resemble each other, they may be differentiated by the stronger pleochroism and idiomorphism, lower birefringence and parallel extinction of the hypersthene.

Olivine. It can scarcely be classed as an essential mineral of the Mount Rainier rocks. In rare cases, it becomes almost as important as the pyroxenes but, out of 200 sections picked at random, olivine was found to be plentiful in only 4 cases. Out of this same number, a few small grains of olivine were detected in 21 cases.

The mineral is present both as a phenocryst, averaging 0.2 mm. in greatest dimension, and as a constituent of the groundmass, in which the granules average .05 mm. in diameter. The shape of each is typically subhedral. In this section, olivine is outstanding because of its clear, clean appearance, the scarcity of cleavage cracks as compared with the pyroxenes, and the lustrous sheen of the interference colors. Of all the phenocrysts, olivine is the least contaminated with inclusions.

As a rule, the mineral is little altered. However, certain interesting alteration and reaction effects have taken place along the peripheries of some of the crystals. In a flow from Spray Park, the olivine is surrounded by a margin of golden-brown bowlingite with a very small 2 V (about 10°). A few grains have wide marginal rims of hornblende, which are, in turn, studded with magnetite dust. Iddings (17) first mentioned this effect in one of the Rainier rocks from the Survey collection. In the lavas, wherein the groundmass is heavily charged with hematite dust, there is a concentration of hematite encircling the olivine, forming deep red rims. At times the iron-rich solutions have seeped along widened cleavage cracks, coloring them a brownish-red.

Hornblende. Hornblende occurs sporadically throughout the Rainier rocks as an accessory, or, in a few limited cases, as an essential constituent. Examples of the latter are found at Edith Creek in Paradise Valley or at St. Elmos Pass between Interglacier and the Winthrop Glacier. Without exception the hornblende crystals are edged with magnetite or are entirely replaced by that mineral. This effect is common to all the described Cascade volcanoes. When the groundmass is hematitic, the surrounding rims or pseudomorphs are also of hematite or limonite.

The hornblende is of the basaltic or oxyhornblende variety and occurs as long, euhedral prisms, or as stubby basal pinacoids with the characteristic cleavage. The length varies from 0.3 mm. to 0.6 mm. with the average being closer to the smaller figure. The pleochroism changes from a greenish-yellow (X), to a deep reddish-brown (Y and Z), and the extinction ($Z \wedge C$) is from 0° to 1°. In addition to the large quantity of magnetite, both plagioclase and apatite are present as inclusions. This is quite comparable to the hornblende described by Ransome (25) from Goldfield, Nevada.

After a petrographical examination of a number of rocks from Mount Rainier, one is strongly impressed by the monotonous regularity and repetition of the few

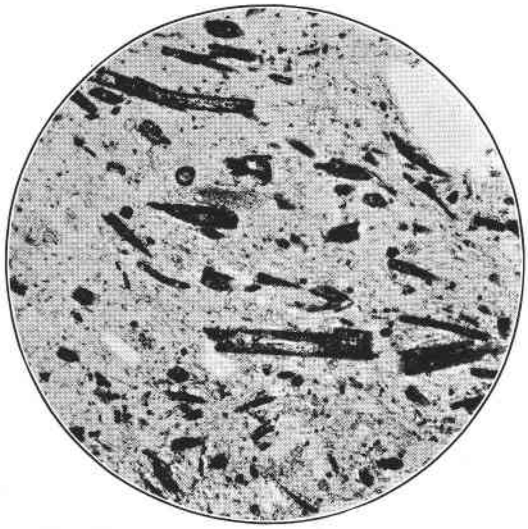


FIG. 21. Hornblende andesite from St. Elmos Pass. (x25, plane light. The black, elongated crystals are hornblende now largely replaced by magnetite. Note the fluxion structure.)

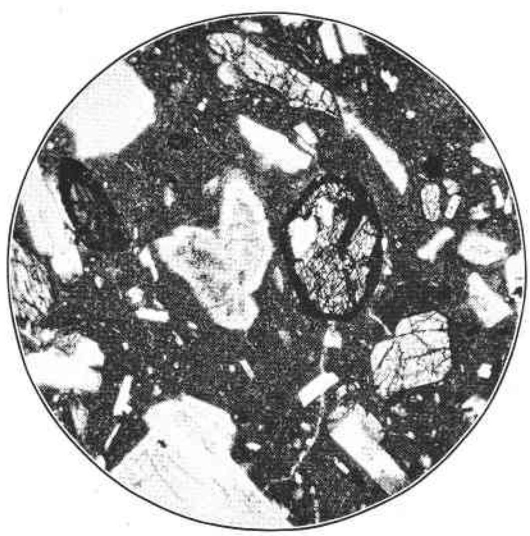


FIG. 22. Hornblende andesite from Edith Creek, Paradise Valley. (x25, plane light. Both the basal and prismatic sections of hornblende are rimmed by a border of magnetite.)

constituent minerals. They not only vary little in kind, but maintain a constant size and shape and relation to their associates. The only relief is to be sought in the diversity of the groundmass. Smith (30) well appreciated this condition when he stated:

> The megascopic differences are mostly referable to the groundmass characters; the color of the rock being dependent on the color and porportion of glassy base present. Therefore, the degree of crystallization of the groundmass constituents is of more importance in determining the megascopic appearance than is the mineralogical composition.

In the pages to follow, the types of groundmass will be mentioned according to their percentage of glass; the holohyaline coming first. Succeeding this will be the description of some unusual textural features.

Holohyaline Groundmass. Approximately 16 per cent of the Rainier rocks have a holohyaline groundmass. These vary in color from shiny black, brilliant red, brown, to almost white. Of all the colors, black is the most characteristic, and the converse is generally true that all the black rocks have a glassy groundmass. A number of black specimens from the crater rim at the summit show, in thin section, a dark brown, glassy base, crowded with magnetite dust and innumerable crystallites, probably of feldspar. In another black specimen from Old Desolate, the glass is also dark brown and contains microliths of feldspar 0.03 mm. in length and, in addition, granules of magnetite and prisms of apatite one-third the size of the feldspars.

In the brilliant red varieties, the glass is so full of hematite dust as to be almost opaque. Specimens of this type are numerous on the north side of the mountain in the vicinity of Seattle and Spray parks and also above the 11,000-foot contour line.

Less brilliantly colored than the red andesites and agglomerates, the pumice fragments so liberally scattered over the Park are shades of dirty brown to black. In thin section, the glass varies from a deep black through all shades of brown to colorless.

A milky-white lava was encountered on the west side of the Winthrop Glacier at an elevation of 6,000 feet. The microscope revealed the base to be a clear, colorless glass sporadically studded with a few grains of magnetite.

With the exception of certain pumice fragments, all the above mentioned rocks contain the usual phenocrysts. The glassy groundmass imparts to the andesites a brilliance in color and a lustrous freshness that makes them easily separable from the more holocrystalline varieties.

Hypo- and Holocrystalline Groundmass. The hypocrystalline base is found in approximately 80 per cent of the Rainier rocks, while the holocrystalline type is limited to but 4 per cent. Because of the small percentage of the holocrystalline material, and its insensible gradation into the hypocrystalline, it is convenient to group the two types together.

Contrasted with the dark holohyaline bases, the rocks of this group are normally medium to light gray in color. Abundant and easily accessible exposures of the light gray rocks may be seen along the Longmire-Paradise road at the Ramparts, Miller cut-off, Mazama Ridge and at Paradise. On the other side of the mountain, at Yakima Park, the nearest Rainier lavas with the hypocrystalline base outcrop on top of Burroughs Mountain.

The groundmass of these rocks, as seen under the microscope, presents a wealth of textures ranging from predominantly glassy to holocrystalline. The more glassy bases contain innumerable thin microlites and crystallites of feldspar, and less frequently augite and hypersthene. Magnetite dust, or granules, are never lacking. With a few exceptions, the glass is not at all conspicuous because of its lack of color. The flows outcropping at Frog Heaven and near the highest peak on Burroughs Mountain are exceptional in that their base is a coffee-brown glass and, were it not for the myriad of incipient minerals, these would belong to the holohyaline group.

As the percentage of glass diminishes, the narrow microlites and crystallites tend to widen, enlarge and to assert a little more sharply their crystallographic habits. The resulting laths of plagioclase, 0.02 mm. in length, are normally felted in a hyalopilitic texture; less commonly they are aligned in a sub-parallel fashion indicative of flowage. Hypersthene assumes a size and tabular shape very similar to the plagioclase, while the augite forms sub-rounded granules 0.01 mm. or less in diameter. When clear, the colorless, glassy residuum has an index of refraction of 1.511. However, magnetite dust or granules are so universally present that a dull, dusty-gray color is typical of more than 60 per cent of the Rainier lavas. It is with difficulty that the microlithic laths can be distinguished in so turbid a base; only the clear phenocrysts are really outstanding. The dull, platy andesites of the Cowlitz rocks are a beautiful example of the dusty, gray, magnetite-charged base.

As the matrix becomes more and more feldspathic, a pilotaxitic texture is universal. In this instance, the ubiquitous magnetite no longer is in a dusty form but rather is present as small grains, averaging 0.03 mm. in diameter. With the concentration of the magnetite into grains, the cloudiness so characteristic of the hyalopilitic types disappears and the pilitic base is crisp and clear. The feldspars of the groundmass have also grown in size until they are scarcely distinguishable from the smaller, or second generation, phenocrysts, and, indeed, they may be one and the same thing. The augite and hypersthene have increased their dimensions in proportion to the feldspars and attain lengths of 0.1 mm.

Miscellaneous Features of the Groundmass

Blotchy Groundmass. At least 20 per cent of the rocks from Mount Rainier have a peculiar patchy effect in the groundmass. The blotches are irregular in shape, typically with rounded or sub-rounded margins and averaging slightly larger than the phenocrysts in size. These are caused by the concentration of the magnetite dust in patches, and noticeably darkening the pale or colorless glassy matrix. Less frequently, as in a specimen taken near Sluiskin Falls, the blotches are dark, glassy areas in a lighter and more holocrystalline portion of the groundmass. Williams (42) mentions similar blotches from Mount Diller.

Open Textured Andesites. Along the base of Gibraltar, on the summit route, is an interesting occurrence of a highly porphyritic material which contains a min-

FIG. 23. Andesite from Panorama Point. (x25, plane light. Note the peculiar blotchy effect in the groundmass. The darker areas represent a concentration of magnetite and kaolinitic material.)

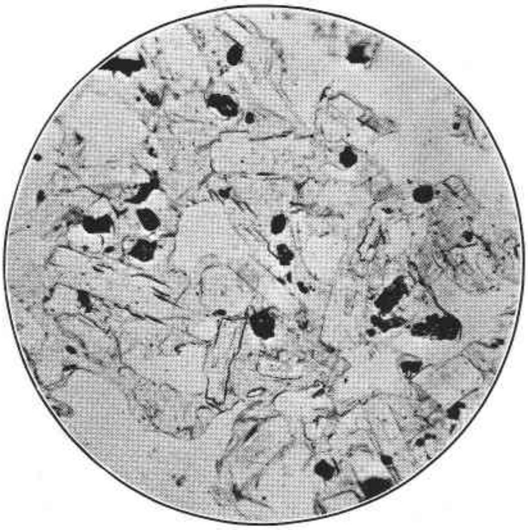


FIG. 24. Andesite from Gibraltar. (x25, plane light. Diktylaxitic texture in a porphyritic andesite in which there is a minimum amount of glassy matrix.)

imum amount of glassy residuum. The phenocrysts are plagioclase, augite, and hypersthene—all presenting idiomorphic outlines. These average 0.7 mm. in length and have a more rectangular and stubby shape than is usually characteristic of the Rainier phenocrysts. The base is a colorless to pale-brown glass, present in sufficient quantity to serve only as a binding agent to hold the phenocrysts together. In the interstitial areas between the large crystals, the glass is wanting. The resulting effect is very similar to the diktytaxitic texture as described by Fuller. (12) The feldspars, in this case, are more stubby than the "delicate laths of light-gray labradorite" mentioned in the original description. However, similarities are to be found in the net-like arrangement of the feldspars, and the ends of the minerals protruding into the cavities. In both cases the residuum must have possessed sufficient fluidity to permit its easy escape from the crystal mesh.

PHYSIOGRAPHY AND GEOMORPHOLOGY

INTRODUCTION

In discussing the physiographic features of the Park, a division should be made between the cone of Mount Rainier and the upland surface of the Cascades upon which it rests. Structurally, the higher Cascades in the vicinity of the mountain are a series of flows having either a horizontal attitude or thrown into gentle, undulating folds; while Rainier is composed of pyroclastics and flows all dipping away from a central vent. Both in time and in structure the rocks of the Cascades are separated from those of Rainier by a marked unconformity. Even topographically, the huge mass of the cone stands out in bold relief; towering 10,000 feet above the range beneath. So it is readily seen that this separation is necessary.

It is to be expected that the attention of the Park visitors should be attracted to the majestic summit and the spectacular glacial system of the mountain, while all else receives minor consideration. The glaciers, occupying one-tenth the area of the Park, are the only features which have received ample mention in the literature. Two excellent and detailed reports, as well as several smaller papers, have been published describing the glaciers. The remainder of the volcano, or another one-tenth of the Park, has a geologic literature (petrographic) totalling approximately 12 pages. No papers have been published dealing directly with the geology of the other eight-tenths of the Park.

Omitting for the time being all reference to the volcano, an attempt will be made to review, briefly, the literature on the Cascades.

THE CASCADES

Previous Literature

Practically the only reference concerning the physiographic development of the Cascades in the vicinity of Rainier is the following short paragraph by Russell (27) in the 18th Annual Report of the United States Geological Survey for the fiscal year 1896-1897:

> As has been determined by Bailey Willis, the mountain stands on a slanting peneplain, which consists of granites, schists, and coal-bearing Tertiary rocks; that is, the region where Mount Rainier is situated was eroded during late Tertiary times until it was reduced to a plain practically at sea level. Such a plain is known among geographers as a peneplain. This peneplain was then upraised and tilted so as to slope gently westward. Since the plain was elevated it has been deeply dissected by erosion, and the land masses between the sunken stream channels have been worn into mountain forms. The general level of the summits which mark approximately the position of the tilted peneplain, in the region adjacent to Mount Rainier, on the north, is about 6,500 feet.

The peneplain idea contained in this brief statement was destined to be the main thesis in Cascade physiography for the ensuing 30 years. Although first published by Russell, it is interesting to note that he gives full credit for the idea to Bailey Willis.

To explain this fact, it is necessary to review some of the preceding events. In 1881 and 1884, Willis had the opportunity to visit the Cascades in central Washington but "took little note of the physiographic aspects." (44) In 1892, Russell made a brief reconnaissance in central Washington, mainly in the interest of artesian water, but his observations carry no allusion to a Cascade peneplain.

In the meantime, Willis had spent eleven years in the Appalachians where peneplains are remarkably well displayed. Returning to Washington in 1895, he was impressed at once by the uniform altitudes "which might reach or fall little short of an ancient plain."

In 1898, Russell published his statement concerning the Cascade peneplain; the first mention of such a feature in the literature. Later, in 1900, after working in the northern Cascades, under the direction of Willis, Russell (26) said:

> The Cascade mountains, as we know them, seem to have been carved from an upraised peneplain. This plain we term the Cascade peneplain and the plateau may be conveniently designated the Cascade plateau.

From the years 1895-1900, Willis carried on extensive field work in the Wenatchee-Chelan district. Presenting the results of his efforts in 1903, he interpreted several stages of topographic development for the eastern Cascades in which the initial stage (Methow) was a peneplain—the Cascade peneplain of Russell. This was followed by other stages of dissection; all described in considerable detail. Willis (44) infers in this paper that Russell arrived at the peneplain hypothesis simultaneously with himself, and perhaps independently, while Russell was working in the northern Cascades. It is felt that both men are responsible for the hypothesis although it is not clear as to the amount each man influenced the other.

It is noteworthy that at the turn of the century geologic investigations were confined to the eastern and northern portions of the Cascades, especially near the towns of Ellensburg and Wenatchee and farther north from Chelan to the Canadian border. Following one another in rapid succession, a number of papers appeared, involving the structural and physiographic problems of this area. These were largely the results of the efforts of Willis and Russell; however, a third man, G. O. Smith, had been working in the Cascades and continued his investigations many years after the other two men had withdrawn. Here was an excellent opportunity to test the peneplain hypothesis. Smith (31) was not convinced by such evidence as uniformity of summit levels and maintained a critical skepticism until further proof was forthcoming. His attitude is exemplified in the following paragraph:

> A general uniformity of altitude of the ridges and peaks of the central portion of the Cascades may be made out in certain districts, but so frequently are other peaks seen which rise above this level that this class of evidence taken alone is far from conclusive. Indeed, this is best appreciated by those who have been most earnest in their search for traces of the old peneplain. Furthermore, the date of the supposed planation has not hitherto been determined even approximately. The identification of possible remnants of the old lowland, if such a lowland existed, becomes most essential to the investigation of the later history of the Cascade region.

The further proof which Smith demanded was later supplied by himself (32) while carrying on field investigations in the Ellensburg-Yakima district. Here the surface rocks consist, for the most part, of soft, friable sandstones and loose conglomerates of the Ellensburg formation and the hard, compact Yakima basalt. The lavas and sediments have been thrown into a series of gently dipping anticlines and synclines, trending in a northwest-southeast direction. The anticlinal ridges were thought to have been slightly elevated and then remained relatively stationary until erosion had effaced their topographic expression. According to Smith, both the compact, resistant basalt and the loosely consolidated sediments were bevelled to a common level during this erosion interval.

Smith sums up the evidence by stating: (31)

> Such perfection of planation could not be expected much short of reduction to a base-level, so that the natural deduction from these observed facts is the former presence of an essentially level lowland over the area.

Going into more detail, he described a particular locality at Kelley Hollow which he regards as "the type locality for the recognition of the lowland."

After mapping the Ellensburg quadrangle, Smith (28) (33) moved northward and, in 1904, described the Mount Stuart quadrangle. In this latter publication he declares:

> The approximately level plain or peneplain is excellently preserved immediately south and is fully described in the Ellensburg folio. In the Mount Stuart quadrangle, traces of the peneplain can be seen along the southern slope of Table and Lookout mountains and, on the mesa, between Yakima River and Dry Creek.

Thence, moving westward to the adjoining Snoqualmie quadrangle Smith (34) observed:

> The absolute identification of this Pliocene lowland surface is difficult outside of the region bordering the valley of the lower Yakima river. In the heart of the range it cannot be recognized and the only places in the Snoqualmie quadrangle where the old surfaces may possibly remain are in the southeastern corner.

It is to be remembered that the Snoqualmie quadrangle lies immediately to the northeast of the Mount Rainier National Park sheet. The southwest corner of the former touches the northeast corner of the latter and, as may be expected, the two areas have much in common.

The preceding pages demonstrate clearly the universal acceptance of the peneplain hypothesis among the early workers in the eastern Cascades. Although cautiously avoided by Smith, a tendency existed, either consciously or unconsciously, to apply the hypothesis over the entire range. A case in point is the statement of Willis': (44)

> South of the 47th parallel the extent and attitude of the peneplain are not well known, *except that at an altitude of about 7,500 feet it forms the platform upon which stands the volcanic cone of Mount Rainier*, and probably extends in a similar manner beneath Adams, Hood, and other volcanoes in Oregon.

The first discordant note in adherence to the peneplain idea was offered by Daly (5) in 1912. Working for a number of years along the Canadian boundary, Daly took a keen interest in the processes of alpine sculpture and felt they were sufficient in themselves to explain the present land forms, especially in regard to the accordant summits. He pointed out that seven different conditions of erosion worked together in producing an accordance of summit levels in an ideal alpine range, undergoing its first cycle of physiographic development. Carrying his ideas southward, he applied them to the findings of Willis, Russell, and Smith, and, although he never worked in the area, severely criticized their work on peneplanation. Daly (6) also objected to the shortness in time allotted to post-peneplain sculpture, wherein the plateau, raised from 4,000 to 9,000 feet lost practically all traces of its former plain-like surface.

For almost 25 years the geology of the central Cascades remained practically untouched. In the years 1925-27, Waters became interested in the Wenatchee-Chelan district and worked out the geology in detail. After obtaining accurate information regarding the underlying structure, he demonstrated in a clear and decisive manner the error of some of the former physiographic interpretations. Waters (38) remarked:

> As a result of his own work in the Wenatchee-Chelan district, the writer has come to radically different conclusions as to the origin of the physiographic features of the district from those advanced by Willis.

After a careful description of each locality mentioned by Willis as remnants of the peneplain (Methow) surface, Waters concludes:

> In summary, then, it may be stated that of the areas marked as remnants of the Methow plain by Willis, three are constructional surfaces of the White Hill basalt, one is a structural platform in gneiss, and the remaining groups are surfaces that represent the undissected top of the Yakima basalt with its capping of wind-blown soil. Not one of them preserves the features of an erosion surface remnant.

After visiting the locality offered by Smith as proof of planation, Waters agrees with the evidence, saying:

> The writer has visited the type locality (Kelley Hollow) of this peneplain which Smith calls the Cascade lowland and can corroborate Smith's statements that the erosion surface there bevels both the upturned Yakima basalt and the unconsolidated Ellensburg strata to a common level.

Recently Waters suggested that this surface might well represent a pediment. (38)

In 1935, Buwalda (3) presented a paper concerning the postulated peneplain in the Yakima region. Quoting from the abstract it reads:

> Evidence presented for peneplanation consisted of smooth, supposedly bevelled surfaces on crests and flanks of such basaltic ridges as Cleman mountain and across both basalt and sediments at one locality, Kelley Hollow, and supposed entrenched meanders of Yakima river between Yakima and Ellensburg. The writer's interpretation is that the smooth basaltic crests and flanks mapped by Smith on plate 5 are not bevelled but structural surfaces (dip slopes), locally lowered on the crests by recent stripping to an underlying basaltic layer. The supposed peneplain remnant at Kelley Hollow was cut across a small thickness of basalt in the present cycle by tributaries graded to the existing but slightly higher Wenas creek.

In summary, it may be said that at the end of the nineteenth and the beginning of the twentieth century the workers in the geology of central Washington were imbued with the idea of a former peneplanation of the Cascade range. They regarded its present surface as an expression of dissection suffered during the second stage of physiographic development. Minor modifications were attributed to transverse upwarps and anticlines. Since 1912, and especially in more recent years, this general conception has fallen into disfavor.

It is quite necessary to consider first, the pre-Rainier topography, then the river pattern, and, finally, the general structure of the range within the Park, before attempting a discussion of the peneplain hypothesis in that portion of the Cascades contiguous to Rainier.

Pre-Rainier Topography

At least during a good portion of Pleistocene time the mountain has protected 100 square miles or more of the Cascades from dissection. A search along the margin of the cone should reveal some evidence as to the character of the pre-Rainier topography. The unconformity between the Keechelus series, or granodiorite, and the Rainier lavas is usually sharply defined and may be studied at a number of localities. At the snout of the Nisqually Glacier the upper surface of the oldest rocks is but slightly above the 4,000-foot contour line while a mile farther eastward, in Paradise Valley, the contact is 5,000 feet high near the settlement of Paradise, and 5,700 feet above sea level at Sluiskin Falls. Thus the pre-Rainier relief must have been at least 1,500 feet in this particular area. Relief of a similar magnitude is shown by the contact in the Mystic Lake region. The Rainier lavas extend as far down as the 6,000-foot divide where the Moraine Creek trail crosses over to Mystic Lake. This same contact attains a height of more than 7,200 feet adjacent to the Winthrop Glacier. On the opposite side of the Winthrop, the granodiorite outcrops just below St. Elmos Pass (7,400 feet), but the Rainier lavas cover both the granodiorite and the Keechelus rocks down as low as 6,200 feet in places along the margin of Burroughs Mountain in Berkeley and Yakima Park. In Ohanopecosh Park and at Panhandle Gap the contact undulates between 6,000 and 7,000 feet.

The greatest relief, however, is preserved in the vicinity of the Tatoosh Range whose peaks average 6,500 feet in elevation. The Rainier lavas meet and closely follow the configuration of the basal and northern end of this range. On the Longmire side, the lavas from the volcano outcrop as low as 3,000 feet above sea level; while 1½ miles to the eastward, at Eagle Peak, the older rocks tower 3,500 feet above the contact. In this case, a question might be raised as to the possibility of uplift subsequent to the outpourings of the Rainier lavas. The idea of faulting along the northern face of the range was entertained by the writer during the first few weeks of field work while mapping in the Paradise-Indian Henry region. The seemingly straight and abrupt escarpment, as viewed from the northward, suggested a fault block origin for the range. Later, while searching for evidence to either confirm or deny this interpretation, all proof tended to point away from this fault block conception.

The view from any of the peaks from Eagle to Stevens shows the plan of the Tatoosh Range to be that of a large "U" with only the curved portion, or the bend in the letter falling within the Park. The two prongs of the letter point southward and are separated from each other by the canyon of Butter Creek.

Such a shape is far from characteristic of fault block mountains. Even the steep northern face of the Tatoosh was found to differ little from its many neighbors, such as the Sourdough Mountains and the Cowlitz Chimneys. This abruptness of the northern faces of so many of the ranges is thought to be due to causes other than faulting and will be described later in this chapter on physiography.

A second point against faulting is provided by the contact of the Rainier lavas and the granodiorite on the north side of the Tatoosh Range. One of the most accessible exposures showing this relationship is at Narada Falls. Here the Rainier lavas are decidedly columnar with the long axis of the columns oriented at right angles to the steep surface of the granodiorite. The Paradise River flows across the lavas and at Narada Falls plunges over the ends of the columns into the narrow gorge marking the boundary between the lavas and the granodiorite. The ends of the columns abutting against the granodiorite show no evidence of post-Rainier faulting, but, instead, display an undisturbed attitude with the normal chilling effects.

A third point against post-Rainier faulting is indicated by the tongues of lava both to the east and to the west of the range. If a hypothetical fault plane were extended, for example, into the Ramparts, there should be a marked displacement in these lavas. On the contrary, no uplift of the southern portions of these tongues can be discerned. This evidence points away from a post-Rainier faulting. Uplift by folding is also untenable as forces of sufficient magnitude to bow up so great a range would cause marked warping or intense folding in the surrounding lava tongues.

In summary, and, considering the above evidence, the general relief prior to the outpouring of the Rainier lavas is considered to have been from 1,000 to 3,000 or more feet.

The Mount Rainier-Cascade contact around the mountain undulates in an irregular fashion between elevations of 3,000 and 7,000 feet. The lowest point is near Longmire on the southwest side of the mountain while the highest is on the north and west sides in the Summerland-Steamboat Prow-Winthrop Glacier region. Thus the buried topography might well have had a relief of 4,000 feet.

Pre-Rainier River Pattern

On the eastern side of the Cascades, the rivers, with but few exceptions, are guided in their courses by the underlying structure which trends generally in a northwest-southeast direction. On the western side of the range, this condition is not so pronounced and it is believed that the streams are more consequent, merely draining the westward slopes of the Cascades and paying little heed to the underlying structure. Such rivers as the Skagit, Nisqually and Cispis are offered as examples. In so far as the structure has been determined, these rivers pass over hard and soft rocks alike. In the Park the pre-Rainier drainage pattern was not unlike that of the western Cascades at the present time. Although the major rivers had not entrenched themselves as deeply into the range as those found today, nevertheless they are thought to have been parallel and pursued a consequent westerly course as a result of the general north-south upwarp of the Cascades.

Two rivers, the Cowlitz and the White, are rather exceptional because of their wide swing or detour around the Park. The former originates in the glacier by the same name and parallels the main divide of the Cascades for 12 miles before swinging westward in a sweeping arc and finally emptying into the Columbia River. The latter emerges from under the Emmons Glacier, flows eastward up to within 3 miles of the Cascade divide, turns northward for a distance of 20 miles, then westward until it empties into Puget Sound.

At first glance, the courses of these rivers would probably be attributed to the influence of Mount Rainier as the result of superimposing a radial drainage pattern on one in which the original streams were essentially parallel and westward flowing. However, certain evidence suggests that the courses of these rivers were determined prior to the formation of Mount Rainier.

An examination of the topographic maps, both to the north and to the south of the Park, indicates a difference in elevation of the Cascade peaks; those adjacent to Mount Rainier being somewhat higher than those farther removed. Such peaks as the Cowlitz Chimneys, Goat Island Mountain, the Palisades, Old Desolate, and the like, are all within the Park and all average more than 7,000 feet in elevation. To the north, in the Cedar Lake quadrangle, the highest peak to the north of the White River is Mount Defiance with an elevation of 5,590 feet. In the opposite direction, and south of the Cowlitz River in the Steamboat Mountain quadrangle, the highest peaks attain an elevation of approximately 5,700 feet; Mount Adams excepted. Thus the peaks contiguous to Rainier are at least 1,000 feet higher than those farther to the north or to the south.

This mass may be considered, therefore, as a positive area or one which has been raised above the adjoining territory (probably by warping) in a system where differential uplift is not uncommon. (Cf. Snoqualmie Folio, page 12.) The exact time of elevation, whether it be pre- or post-Rainier, or an attendant phenomena associated with the formation of the volcano, is a moot question. However, an early a time as possible is looked upon with the greatest favor for the following reasons:

Consider for a moment the depth to which the above mentioned rivers have entrenched themselves in the Cascade upland. The Cowlitz has an elevation of only 1,054 feet at Lewis, located several miles east and south of Mount Rainier. Here the river is a braided stream, lazily winding across its wide flood plain. Because of the width of the flood plain, the local inhabitants refer to this feature as the Big Bottom country.

The entrenching of this river 4,000 feet into the Cascades has been a lengthy process, and, added to this, is the time-consuming work of valley widening. Perhaps even a better conception of the relative ages of the river and Mount Rainier is afforded by comparison with the Nisqually, as the relations of the latter are well known and easily observed. From facts gathered within the Park, and presented above, the valley of the Nisqually was shown to have been carved to a depth of several thousand feet in the older (Keechelus) rocks. At a distinctly later time, tongues of lava from the volcano flowed into this old valley, partially filling it. (Note, especially, the Ramparts on the geological map.) This type of evidence points to a pre-Rainier origin for the Nisqually Valley.

The Cowlitz Valley is not markedly different from the Nisqually. Both streams are firmly entrenched; their courses are fully graded up to within a few miles of their sources and each has commenced the tedious work of valley widening. If any discrepancy in time does exist within the two, the Cowlitz should be favored with the greater age. It has not only cut 1,000 feet lower into the range but also has greatly exceeded the Nisqually in valley widening. All this was accomplished under the handicap of a greater distance to base level; the former river being more than twice as long as the Nisqually.

Even more direct evidence as to the pre-Rainier age of the Cowlitz is afforded by the tongue of Rainier lava occupying the Muddy fork of the river. The eroded ends of the flows extend down as low as 3,000 feet, and it follows that the lower course of the river must have been below that figure prior to lava-filling. If the valleys previously drained to the northwest, instead of to the south, as they now do, then the later lava flows would probably dam the valleys and lakes would have been formed. This, however, does not seem to have been the case. No lakes are present now and it is doubtful if these valleys were ever filled with water as a result of lava damming.

It is felt that the presence of these lava tongues occupying previously deep valleys in the older rocks is sufficient proof to warrant the interpretation of a well-established drainage pattern prior to the outpourings of the Rainier lavas. As the White River is almost identical to the Cowlitz, it is not considered as being worthy of special mention.

In summary, the writer postulates that drainage channels marked the pre-Rainier surface of the Cascades, producing a relief varying from 1,000 to 2,000 or more feet. The river pattern in a wide radius about Mount Rainier is that of a series of parallel and westward flowing streams. Such an arrangement suggests a normal, consequent drainage on the western side or slope of the range. Modifying this general pattern is the high land mass on which the volcano is located, causing certain rivers to be deflected in sweeping arcs around the Park before resuming their westward journey in common with the other Cascade rivers.

Pre-Rainier Structure

The structure of the upper portion of the Cascades adjacent to the mountain has been mentioned in the section dealing with the Keechelus series. It is desirable to reiterate briefly this information as the structure of this formation is frequently expressed in the topography of the present Cascades.

The lower portion of the Keechelus, averaging 2,000 feet in thickness, is composed of extremely massive porphyries and breccias. Any indication of attitude is usually lacking but, when it can be ascertained, a moderate folding is usually indicated. The younger facies of this formation is a series of lava flows totalling 300 feet or more in thickness. These lie in a horizontal position or are thrown into gentle folds. Both old and young facies are amply exposed; the older forming extensive outcrops in the southern half of the Park and the younger in the northern half.

Undissected remnants of the upper Keechelus flows are well preserved at the following localities:

At Panhandle Gap, from 7431 down to the divide, where the Wonderland Trail crosses from Summerland to Ohanepecosh Park, the dip slope of the lavas and the surface coincide, both dipping approximately 13° to the west.

From the Palisades over toward Marcus Peak, a structural saddle in the Keechelus is well-preserved and is expressed topographically.

Fig. 25. Lake Leigh from near Panhandle Gap. (Looking west toward the mountain; Little Tahoma on the left. Note the flat-topped surface in the right foreground; this is one of the many stubs of the Keechelus surface on which the Rainier lavas were deposited.)

Dip slopes are also indicated in Moraine Park, Bee Flat, Goat Island Mountain, the north side of Yellowstone Cliffs, and many other localities too numerous to mention.

Many stubs of the Keechelus surface, too small to be represented on the topographic map, are scattered about the Park. (Cf. Panhandle Gap, Figure 25.)

Unfortunately, most of the remaining peaks have been so modified by glaciation that any suggestion of structural control of their form has been effaced. Examples are found in peaks like Mother Mountain, those in Chinook Pass, Unicorn Peak, and the like. Although lacking in structural control, the horizontal or slightly warped position of the lavas in these peaks is readily observed.

It is to be expected that in pre-Rainier (and also pre-glacial) time the topography would be controlled, in a large measure, by the attitude of the younger Keechelus flows comprising the upper surface of the Cascades, especially in the northern half of Mount Rainier National Park. The structural surfaces of these flows at that time were probably little modified and far more extensive than the meager remnants we have today. The influence of the local warpings undoubtedly was reflected in the courses of the rivers. However, other forces were active, also, culminating in a general north-south uplift, and probably overshadowing any widespread attempt at structural control of the rivers.

Conclusions

In conclusion, the present, as well as the pre-Rainier surface of the Cascades is regarded as being due to a number of processes. The older porphyries and breccias of the Keechelus series have had a long and complicated history. Where their structure can be determined, (and this is better observed outside the Park than within), these older rocks have suffered pronounced folding, and possibly concommitant igneous invasion. Much less disturbed are the younger and capping lava flows of this same series which either retain their horizontal position or have been gently warped into low, undulating folds. Both the older and younger facies of the Keechelus were uplifted, probably a number of times and different amounts in the various areas, but sufficiently to cause vigorous dissection to be initiated. This resulted in canyons and valleys being carved to a depth of 3,000 feet into the upland. In the vicinity of Mount Rainier, the Cascades are regarded as now being dissected to maturity in the first cycle of physiographic development.

As pointed out by Daly, (5) the accordance of summit levels, so often mentioned in the literature, should not be construed as meaning an equality of heights. The Cascade peaks within the Park vary from 4,500 to well over 7,000 feet in elevation. The higher of these are not segregated to any particular area but are intimately admixed with the lower ones. Thus an imaginary surface determined by the summits of the peaks and ridges would have a relief of 2,500 feet.

The greater portion of the Cascades adjacent to Mount Rainier are composed of massive Keechelus rocks wherein the pyroclastics and breccias have been so indurated that they differ little from the flows and porphyries in hardness.

In a mountain range 6,000 feet in elevation and in which the rocks are relatively homogeneous in offering resistance to erosion, it is felt that a relief of 2,500 feet in the summit levels is to be expected in the normal processes of erosion in the first cycle. It does not seem that the accordance is sufficiently striking to demand the introduction of the $n+1$ cycle.

The writer prefers to account for the summit levels within the Park as a constructional, rather than a destructional, feature and resulting from the outpouring and accumulation of volcanic material. This upland has subsequently undergone a minor amount of deformation in the form of gentle warping. Since the time of inception, it has been deeply dissected by the action of streams and ice, resulting in the present topography.

The writer concurs with Smith in regard to the bevelling, so often quoted from the Yakima and Wenatchee-Chelan districts, as finding no expression near the main divide of the Cascade Range. No evidence has been found supporting peneplanation in Mount Rainier National Park, and to the northeast in the Snoqualmie quadrangle Smith finds: (34)

> The absolute identification of this Pliocene lowland surface is difficult outside of the region bordering the valley of the lower Yakima River. In the heart of the range it cannot be recognized.

Summary

In the preceding discussion, evidence has been presented which points to the seeming accordance of summit levels in the Cascades contiguous to Rainier, as being the result of aggradational agencies, largely in the form of lava flows. This differs from the commonly held belief that the surface was degradational in character and shaped by long, continued erosion to a featureless plain. At this point the writer wishes to emphasize the fact that no attempt is being made to disprove the existence of a Cascade peneplain and this is especially true of the eastern portion of the range. It is felt, however, that evidence is not only lacking to establish the presence of a former peneplain near Mount Rainier, but that the introduction of such a feature is, indeed, unnecessary to account for the present surface of the range.

Bearing more directly on the general peneplain problem is the work now being carried on by Professor J. H. Mackin of the department of geology of the University of Washington. His conclusions will be based on field work and on the interpretation of an extensive series of projected profiles across the Cascades.

THE CONE OF MOUNT RAINIER

The Summit Area

The summit of Mount Rainier is characterized by three distinct peaks; all above 14,000 feet in elevation. They define a triangular summit area so broad that from no point about the base can one see the actual top of the cone. As viewed from Longmire, or Paradise, the highest point of the mountain is judged to be Point Success; while, if the observer happens to be in the Mowich Lake region, the prominence of Liberty Gap seems highest. From the Yakima Park side, the third point or the crater rim, is readily seen and appears to out-top any of the other points. This latter case is due more to the perspective than to any true evaluation of their respective heights. The actual summit is a small mound of snow on the northern side of this crater rim, and, because it was once thought to be the highest point in the United States, it is known as Columbia Crest.

A closer examination of the summit area leads to the determination of three more or less distinct craters. The one just mentioned is clearly and unmistakably defined. The black rocks protruding through the snow and ice mark out an almost perfect circle approximately one-quarter of a mile in diameter. The rim is composed of sub-rounded boulders several feet in diameter, intermingled with smaller pyroclastics. There is an abrupt drop for a distance of 30 feet or more on the inner side of the crater where the floor is lined to an unknown depth with snow, forming a

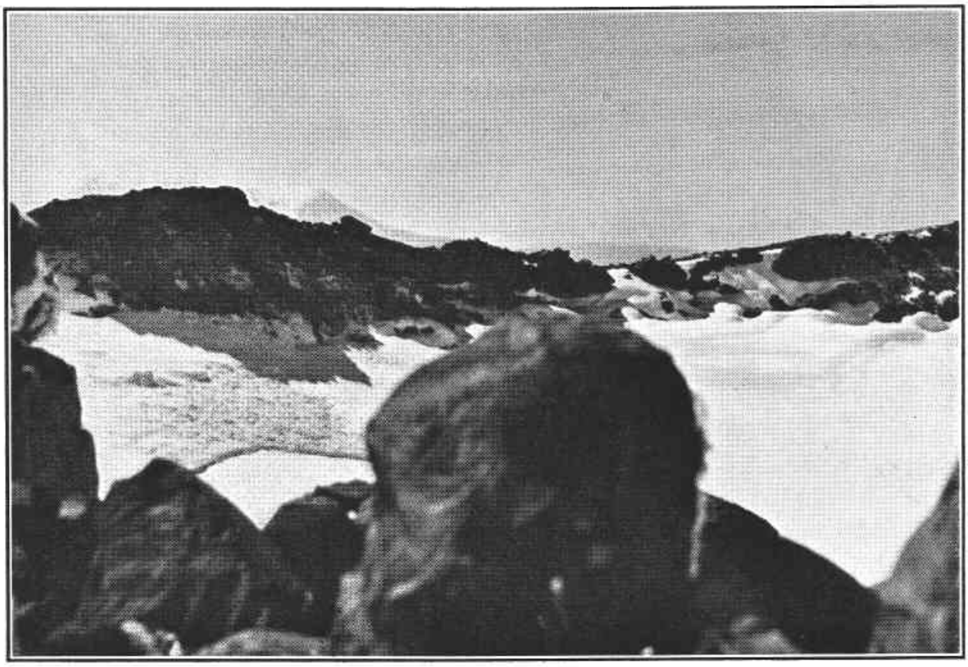


Fig. 26. A view looking south from the crater rim at the summit of the mountain. (The snow and ice-covered floor of the crater is seen in the foreground. Mount Adams is in the distance.)

shallow saucer-shaped depression. Jets of steam, not containing any detectable traces of sulphur, issue from the loose rocks and also from under the ice on the floor, melting out irregularly-shaped caverns adjacent to the rim. These provide a welcome haven of refuge from the icy blasts so everlastingly present at the summit. The steam jets are thought to be a most important factor in keeping the rim free of snow.

Another crater, slightly larger in diameter and somewhat lower in elevation, encloses the smaller one, just described, in an eccentric fashion. The larger one, however, is not so easily distinguished as the greater part of the rim has either been destroyed by erosion or has been completely covered by snow. The point where the two craters come closest together, and almost touch, is marked by a rounded mound of snow—Columbia Crest. Matthes (21) logically explains the mound as being due to furiously-driven westward winds,

> . . . whipping through the breach in the west flank of the mountain between Point Success and Liberty cap, eddying lightly as they shoot over the summit and there deposit their load of snow.

A third crater, much larger and enclosing the other two, is now greatly modified, retaining only such remnants as Liberty Cap and Point Success, attesting to its former size. Russell (27) has advanced a tenable and plausible hypothesis for the formation of this entire summit area. The writer advisedly used the word "hypothesis" in this case for, in his experience, such field work as can be accomplished on the summit of Mount Rainier leads to few definite conclusions. The only points of actual outcrop are along the rim of the smaller and portions of the medium-sized crater, and at Point Success; all else is covered by snow or ice. The most fruitful information is concealed in inaccessible faces, such as Willis Wall and the head of the Sunset Ampitheater. This necessitates making observations from afar; a most unsatisfactory method.

In a brief summary, Russell (27) states:

> The profiles of the mountain and the character of its summit show that at the time of its greatest perfection and beauty it rose as a tapering cone with gently concave sides to a height about 2,000 feet greater than its present elevation. At a later date it was truncated, probably by an explosion, which removed the upper 2,000 feet and left a summit crater from 2 to 3 miles in diameter.

The writer hesitates to attribute the present configuration of the summit area to one huge explosion removing the upper 2,000 feet. The distribution of the pyroclastics and their alternation with lava flows on the upper reaches of the mountain suggest intermittent explosive activity, probably breaching first one side of the crater and then the other.

Some doubt might also be raised to the suggestion that the volcano ever attained a height of 2,000 feet above its present elevation. To reconstruct the sloping flanks until the height approached 16,000 feet it would be necessary to diminish the diameter of the crater to a few feet. It does not seem possible that such thick and viscous flows issued from so small an orifice.

The crater might better be regarded as having a rather large diameter and modified at various intervals by a number of violent explosions, as well as by glacial erosion.

Glacial Erosion

The entire upper portion of the mountain is covered by nevé fields. As these have been adequately and vividly described by Matthes and Russell, the reader is referred to these papers. (21) (27)

However, the effects of glacial erosion have not been treated so fully and, in the pages to follow, some of the resulting land forms will be described briefly.

Cleavers. Between the elevations of 10,000 and 13,000 feet are numerous long walls of rock, arranged in a radial manner, with the summit as the common center. Both on the map, and locally, these are known as "cleavers" for they stand immovable, splitting the ice in its descent. Most famous of the cleavers is the blocky mass of Gibraltar. This wall, as seen from Paradise, is sufficiently large to give the entire upper portion of the mountain a bulky, broad-shouldered appearance. When viewed from Camp Muir, or any points along the Cowlitz or Ingraham Glaciers, the form is not so imposing as one is looking parallel to the long axis of the mass.

It is interesting to observe that vertical walls more than 1,000 feet in height should be carved on either side while the top has remained relatively unchanged. That the upper surface of Gibraltar is a dip slope is obvious to anyone making the summit trip. Along the "chutes," where the upper ice is first encountered, and at Camp Comfort at an elevation of 12,679 feet, the dip slope of the loosely consolidated pyroclastics can be recognized as coinciding with the upper surface of the cleaver. Stripping could easily be effected in such loose material, but, judging from the height of Gibraltar and its position in regard to the summit, it is doubtful if the mass ever attained an elevation much greater than at present. The upper surface of Gibraltar has undoubtedly been covered countless times by snow and also been attacked by the agents of subaerial erosion.

Other cleavers, but slightly less magnificent than Gibraltar, are Cathedral Rocks, Success, Puyallup, and Wapowery cleavers. In the process of cirque and valley widening the cleavers are fashioned principally by the undercutting of the ice. Working most vigorously on either side, the glaciers carve sheer and almost parallel walls. As the undercutting continues, the walls come closer and closer together until the thin cleavers we see today are all that survive. In the not too distant future even these bold remnants will narrow to such an extent that they will finally collapse and, perhaps, eventually be smothered by ice. (Note the small rock outcrop at an elevation of 9,432 feet on Emmons Glacier.)

Wedges. At an elevation of about 10,000 feet, the wedges come into prominence. The wedges probably represent modified forms of the cleavers but, nevertheless, closely rival them in beauty and in interest. As the broad nevés of the upper slopes descend, they choose certain paths, probably determined by previously formed valleys, and, sinking deeper and deeper into the rocks, their courses become firmly established. Because of the confinement in narrow canyons and the ablation effects of lower elevations, the longer or primary glaciers diminish considerably in area as their termini are approached. The interglacial divides now assume the form of giant V's with their apices pointing toward the summit. Two excellent examples

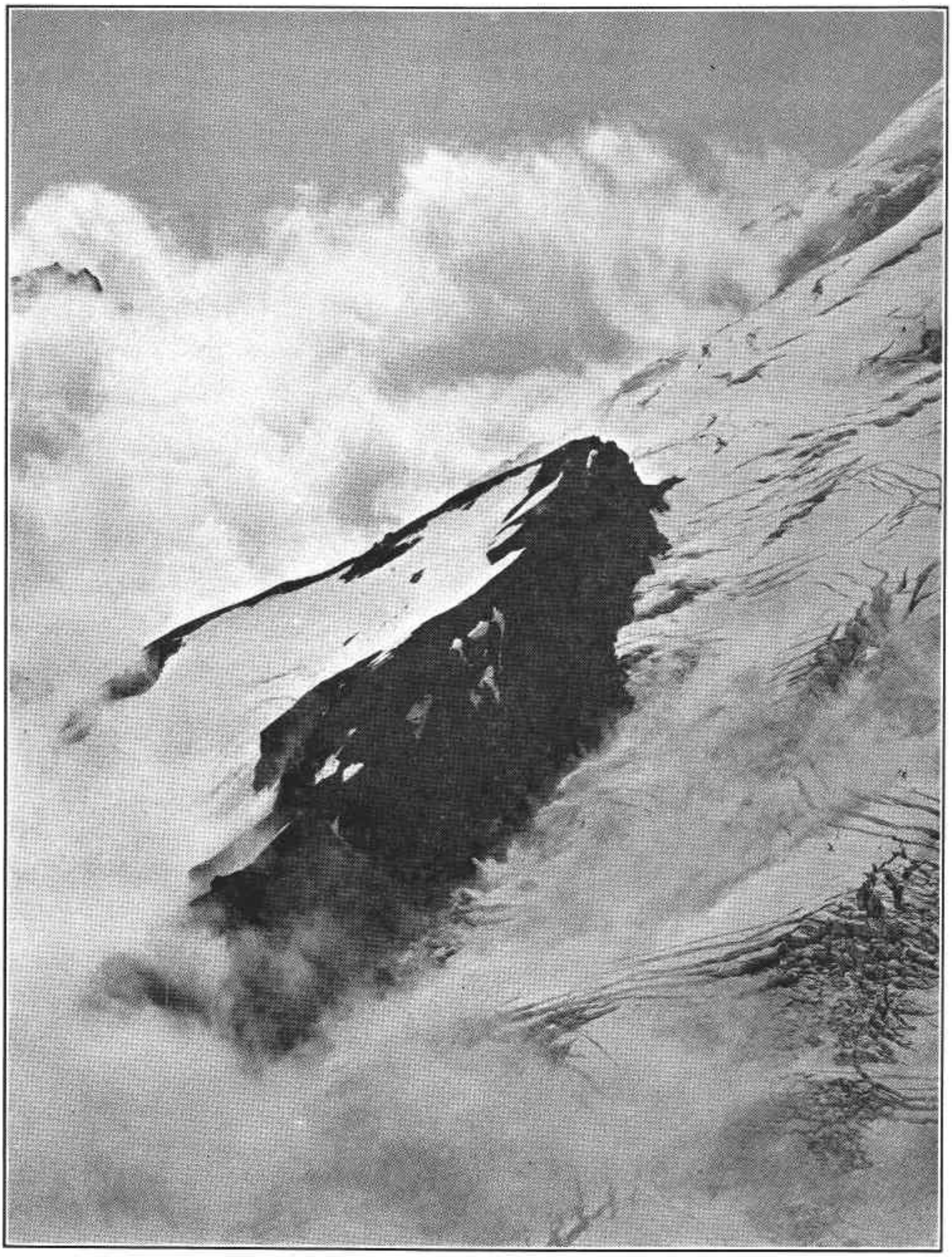


FIG. 27. Steamboat Prow and The Wedge. (Looking southeast from above the Winthrop Glacier, elevation 10,000 feet. This photograph was loaned through the courtesy of the 116th Photo Section of the Washington National Guard.)

are provided in The Wedge (Steamboat Prow) and Little Tahoma. Russell (27) suggested the use of the word "Tahomas" as a generic name for these rock masses from the type locality of Little Tahoma. The writer is inclined to favor The Wedge as an equally desirable type and to use the name "wedge," both as a generic term and a descriptive one, mainly because it is self-explanatory. Undoubtedly The Wedge formerly headed much higher on the mountain's flank, perhaps extending upward in the form of a long attenuated cleaver. Continued abrasion by the Emmons and Winthrop glaciers has reduced it to successively lower levels. Even today, the dividing ice is still sharpening, and shortening, the remaining stub. Little Tahoma is a more spectacular wedge because of its greater elevation and larger size and must be considered an equally worthy representative of this type of land form.

On the southwest side of the mountain, glaciation has not progressed to the same extent as it has on the northeast side. The Success, Wapowery, and Puyallup cleavers, Ptarmigan Ridge, and the like, remain as lines of rock from the base of Rainier up to approximately 12,000 feet. With continued erosion these will be reduced in elevation by the impinging masses of ice until they, too, will become wedges. But slight changes are needed to cause the long rib of rock between Mineral Mountain and Avalanche Camp to alter from a cleaver into a wedge. With continued erosion at the ice fall of the Nisqually Glacier adjacent to Gibraltar, the Cathedral Rocks and the Cowlitz cleaver will be shaped into a striking wedge. Many other examples could be cited, indicating this same process.

Interglaciers. An interesting associate of the wedges are the interglaciers. These are formed, for the most part below the 9,000-foot contour line and occur on the back slopes of the wedges. Conforming to the general pattern of the wedges, the highest reaches of the interglaciers are represented by points; the lower portions are more extensive as the ice spreads out in thin aprons. The type example is the Interglacier lying on the back of The Wedge. Similar ones are the Fryingpan and Whitman glaciers on the back slope of Little Tahoma and the unnamed ice mass to the west of the Winthrop Glacier. Perhaps the Van Trump, Pyramid and many other glaciers could also be considered as belonging to this same class.

The effect of the interglaciers is to cover and sink into the back slope of the wedges in such a way that only a scant rim of rocks are exposed on either side and at the prow. The result is a skeletal form of a "V," composed of rocks projecting through the snow.

It may at first seem anomalous that glaciers as prominent as those just mentioned should form at elevations as moderate as 6,000 to 9,000 feet. Surrounded as they are by a rock wall and perched on the back slopes of the wedges, the manner of emplacement clearly precludes any chance of the longer, primary glaciers adding to their volume. The only other feasible explanation is to account for them by precipitation in sufficient amount to withstand the wasting effects of the lower elevations. Matthes has pointed out that the precipitation on lofty mountain regions is heaviest at moderate altitudes, while higher up it decreases markedly.

In the Rainier region, the height of the storm clouds is, in a large measure, regulated by the height of the Cascade Range, for it is really this cooling mountain barrier that causes the moisture-laden winds from the Pacific to condense. As the storm clouds are seldom much elevated above the skyline of the range, the greatest precipitation occurs at a relatively moderate height. The zone between 8,000 and 10,000 feet is perhaps most favorable for the development of glaciers. Below an altitude of 8,000 feet, the ice rapidly wastes away in the summer heat; while above 10,000 feet, the snowfall is relatively scant. The result is manifest in the distribution and extent of ice on the cone.

Asymmetrical Topography as a Result of Selective Glaciation. The glacial erosion of the base of Mount Rainier is so intimately connected with the ice sculpture of the Cascades that any attempt to describe the two separately is inadvisable. Hence the following discussion may apply equally well to the lower flows of the mountain or the upper flows on the range on which it stands.

One of the most interesting phenomenon is the selective manner in which the ice has attacked the previous topography. Recalling the description of the wedges given above, it will be noted that they represent more advanced stages of dissection than do the cleavers from which they are derived. The best examples of wedges are on the north and east sides of the mountain; while the cleavers attain their finest development on the south and west sides. This evidence suggesting greater ice erosion on the north and east slopes is supported by other facts.

The most extensive mass of ice at the present time is on the northwest side of the mountain at the heads of the Emmons and Winthrop glaciers. In broadest dimension this ice field is approximately 3 miles wide. The second largest width is on the north side where a 2-mile wide nevé finally divides into the Carbon and Russell glaciers. It is readily seen that the largest glaciers, and, as a consequence, the most intense glaciation is operative on the northeast side of the mountain. If conditions of elevation, prevailing wind direction, and distribution of precipitation were not markedly different during the time of maximum glaciation, then we may assume the northern slope has been favored in the amount of ice sculpture since Pleistocene time. Testimony of long-continued erosion is offered by the steepest face on the entire mountain—the cirque head of Willis Wall. Exposed to the northward, this wall drops 4,500 feet in elevation in a horizontal distance of approximately ½ mile.

About the base of the mountain the distribution of glacial erosion confirms the evidence offered higher up on the cone. On the steep northern face of the Tatoosh Range, small glacierets still persist as Unicorn and Pinnacle glaciers. Even better examples are the Sarvent glaciers on the ridge between the Cowlitz Chimneys and Panhandle Gap. These are the largest of the glacierets and are confined to the northern face of the ridge. In Spray Park, a small, unnamed glacieret originates at an elevation of 6,500 feet on a northern slope. Also, near the Colonnades, another small ice patch forms below 6,700 feet. Nowhere in the Park has any ice been encountered originating on a southern slope at so low an elevation.

Proof of selective glaciation, not involving actual ice masses, is also available. At a number of localities perfect cirques have been carved on the northern side of ridges whose southern faces are unmodified by glacial action. The frequently-visited Sourdough mountains are scalloped on the north by many cirques, extending from Mount Fremont to Dege Peak. The smooth, unscarred southern slope, however, makes an ideal location for the settlement of Yakima Park. Two small, incipient basins occur on the southern side of the Sourdough Range, but these can be accounted for easily as they lie to the west and north, respectively, of the overshadowing Burroughs Mountain. On the Panhandle Gap-Cowlitz Chimneys Ridge, the Sarvent glaciers are still nestled in their self-made cirques, facing northward, while the other slope is an undissected plane dipping gently to the southeast. The Cowlitz Chimneys are carved into spires and aretes by small glacierets formerly occupying the western slope. Many more instances could be cited showing the same relationships on the opposite sides of the various ridges. Quite a number of the higher promontories have been glaciated on both sides, as, for example, the Tatoosh Range. Butter Creek drains what may be considered the back slope of the range in a southeasterly direction. This river has been glaciated for the greater part of its course. At first this appears to be an exception to the general rule of having the northern slopes glaciated, while the southern slopes are either unglaciated or but slightly modified by ice. A close examination of the Mount Rainier quadrangle topographic map shows Butter Creek to lie immediately east and slightly north of Dixon Mountain—a long ridge averaging 6,000 feet in elevation. This mountain parallels Butter Creek, towers 2,000 feet above it and the horizontal distance between creek bottom and the crest of Dixon Mountain is but ½ mile. Hence the valley, which seemingly presents an exception to the general rule, is little different from its associates in the position of the steeper slopes and greater glaciation. The above localities suffice to show that an asymmetry of crest line does exist within the Park, both in regard to the surface of the Cascades, and to the volcano. Now, let us consider the reason.

A structural control of the Park's topography would easily account for the steep northern faces of the ridges. In the preceding pages, the Keechelus series was mentioned as containing an extremely massive lower portion, practically devoid of structure, and an upper series of lava flows, gently warped. The structure of the upper Keechelus undoubtedly has been very influential in shaping the present topography. The asymmetry, however, is developed whether aided (tilted to the south) or hindered (tilted to the north) by the attitude of the series. Unequal declivities also occur on perfectly horizontal structure and on massive granodiorite, both of which should be neither an aid nor a hindrance to the formation of asymmetrical divides. Yet the higher points in this region are decidedly asymmetrical in cross-section. The Sourdough Mountain may or may not attribute its shape to the underlying structure. An effort was made to determine if Yakima Park was situated on the upper Keechelus lavas or whether it owes its present configuration to selective erosional agencies. Proof was lacking to show conclusively either view but both factors seem to have had a hand in shaping the Sourdough Mountains. On Burroughs Mountain, where the Rainier lavas dip very gently to the northeast, the

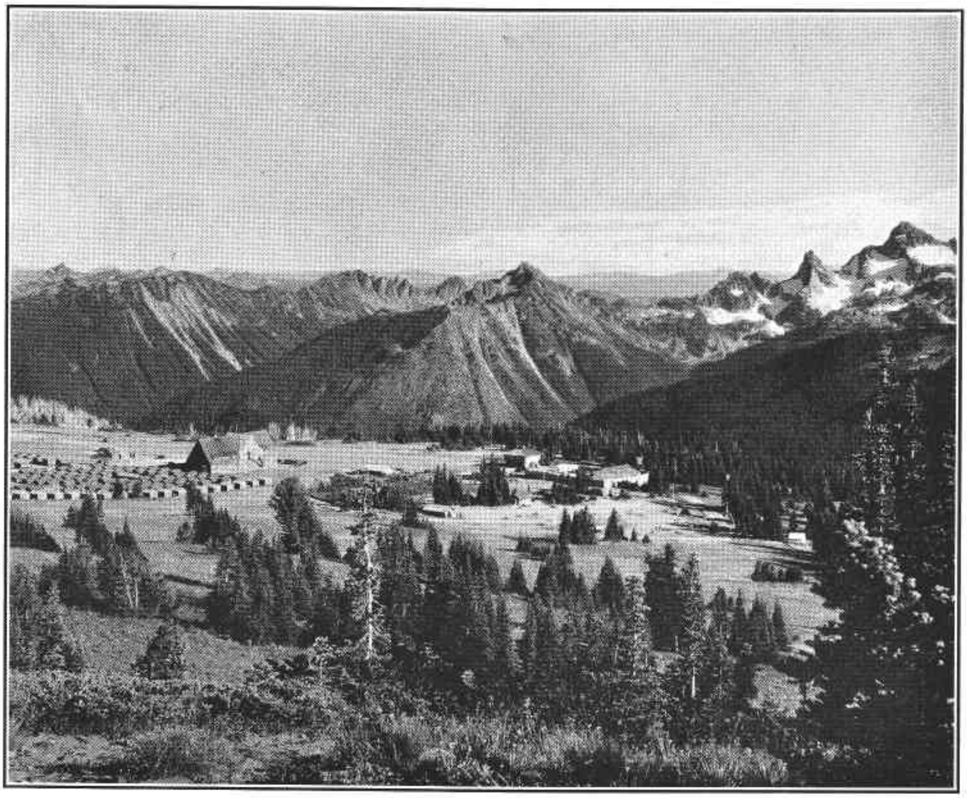


FIG. 28. Yakima Park from the Sourdough Mountains. (Looking southeast. Note the smooth and undissected surface of Yakima Park as compared to the rugged, glaciated, northward-facing slopes. Sarvent glaciers in distance on the right. Tamanos Peak in the center of the picture in the middle distance.)

cirque at Berkeley Park on the northern side is in no way influenced by the structure; the southern slope, although over-deepened by the Emmons and another glacier once occupying the Interfork of the White River, is not modified by cirques. Other localities where structure has been a negligible factor in accounting for the steep northern (or western) cirque-marked faces are: Goat Island Mountain, Tamanos Mountain, Cowlitz Divide, Mount Ararat, Mount Wow, and others. It seems certain that a structural control will not account for all these abrupt northern faces. Perhaps a more abundant plant growth has been influential in protecting the snow-free slopes from erosion. The present distribution of plant life gives little light on this subject. The relative abundance of shrubs or grass on either side of the ridges is not striking enough to suggest this as a plausible reason. It is true that plants and soil are lacking from many of the northern slopes, but this might well be a result of their excessive steepness rather than a cause.

It seems reasonable to assume that the steep northern or western faces we find today are caused by the glaciers which now occupy them or by glaciers now vanished but which have left abundant proof of their former presence. This explanation is proffered rather than one whereby the glaciers and snowfields are the result of landforms brought about by some other cause. Snow and ice are thought to have persisted longer, and been more concentrated on the northern sides because of two reasons: insolation, and, the accumulation of wind-driven snow on the leeward side of the ridges. The former reason is regarded as being the more important, especially at the lower elevations.

The prevailing wind direction in the vicinity of the Park is from the west or southwest. Driven by these winds, the snow accumulates on the leeward side of obstructions, whether they be large or small, and piles up in sizeable drifts. At moderate elevations (5,000-6,000 feet) and below the timber line, the transporting power of the wind is not so effective. The trees afford a certain measure of protection. The temperature is usually sufficiently high to assure a heavy, moist snow difficult of transport. Above timber line and, as one goes higher and higher, the conditions for drifted snow are more ideal. The wind velocity is many times stronger than at timber line and the temperature is low enough to maintain a dry, powdery snow readily capable of transport.

Insolation is somewhat analogous to the wind-driven snow in that both increase in effectiveness at the higher altitudes. It is a well known fact that as the elevation increases the air becomes more rarified and offers less resistance to the sun's radiant energy. As one goes higher the result is a wider divergence between sun and shade temperatures and a corresponding increase in the degree of insolation. As the snow and ice fields on the northeastern slopes are sheltered from the sun they endure much longer and are more effective eroding agents than their neighbors on the opposite slopes. As the small glaciers commence to deepen their beds and sink more and more into the protecting shadows of the ridges above, they prolong their own lives. The result is an additive process whereby a small glacier, once gaining the advantage of a slightly more sheltered position, will aid itself in accumulating more of the wind-driven snow and preserving it much longer from the sun's rays than those less favorably situated. The greater accumulation and protection makes the glaciers just that much more able to entrench themselves still farther and thus become even more protected.

The steep northern faces and the relatively moderate southern slopes produce an asymmetry of crest lines which is by no means an unusual feature, although it has never been described and explained in any of the literature on the Cascades. Gilbert (13) first mentioned the asymmetry of crests in the Sierras of California. Later, Bowman (2) described the asymmetry of the volcanic peaks in southern Peru. In this instance, the steeper faces were on the southern side as the area is south of the equator and the insolation effects would be reversed. Recently Tuck (37) published a paper on the asymmetrical topography in south-central Alaska. He points to insolation as being the dominant factor in causing the differential erosion of the present topography. Tuck also offers proof that the interstream divides have been shifted southward since pre-glacial times.

In summary, the asymmetrical topography of the Park is attributed to the more vigorous glacial erosion, as represented by the northward facing slopes, as compared to non-glacial or less glaciated areas, as represented by the southern slopes. The factors causing this selective distribution are: firstly, insolation, and, secondly, the greater accumulation of wind-driven snow on the leeward side of the ridges.

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