A GRANODIORITE STOCK IN THE CASCADE MOUNTAINS OF SOUTH-WESTERN WASHINGTON

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CONTENTS

INTRODUCTION

The presence of a body of granitic rock near Silver Star Mountain in the Cascade Range of south-western Washington has been known to prospectors and mining men of the region for more than fifty years, but no material on the geology of the immediate region has been published. Allen[1], in an unpublished thesis, described the granitic rock as a quartz diorite and called the mass "Silver Star Formation" after the highest peak in the area. Any work that may have been done in connection with mining operations within the area is not publicly available.

The aims of the study summarized in the following paper were, in the main, twofold: (1) to map, both areally and structurally, the intrusive and as much of the surrounding rocks as necessary to determine the time and mechanics of intrusion, and (2) to determine the petrographic character and the petrologic history of the intrusive body and its surrounding rocks.

The work was made possible by a grant from the research fund of the Ohio Academy of Science and was greatly furthered by the able work of the writer's field assistant, Mr. R. H. Howe. The co-operation and assistance given by the U. S. Forest Service men of the Columbia National Forest is also greatly appreciated.

[1]Allen, J. E. "Contributions to the Structure, Stratigraphy, and Petrography of the Lower Columbia River Gorge." Univ. Oregon M.A. Thesis, 1932.

Suggestions made, both in the field and in the preparation of the manuscript, by Dr. J. L. Rich have been particularly helpful.

Location. The area examined lies in the western portion of the Middle Cascades about twelve miles north of the western end of the Columbia River Gorge. It consists of a rectangle eight miles north-south by five miles east-west, the south-west corner of which is that of Township 3 North, Range 5 East, Willamette Meridian. The area thus described comprises forty square miles, the northern three-quarters of which are within the Columbia National Forest boundaries.

The region may be reached from Portland by U. S. Forest Service roads connecting with the state highway system of Washington at either Hemlock or Yacolt.

Drainage. The area is drained by the headwaters of both the Washougal River and the South Fork of the Lewis River. The Washougal is a south flowing stream entering Columbia River near Camas, Washington. The Lewis flows to the west, is joined by the North Fork, and enters the Columbia near Woodland, about thirty-five miles downstream from the mouth of the Washougal. The headwaters of these two streams have dissected the area in a dendritic manner to a mature stage with a relief of from 2500 to 3000 feet. A divide, along which are located the highest peaks of the immediate area, separates the opposing headwaters of the Lewis and the Washougal. This divide trends from the north-east corner of the area in a direction a little west of south to the summit of Bluff Mountain, in section 16, where it turns at right angles and trends east-west to the summit of Silver Star Mountain.

The greatest precipitation occurs in the winter months and is, in the higher portions of the area, frequently in the form of snow which forms enormous drifts in the deeper canyons. These drifts linger till past mid-summer in most years and are largely responsible for the perennial character of many of the smaller streams near the heads of the canyons which would otherwise be without water in the late summer.

Since the destruction of the forest cover in the great fires of 1902 and 1929 the runoff has been much more rapid than formerly. The effects of this increased runoff are shown to best advantage on steep soil-covered slopes by the development of young gullies, and, in some cases, by complete removal of the thin soil mantle. Another noticeable effect is the increased severity of the spring freshets that accompany the warm spring rains. Quantitative data on this increased runoff can not be obtained as no figures for the precipitation or runoff in the immediate area are available.

Topography. As was stated under the heading of drainage, the region is a maturely dissected plateau, largely of lavas, with a relief averaging close to 2000 feet and locally reaching a maximum of 3000 feet. The main divide between the Lewis and Washougal drainage basins attains elevations as great as 4400 feet A. T. and has saddles, where strong opposing tributaries have been active, as low as 2900 feet A. T. The general eleva-

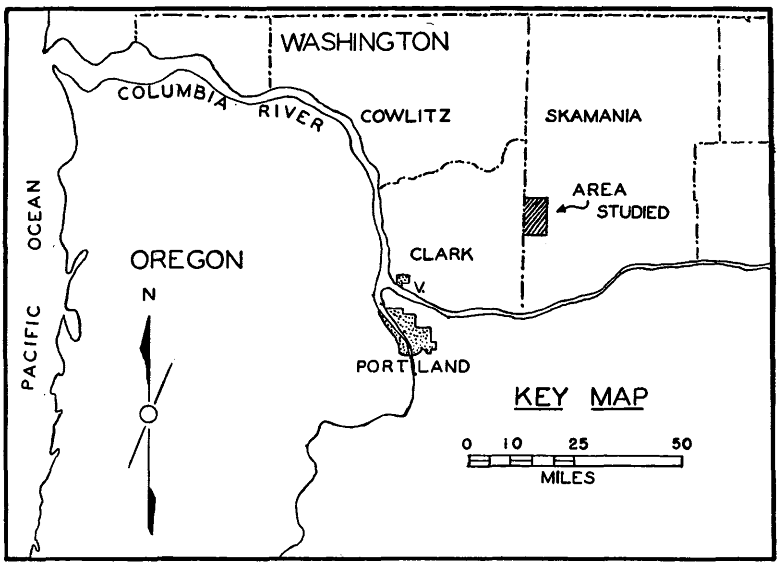

Fig. 1. Location Map.

tion is, however, near 3200 feet A. T. From this main divide branch long steep spurs separating the canyons and the smaller gullies occupied by the individual headwaters. These spurs are very steep, sloping from the elevation of the main divide down to the level where the two streams join; the slopes of the spur crests often are as great as 2000 feet per mile. Their sides are more precipitous, in some cases being vertical cliffs from a few tens of feet up to 1200 feet in height, but more commonly being live talus slopes resting at the angle of repose. These talus slopes, best developed on the granodiorite, cover a large portion of it and are in a few instances more than a mile in length.

At the heads of some of the larger canyons are small cirque-like basins in whose bottoms are depressions as much as seventy-five feet deep and 150 yards in diameter. These are separated from the head of the canyon proper by a rock rim or lip. Often these basins are occupied by small tarns, and snowdrifts persist in a few until late summer. No glacial striae were found on the rock lips; and, consequently, these basins are believed to be the result of erosion by small glaciers, not extensive enough to have moved very far out of their cirques.

The summits of the ridges when viewed from one of the higher peaks exhibit the same strikingly accordant skyline that is evident in the Cascades further north. This accordance has been treated by Willis,[2] Russell,[3] Smith,[4] and others as representing the trace of an old erosion surface called by them the Cascade peneplain. Regardless of whether or not it represents a true baseleveling, this accordance of summits as viewed on the skyline is one of the striking features of the topography of the region.

AREAL GEOLOGY

Eagle Creek Formation. The rocks of this area fall naturally into three distinct lithologic units. The oldest of these is the Eagle Creek formation (Warrendale formation of Hodge[5] and others) of probable Oligocene age (now considered lower Miocene by Chaney[6]) consisting of volcanic tuffs and breccias, bajada conglomerates, and minor amounts of intercalated andesitic lava flows near the top of the formation. The Eagle Creek is typically exposed in the central portions of the Columbia River Gorge where it has been described by Chaney[7] and Hodge[5] and is also widely exposed in its numerous variations in the greater part of the Washougal basin. This formation outcrops along the eastern margin of the area under consideration, especially good exposures being noted in parts of sections 21,

[2]Willis, Bailey. "The Physiography and Deformation of the Wenatchee-Chelan district, Cascade Range." U. S. G. S. Prof. Paper 19, pp. 41–95, 1903.

[3]Russell, I. C. "A Preliminary Paper on the Geology of the Cascade Mountains in Northern Washington." U. S. G. S. 20th Ann. Rpt., pt. 2, pp. 83–210, 1900.

[4]Smith, G. O. "Contributions to the Geology of Washington: The Geology and Physiography of Central Washington." U. S. G. S. Prof. Paper 19, pp. 9–38, 1903.

[5]Hodge, E. T. "Progress in Oregon Geology Since 1925." Northwest Science 6: 44–53, June, 1932.

[6]Chaney, Ralph W. Personal communication, April, 1936.

[7]Chaney, Ralph W. "The Flora of the Eagle Creek Formation." Chicago Univ. Walker Mus. Cont., Vol. 2, No. 5, pp. 115–181, 1920.

22, and 28 near the headwaters of Dougan Creek. Exposures of the Eagle Creek formation also occur in the canyons of Silver, Bluebird, and Bear Creeks along the eastern margin of the area; but, in these basins, they were not differentiated on the map from the overlying Skamania andesites.

The Eagle Creek as exposed within the mapped area consists mainly of cream colored vitric tuffs which usually weather to a yellow or white colored soil. Varicolored tuffs, usually green or red, are also found as are some greenish and purplish breccias. The tuffs may pass through the complete range of color within a distance of twenty-five feet along the strike. The lack of assortment and usual lack of bedding of any regular nature within these tuffs suggest a subaerial mode of accumulation. At many places, however, the tuffs and breccias have been reworked by streams; and the bedding shows, in these cases, that accumulation was governed by fluviatile and occasionally lacustrine conditions.

Skamania Andesites. The Eagle Creek beds are overlain by a thick series of andesites among which are intercalated minor amounts of breccia and other pyroclastic material. Within the area the contact is nowhere definitely exposed, although in many places it can be approximated within five feet. East of the mapped area, in the Washougal basin, the andesites overlie the Eagle Creek in places disconformably and in other places with a distinct angular unconformity representing a period of considerable erosion. At still other localities, notably on the east edge of the mapped area the andesites interfinger with the tuffs suggesting at least partial contemporaniety or overlapping of the deposition of the tuffs and the extrusion of the andesites.

These andesites compose the bulk of the country rock into which the granodiorite stock forming the subject of this paper was intruded, and are the most wide spread of the formations within the mapped area. They are in the form of rather thin and extensive flows that were probably extruded in a very fluid form. Locally these flows may have had rather high initial dips, a fact that complicates quantitative determination of later folding. In the lower two-thirds of the series the flows are mildly folded—the maximum dips recorded being about thirty-five degrees. This figure rarely exceeds ten degrees, the steeper dips being noted in only a few places near the contact with the intrusive rocks. The upper third or about 800 feet of these flows, exposed only on the upper portion of Silver Star Mountain, is nearly flat lying, the maximum dips recorded being two degrees in a westerly direction. This upper portion has also suffered less alteration than the lower partially propylitized andesites.

These lavas support most of the steep cliffs within the area, also most of the higher peaks such as Bluff and Silver Star mountains as well as most of the higher portions of the divides. They are the most conspicuous and best exposed rocks in the area and over wide areas in adjacent portions of Skamania County. For this reason the name Skamania is proposed for this series of andesites.

No definite age has been assigned to this series of lavas, but, in the opinion of the writer, they are the probable equivalent of the widespread Keechelus series so prevalent in the Cascades a few tens of miles to the north. This opinion is based on the following facts: (1) the petrographic character of the andesites in the mapped area and that of the Keechelus as described by Coombs[8] and others is very similar; (2) the Columbia River Basalts exposed in the Columbia River Gorge appear to abut against the lower portions of the Skamania andesites; therefore, these andesites, in the lower part, must be pre-Columbia basalt or, in other words, pre-middle Miocene which corresponds with the supposed age of the lower Keechelus lavas as suggested by Warren;[9] and (3) the Skamania andesites are divided in the same manner as the Keechelus into an upper and lower division. As in the Keechelus, the lower division of the Skamania has undergone more folding and metamorphism than the upper division.

Lavas later than the andesites of the Skamania series occur as intracanyon flows in the canyon of the Lewis River four miles west of the area and in the canyon of Wind River a few miles to the east. Those in the Lewis River near Sunset Guard Station have been trenched by the river in a narrow gorge exposing old andesitic and dioritic stream gravels cemented together by the andesite of the late flow. The age of these intra-canyon flows is probably Pleistocene.

Silver Star Granodiorite. The third lithologic unit within the area is a stock of granodiorite with subordinate amounts of

[8]Combs, H. A. "The Geology of Mt. Rainier National Park." Univ. Wash. Pub. in Geology, Vol. 3, No. 2, pp. 131–212, 1936.

[9]Warren, Walter. "Tertiaries of the Washington Cascades." Pan-Am. Geologist, Vol. 65, No. 4, pp. 241–247, 1936.

augite diorite and quartz diorite near the borders of the mass. The stock is an elongate body about ten miles long and varying in width from one and one-half to two and one-half miles. Its long axis trends north twenty degrees east. Its walls are very steep as proven by the fact that very deep canyons cutting into the country rock a short distance from the walls do not expose any mappable areas of intrusive rock. Small spots of granodiorite were observed in Star Canyon and in the canyon of Dougan Creek but were not mapped. The southern boundary of the stock, extending to the south for a distance of about a mile, was traced but not in enough detail to be drawn on the map.

This stock cuts the Eagle Creek formation and the lower portions of the Skamania andesites, producing contact metamorphic phases in both formations and sending small dikes and stringers of granodiorite and aplite into both the tuffs and andesites. The upper third of the andesites does not seem to have been intruded by this granodiorite. At least no dikes or other evidences of intrusion cut the upper andesites and they have not been subjected to the degree of propylitization that characterizes the lower portions of the series. It would thus appear that there has been some time interval between the extrusion of the lower and the upper divisions of the Skamania series. During this interval the intrusion of the granodiorite occurred.

Swarms of xenoliths near the contacts with the andesite and larger inclusions of tuffs and andesites in the upper portions of the intrusive rock indicate that stoping processes had a role in the emplacement of the mass. Some of these inclusions are large enough to have been roof pendants of considerable size. These inclusions are quite thoroughly metamorphosed, usually to hornfels.

The granodiorite is strongly jointed—a fact that allows frost action on the high peaks, such as Little Baldy, to rive the outcrops into rhombic and platey fragments with the consequent production of the long talus slopes previously mentioned. Good outcrops occur only in the stream bottoms and occasional cliffs not yet covered by talus. The boundaries of the stock, where drawn in dotted lines, can be approximated within a very few feet; but the actual contact is covered. This lack of suitable outcrops is also responsible for the paucity of structural measurements.

PETROGRAPHY

Eagle Creek Formation. The Eagle Creek formation, as exposed in the area, consists of vitric tuffs usually white or cream colored, and, less commonly, of greenish and reddish hues. The color, in most cases, seems to depend upon the character of the oxidation of the iron compounds within the glass at the time of formation. The material composing these tuffs ranges from partially kaolinized shards less than 0.05 mm. in diameter to coarse fragments of vesiculated pumiceous material up to three inches in diameter. This pumiceous material has been indurated and made resistant by compaction and cementation. The cement in the majority of cases is silica, although enough kaolin is present in most cases to also act as a cement.

In places where the tuffs have been subjected to hydrothermal solutions emanating from the intrusive body they have been entirely replaced by silica forming a very resistant quartz rock in which are preserved the shard structures of the original tuff. Good outcrops of this silica rock occur in the low saddle in section 21 just south of Bluff Mountain.

Skamania Andesitic Series. The rocks composing this series consist, in the main, of gray porphyritic andesites with subordinate amounts of tuffs and breccias. The pyroclastics are petrographically very similar to the coarser phases of the Eagle Creek, possibly a little more pumiceous.

The andesites of the lower portion of the series are characteristically gray or greenish-gray in color and are nearly always porphyritic, the phenocrysts being striated grayish-white feldspar. The flows in this portion are usually much jointed with epidote and other minerals frequently developed within the joint cracks.

Examination of thirty-five slides from the lower portion of the andesite series brings out the following general characteristics. All sections examined were porphyritic with phenocrysts of corroded and markedly zoned plagioclase embedded in a pilitic to intersertal and, infrequently, diabasic groundmass of plagioclase laths, granular augite, and anhedral magnetite, together with varying amounts of chlorite and similar minerals developed from the ferromagnesian constituents. The phenocrysts range in size from 1 to 6 mm. and average about 3 mm. in diameter. They are blocky and exhibit a marked tendency toward a glomeroporphyritic habit. Their composition ranges from An 50 to An 30 with the average being close to An 35. Where zoned the core has the more basic composition. Usually the composition becomes more acid outward with each zone although rarely some reversals of zoning do occur. Small veinlets of orthoclase are developed in fractures traversing these phenocrysts especially in those sections made from specimens taken from close to the intrusive body. Twinning is after the albite, Carlsbad, and pericline laws with all three commonly developed on one individual. These phenocrysts form from 20 to 35 per cent of the rock.

The plagioclase laths in the groundmass vary in size from 0.01 mm. up to 0.5 mm. in length averaging about 0.3 mm. They vary in composition in the various flows from basic to medium andesine and in one of the most basic of the flows are an acid labradorite. Twinning is commonly after albite and Carlsbad laws, pericline twinning being rare. Often these laths are arranged in a marked fluxion structure. These second generation feldspars comprise from twenty-five to forty per cent of the rock.

The ferromagnesian minerals are nearly always altered to chlorite and similar minerals, but, where fresh, are anhedral grains filling the interstices between the feldspar laths. These minerals may be either augite or hornblende—usually augite and in rare cases hypersthene. There may have been considerable amounts of hypersthene in some of the rocks but it has since become chloritized. A very few thin sections show relicts of what were probably hornblende phenocrysts.

The augite of the groundmass occurs as anhedral grains rarely exceeding 0.05 mm. in diameter, is pale yellow in plane light, and sometimes shows a faint pleochroism. N_m averages about 1.69. This augite makes up 15 to 25 per cent of the rock. Magnetite, in the form of small anhedral grains and dust, is scattered through the groundmass and makes up about ten per cent of the rock. Epidote developed within the plagioclase phenocrysts and chlorite from the pyriboles sometimes totally destroy the former minerals.

The upper division of the Skamania andesites is characterized by fresher rocks of the same general types as those described for the lower division. These rocks are, however, generally more vesicular and in some cases have partially hyaline groundmasses. The rocks are in thin flat-lying flows exposed only on the upper portions of the main mass of Silver Star Mountain. A few quartz and carbonate veins cut these flows, some of the vesicles are filled with chalcedony or dolomite, and some of the ferromagnesian minerals in the groundmass are chloritized. Otherwise the rocks are nearly fresh as contrasted with the propylitized rocks of the lower division.

Microscopic examination of 15 slides from these flows shows the following characteristics. Except in a few holohyaline flows of little importance all of the flows are porphyritic with phenocrysts of medium andesine averaging about 3 mm. in length. These phenocrysts are hypidiomorphic, exhibit strong zoning, marked corrosion, and a tendency toward a glomeroporphyritic habit. Combined Carlsbad and albite twins are very common. These phenocrysts comprise from 15 to 30 per cent of the rock.

The groundmass consists of a pilitic, intersertal, or, less commonly, a diabasic aggregate of plagioclase laths, anhedral grains of pyroxene and magnetite, and, commonly, small amounts of glass. The feldspar laths range from acid labradorite to medium andesine with basic andesine being the average composition. The pyroxene is usually augite and much less commonly hypersthene. Grains of pyroxene averaging less than 0.03 mm. fill the interstices between the feldspar laths which range from 0.01 to 0.65 mm. in length. The second generation plagioclase comprises from 25 to 40 per cent of the rock, the pyroxene from 15 to 25 per cent, and the anhedral magnetite from 5 to about 12 per cent. Fluxion structure, aligning the phenocrysts and the second generation laths, is usually present and is developed to a marked degree in some of the sections studied.

Silver Star Granodiorite. The rock composing this body consists of a mass of granodiorite with subordinate amounts of augite diorite and quartz diorite developed near the periphery of the stock. Aplite dikes and hydrothermal rocks rich in quartz, tourmaline, and sericite are also developed locally within the mass.

The granodiorite is a light colored aggregate of white plagioclase, sometimes tinged pink with the development of orthoclase, clear colorless quartz, and black to greenish biotite and hornblende crystals the color of which depends upon the degree to which chloritization has progressed. In most cases, the minerals can be distinguished megascopically, the grain size often being as large as 6x9 mm.

Microscopically the rock exhibits a holocrystalline granitic texture with the minerals, both light and dark, not uncommonly aligned in a sub-trachitoid structure. In some instances, the larger plagioclase crystals impart a sub-porphyritic appearance to the rock.

The plagioclase is hypidiomorphic, generally corroded and strongly zoned. The composition of the cores averages basic to medium andesine, each zone becoming richer in Ab to an outer zone of albiclase, or, less commonly, albite. Many of these plagioclases have a final rim of orthoclase. This orthoclase also commonly fills fractures developed in the plagioclase crystals. The plagioclase comprises about 55 per cent of the rock.

10 to 25 per cent of the rock consists of interstitial and anhedral orthoclase—in some instances as clear as the quartz, which it closely resembles optically—but more generally "dusty" with sericite.

Clear anhedral quartz shares with the orthoclase the interstices between the earlier formed minerals. The two are commonly intergrown in a myrmekitic intergrowth showing contemporaniety of crystallization. The quartz granules average from 0.5 to 1.2 mm. and make up from 10 to 25 per cent of the rock.

The dark minerals may be uralitized pyroxene, or, more commonly, hornblende or biotite with varying amounts of chlorite and secondary dusty magnetite. A little subhedral magnetite was developed early. These dark minerals are crowded into the interstices between the plagioclase feldspars and make up about 10 per cent of the rock. The biotite, where developed, is a lustrous black variety with 2V estimated at about 5 or 6 degrees and is strongly pleochroic, the formula being X pale yellowish brown, Y reddish brown, and Z very dark brown to black. Inclusions of apatite and of titanite are developed in the plagioclase and to a lesser extent in the quartz.

The more basic phases, as exposed at many places near the walls of the stock are characterized by more lath-like plagioclase crystals, little or no quartz and orthoclase and larger amounts of pyroxene, usually augite. The plagioclase is ordinarily basic andesine. These more basic rocks make but a very small percentage of the total in the stock. Intermediate between these and the true granodiorite is a diorite very similar to the more basic diorite but with 5 to 12 per cent quartz and a little orthoclase.

Aplite dikes developed at a late magmatic stage are composed almost entirely of quartz and pink orthoclase with very small amounts of biotite and of sulfide minerals. Myrmekitic intergrowth is common and the orthoclase is commonly sericitized or even kaolinized to a considerable extent.

Metamorphic Rocks. The metamorphic rocks in this area are all products of thermal or hydrothermal processes accompanying the intrusion of the stock. The thermal metamorphism at places along the contacts between the stock and the andesites produces hornfelses of sugary grained recrystallized feldspar, augite, and magnetite, with considerable quartz being introduced in some instances. Where this action has been less severe at a distance from the contact, relicts of the original minerals remain, and the hornfels is very poorly developed. At a greater distance the effects become less marked, until, at a distance varying from a few feet to several hundred, the only effect has been a propylitization of the andesites. This propylitization consists, in the main, of the development of epidote and chlorite within the andesites and the introduction of large amounts of pyrite and quartz. The replacement of the tuffs in the Eagle Creek formation by silica was mentioned previously.

Other hydrothermal effects, both within the intrusive and in the wall rocks, consist of (1) epithermal quartz-sulfide veins carrying low values in base metals and small amounts of gold, (2) quartz-tourmaline-sericite replacements occurring in shatter zones and as small veinlets in the granodiorite, and (3) silicification and orthoclasization of areas in the granodiorite apparently after consolidation of the mass.

The genesis of the ore deposits within the area is being studied and reported in a separate paper by the writer's colleague, Mr. R. H. Howe.

The tourmaline-quartz replacements are shown to best advantage in the large shatter zone shown on the map as crossing sections 33 and 34. Solutions rich in boron and silica have bleached the granodiorite and produced a luxullianite rock consisting of quartz, schorlite, and sericite. In some instances, the tourmaline aggregates make up 90 per cent of the rock. Small veinlets of tourmaline in bleached and silicified portions of the granodiorite occur at the mouth of Summit Creek. The tourmaline is of the schorlite variety; N_m being 1.66 and the pleochroic formula X pale brown, Z greenish-black. Basal sections show a very marked zonal growth.

The granodiorite in certain areas within the stock, such as in the north-east portion of section 8 and in the north-central portion of section 21 (in the south part of the area) appears pink in the hand specimen and has a dearth of ferromagnesian minerals. The original granodiorite, in these instances, shows evidence of having been replaced by orthoclase and quartz after consolidation of the granodiorite. Remains of some of the original minerals and structures of the normal granodiorite have been observed in a number of thin sections made from this altered rock. It is believed that this rock represents a result of orthoclasization after the main mass had consolidated, the potash and silica being introduced either by hot waters or by gaseous emanations.

PETROLOGY OF THE STOCK

Field observations and examination of about fifty selected thin-sections from the stock shows a distinct gradation in the body from a quartz-free dark colored augite diorite, occurring at places near the borders, to a granodiorite, approaching a quartz monzonite in composition in the more central portions of the stock. No distinct zoning occurs and, in places, the more acid portions of the stock are in direct contact with the wall rocks, but, in a general way, it may be said that the dioritic phases are definitely border phenomena.

If the original magma at the time it was intruded had had the composition of a quartz diorite, it could form a series ranging from augite diorite near the borders to the quartz-orthoclase aplite dikes developed at a very late magmatic stage by the process of fractional crystallization. If, however, a magma with a composition essentially that of a granite was intruded into a country rock consisting mainly of andesite by processes involving stoping and assimilation, a similar basic border could also be produced.

Samples taken from the acid central portion in section 33 and from the wall phase in section 16 for chemical analysis resulted as follows:

	Acid Phase	Basic Phase
SiO_2	65.90	58.07
Al_2O_3	15.72	16.54
FeO	3.05	4.26
Fe_2O_3	1.11	2.47
TiO_2	.45	.61
MnO	.06	.17
CaO	4.78	7.32
MgO	2.39	4.94
K_2O	1.94	1.34
Na_2O	3.62	3.32
H_2O (—105C)	.16	Nil.
H_2O (+105C)	.76	.70
CO_2	Nil.	Nil.
P_2O_5	.11	.12

F. H. Herdsman, Analyst, Glasgow, Scotland.

These analyses were plotted on a diagram with the analyses of the Mount Stuart and Snoqualmie granodiorites published by G. O. Smith[4], an augite diorite from Bohemia, Oregon, and a granite from Nimrod, Oregon, published by Buddington and Callaghan[10]. All of these analyses are from intrusives of a nature similar to the Silver Star stock, in the same belt in the Cascade Mountains, and probably nearly of the same age. A fairly representative variation diagram for the Cascade intrusives of this type was obtained (Figure 2). The alkali-lime index for the series of analyses used in this diagram is 62.5 which compares with 61.6 reached for the Cascade intrusives of Oregon by Buddington and Callaghan.[10] This number definitely places these rocks in the calcic group as defined by Peacock.[11]

If the dioritic border be taken as an early roof or wall phase in the crystallization of the stock then the course of differentiation within the mass can be shown chemically by the diagram. The curves for the decreases in magnesia, iron, lime, and alumina, as well as those for increasing potash and soda with increasing silica follow the same trends for the stock as for the whole Cascade region. This chemical change is shown mineralogically by the increase in the acidity of the feldspars from basic andesine in the dioritic border phases to albiclase and even orthoclase in the granodiorite, by the development of relatively large amounts of free quartz in the more acid phases, and by the change from the pyroxenes of the diorites to the smaller percentages of amphibole and biotite in the granodiorite. The feldspars are almost always zoned with the cores having the more basic composition. This fact shows that in all phases of the stock the early formed crystals were removed from the reacting system by the formation of a more acid zone. As these basic cores were prevented from reacting with the remaining liquid, an acid differentiate would thus be formed.

Xenoliths in all stages of assimilation were noted at many places near the borders of the stock. These range with distance from the contact from angular blocks of fresh andesite to barely discernible ghosts made visible by concentrations of hornblende needles. The andesite clearly has been assimilated by reaction

[4]*Op. cit.*

[10]Buddington, A. F., and Callaghan, Eugene. "Dioritic Intrusive Rocks and Contact Metamorphism in the Cascade Range of Oregon." Am. Journal of Science, 5th ser., Vol. 31, pp. 421–449, June, 1936.

[10]Buddington, A. F., and Callaghan, Eugene. *Op. cit.*

[11]Peacock, M. A. "Classification of Igneous Rock Series." Jour. Geology, Vol. 39, pp. 54–67, 1931.

with the invading magma and the possibility exists that some of the border phases could be the result of contamination of a much more acid magna. Such contamination would of necessity be a localized phenomena and would not greatly effect the course of differentiation within the stock.

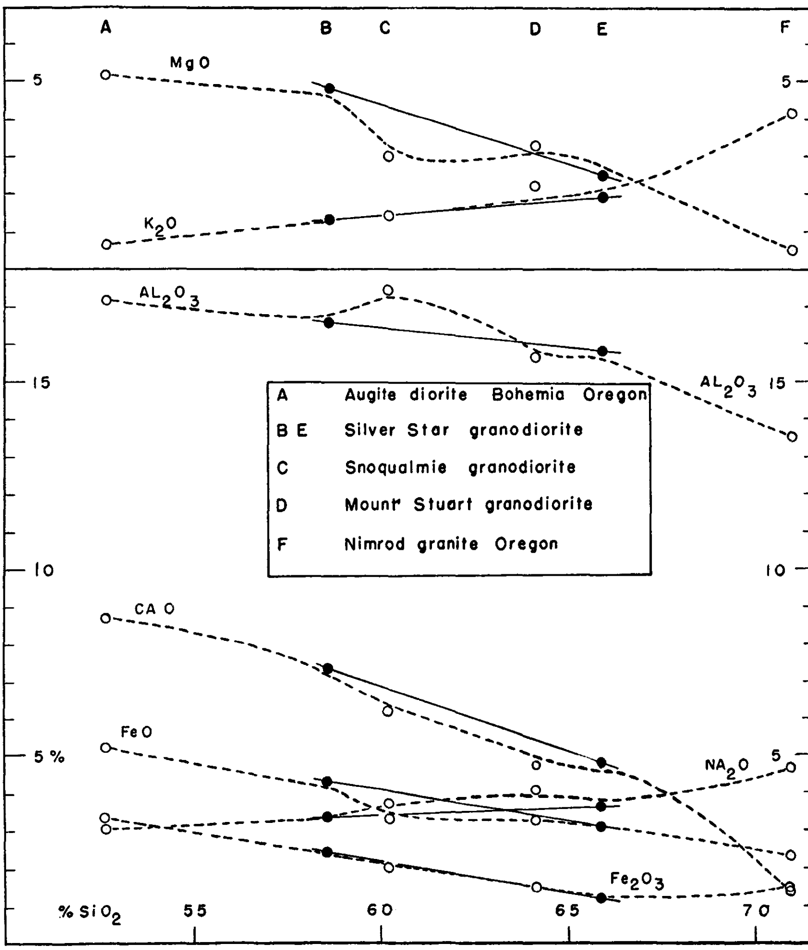

Fig. 2. Variation Diagram for some Cascade Intrusives.

At many places where the basic border of the intrusive is absent the more acid phases are in sharp intrusive contact with the andesite wall rocks. It is believed that at these points portions of the roof including the basic border were stoped into the still liquid acid differentiate and foundered.

GEOLOGIC STRUCTURE

An attempt was made to determine the mechanics of emplacement for this stock using some of Cloos' methods as outlined by Balk.[12] Although a number of measurements were obtained, suitable exposures are so few and so many of these exposures, especially away from the walls, are of so nearly structureless rock that the interpretation of these data should be taken as only suggestive. Although available data were taken from all exposures in the area, so much of the granodiorite is covered by talus that the structural observations necessarily appear somewhat sketchy.

Elongation within the mass is shown in a few places by schlieren, and, less frequently, by a linear parallelism of mineral grains. The best developed of these lineal features occur near the walls and trend parallel or nearly parallel with the local trend of the contacts. The few observations obtained in the central portions of the mass show a rather consistent east-north-east trend varying from north 60 east to north 80 east.

Primary Flow Layers. In a few places along the borders of the mass some of the more resorbed xenoliths and their reaction minerals, principally hornblende, are drawn out in long streaks (schlieren) that are roughly parallel to the walls of the stock. These streaks, in places, form well developed flow layers the strike and dip of which can be measured, but in no case was a consistent pitch of the elements within these streaks apparent. In the north-west corner of section 33 along the Yacolt-Hemlock road a well defined system of streaks and platey structure dips 76 degrees N3OW, and in the north-east quarter of section 16 a similar system, less perfectly developed, dips 45 degrees S80E. In both cases, these flow layers dip at rather steep angles away from the stock and under the wall rocks.

In the interior of the stock poorly developed schlieren and elongated inclusions were noted just west of the center of section 4 in the bed of Copper Creek. These layers dip 20 degrees N10W. This last measurement was taken one-half mile east of the west wall of the stock.

Mineral Parallelism. In most of the exposures of the granodiorite the nearly equidimensional character of the mineral grains precludes any development of marked mineral align-

[12]Balk, Robert. "Structural Behavior of Igneous Rocks." Geol. Society Am. Mem. 5, 1937.

ments. However, in places near the walls and near the flow layers mentioned above there exists a linear parallelism of

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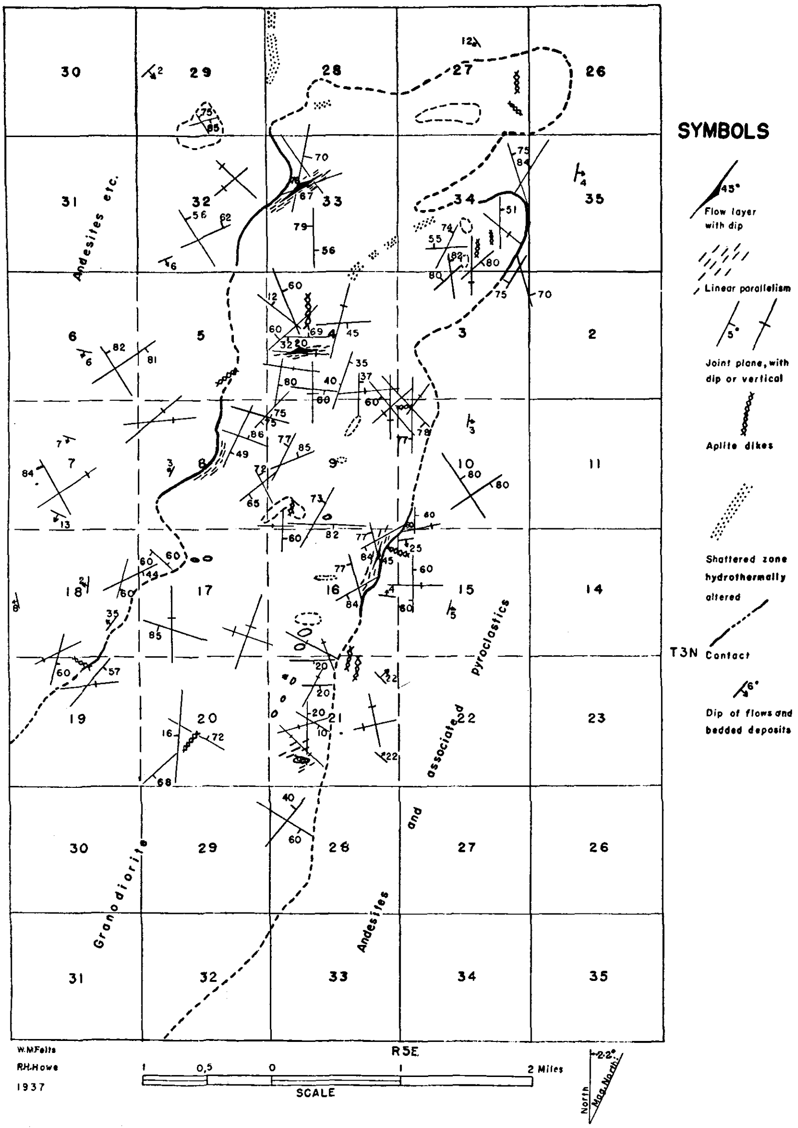

Fig. 3. Structural Map.

mineral grains, both light and dark, but principally lines formed by the alignment of hornblende needles from the more resorbed xenoliths near the contacts. The general strikes of these lineal elements are shown on the map near the schlieren noted above and also near the center of section 8 and in the south-west quarter of section 21. In most cases no pitch or dip could be obtained for these linear elements, although those in sections 8 and 16 seem to pitch to the south at high angles.

As was the case with the flow layers, an inspection of the map will show that two principal trends exist. Near the walls the strike of the flow layers and of the mineral parallelism is roughly parallel to the walls, but in the more central portions of the stock the trend swings to the east-north-east.

Joints. Wherever the granodiorite is exposed, in cliffs and in the stream beds, the joints are plentiful. The more persistent of the joint systems, both within the granodiorite and within the wall rocks, are shown on the accompanying map. Within the intrusive there are no extensive well defined systems of joints such as are commonly found in many intrusives which were intruded under pressures great enough to greatly deform the wall rocks. Instead the joints seem to be governed by purely local factors.

Not enough flow structure exists to designate any of the joint systems as "cross joints," but it is worthy of note that a weak general system of tension joints prevails. This system trends approximately parallel with the long axis of the intrusive. The joints in this system are usually vertical or high angle and are frequently filled with aplite dikes. Since they cross the flow lineations that exist in the central portions of the stock at rather high angles, and, since they are followed by the aplitic dikes, they are probably weakly developed cross joints. Near the borders where these joints follow the same trends as the flow structures they would be classed as longitudinal joints. In any case, these high angle joints trending parallel to the walls of the stock indicate a weak doming.

Near the walls of the stock appear sets of gash fractures usually dipping into the intrusive at varying angles and commonly filled with aplite dikes. These fractures are attributed to friction between the wall rock and the moving mass of the intrusive.

Definite sets of conjugate joints exist (1) near the borders of the stock both in the granodiorite and in the country rock, (2) in the wall rocks at a considerable distance, usually from one-half to one and one-quarter miles from the contact, and (3) scattered within the intrusive mass.

Joint systems of the first type intersect at sharply acute angles and are believed to be the result of frictional drag between

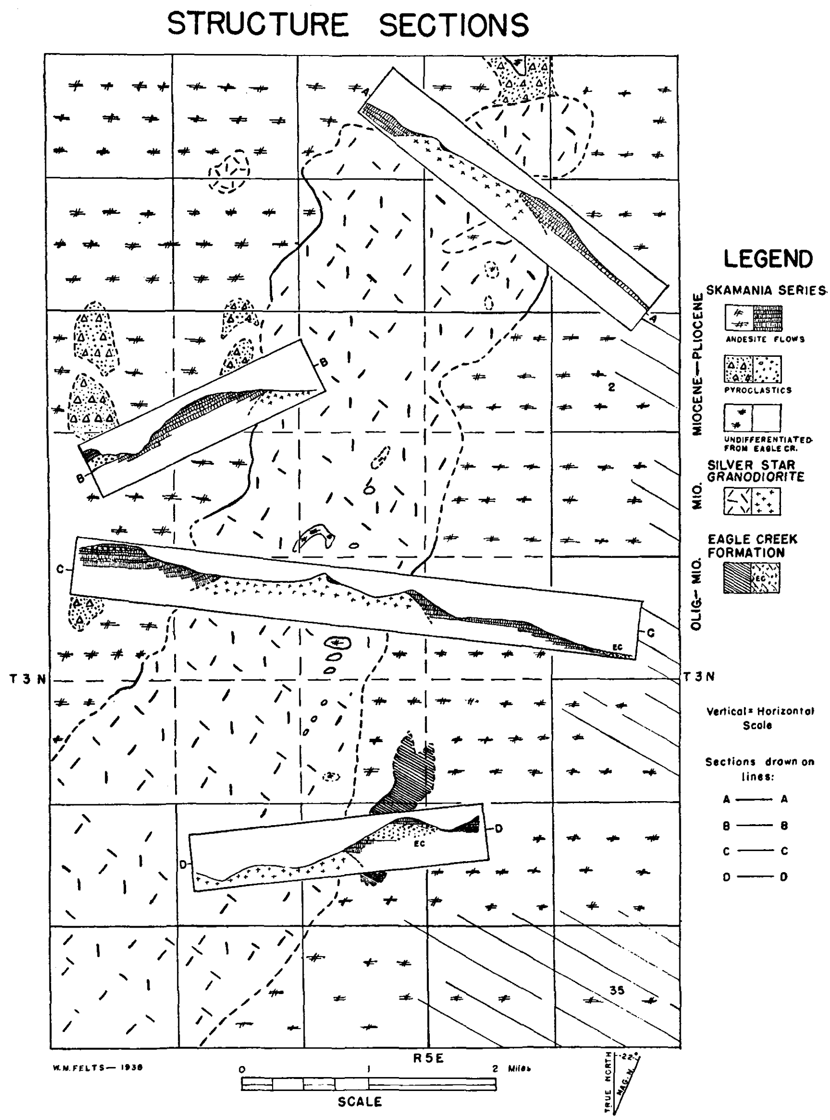

Fig. 4. Structural Sections.

the moving intrusive and the wall rocks. The conjugate joints of the second type intersect at nearly right angles and are believed to be the result of shear due to an almost horizontal thrust away from the intrusive during emplacement. Conjugate systems of the third type within the granodiorite do not conform to any single system and are probably best assigned to cooling strains. Some of these latter joints are actually faults of small displacement offsetting aplite dikes which fill previously formed longitudinal joints.

In the north-west corner of section 17, and in the north-west portions of section 15 and adjoining portions of section 10 are systems of conjugate joints with a common strike and with dips of 60 degrees to each side. These joints are interpreted as shear planes developed in rigid brittle andesite. Under such conditions, Hartmann's law may be applied to their analysis and the direction of maximum compressive stress would then be determined by a line normal to the line of intersection of the two joint planes and contained in the plane bisecting the acute dihedral angle between the joint planes. In the case of these conjugate joints the direction of this force was vertical.

Conclusions. The above data are believed to indicate that the stock was intruded along a line trending approximately N20E. The lack of serious deformation in the wall rocks and the lack of well defined flow structures and joint systems within the mass of the stock suggest that doming and thrusting aside of the country rock was secondary to stoping in the processes of emplacement, at least in the now visible portions of the stock.

The swarms of xenoliths near the contacts many of which are almost completely resorbed are direct evidence of stoping and assimilation. Just what proportion of the total displacement this process represents is not clear.

The flow layers, where noted, tend to arch toward the center of the stock, the systems of steep joints trending parallel to the long axis of the stock can be interpreted as indicating a weak doming, but analysis of the flow structures and joint systems fails to produce any consistent results. It is believed that this relatively small and shallow intrusive was emplaced principally by stoping processes, at least in its visible portions, with consequent local development of flow patterns and joint systems. Under such conditions the determination of the mechanics of emplacement by the methods of Cloos and Balk becomes much less reliable than in deeper seated bodies intruded under greater confining pressures, under conditions where stoping has not played an important part.