GEOLOGY OF MT. MCLOUGHLIN

by

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A THESIS

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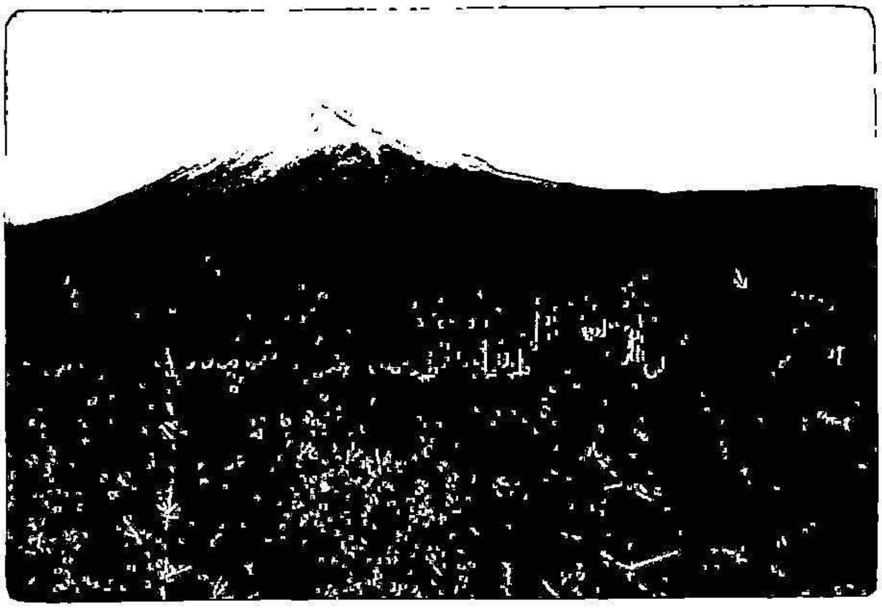

Mt. McLoughlin viewed from the southeast

INTRODUCTION

The purpose of this investigation is to contribute information about High Cascade volcanoes by studying one of them, Mt. McLoughlin, in detail. The study provides data on 1) the distribution and abundance of rock types, 2) the geologic history of the area, 3) the structural and contact relation of the High Cascades to the Western Cascades, and 4) the variation and evolution of rock types.

Description of Area

The mapped area is entirely within the Cascade Range geomorphic province. This province is a north-south linear belt of Eocene to Recent volcanic rocks, 40 to 70 miles wide and nearly 700 miles long. The range extends from Mt. Lassen in California north to Mt. Garibaldi in British Columbia, cutting Oregon and Washington into a western third and an eastern two thirds, (figure 1).

The mapped area (115 square miles in Jackson and Klamath Counties) includes a major portion of the Mt. McLoughlin quadrangle and parts of the Lake O' Woods quadrangle to the east and the Rustler Peak quadrangle to the north. The quadrangle maps are part of the 15' series and were first published in 1955 by the U.S.G.S. at a scale of 1:62,500. The area is bounded on the east by a north-south trending normal fault, which may be related to the faults that form the Klamath graben to the east. The west and south boundaries are near the west fork of Willow Creek and the south fork of Little Butte Creek respectively. Both of these creeks expose underlying Oligocene pyroclastic deposits. The northern boundary is the south fork of Fourbit Creek. It marks the northern limit of Mt. McLoughlin lavas. Between the confluence of Fourbit Creek and Willow Creek is a flat area known as Parker Meadows. It is formed from stream deposits which were later covered by younger flows of olivine andesite. Figure 2 shows these major geographic features.

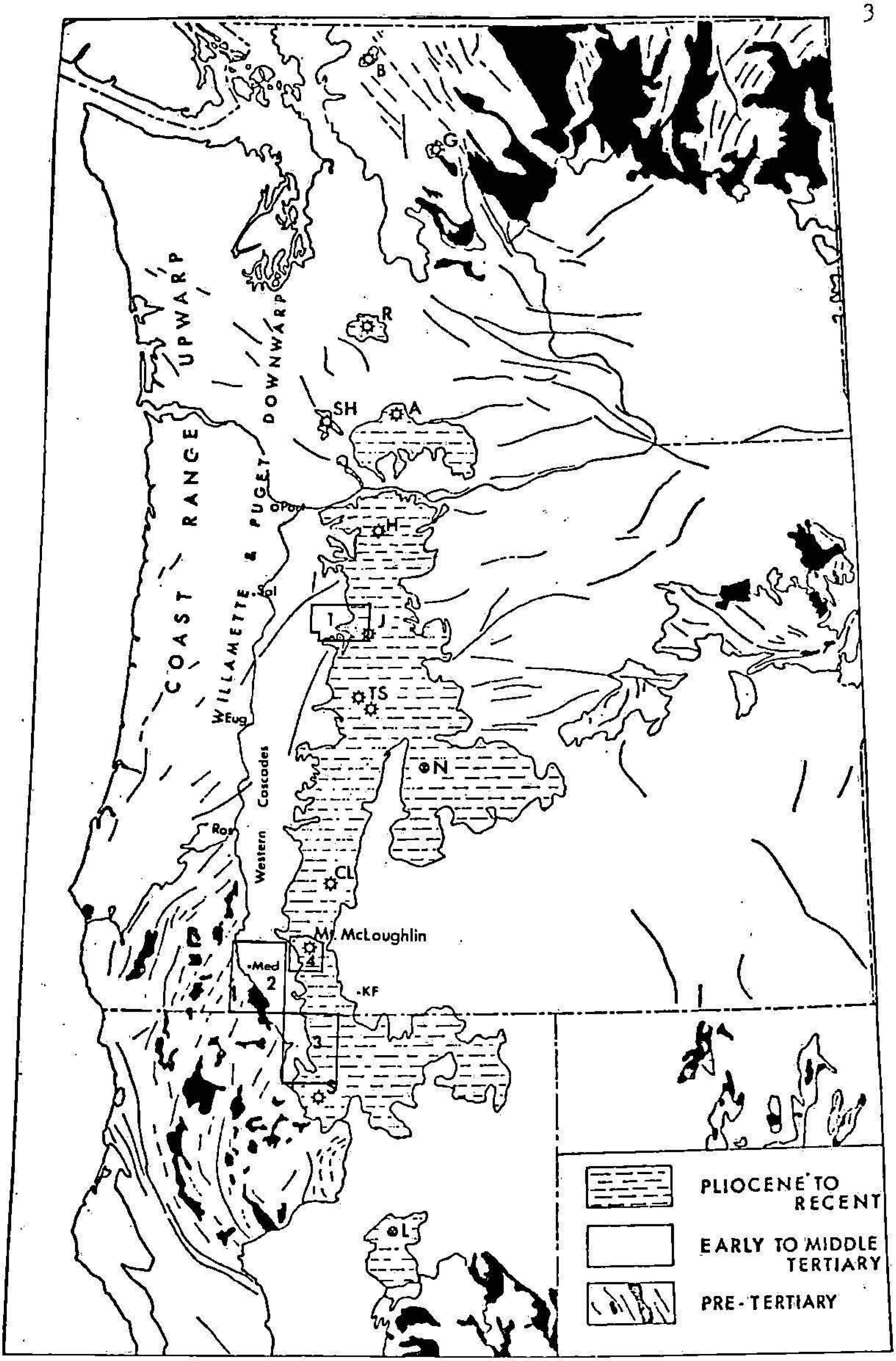
B
G
R
SH
A
H
J
TS
N
CL
L
COAST RANGE UPWARP
WILLAMETTE & PUGET DOWNWARP
Western Cascades
oPor
Sal
Eug
Ros
Mt. McLoughlin
Med
KF
1
2
3
4
PLIOCENE TO RECENT
EARLY TO MIDDLE TERTIARY
PRE-TERTIARY

Figure 1. Tectonic map showing the spatial relationship of the High Cascades in Washington, Oregon and northern California and the Western Cascades in Oregon to pre-Tertiary structures. Labeled peaks and centers are B-Mt. Baker; G-Glacier Peak; R-Mt. Rainier; SH-Mt. St. Helens; A-Mt. Adams; H-Mt. Hood; J-Mt. Jefferson; TS-Three Sisters; CL- Crater Lake; S-Mt. Shasta; L-Mt. Lassen; N-Newberry Crater; and ML-Medicine Lake. Black areas are pre-Tertiary intrusions and lines are fold axes. Map is modified from Wise (1969).

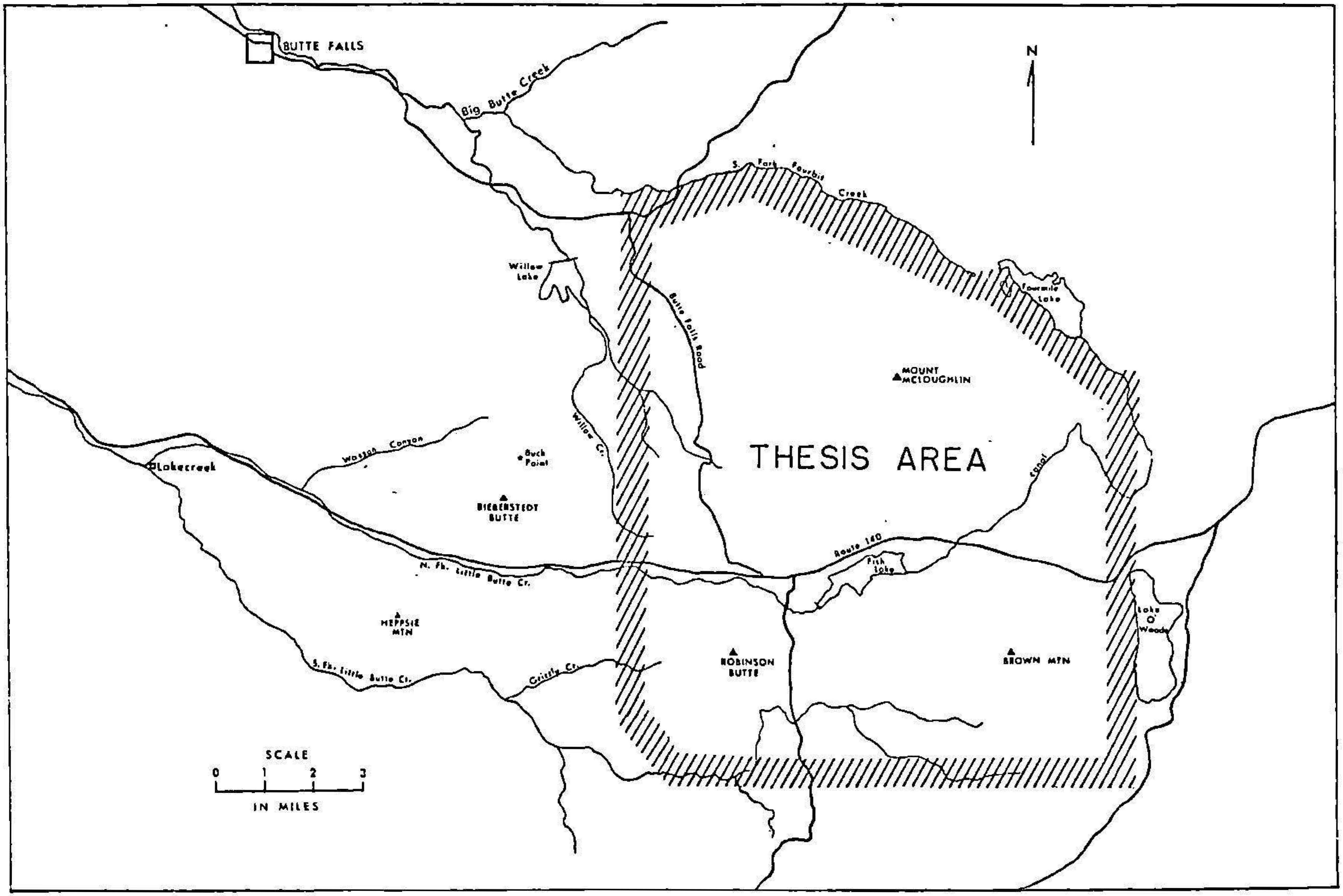

Figure 2. Location map.

Access

The area can be reached by traveling 40 miles east from Medford or 30 miles west from Klamath Falls on U.S. Highway 140.

A network of cinder surfaced Forest Service roads provides access to nearly all portions of the area in the summer months. In the winter months, Highway 140 is kept open by repeated plowing of the pass which is 5,200 feet in elevation. All other roads are left closed after the first heavy snow in the fall until the following May. Vegetation, soil and colluvium cover most of the area, except the youngest lava flows, and restrict good outcrops mostly to roadcuts. Traveling on foot through the area, even along streams, is hampered by a thick growth of alder, madrone, and hazel which has grown up over logged areas. The northwest flank of Mt. McLoughlin is an unpenetrable dense growth of live oak, snow brush and manzanita brush which has grown over an old burn. Two Forest Service trails at one time passed through this brush toward Mt. McLoughlin, but they have not been maintained in recent years. The trails are now difficult to recognize and barely passable.

Physiographic Features

The principal features of the area are Mt. McLoughlin, a composite volcano; and Robinson Butte and Brown Mountain, two shield volcanoes immediately to the south. Elevations range from 3000 feet on basalt-covered Parker Meadows in the northwest corner, to the top of Mt. McLoughlin at 9495 feet. Mt. McLoughlin, formerly known as Mt. Pitt, is the highest and the most prominent peak between Mt. Shasta and Crater Lake.

Fresh lava flows cover most of Brown Mountain and portions of the flank of Mt. McLoughlin. Some of these flows have a few trees and bushes on them but others are barren. There are a few cinder cones in the area, but they are old enough to have a forest cover. Land forms are constructional and only slightly eroded except where glaciers cut into the upper slopes of Mt. McLoughlin, the head of Willow Creek and Little Butte Creek in the west and south, respectively. The fault scarp near the east boundary of the mapped area is a tectonic feature.

Culture

The area is almost entirely within the Rogue River and Winema National forests. The principal land use is logging. Most new roads are made by logging companies and then selected ones are maintained by the Forest Service. Some areas are now being logged for the second or third time because the pine forests "grow fast" in this climate of cold wet winters and hot dry summers. Experimental plots and other hand planted groves of Ponderosa pine have been planted over many clear-cut areas in the past 20 years.

There is no farming in the area. Hay is grown for winter cattle feed a few miles to the west in the larger meadows and clearings. Cattle are allowed to graze on federal lands during the summer.

The area is extensively used for recreation. It has six large campgrounds, and at Fish Lake and Lake O' Woods there are resort facilities and summer homes. There is fishing and hunting in season, camping and picnicing, boating, swimming, and water skiing on the resort lakes, hiking on the Oregon Skyline Trail and on the trail up Mt. McLoughlin, snow-mobiling in the winter, and sightseeing all year round.

Most of the thesis area is an important water shed for the city of Medford. The outflows of Willow, Fourmile, and Fish Lake are regulated. Willow Lake is completely man-made, while Fourmile and Fish Lake are natural but have had their capacity increased by cement retaining walls around their outlets. Water flowing out of Fourmile Lake is diverted by canal into Fish Lake, and the overflow of Fish Lake is discharged into the North Fork of Little Butte Creek. The headwaters of Beaver Creek are siphoned across the upper canyon of the South Fork of Little Butte Creek and into Howard Prairie Reservoir.

Methods of Investigation

Field mapping and sampling were done in the summers of 1968 and 1971. Flows, vents, and different lithologies were plotted on 15' quadrangle maps enlarged to a scale of 1:32,000. Forest Service fireman's maps and aerial photographs taken by the U.S.G.S. in 1955 at a scale of 1:63,000, were used in the field, but because of their small scale and poor reproduction quality, they were of limited use. A newer set of photographs covering the area surrounding Mt. McLoughlin was purchased in February 1972 to map detailed features on the mountain and around its base. These photographs were flown in August 1971 and are at a scale of 1:16,000.

Nearly 140 rock samples were collected. Of these, 90 were selected for thin sectioning and 35 were chosen for chemical analysis. Trace element abundances were determined in ten samples by instrumental neutron activation techniques (INAA). Major elements, except Na_2O, were determined by the X-ray fluorescence. Sodium abundances were obtained using INAA.

Of the thin sections studied, modes were determined on 10 samples by counting 300 grains per slide. The universal stage was used to measure optic angles of pyroxenes, and immersion oils were used to determine the index of refraction of pyroxenes and olivines. These measurements were used to estimate the composition of olivine and pyroxene phenocrysts of selected samples. The anorthite contents of phenocryst and ground mass plagioclases were determined by using combined albite and Carlsbad twins after the method of Tobi (1963).

Previous Studies

Callaghan (1933) was the first to divide the Cascade Range into two linear belts, the older Western Cascades and the younger High Cascades. Thayer (1936-1937) further developed concepts of the structure and stratigraphy of the range and was the first to recognize the predominance of basaltic rocks in the High Cascades which underlie the more spectacular but less voluminous strato-volcanoes.

The earliest paper describing Mt. McLoughlin was entitled "Notes on Mount Pitt" by Arthur B. Emmons which was read before the California Academy of Sciences in 1885. Emmons visited the mountain in the summer of 1875 to measure its height barometrically and to study its geology. He sampled the coarse- and fine-grained rocks of Mt. McLoughlin and described the huge "crater" on the north side. There was no further significant description until a paper on Mt. Thielsen by Howel Williams appeared in 1935. Williams listed Emmons' analysis of a coarse-grained rock and noted that the rock was notably lower in sodium and higher in potassium than were Crater Lake rocks.

Seven years later, Williams (1942) published his well-known monograph on Crater Lake which included a reconnaissance of the Cascades between Crater Lake and Mt. Shasta. The brief history and description given in this reconnaissance and in Emmons' "notes" are the only published descriptions of Mt. McLoughlin. No previous geologic map of the volcano has been published, although a small scale cross-section and block diagram was given by Williams (1942).

The Medford 30' quadrangle map published by the U.S.G.S. was authored by Francis Wells and his co-workers (1956). The map includes most of the section of Western Cascades east of Medford and terminates about four miles from the thesis area. In an accompanying text, Wells divided the rocks of the Western Cascades into the Colestin, Roxy and Wasson formations, and the Heppsie Andesite. He grouped the Roxy and Wasson formations into the Little Butte Series.

The Oregon State Department of Geology and Mineral Industry published the Butte Falls 30' quadrangle map, produced by Wilkinson and others (1941). This map was printed well before the Medford map even though

Wells completed his field work in 1938. Wilkinson's map roughly outlines the major lithologic units. A bulletin was to accompany the map but the State Department of Geology never received the text.

Williams (1957) produced a geologic map of the Bend quadrangle which was also published by the Oregon Department of Geology. This map and accompanying text included a reconnaissance map of a portion of the High Cascades from the Three Sisters south to Crater Lake. In the text, Williams lists criteria to be used in distinguishing Western and High Cascades rocks.

Dallas Peck and others (1964) in U.S.G.S. Professional Paper 449 reviewed and described a large area of the Western Cascades between the South Umpqua River and the Columbia River. Their purpose was to determine "the gross aspects of volcanic stratigraphy, the geologic structure, and distribution of major geologic units."

A general summary of the geology of the Cascade Range with an exhaustive list of references is included in the Oregon State DOGAMI bulletin #64 (Griggs, 1969).

REGIONAL GEOLOGY

General Features

The Cascade Range in Oregon is a long, thick, pile of Cenozoic volcanic rock. Lavas and pyroclastic rocks ranging in age from Eocene to late Miocene make up most of the western two thirds of the range. During the Miocene epoch, the rocks were uplifted, gently folded, faulted, intruded by shallow stocks, generally altered to a greenish hue, and then deeply eroded. Where attitudes can be determined, the rocks dip gently to the east until they are partially overlain by fresher undeformed flows from shield volcanoes of Pliocene to Recent age. These shields coalesced to form a high, narrow plateau between the older lavas to the west and the high lava plains of Central Oregon. Situated on this undulating plateau is the long chain of Pleistocene strato-volcanoes, numerous cinder cones, and some fresh pre-historic lava flows. Callaghan (1933) divided the Cascades into two north-south belts. He called the older deformed rocks to the west the Western Cascades, and the younger undeformed rocks along the eastern edge of the range the High Cascades. Both terms are loosely used as physiographic areas as well as rock series units.

Western Cascades

The volcanic rocks of the Western Cascades presumably overlie the Umpqua Formation or its equivalent. The lower portion of this formation is a sequence of submarine lavas and breccias with associated dark shales of deep marine origin. It is exposed in the Roseburg area. The upper part of the sequence consists of marine sandstones and conglomerates which grade laterally into tuffs toward the east. South of Roseburg, the Umpqua Formation overlies upper Cretaceous marine sediments which in turn rest upon a Pretertiary "basement complex." The basement rocks consist of Jurassic sediments, Triassic schists, "older" undated schists, and large fault-bounded bodies of serpentine and peridotite. All of these rock types have been intruded by Jurassic to Cretaceous granitoid dikes and stocks. These plutonic rocks are exposed in the Klamath Mountains forty miles to the southwest of Mt. McLoughlin, and in the Blue Mountains in north-central Oregon. After implacement of the plutons but before the creation of the Cascade lineament in late Cretaceous time, small bodies of marine sandstone and shale were enfolded on top of the basement rocks. Trends in the Pretertiary rocks and the pronounced crosscutting of the Cascade Range are shown in figure 1.

Volcanic rocks of early Tertiary age are found not only in the Western Cascades, but also over a wide area in eastern Oregon. Presumably these two sequences were deposited in the same tectonic basin, are roughly equivalent in age, and were at one time continuous beneath the High Cascades. Rocks which make up the Western Cascades were deposited on the western edge of a large basin. Because of the great thicknesses exposed today, it appears that the western portion of the basin deepened into a north-south trough. The subsidence may have been self-generating. That is to say, as the outpourings of lava and pyroclastics continued, they sank under their own weight. The terrain maintained itself above sea level, but never attained great height. The rocks in this belt are varied lava flows, ignimbrites, tuffs and breccias, and minor lacustrine and fluviatile interbeds. Many of the rocks are of local character so that upon comparison, different sections of the Western Cascades differ greatly in lithology and thickness. The only persistent horizon is a light colored silicic ash unit near the center of the section. Its thickness ranges between 0 and over 5,000 feet. Peck and his co-workers (1964) thought that the source vents for the Western Cascades were aligned in north-south belts which moved progressively eastward with time.

During late Miocene time, after more than 10,000 feet of rock had accumulated, the belt was uplifted, folded, faulted and intruded by shallow stocks. The folding is best observed in a series of broad NNE trending anticlines and synclines in the North Santiam River section east of Salem (Thayer, 1937). The faulting is best seen in the range south of the Middle Fork of the Willamette River. Here, the interbedded sediments show a consistent dip of 5 to 10 degrees to the east or northeast; northwest-trending faults are the major geologic structure (Peck et al., 1964).

The shallow intrusions are thought to be contemporaneous with uplift and faulting. Stocks have yielded radiometric ages as old as Oligocene, but there is evidence that deformation continued to late Miocene time. Mineralization accompanied the intrusions and large areas of the surrounding rock have been propylitized, so that the rocks have a characteristic greenish hue. The uplifting of the belt created a plateau thousands of feet higher than the previous elevation. This plateau was vigorously attacked by erosive forces and by early Pliocene time it had been maturely dissected. Griggs (1969) estimates that nearly half of the section is still depressed below sea level.

High Cascades

To the east and partially overlying the Western Cascades is the younger volcanic belt which Callaghan named the High Cascades. Nearly all the rocks in this series were extruded as lava flows, some of which are several miles in length. West of the crest lavas formed intercanyon flows down stream and river canyons. The more viscous flows formed a high narrow plateau of coalescing shield volcanoes with a chain of high peaks spaced along the crest.

The predominant rock types are basaltic andesite, 53-57% silica. Andesite, 57% silica, is only a common rock type near high peaks and the more silicic differentiates are confined exclusively to these peaks.

Rocks of the High Cascades are generally assumed to range in age from early Pliocene to Holocene (Griggs, 1969). Some of the early lavas are known to interfinger with Pliocene nonmarine sediments to the east but, in most areas, direct dating is not possible and the ages of rocks can only be inferred by such criteria as stratigraphic position and amount of weathering and erosion. The high peaks are considered very young since many have post glacial flows and no rocks of reversed magnetic polarity have been observed on them.

Pleistocene to Recent normal faults have broken the lavas, especially south of Crater Lake, but no tilting or warping has been detected. Faulting in the High Cascades is only prominent south of Crater Lake. The faults trend north-south and some have measured displacements on the order of 800 feet.

WESTERN CASCADE STRATIGRAPHY

The sequence of lower Tertiary rocks that overlies the rocks of the Klamath Mountains has a regional northeast dip away from the Medford-Ashland valley and, therefore, presumably extends beneath the High Cascades and Mt. McLoughlin. The rocks exposed in Bear Creek valley and the canyons of Little Butte Creek have been described by Francis G. Wells in "The Geology of the Medford Quadrangle, Oregon-California" (Wells and others, 1956). Since my interest in this sequence in the field was limited, the following descriptions, except where noted, are summarized extensively from Wells' text.

Hornbrook Formation

In the Medford-Ashland valley, the first marine sediments which lap on the Klamath Mountains are Upper Cretaceous sands of the Hornbrook Formation. The sands are nearshore in character; they are "fairly uniform in texture and composition and consist of well-bedded, hard, fine-grained greenish-gray arkosic sandstone with local lenses of coarse conglomerates and sandy shale." The sands have a maximum thickness of 600 feet in Oregon but further south in California they attain a thickness of 2,000 feet. Fossils found by Peck and Imlay (1956) were considered Cenomanian and Turonian in age.

Umpqua Formation

Resting disconformably on the Hornbrook is the Umpqua Formation of lower Eocene age. Farther north near Roseburg, the Umpqua is predominantly submarine volcanic rocks and dark shales, but in the Medford valley it consists mostly of tuffaceous sand with lenses of shale and gravel. Some of the shale is carbonaceous and east of Ashland small seams of coal have been mined. The sediments contain fossil leaf prints and poorly preserved molluscs. Near Ashland, the formation dips generally 20 to 25 degrees to the northeast and is estimated to be nearly 8,000 feet thick.

Intrusive Bodies

The Umpqua and all later Western Cascade formations up to Pliocene in age are intruded by dikes and sills of various compositions. Although Wells collectively groups them as Pliocene (?), there are probably many episodes of volcanism represented, ranging in age from late Eocene to Pliocene. Thus, the intrusions may be vent feeders, or their offshoots, which have supplied the volcanic material for later formations but have only recently been exposed by erosion.

Colestin Formation

North of Medford near the town of Eagle Point, the marine Umpqua sands grade upward into a variety of stratified continental volcanic fragmental material which Wells named the Colestin Formation. The stratified rocks interfinger with flows, lahars, and agglomerates of predominantly andesite and rhyolite composition. The Colestin Formation has a maximum thickness of 2,000 feet. Leaf prints found at the top of the formation near the California border suggests a late Eocene age. In this southern exposure area there is an angular discordance between the Umpqua and Colestin rocks.

Roxy Formation

Between Medford and the Siskiyou Pass the Colestin Formation is not exposed. In its place, lying unconformably upon the Umpqua, is the Roxy Formation, named by Wells as the lower unit of the Little Butte Series. Wells described the Roxy as "a great variety of volcanic rocks, including dense andesite, platey porphyritic andesite, vesicular and scoriaceous rock, glassy rock or vitrophyre, blocky flow breccias, and direct products of explosive eruptions ranging from bomby agglomerates to fine-grained tuff." The contact between the Colestin and Roxy is defined by Wells as "the top of the uppermost layer of waterlaid pyroclastics that is succeeded by at least 100 feet of flows with or without interlayered nonwaterlaid pyroclastics." Leaf prints found in the Roxy have been correlated with early Oligocene flora of central Oregon. Wells estimates the Roxy to be nearly 2,000 feet thick.

Wasson Formation

The Wasson Formation, the upper unit of Wells' Little Butte Series, rests with apparent conformity on the Roxy formation. The Wasson

Formation consists mostly of siliceous tuffs. Wells divided the formation into four members. All members are present and well exposed in Wasson Canyon but south of the south fork of Little Butte Creek only one member persists. No members are mapped south of Dead Indian Highway. Wells has the Wasson terminated in the north, near the top of the Medford sheet, by a fault. Leaf prints found in Wasson Canyon were said to resemble middle Oligocene fossils of eastern Oregon.

The description of the Wasson Formation is confusing and, because of vague references to the different members, the text seems to conflict with the map explanation of the rock types. The bottom member in the legend is described as a "buff fine-grained tuff with fragments of flow rock." The probable text description is "a bed about 300 feet thick of massive, dirty-yellow tuff consisting of some angular fragments in a basaltic tuff matrix."

The second member in the legend is described as "pyroclastic rocks of dacitic or rhyolitic composition." In the text, this member is mistakingly described as "about 300 feet of platey andesite flows and agglomerates." One of the possible causes of this error could be the fifteen year time period between field mapping and writing of the text, even though Wells revisited the area in 1951. Since the thickness of these silicic pyroclastic units is not given, it has been estimated from the map at near 300 feet.

The third member of the Wasson Formation is the "most conspicuous and extensive layer . . . a chalky white tuff." Wells described it further as "about 250 feet thick and in most places does not show distinctive bedding but breaks off in flakes or thin slabs. It is uniformly fine grained and of siliceous composition."

The fourth and uppermost member of the Wasson Formation consists of 300 feet of lavas and agglomerates. It varies "from red flow breccia to scoriaceous and vesicular flows." Wells considered it andesitic in composition.

Wasson in Thesis Area

In the Medford quadrangle, the Wasson ash dips gently to the northeast and disappears under the overlying lava flows. On the west side of the thesis area, faulting has brought the ash back to the surface, so that the third and fourth members of the Wasson have been repeated. As is shown on plate 1, a northwest trending normal fault crosses route 140 at mile post 25.6 in section 1. This structural relationship is affirmed by a water-lain ash bed found in a roadcut at mile post 26.3. The bed dips approximately 8 degrees to the northeast and is cut by a small three foot fault which shows that the west block is down. With the aid of a cross-section drawn perpendicular to the strike, the stratigraphic displacement of this fault, using a 5 degree dip, is estimated to be at least 2000 feet, cross-section A of plate 1.

In the appendix is a road log along route 140 between mile posts 19 and 35. It describes the geology seen from the highway from the base of the Wasson ash in the Medford quadrangle through the High Cascade lavas near the summit of the pass. Although nearly 300 stratigraphic feet of ash is exposed along the highway in the thesis area, no distinct mappable horizons, such as Wells found, were noted. Outcrops are poor over a wide section, both laterally and vertically. The Wasson ash generally has subdued topography and a thick soil covering.

What is thought to be stratigraphically the lowest Wasson outcrop in the thesis area is exposed along State Highway 140 at M.P. 25.8. It is a massive red, brown and grey mud flow unit which consists mostly of light and dark pumice fragments with a small amount of ash and small lithic fragments as the coarse matrix. Because of its seemingly low stratigraphic position and its lithology, it is considered a possible outcropping of the second Wasson member.

The rest of the ash is mapped as the third Wasson member and most of it is regarded as non-welded ignimbrite deposits. It consists of varying proportions of lithic fragments and flattened pumice surrounded by a light-colored silicic dust. The following descriptions of selected exposures will attempt to show the variations on this generalized lithology.

At M.P. 26.0 route 140, there is a high road-cut of a massive white to grey ignimbrite with abundant pumice and lithic fragments. At M.P. 26.3, the road-cut is in a buff colored ash without lithic fragments. It is massive and has an air or water-lain white ash bed cutting through it.

In sections 25 and 26 of upper Willow Creek, the ash again has pumice and lithic fragments but part of the matrix contains abundant plagioclase crystals and rare quartz. The color of the ash can change noticeably over a few tens of feet to many different pastel shades. Cream, grey, buff, brown and pink are the dominant colors. Four and one-half miles west of Butte Falls there is a road-cut in Wasson ash similar to the Willow Creek lithology which has a bright green ash matrix.

Not all of the Wasson tuffs are loose ignimbrite deposits. The top unit in the floor of the south fork canyon is a medium grey welded tuff. Because of poor outcroppings, its stratigraphic relation to loose ash higher on the north canyon wall is unknown.

Wells' map shows that the fourth member of the Wasson is more restricted in area than are the underlying tuffs. Along route 140 from mile post 21.8 to 25.6, roadcuts expose over a thousand feet of red flows and agglomerates. The exposure along its strike, which is approximately NW, is only seven miles. North of Salt Creek and south of the south fork of Little Butte Creek this member was not mapped by Wells.

There are a variety of lithologic and textural types in the fourth member. Flow agglomerates are more common low in the section while vesicular flows and tuffaceous agglomerates are more prevalent high in the section. Along the road that follows the south fork, the lower part of this member is represented by several thick beds of black agglomerate. Massive outcrops tens of feet high consisting of blocks of black vesicular rock several inches in diameter are held together with little or no ash. Lava flows are inconspicuous in this section. Toward the top, there is a persistent dirty brown tuffaceous agglomerate, and here the inch-wide fragments of scoria are completely separated by the ash which makes up about 50 percent of the rock.

In many places, especially along ridge tops where weathered surfaces may be preserved, the flows and agglomerates have been altered to a light purple and grey mass. It is possible that there was a substantial time lag between the last agglomerates and the first Heppsie flows. This lag could account for the deep weathering of the rocks.

There are several possible source vents for the agglomerates along the west edge of the thesis area. A string of rounded knobs trends approximately N60W just north of route 140 between mile posts 25 and 26, in sections 31 and 36. The speckled-grey to black color of these proposed vents differs from the dark reds and greens of early flows of this member, but later fourth-member deposits tend to contain more ash, are lighter in color, and commonly contain blocks of lava similar to rocks surrounding the vents. Directly west of Robinson Butte in sections 7, 12, and 18, there are several more eroded knobs which may be fourth-member vents. The rocks, which are a very light-grey pyroxene andesite, are distinct from all others in the area.

Because of the great disparity in lithologic features, it is doubtful that this last member should have been included with the tuffs as part of the Wasson formation. If it is not important enough to be mapped separately, it would be more logical to include it as a basal member of the overlying Heppsie Andesite.

Heppsie Andesite

Above the fourth Wasson member a thick series of andesite flows dip eastward out of the Medford quadrangle and under the base of the high Cascade lavas. Wells named these flows the Heppsie Andesite after Heppsie Mountain located between the forks of Little Butte Creek. He described them as "typical 'andesites of the Western Cascades' of other writers." "In general, they are thickly bedded, massive though locally platy, gray to blue-gray porphyritic rocks with a microcrystaline groundmass in which are varying amounts of phenocrysts of either hornblende or pyroxene or both." Since the flows rest on Oligocene tuffs and are capped by High Cascade lavas of a presumed Pliocene age, Wells considered them Miocene. Thickness varies greatly because of active erosion but at Bieberstedt Butte just off the map to the east, the Heppsie andesite may exceed 1,500 feet. Wells did not find an unconformity between the Wasson formation and the Heppsie andesite in the Medford Quadrangle, but notes that there is one indicated on Wilkerson's Butte Falls map, the quadrangle directly to the north of the Medford map. Peck (1964) considers the Heppsie Andesite to be equivalent to the upper part of the Sardine formation.

Heppsie Andesite in the Mt. McLoughlin Area

The areas mapped as Heppsie Andesite on plate 1 may actually contain many variations of the basic lithology described by Wells, except that olivine should be substituted for hornblende. No rocks with hornblende phenocrysts were found, whereas olivine is common as phenocrysts.

At the head of the canyon of the South Fork of Little Butte Creek, there are many tens of flows of a dense blue-grey lava that directly overlie a welded ignimbrite. The flows are massive, 10-20 feet thick, fine grained, and contain dull, light green olivine phenocrysts. A few flows have pyroxene as the dark phenocryst. The flows continue up to the base of the High Cascade lavas.

In the west branch of Willow Creek canyon, a light grey lava overlies Wasson tuffs. The rock is fine-grained, platy, and contains dark olivine phenocrysts. Most of Juniper Ridge consists of this same rock type.

Two eroded Heppsie vents are exposed near the head of the east branch of Willow Creek. The one located near the center of section 19 is a dense medium grey andesite with black olivine phenocrysts. The associated lavas next to the vent closely resemble the flows in South Fork canyon. They are dense, medium-grey andesite with opaque yellow-green olivine phenocrysts. A similar rock outcrops on the east edge of Juniper Ridge and was sampled in a roadcut near the southern edge of section 7 on the Butte Falls road.

A second Heppsie vent is located near the center of section 20. The rock contains black ghosts of olivine along with relatively fresh olivines which have rust-colored rims. Clustered phenocrysts of plagioclase and the fresh olivine are present. Chemical analyses of the two vents show that they appear to be the same.

Another source for the Heppsie Andesites is an eroded knob at the North Fork Little Butte Creek Forest Camp located at the northeast base of Robinson Butte. It is a multiple vent which includes two Heppsie lithologies. The first type is a medium-grey-massive rock containing yellow-green olivine phenocrysts. The second type is a light-grey-platy rock which has black olivines.

HIGH CASCADE SERIES

The High Cascade lavas were first designated as a separate series by Callaghan (1933). He reconnoitred the crest of the Oregon Cascades and came to the conclusion that it was "convenient to divide the Cascade Range south of Mount Hood in two parts, the Western Cascades and the High Cascades, on the basis of a pronounced unconformity in the stratigraphic sequence of lavas."

Thayer (1937) studied the North Santiam River section and also agreed that there was a marked unconformity between the Western and High Cascades along the entire length of the range in Oregon. He then divided the High Cascade lavas in the North Santiam area into four sub-series. The oldest lavas he named the Outerson basalts. They were assumed to have erupted during Pliocene time along the east scarp boundary of the uplifted Western Cascades. The Outerson lavas were greatly eroded before the next episode of volcanism which came later in Pliocene and early Pleistocene time. These later lavas were named the Minto basalts and they make up the greater part of the High Cascades in this region. They form the broad bases of volcanoes found near the present crest of the range. The Minto lavas were also deeply dissected before the next series, the Olallie lavas, were erupted. Olallie flows consist mainly of andesite and basalt and form the high peaks and the small, steep-sided shield volcanoes along the crest.

Contemporaneous with the Olallie lavas were the Santiam basalts which are the fluid intercanyon flows in many of the stream valleys.

Williams (1949) in describing the rocks of the Macdoel quadrangle of northern California divided the high Cascade lavas in another manner. The first lavas were quiet extrusions of basalts which formed broad, coalescing shield volcanoes, and were thought to be of Pliocene age. They rest directly upon middle Tertiary tuffs. Volcanism continued sporadically into the Pleistocene. Different relative ages of the volcanoes resulted in their being in various stages of erosion when a noticeable change in rock type occured. A few shields were covered by late Pleistocene pyroxene andesites similar to the lavas of the high peaks; others were covered by Recent flows of basalt or andesite, while some were left unchanged except for erosion.

Williams' account of Cascade History contrasts with Thayer's in that: 1) there are no lavas comparable to the Sardine in his Western Cascade stratigraphy, 2) there is no distinct double cycle of erosion as after the Outerson and Minto basalts, and 3) there are no lavas comparable to the Santiam basalts although similar "mesa basalts" outcrop to the east and southeast.

Some of these differences could be due to individual interpretation but it is more likely that the histories of the two areas are substantially different in their details even though the general sequence of events and rock descriptions may seem the same. Only after many more parts of the Cascade range have been studied in detail will it be possible to distinguish events that are unique to certain areas from those that are part of the overall sequence of High Cascades history.

In mapping the rocks of the High Cascades, I found that rock types of different ages may be very similar when weathered, and even different lithologies of comparable age tend to grade into one another. This makes the mapping of lithologies very difficult and for this reason there are many places where only approximate boundaries could be delineated.

Because lavas are extruded intermittently, the High Cascades must have many erosional surfaces, but only two unconformities shall be recognized besides Pleistocene glaciation. I shall treat the history of the High Cascades as divided into Plio-Cascades, olivine basalts, Fish Lake series, Mt. McLoughlin and associated lavas, and post-glacial lavas. The first unconformity is a weathered surface on the Plio-Cascades and the second is the faulting which occured after the Fish Lake series.

Plio-Cascades

The Plio-Cascades consist of basaltic lavas which formed broad, coalescing shield volcanoes. The first flows erupted presumably during late Pliocene time upon a faulted surface of eroded Heppsie andesite. The present outcrop areas cover only about ten square miles in the thesis area, mainly southwest and southeast of Mt. McLoughlin. Other outcrops south of the mapped area suggest that, as in the Macdoel quadrangle, old High Cascade volcanoes underlie much of the younger lava.

Two Plio-Cascade volcanoes have been left uncovered on the southwest side of Mt. McLoughlin. One is located at Rye Flat in section 27 and the other is east of Dogwood Spring in section 16. At Rye Flat, magma cooled in the upper conduit to form a light brown-grey, fine-grained gabbro. Elsewhere, the rock is massive, blue-grey basaltic andesite. Although the vent areas appear to be slightly eroded, the slopes are smooth and close to their original form even though the slopes are also deeply weathered. Fresh rock is found in some of the deepest highway cuts where one can see the massive interior of flows. Elsewhere there is only intensive spheroidal weathering, figure 3.

Olivine Basalts

After the Plio-Cascades shield volcanoes became extinct, the Mt. McLoughlin area was quiet for some time. Erosion was not pronounced but weathering was deep. When this break ended, there was an outpouring of basalts which were chemically distinct from Plio-Cascade lavas.

Olivine basalts are found covering a large area north of Mt. McLoughlin, but are mostly covered by younger lavas in the mapped area. They are assumed to range in age from Pliocene to Pleistocene. Although several intercanyon flows of olivine basalt overlie a glassy flow of early Fish Lake series in the valley of Big Butte Creek west of Butte Falls, most of the basalts appear to be older than Fish Lake lavas. No olivine basalts were erupted while Mt. McLoughlin was being formed and there are no Holocene basalts.

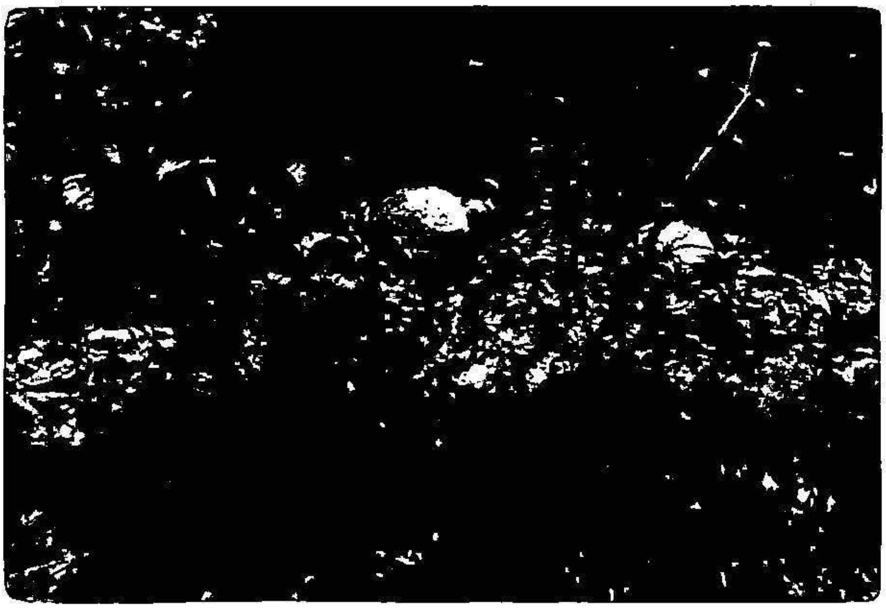

Figure 3. Outcrop in roadcut at M.P. 29.9 showing intense spheroidal weathering of Plio-Cascades.

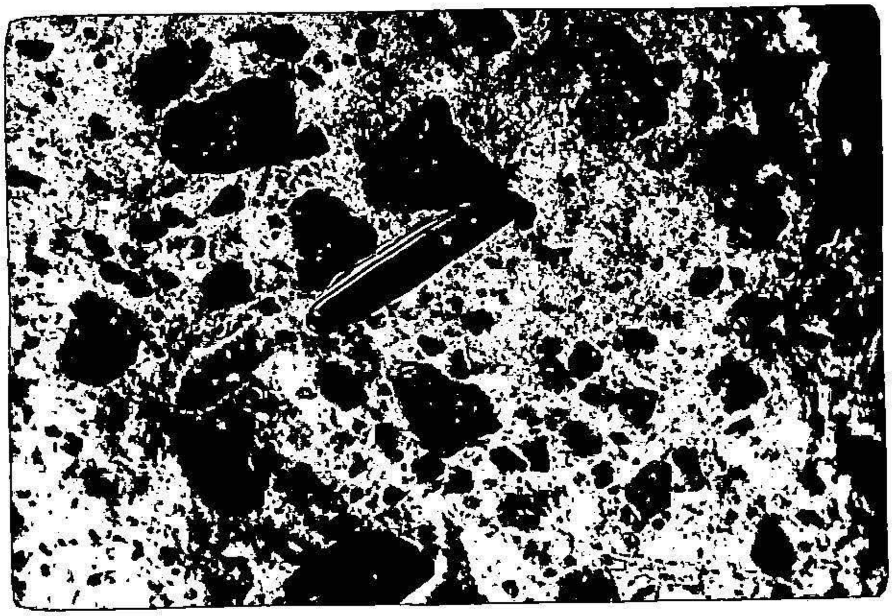

Figure 4. Tuffaceous agglomerate from the early pyroclastic cone of Mt. McLoughlin.

Fish Lake Series

While olivine basalts were still being erupted, another rock type of distinct character began pouring out. The centers were aligned north-south and are located on the east edge of the map. The oldest flow outcrops at the west end of Fish Lake and for this reason lavas of this episode are referred to as the Fish Lake series.

The first flows of the series were very fluid, glassy andesites. They formed flat surfaces, such as shown by the topography immediately east of Robinson Butte, and they traveled many miles down stream channels to form intercanyon flows. One flow traveled more than ten miles down the valley of Big Butte Creek from its source near the High Cascades. It can be seen outcropping along the highway 4.0 miles west of Butte Falls.

The rock is distinctive in hand specimen. It is a glassy black lava and contains large clear blades of plagioclase phenocrysts whose cleaved surfaces flash reflected light. The plagioclase is commonly found clustered with phenocrysts of augite, hypersthene and olivine. The rock is massive and has a hackly fracture. Succeeding flows were less glassy and have a dark to medium grey color. They were also more viscous and formed short, thick flows, but the rocks still have the same distinctive plagioclase, massive texture, and fracture. These less glassy rocks are found southwest of Brown Mountain in sections 23 and 24, and they still have the topographic form of flows. Two small windows of this rock type at the northwest and south base of

Mount McLoughlin (plate 1) are the youngest lavas of this series known to underlie that area. A possible source vent for these early lavas was found in the northwest corner of section 21 south of Robinson Butte. Most of the vents are assumed to lie further east beneath younger flows.

The early flows of the Fish Lake series have a narrow range of silica content between 56-67%. Higher in the section south of Brown Mountain, the silica content of the lavas increases to 57 to 61%. These lavas will be referred to as the late differentiates of the Brown Mountain Series; they are light grey with white patches of plagioclase phenocrysts. Clusters of phenocrysts, which include clino-pyroxene and olivine, are still abundant. The most silicic lavas, with 59 to 61% SiO_2 tend to be platy, and femic phenocrysts are seldom seen in hand specimen.

Present physiography indicates that most of the late differentiate lavas in the Fish Lake series came from vents aligned along the north-south trending Applegate Ridge southeast of Brown Mountain. Perhaps other sources have been hidden by the Recent lavas of Brown Mountain. After volcanic activity ceased, movement along north-south fractures cut several volcanoes in half, including Rye Spur east of Mount McLoughlin and those aligned on Applegate Ridge.

Some investigators in the High Cascades believe that the shield volcanoes were actively being built at the same time that the high strato-volcanoes were forming, Williams (1942, 1949, and 1957), Wise (1969), and Griggs (1969). This is also true in much of the region surrounding the thesis area. But the volcanoes of the Fish Lake series became inactive during the first half of the Pleistocene epoch, and their lavas were faulted before the early phases of Mount McLoughlin. In this respect, the Fish Lake series of andesites and the olivine basalts found north of Mt. McLoughlin hold a position in the history of the High Cascades similar to Thayer's Minto basalts. Since many of the old volcanoes in the Macdoel quadrangle were later covered by younger Pleistocene lavas, it is possible that this area also had a corresponding break in its history. The lack of chemical analysis in both the North Santiam and Macdoel areas makes further comparisons along this line speculative.

The nearest volcanic activity outside of the thesis area that may be contemporaneous with Mount McLoughlin is Pelican Butte and the Mountain Lakes volcanic center located to the northeast and the southeast, respectively.

Mount McLoughlin and Associated Lavas

The first eruptions of Mount McLoughlin were no doubt violent, for glaciation has exposed pyroclastic deposits in the core of the mountain which affirm an explosive beginning. This debris formed a tall cone on what had been an undulating terrain of broad shield volcanoes of the Fish Lake series. The pyroclastic rocks consist of well consolidated tuffaceous agglomerates with some minor lapilli beds. No outcrops were found containing beds of pure ash, nor were any Strombolian bombs or lava flows found interbedded in the agglomerates.

The cinders are dark grey to black and commonly have phenocrysts of plagioclase and olivine. The fresh light grey ash makes up as much as half of the rock (figure 4). In places the ash is light buff or rust colored from hydrothermal alteration. This sulfataric activity was less intense than Williams (1942) inferred from his reconnaissance studies.

The relatively high elevation at which some of the pyroclastic rocks are found suggest that the cone probably attained a height of 3,000 feet above the surrounding terrain. However, cones which consist only of tephra are not known to exceed 1500 feet. They then reach a point of instability and begin slumping. To reach this great height, Mt. McLoughlin's early cone may have been strengthened by an occasional lava flow (although none are exposed) or the cone grew on an older platform volcano. This pre-McLoughlin volcano, if present, would have been between one and two thousand feet high so that the present depth of erosion has not exposed it. Perhaps it was similar to the form which Brown Mountain has today.

When explosive activity ceased, flows from the summit area completely enveloped the cone, forming what McDonald (1972) has called an armored volcano. These flows are very uniform in composition and texture. Most seem to have been erupted from a central conduit with perhaps a few coming from nearby offshoots. All of the flows are highly vesiculated but, because phenocrysts are so numerous, round vesicules are lacking. Instead, there are many small, interconnecting pore spaces. The lavas are porphyritic andesites which, like many of the large Cascade peaks, contain large phenocrysts of olivine, plagioclase, clinopyroxene, and sparse hypersthene. The long dimensions of the largest crystals reach ½ centimeter and olivine attains twice that size. Plagioclase crystals are white, clinopyroxene dark green, hypersthene dark red-brown, and olivine a vitreous light yellow-green.

Twenty-one flows were examined closely in the headwall of the northeast cirque, (figure 5). The lavas range from one to three meters thick. Individual flows are fairly uniform in thickness and show no pronounced changes of dip. The centers of the flows are solid but the tops and bottoms consist of scoria, which in places accumulated to thicknesses greater than the solid centers. Because there is no inter-bedded ash, the rubble is considered to come entirely from the moving flow surfaces. The possibility remains that a portion of the rubble consists of bombs that were thrown out between flows.

The predominant color of the lavas is dark grey but there is a range from black to red. The red color is from the original oxidation state of the lava. No chemical weathering of the lavas is evident but the loose rubble between the flows make them susceptible to erosion.

During this period of flow accumulation, only small volumes of lava were erupted at one time. Therefore, none of the flows originating near the summit was able to flow far from the mountain even if they reached the base. The high viscosity of the lavas is shown by the fact that they were able to flow only on the steep slopes of the cone, and the change in gradient at the base of the cone was enough to halt them.

The last magma cooled in the top of the conduit to form a massive

Figure 5. Flows exposed in the headwall of the northeast cirque.

Figure 6. Stage three, blocky lava at northwest base of Mt. McLoughlin.

green rock. Erosion has stripped the surrounding rock so that it now stands as a monolith 100 feet high and 50 feet wide. Aside from the less glassy groundmass, the rock is not noticeably different from the lavas in thin section.

Lavas of Associated Vents

The growth of Mt. McLoughlin was contemporaneous with the formation of Robinson Butte, the eruption of flows covering the ridge southeast of the mountain, and the growth of a few cinder cones.

The flows covering the southeast ridge are merely a thin covering on older topography. Several source vents are shown on the map. Three are in section 18 just north of the McLoughlin trail. They were either implaced as viscous plugs or their lavas were eroded away by glaciers. A fourth vent is located in section 17 just east of Frey Lake and still another is in section 33, three miles to the southeast. These flows are highly porphyritic and similar in texture to the main cone lavas. The Frey Lake flow has very large (½ cm) euhedral phenocrysts of dark green clinopyroxene.

Robinson Butte

In plan view (Plate 1) Robinson Butte is elongated in a north-south direction. This was caused by a shift in the central vent ½ mile to the south during a late stage of its growth. Williams (1949) noted that many volcanoes in the Macdoel quadrangle are elongated either north-south or approximately N30°W. He suggests that this is caused by lavas coming up along two sets of fault fractures. In Butte Valley, to the east of the volcanoes, faults have been mapped which have similar north and northwest orientations.

Because Robinson Butte has not been deeply eroded, one can only speculate on the rock type which makes up its bulk. The last flows that erupted from the north vent are medium red-grey andesites similar in texture and phenocrysts content to main cone lavas. The last eruptions from the younger vent produced a basaltic cinder cone on the crest of the butte, but erosion and vegetation have now effectively obscured it. Two other cinder cones were built on the south flank of the butte during this late phase activity.

As on Mount McLoughlin, most Robinson Butte lavas did not travel far past the base. There is no evidence of intercanyon flows down the nearby canyons of the North and South Forks of Little Butte Creek, but one flow traveled two miles down the head of Grizzly Creek. A few flows fanned out on Robinson Prairie to the southwest and one formed a mile long lobate feature at the southeast base of the butte.

Cinder Cones

In addition to the three cinder cones on Robinson Butte, there is one on the north side of Juniper Ridge in section 1 and another, named Pearce Point, located one mile north of Lake O' Woods. All of the cones are composed of a mixture of red basaltic lapilli and small scoria bombs. Very little ash is present. The Pearce Point cone has been excavated for road ballast exposing a vertical north-south dike approximately one meter thick. The rock is dark red like the cinders, and has dark green clinopyroxene and highly oxidized olivine phenocrysts.

Pearce Point is situated along a fault that bisects Rye Spur volcano. The cinder cones on Robinson Butte probably have a similar fault relationship as discussed above. The cone on the north side of Juniper Ridge has no apparent connection with north-south faulting but an older northwest trending fault may be on the north side of Juniper Ridge. Any evidence which may have connected this cinder cone with faulting has been buried under the younger flank lavas.

More evidence of cinder cones being associated with faulting is found outside the thesis area six miles east of Pearce Point. On the north flank of the Wilderness Lakes volcanic center, a north-south string of seven cinder cones is aligned with the west fault of the Klamath Graben.

The lavas of Mt. McLoughlin would belong to Thayer's Olallie group since, by definition, high peak lavas form a part of this group. Flows comparable to the contemporaneous Santiam basalts are not represented in the thesis area and they are not found in the Macdoel quadrangle. However, light grey intercanyon flows similar to the Santiam basalts fill the South Fork canyon of Big Butte Creek northwest of Mt. McLoughlin. These flows have the diktytaxitic texture that is so common to this rock type. There is no evidence that they originated in the thesis area and I believe that their sources were somewhere to the north of Mt. McLoughlin.

Flank Eruptions

On the northwest side of Mt. McLoughlin I have been able to map three different ages of flank lavas which I have labeled stages one, two, and three. The first two stages are interpreted as being contemporaneous with the growth of the main cone of Mt. McLoughlin, with stage three lavas being post-glacial.

Stage One Lavas

The oldest flank eruptions are olivine andesites which are located on the northwest flank of Mt. McLoughlin. The lavas are black, fine-grained and vesicular. The olivines are approximately 1 mm in size. The flows extend for 8 miles down the valley of Fourbit Creek. The flow limits are outlined by Willow and Fourbit Creeks. Big Butte Springs are located near the end of these flows which act as a large reservoir for the springs. The city of Medford has used these large springs as a source of water since the late 1920's. The flat surface of the flows suggests that the lavas were very fluid when they were erupted. The soil and colluvium on top of the flows is now more than a foot deep.

In the valley of Fourbit Creek, stage one lavas in places form a thin covering on a relatively thick deposit of alluvium which appears to be glacial outwash. The sediments, instead, are interpreted as stream deposits which were washed down during the early explosive phase of Mt. McLoughlin. The large quantity of material choked the stream valley and caused ancestral Fourbit Creek to deposit a thick layer of cinders and coarse sand in its channel. A gravel pit in these deposits is located on the west edge of Parker meadows (SW¼, sec. 26) just off the map. The size of the sediments ranges from coarse sand to pebbles several inches in diameter. Most of the rocks are dark, scoriaceous main-cone andesite pebbles.

Stage Two Lavas

After a break of indeterminant length, lavas again erupted on Mt. McLoughlin's flanks. These flows differ from those of the preceeding stage in having a distinct rubbly character, but they are otherwise similar in composition. The rubble may make up one half or more of the flow. In the center of the flow is a solid mass of medium-grey, fine-grained lava containing olivine phenocrysts. In some flows the core may be reddish like the rubble and it may tend to be diktytaxitic in texture. One of these flows crosses route 140 at mile post 31.2 in the west half of section 35. It is thin (c. 20 meters) in the roadcut but fans out on flatter terrain. It forms the bulge in the north shoreline of Fish Lake known as Doe Point. Similar flows can be seen in roadcuts between the Doe Point flow and mile post 32.7.

What appears to be the longest flow in the area is a second stage lava on the west flank of Mt. McLoughlin. Although its source is hidden under a more recent flow, it emerges in section 21 and extends for at least seven miles down the east branch of Willow Creek. I shall refer to it later as the Bear Pan flow since it is near Bear

Pan Spring, section 19, where the flow rubble was quarried for road surface material.

A large area of second stage flows is located near the northwest edge of the map. The flows emerge from under glacial outwash in section 27 and extend nearly four miles west to where Whisky Springs come forth from beneath them. The south fork of Fourbit Creek marks their northern boundary.

Most of the stage two flows are covered with vegetation which includes full grown trees, suggesting that soil formed quickly on the rubbly surfaces. Some vegetated areas grade into small patches of open lava and, since some flows are blocky like stage three lavas, a distinct age difference between the lavas could not everywhere be recognized. This is particularly true in section 36 along route 140 east of Fish Lake.

The sources for flank lavas seem to have been fissures but few vents have been mapped. Some have been hidden by the lavas mounding over their vents while others have no doubt been covered by younger lavas and glacial deposits. Some vents may have been active during more than one stage of volcanism.

Post-glacial (Stage Three) Lavas

There are three different textural types of olivine andesite and one silicic andesite that have erupted during the last episode of volcanism. They are very fresh but none is historic. Judging from their appearance, they may be only a few thousand years old, as are the

Recent flows in the McKenzie Pass area which have been dated radiometrically.

The first type of stage three lavas are coarse-grained olivine-pyroxene andesites. They were erupted from North Squaw Tip and South Squaw Tip, located above the 7000 foot level on the west side of the mountain, and near Rye Spring on the southwest flank. Chemically and texturally these andesites are main-cone lavas but they are block lavas instead of the rubbly flows which came from the central vent.

The second type of stage three lavas is located at the bottom of the northeast cirque in section 12. The rock is a massive, medium-grained olivine-pyroxene andesite. It is light-grey or red-grey in color, and has plagioclase, dark green clinopyroxene, and vitreous honey-colored olivine as phenocrysts. The mafic phenocrysts are very large and are commonly over one half centimeter across. Chemically, these flows are also like the main-cone lavas but their flow texture is quite different. They consist of large angular blocks which form thick, narrow flows, or what is sometimes called coulees.

The third type of lava is a fine-grained olivine andesite which was erupted on the flanks of Mt. McLoughlin after the Squaw Tip lavas. The flows look much like the stage one and two flank eruptions. They are fine-grained, dark, and contain small olivine phenocrysts. Unlike the fluid stage one and rubbly stage two lavas, the stage three lavas form blocky flows as do all post-glacial lavas. On the west side of the mountain stage three flank lavas are vesicular and tend to form long, blocky, steep-sided flows, (figure 6). On the south flank the lavas are not vesicular and form short mounded flows. Some of the mounds cover less than an acre in area and are not individually mapped. Blocks making up stage three flows may be several feet across, producing a coarse textured flow surface. Still, the tops of some flows show moving-lava features such as gutters, pressure ridges, and collapsed tubes.

Brown Mountain Lava

The fourth type of stage three lavas is a silicic andesite which covers Brown Mountain. These lavas look very much like the stage three blocky lavas on the south side of Mt. McLoughlin. Since these two types are found side by side in the field, it is fortunate that there is a way to distinguish between them. The Brown Mountain andesites very rarely contain olivine as phenocrysts, and are among the few lavas in the area which have no phenocrysts. The crest of Brown Mountain is crowned by a cinder cone that still retains its crater. The crater is oval shaped and approximately 100 meters long. The cone consists of fine light-grey andesitic cinders and ash, some of which has washed back into the crater so that it is now less than 10 meters deep. The youngest flows on the mountain postdate the cone and were erupted from a vent on the northwest side of it.

Three Stage Growth

The sequence of the types of eruptions suggest that there were three fairly distinct periods of growth for Mt. McLoughlin. The textures seen in the lavas are in agreement with what one might expect from a volatile-rich magma that is progressively degassing with time. The first eruptions (stage one), being rich in volatiles, are very explosive and produce large amounts of ash. If there are lava flows, they would be expected to be fluid and vesicular.

As eruptions continue (stage two), the magma slowly loses the volatile components and less violent eruptions of less fluid lavas follow. In time, the magma loses most of its volatiles and the lavas are viscous, forming blocky flows (stage three). Cinders and ash are still evident during the last two stages but they are produced in rather minor amounts.

PETROGRAPHY

Wasson Fourth Member

Two samples of the fourth member of the Wasson were sectioned for study. Sample LS-41 is an olivine andesite of an eroded vent just north of route 140 near mile post 26, southwest corner of section 31. This is considered a possible source for the fourth member flow breccias.

Phenocrysts which were once olivine have been completely altered to ore minerals, red-brown iddingsite, and green-brown serpentine. The phenocrysts were not large, less than 1 millimeter, and there is no olivine in the groundmass.

Ortho- and clinopyroxene occur in the rock, both as phenocrysts and in the groundmass. The orthopyroxene phenocrysts are subhedral and more numerous than clinopyroxene. Orthopyroxene, however, is subordinate in the groundmass. Plagioclase is the most common phenocryst phase. Both phenocryst and groundmass plagioclase is strongly zoned. The composition of the phenocrysts ranged from calcic andesine to sodic labradorite. The groundmass, which makes up about one half of the rock, contains mostly plagioclase and pyroxene with small patches of dark grey glass. A few apatite needles are present.

Sample LS-8 is another plug immediately west of Robinson Butte.

The rock is a leucocratic pyroxene diorite in hand specimen. In thin section, one can see that some of the interstitial material, which may have contained glass, has been altered and partially replaced by optically continuous calcite.

Large black phenocrysts of pleochroic bronzite, En 81, attain lengths of over 5 millimeters. Some of the smaller orthopyroxene laths, ½ mm in size, are jacketed with clinopyroxene (figure 7). The large bronzite phenocrysts are slightly rounded but show no reaction on their rims. Olivine is not present but may have been converted to bronzite, because these phenocrysts have many ore granules as inclusions. Clinopyroxene phenocrysts are present but most of them are in clusters with large plagioclase phenocrysts.

Heppsie Andesite

Two types of Heppsie Andesite can be recognized in hand specimen. They have been described in an earlier section as a light grey rock with dark phenocrysts and a medium grey rock with light-colored phenocrysts. Samples LS-2 and LS-58, respectively, are representative of these two types.

Sample LS-2 is an olivine andesite that has olivine phenocrysts (4 percent) set in a felted groundmass of plagioclase laths (72 percent), granular clinopyroxene (17 percent), and ore (4 percent). A small amount of brown glass makes up about 1 percent of the volume.

The remaining 2 percent of the rock consists of "ghosts" of former phenocrysts. Most of these ghosts are now composed of ore

Figure 7. Groundmass orthopyroxene jacketed with clinopyroxene. Scale on all microphotographs is approximately 4 cm = 1 mm, unless otherwise noted.

Figure 8. "Ghosts" of olivine phenocrysts consisting of ore granules and rimmed with clinopyroxene granules.

granules whose aggregate shape shows good crystal outline. The outline is rimmed with clinopyroxene granules while the core of the ghosts is filled with clinopyroxene, orthopyroxene, and plagioclase (figure 8). The former phenocrysts were probably olivines which were unstable and reacted with part of the magma which contained fresher olivine phenocrysts.

The rims and fractures of fresh olivine phenocrysts are stained a dark red-brown. This gives the olivine its dark appearance in hand specimen. The central portions are fairly well preserved. They commonly have good double pyramid or rectangular subhedral shapes and attain lengths up to 3 millimeters. Laths of calcic andesine are ½ millimeter in length. The amount of glass is so small that the rock has an intergranular texture.

In other areas sampled, where flow movement produced platy jointing, the rocks have good pilotaxitic texture. This texture is well developed in section 25, west of Willow Creek campground, figure 9.

Sample LS-58 is of the second type of Heppsie Andesite. Its finer grained size accounts for its darker color. The rocks are from a vent in which the olivine phenocrysts were extensively oxidized to ore. The rectangular crystal outline is not rimmed with pyroxene and the cores still show recognizable olivine. This alteration effect is apparently a phenomenon confined to the vent; lavas from the same vent have the fresher, light green olivine which is characteristic of this second type of Heppsie Andesite.

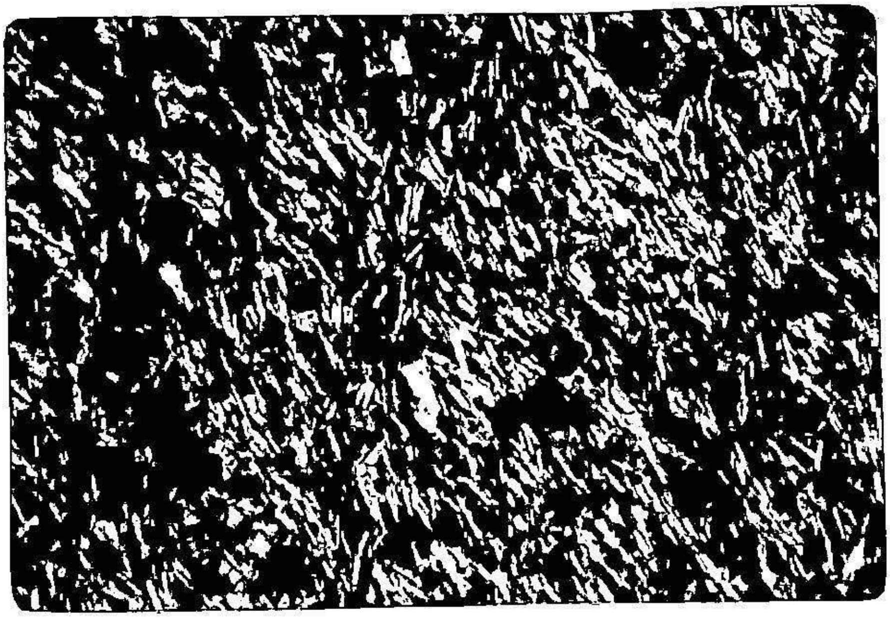

Figure 9. Pilotaxitic texture found in some of the Heppsie Andesite flows west of Willow Prairie Forest Camp.

Figure 10. Apatite needles radiating from glassy areas in a Plio-Cascades lava. Approximate scale is 1 cm = 0.1 mm.

Plio-Cascades

Samples LS-4, a plug rock, and LS-24, its associated lava, are examples of Plio-Cascades olivine andesites. The lava rack contains brown, stained olivine phenocrysts (4 percent), plagioclase (58 percent), clinopyroxene granules (14 percent), ore (5 percent), dusty brown glass (17 percent), and abundant small needles of apatite (2 percent) radiating out from the glassy areas (figure 10). The texture is intersertal although in places there is enough glass to completely surround the plagioclase laths in hyalo-ophitic texture. Olivine ranges in size from 0.1 to 1.0 mm and clinopyroxene less than 0.1. Plagioclase laths are 0.5 mm long and have a composition near An 60.

The plug sample is mostly intergranular with rare small patches of glass. The grains are equigranular and measure about 0.5 mm across. Some of the larger grains of pyroxene are subophitic around olivine and plagioclase. The olivine is very fresh and has clinopyroxene over-growths but a small amount of orthopyroxene is also present. One sample located near LS-4 was sectioned which was intermediate in texture between the two samples described. It has abundant orthopyroxene laths, some of which are coated with clinopyroxene. The plug rock has fewer apatite needles than the lava but they are twice as large (0.1 mm long).

Olivine Basalts

Sample LS-56 was taken from glacial material at the north base of Mt. McLoughlin but derived from the area to the north. The sample contains olivine phenocrysts (8 percent) which form subhedral prisms 1 to 5 mm long. Some of the olivine is granular, less than 1 mm, but there is none in the finer, granular groundmass. Plagioclase phenocrysts comprise 30 percent of the rock and have an estimated composition of An 60-70. The groundmass contains plagioclase (25 percent), granular clinopyroxene (30 percent), ore (5 percent), glass (2 percent), and a few needles of apatite (less than 1 percent).

Fish Lake Series

The Fish Lake Series on the south side of Brown Mountain is a group of andesite flows in which an olivine andesite grades into a silicic andesite.

The striking characteristic of the early flows of this series is the large amount of black glass. In sample I, the glassy groundmass is 70 percent of the bulk in which large ($>1/2$ mm) phenocrysts of plagioclase, olivine and pyroxene are imbedded (figure 11). The glass has a patchy appearance that appears to result from mixing of different portions of the lava which had different stages of microlite development. The microlites, when large enough to recognize, are plagioclase, pyroxene and ore grains.

The phenocrysts consist of sodic labradorite (20 percent), olivine (4 percent), clinopyroxene (4 percent), and orthopyroxene (2 percent). Most phenocrysts are 1 to 3 millimeters in length except for olivine which is less than 1/4 millimeter. The olivine is stained red-brown or rimmed with small grains of ore. The plagioclase and pyroxene phenocrysts are rounded in their outline, zoned, and have

Figure 11. Typical texture of early Fish Lake lavas showing glassy groundmass and large phenocryst phases.

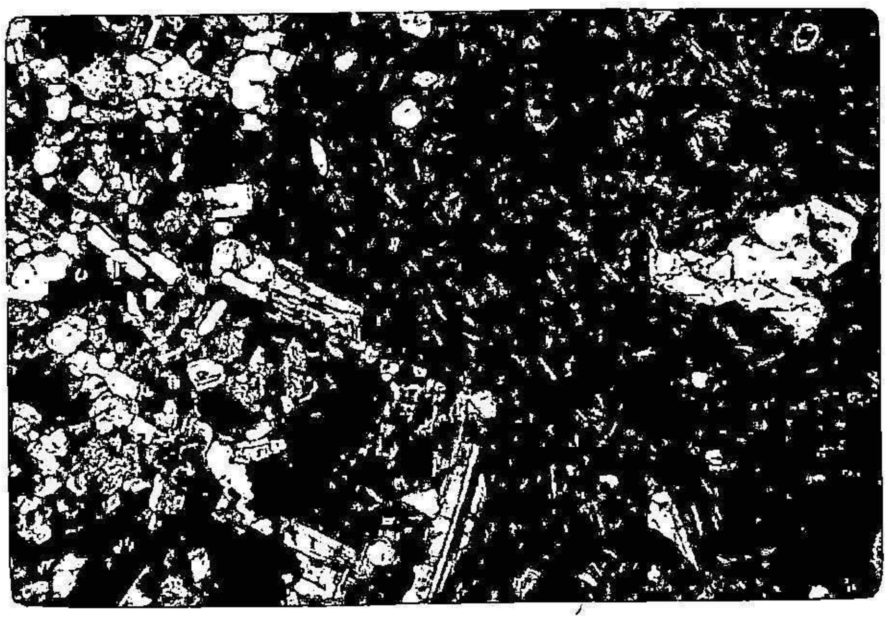

Figure 12. Plagioclase-orthoclase glomerophenocryst commonly found in Fish Lake lavas south of Brown Mountain.

cavities filled with glass. They also contain inclusions of olivine grains.

Another noteworthy feature in this rock, and for the series as a whole, is the common occurance of cumulate phenocryst clots. There are two types of clots. The first is simply a cluster of similar large phenocrysts scattered throughout the rock. The second consists only of plagioclase (70 percent) and orthopyroxene (15 percent). The interstices are filled with glass similar to that of the host rock (figure 12). The plagioclase laths are 1 millimeter in length, or half that of the regular phenocrysts. The composition of the plagioclases is approximately the same. The orthopyroxene grains are much smaller than those in the host rock. They are rounded crystals which may approach 0.25 millimeter in size but are commonly only 0.1 mm.

Younger rocks in this series generally become lighter in color as microlites in the glass grow larger, but this may vary even in a single flow. Sample III is similar to I in having four types of phenocrysts but in a less glassy matrix. The plagioclase again shows strong zoning and resorption. Many of the larger phenocrysts are so spotted with resorption scars and pyroxene inclusions that the twin lines can scarcely be seen. A crystal of this type was found to have a composition in the bytownite range. Other plagioclase grains have less pronounced resorption or none at all. Most of these crystals are smaller and fall in the labradorite composition range.

The olivine content of sample III is approximately the same as in sample I. The grains are commonly stained and show a reaction relationship with their surroundings. Those found in the glass are rimmed with augite and ore granules. Those found in phenocryst clusters have overgrowths of orthopyroxene.

Orthopyroxene was not present as intermediate sized phenocrysts in sample I. In sample III, it appears in small but erratic amounts. It is still the least common mafic phase. Ore grains up to 0.25 mm are now present as small phenocrysts also.

Phenocryst clusters are still abundant and vary in their mineral proportions. All contain plagioclase which usually makes up about half of the volume. The predominant or only mafic phenocryst may be olivine or one of the pyroxenes. A rare third type of cluster was found in sample III. It consists almost entirely of olivine grains (0.1 to .25 mm in size) with a small amount of poikilitic plagioclase.

Sample V is from a later flow which is completely crystaline. There are still four phenocryst phases: plagioclase (45 percent), orthopyroxene (7 percent), clinopyroxene (3 percent), and olivine (<1 percent).

The olivine content is greatly reduced from that of the older flows in the series. When found, it is jacketed with orthopyroxene or has been extensively replaced with granular ore and augite. The clinopyroxene phenocrysts are commonly found in clusters with plagioclase and are less abundant than in previous flows. The amount of orthopyroxene is markedly greater than in earlier flows (from 2 to 7 percent). This increase is a result of the growth of intermediate sized (¼ to ½ mm) euhedral phenocrysts. These crystals lack clinopyroxene jackets.

Phenocrysts of labradorite are zoned from approximately An 60 to An 50 with a thin sodic rim. The zoning of the phenocryst shown in figure 13 is typical. The core is calcic labradorite (An 65), but the next zone is andesine (An 45). It contains many pyroxene inclusions around its outer portion. Next, a more calcic zone of labradorite (An 58) was deposited before the thin rim of oligoclase (An 28).

Crystals less than ½ millimeter in size are considered groundmass. The latter consists of plagioclase (11 percent), pyroxene (2 percent), ore (8 percent), and about 23 percent microcrystaline material.

Mt. McLoughlin Lavas

Fine-grained Flank Lavas

The dark, glassy lavas which were erupted on the flanks of Mt. McLoughlin look very much like basalts but in fact are olivine andesites. Sample LS-39 is typical of stage two flank lavas (figure 14). The rock appears dark because so much of it (39 percent) is dark brown dusty glass.

The only phenocrysts are olivine (3 percent), ½ to 2 millimeters in size. They are rimmed with small pyroxene granules (0.1 mm) and contain grains of opaque spinel (.03 mm). The groundmass laths of plagioclase (An 53, 37 percent) and orthopyroxene (14 percent) are approximately 0.1 to 1 millimeter long. Clinopyroxene (7 percent) is found as coatings on low-birefringent crystals of orthopyroxene laths and also as granules less than 0.1 millimeter in size. Upon

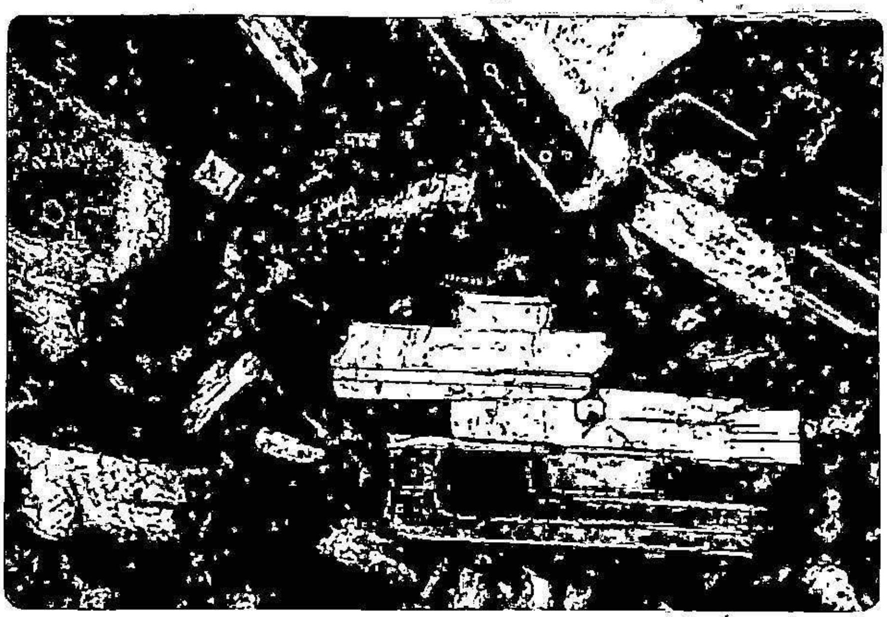

Figure 13. Typical zoning of the plagioclase phenocrysts in the Fish Lake lavas south of Brown Mountain.

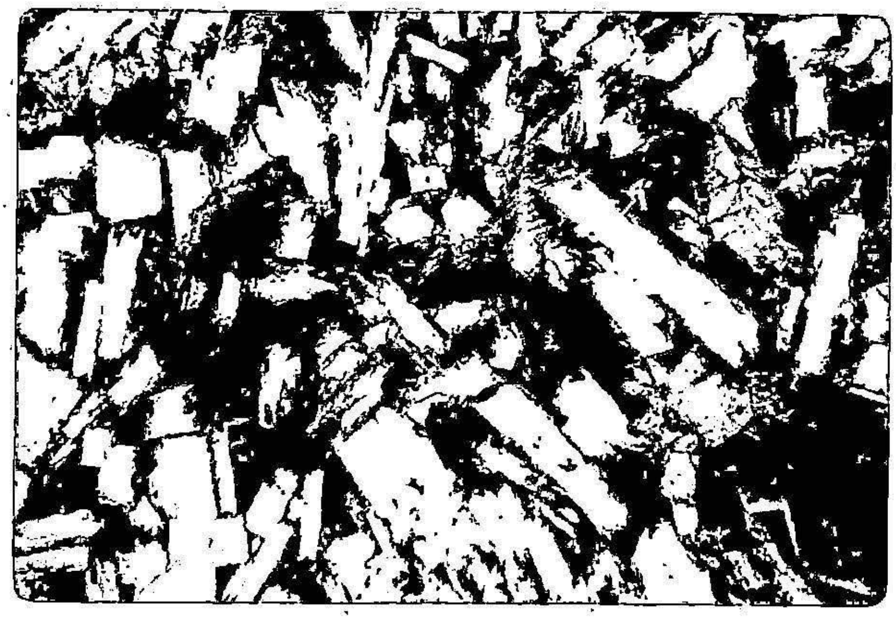

Figure 14. Typical texture of fine-grained flank lavas of Mt. McLoughlin.

quenching, augite needles formed. They are easily seen when they grow out over plagioclase from the glassy areas. The needles are clear except for included ore grains and due to their small diameter show very low birefringence. They are approximately .03 millimeters long and .003 wide.

Sample LS-26 is a stage-three lava erupted on McLoughlin's southeast flank. The rock is very similar to the one just described. The olivine (4 percent) is about the same size and it contains spinel, as do all the olivines examined from dark flank lavas. The composition of the olivine is near Fo 81.

Sample LS-26 contains more glass (51 percent) than LS-39 and the plagioclase laths (33 percent) are about half the size (<½ mm). Orthopyroxene (7 percent) and clinopyroxene granules (5 percent) are also less abundant. The augite needles formed upon quenching are slightly larger and are prominantly grouped in subparallel clusters (figure 15).

Main Cone Lavas

All of the flows which were erupted either from the central vent or high on the slopes of Mt. McLoughlin are highly porphyritic olivine-pyroxene andesites. They contain phenocrysts (½ to 5 mm) of plagioclase, clinopyroxene, and olivine or orthopyroxene. These large phenocrysts constitute ¼ to ½ of the rock and give the lavas the coarse texture seen in hand specimen. In thin section, the texture is hyalopilitic with glass making up 20 to 40 percent of the bulk.

Figure 15. Subparallel clusters of augite needles formed during quenching in a fine-grained flank lava.

Figure 16. Typical texture of the coarse-grained lavas of the main cone of Mt. McLoughlin.

This general description applies to most of the post-glacial flows.

Sample LS-7 is from a stage-two lava which was one of the last flows to erupt from the summit area. It is fairly characteristic of the lavas as a whole (figure 16). The megaphenocrysts constitute 47 percent of the bulk and consist of plagioclase (39 percent), orthopyroxene (2 percent), and clinopyroxene (3 percent). Olivine crystals (3 percent) in this sample are only about ½ millimeter in diameter, but they occur in cumulate clots which are several millimeters across.

The groundmass crystals range in size from 0.1 to 0.25 millimeter and consists of plagioclase (9 percent), orthopyroxene (5 percent), clinopyroxene (1 percent), and ore (1 percent). The remaining 37 percent of the rock is a red-brown dusty glass. It contains microlites of plagioclase, clinopyroxene, and ore which are less than .02 mm in size. Hematite forms small, irregular red patches which are especially abundant surrounding ore grains.

Orthopyroxene in the groundmass is generally larger and more euhedral than the clinopyroxene. Some of the laths are rimmed with clinopyroxene, as is true of most of the lavas of the area. This indicates that hypersthene was the stable phase prior to the eruption and that the change to clinopyroxene (perhaps pigeonite) occured at some time during eruption, or upon quenching.

Phenocryst Petrography

Olivine

Olivine is found in all of the main cone lavas but in a modal concentration of only a few percent. It does not commonly form mega-phenocrysts. Most crystals are 0.25 mm in size and are often found in clusters with plagioclase. Only in some of the post-glacial lavas on the northeast side of McLoughlin is there a noticeable concentration of large phenocrysts of olivine. Sample LS-71 is from one of these flows. The olivine crystals from this sample attain a length of over 1 centimeter. The grains are very fresh with little staining along fractures. There are small orthopyroxene grains around the margins. Some crystals have abundant chromite grains as inclusions, just as in the olivine of the fine-grained flank lavas, while others have none at all.

There are smaller grains of olivine, ½ mm size, in the groundmass of LS-71. One is completely surrounded by orthopyroxene in optical continuity (figure 17). The sides of the orthopyroxene, in turn, are coated with clinopyroxene. The smaller olivine grains do not contain ore inclusions.

Many of the main cone flows studied, including samples LS-3, LS-6, LS-7, and LS-14, have most of their olivine still in small cumulate clusters (figure 19). The grains are commonly stained, rounded, and about ½ mm in size. They do not contain ore inclusions. The interstitial space in the clusters may be filled with poikilitic

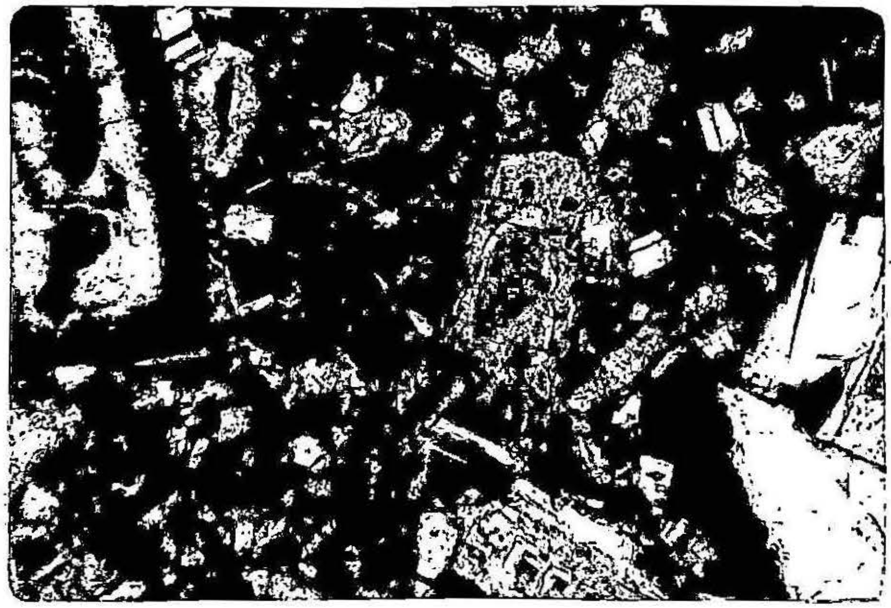

Figure 17. Olivine grain which has been surrounded by orthopyroxene and then by clinopyroxne, all in crystalographic continuity.

Figure 18. Orthopyroxene phenocryst with concentric pattern of olivine inclusions.

plagioclase or ophitic pyroxene.

The 2V of the olivine is very large, near 90°, and almost all of the grains tested had a negative optic sign. This indicates that the molecular content of the olivine is around Fo 80-85. No zoning was detected and it is assumed to be limited to a few molecular percent.

Orthopyroxene

Orthopyroxene is not a common megaphenocryst phase in main cone lavas. In samples LS-6 and LS-7, large phenocrysts are present which are bordered by granular olivine. This is a reversal of the normal reaction series. In the same phenocrysts, olivine may be found as granular inclusions which line up in a concentric pattern (figure 18). In sample LS-7 the olivine inclusions in the orthopyroxenes are numerous, embayed, and several in a group may be optically continuous. This olivine is interpreted as remnant cumulate material in which much of the olivine has been converted to pyroxene (figure 19). No ore granules are present as the by-product of this change, because iron combined with silica from the liquid phase.

Although not common, some clusters of granular cumulate orthopyroxene have interstitial plagioclase. Large pyroxene crystals often have a few inclusions of small plagioclase grains. No pyroxenes were found to have inclusions of the other type of pyroxene.

In thin section, most of the rocks in the mapped area show sub- to euhedral laths of intermediate sized orthopyroxene crystals. In many of the samples studied, these laths were coated with clinopyroxene.

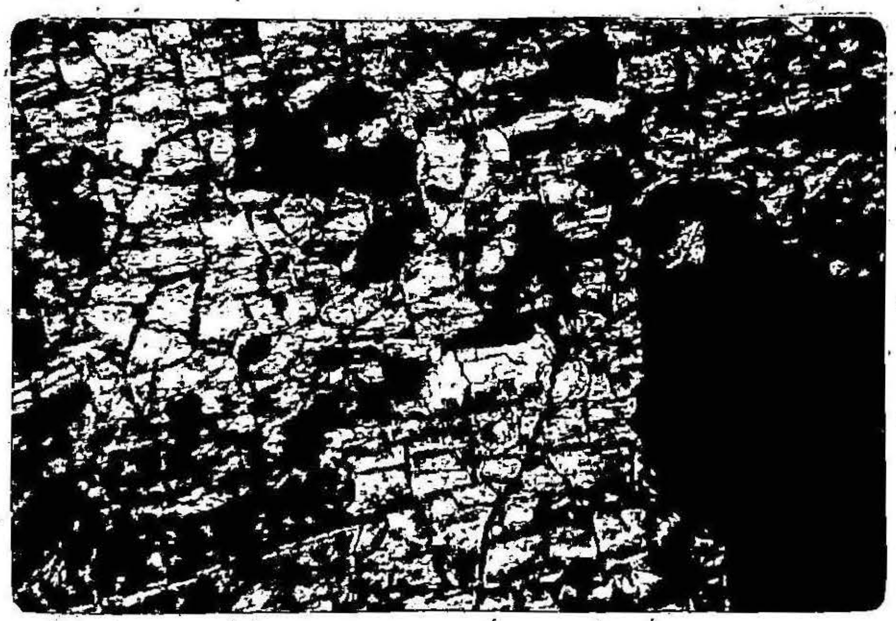

Figure 19. Pyroxene phenocryst with included and partly converted cumulate olivine material.

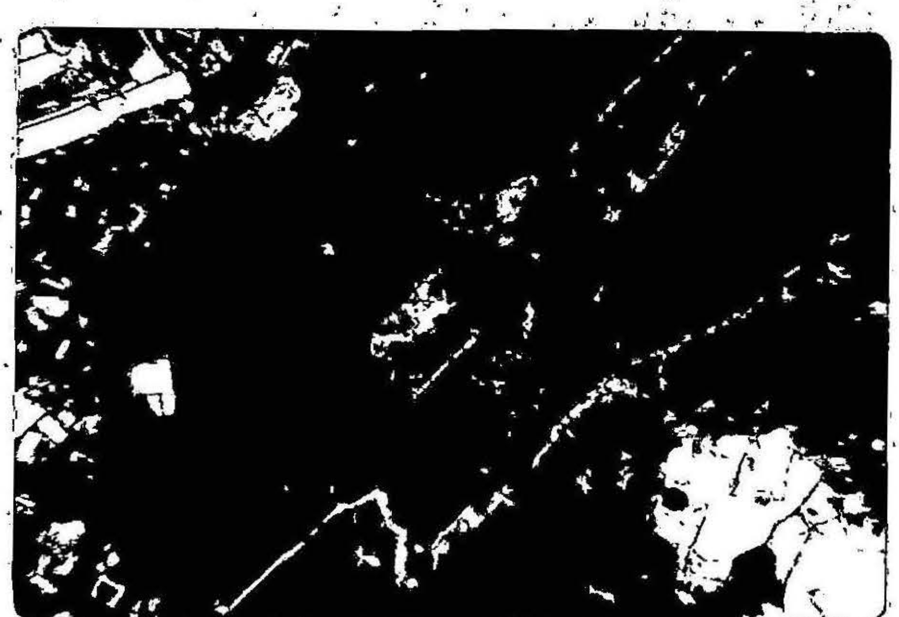

Figure 20. Euhedral, twinned, and zoned clinopyroxene with olivine inclusions.

The birefringence ranges from a dark grey to yellow-orange and only laths which show the lowest birefringent colors are seen to be coated. This indicates that the clinopyroxene prefers to grow on the (100) faces of the orthopyroxene crystals.

As in the olivine crystals, optic angles of the orthopyroxene megacrysts are very large and their optic signs are negative.

Clinopyroxene

Megacrysts of clinopyroxene occur in all of the main cone lavas studied. Modal concentrations in many sectioned samples appear to be less than 1 percent. In sample LS-6, one of the last flows to come from the summit area, the mode is near 8 percent. The crystals are characterized by numerous inclusions of olivine and plagioclase. Some inclusions are very large compared to the size of the pyroxene grains, (figure 16). There are also resorption fillings of glass and plagioclase. Orthopyroxene is sometimes seen as small grains on the rims, but most of the crystal outlines show no reaction with the liquid.

As noted with orthopyroxene, some crystals of clinopyroxene in sample LS-7 occur as ophitic overgrowths in remnant olivine cumulate material. Faint zoning can be seen in some crystals which have been cut close to basal sections. It is not uncommon for the phenocrysts to be euhedral and twinned, (figure 20).

Phenocryst Composition

Many of the rocks studied contain large mafic phenocrysts and it was fairly easy to pick the grains from the crushed rock. Once the grains were separated and finely crushed, a small quantity was sprinkled on a glass slide with a drop of calibrated index oil. When a favorably oriented grain is found, the refractive index of a principle crystal ray can be determined by matching it with that of the index oil that surrounds it.

The index of the beta ray was used in olivine and clinopyroxene and the gamma ray in orthopyroxene. The beta ray in olivine and the gamma ray in orthopyroxene vary directly with the Mg to Fe ratio in the mineral lattices so that once the ray indices are determined, the mineral compositions can be read from the graphs drawn by Poldervaart (1950).

To estimate the compositions in the clinopyroxenes, both an index and the 2V of the mineral is needed, because the composition varies with the three major components of calcium, iron, and magnesium. Clinopyroxene data was plotted on the graph drawn by Hess (1949).

Accuracy of index determinations for olivine and orthopyroxene was approximately ± .002 which corresponds to error in the molecular content of ± 1 percent.

Because of the high index of clinopyroxene beta rays, the index oils had to be mixed to give approximate intermediate values. Thus, the accuracy for this mineral was on ± .005 which gives a large molecular error of $\pm$ 5 percent. The 2V measurement varied several degrees from grain to grain in one thin section, ranging from 52 to 56 degrees. The combined errors and variation produced a very approximate chemical composition for the clinopyroxenes using petrographic techniques. Assuming there is a continuous range of 2Vs from 52 to 56 degrees, the clinopyroxene compositions fall in the calcic augite field of Poldervaart and Hess (1954).

In tables 9 and 10, page 113, are listed chemical analyses of phenocrysts from rocks of Mt. McLoughlin and Crater Lake. The phenocrysts were picked from crushed rock, mounted in epoxy, and analysed with the electron probe. All analyses were provided to me by William P. Leeman of the Center for Volcanology, University of Oregon.

Data for the pyroxenes are plotted on a quadrilateral diagram in figure 21. The clinopyroxenes from both centers form a tight grouping in the calcic augite field. The orthopyroxenes have a range in compositions from bronzite (En 80) to hypersthene (En 65). Tie lines connect analysed pyroxene pairs from the same sample.

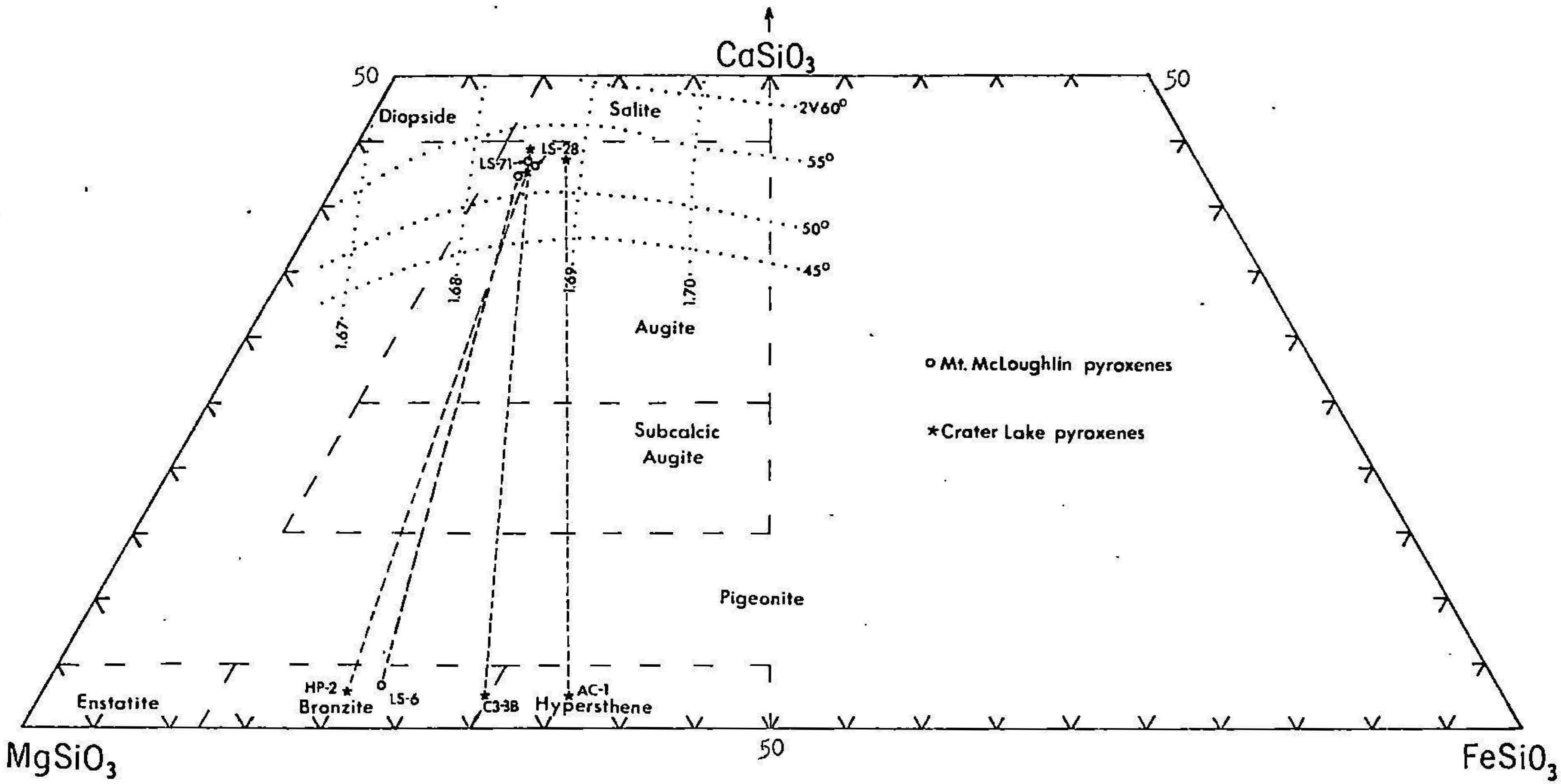

Figure 21. Pyroxene quadralateral with compositions of pyroxenes from Mt. McLoughlin and Crater Lake andesites. All points are microprobe analyses by William P. Leeman, (1973 unpublished data). Analyses are listed in tables 9a and 9b. Nomenclature by Poldervaart and Hess (1951). Refractive indices and 2V optical properties from Hess (1949) and Muir (1951).

Plagioclase.

The composition of plagioclase feldspars was approximated by using the combined albite-Carlsbad twin technique. In this method, angles between the twins are measured on a favorably oriented grain by rotating the stage of the microscope, and then plotting these angles on a chart to estimate the anorthite content. The chart used was a high temperature one drawn by Tobi (1963).

When possible, three separate measurements were taken on a favorable grain. These conform to three natural divisions in the crystal of core, outer zone, and rim. In main cone lavas, the cores are assumed to have been crystalized at a great depth and range in composition between An 50-60. The largest crystals generally show resorption features and their cores are sometimes more calcic than An 70. The outer zone is assumed to have crystalized at a shallower depth than the core and ranges in composition from An 40-50. The outer rim is believed to have crystalized during eruption and is commonly An 30-40.in composition.

The large plagioclase phenocrysts in nearly all of the lavas of the area are characterized by extreme normal, oscillatory, and patchy zoning. These types of zoning are common in orogenic andesites as a whole. The core has normal and patchy zoning, the outer zone normal and oscillatory zoning, and the rim normal zoning.

Normal zoning is commonly believed to be the result of simple crystal fractionation as proposed by Bowen (1934). In this process both the liquid and the crystals become progressively more sodic as crystalization proceeds.

The commonly held interpretation for oscillatory zoning is that it results from periodic slight increases in volatile pressure. After a pressure increases, crystalization of plagioclase is more calcic and this reversed zone is then followed by normal zoning as the effect of the pressure increase is reduced. Several episodes such as this can produce a series of reversals or oscillatory zoning.

Patchy zoning is a term proposed by Vance (1966) to describe the mottled cores of feldspar crystals. The patchy appearance is caused by resorbtion blebs being filled with more sodic plagioclase in crystalographic continuity. Some resorbed areas contain clear glass and some have very small poikilitic inclusions. The inclusions are interpreted as the crystals formed from the other components of the trapped liquid in the cavity. This is evidence that the resorbtion features were caused by a cavity forming process and not merely by ion exchange within a stable crystal lattice framework.

For the cause of patchy zoning, Vance proposed that resorbtion of the calcic centers of crystals is caused by a decrease in pressure resulting from upward movement of magma. While some resorbtion is taking place in the cores as pressure diminishes, the magma is also cooling. The temperature drops until it intersects the liquidus at a point where a more sodic phase is deposited in the central cavities and at the rim.

In his argument, Vance used a set of hypothetical liquidus-solidus curves for the albite-anorthite system which were extrapolated from the limited knowledge of the system at that time. I have visually compared Vance's curves with those that have since been determined by Yoder (1969). If Yoder's curves are a closer approximation of how plagioclase crystalizes in a magma chamber, then those drawn by Vance are much too flat in the solidus and should be suspect.

Although Vance's explanation for patchy zoning is still possible, I prefer to invoke a volatile pressure buildup-and-release mechanism as a more plausible means of producing these features.

Because of the explosive character of orogenic andesites, many workers have assumed that these lavas maintain a high but variable volatile pressure and that most of this is due to water in the system. Volatile pressure buildup before an eruption and the amount of pressure release during an eruption should have a marked effect on the crystallization history of plagioclases in the magma chamber. Using P(pressure) = 1 bar as a reference pressure, Yoder (1969) has shown that a moderate increase in the water pressure, P_{H2O} = 150 bars, causes a larger shift in the plagioclase system than a large increase in dry pressure, P = 10kb, and in the opposite direction (figure 22).

My argument is as follows: A small but sudden isothermal increase in volatile pressure on a magma would lower the liquidus-solidus curves. The equilibrium liquid could then be more calcic than the crystals and resorption could occur. If this pressure is later rapidly released, the curves would then be raised, presumably high enough for a more sodic phase to crystalize in the resorption holes and on the rim.

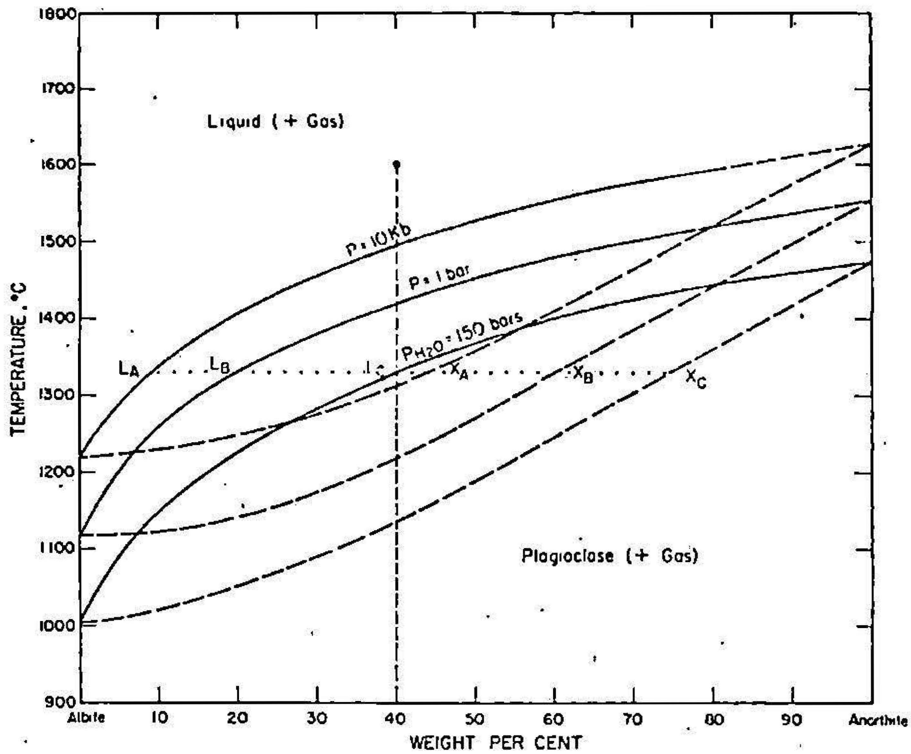

Figure 22. The albite-anorthite system at 1 bar and 10 kb and the hydrous system at 150 bars. Adapted from Yoder (1969).

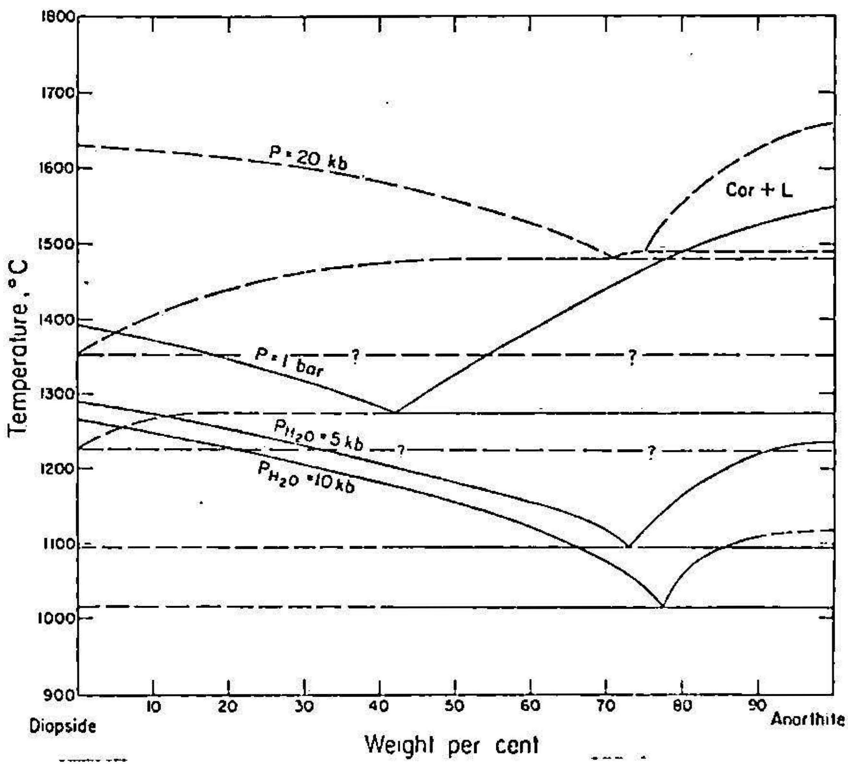

Figure 23. The diopside-anorthite system at 1 bar and 20 kb dry and at 5 and 10 kb wet. Adapted from Yoder (1969).

Associated Vents

Several volcanic vents are located on the ridge that trends southeast, away from Mt. McLoughlin. The lavas are coarse-textured, porphyritic andesites and basic cumulate andesites which are believed to be contemporaneous with the second stage growth of the main cone.

Sample LS-28, a Frey Lake lava, is a pyroxene andesite which contains megaphenocrysts of clinopyroxene over 0.5 cm across. In thin section these are seen to be tight clusters of clinopyroxene with individual crystals ranging from 0.5 to 3 mm in size. They constitute nearly 4 percent of the bulk of the rock.

Twinning of the grains and inclusions of olivine and plagioclase are common features. Some olivine inclusions are embayed and several may go extinct at once under crossed nichols. This indicates that original cumulate olivine has now been changed to pyroxene, (figure 24). Many crystals not in clusters are euhedral.

Olivine is not conspicuous in hand specimen since the granules are generally less than 0.5 mm. This mineral makes up nearly three percent of the mode. Small crystal clusters consisting of granular olivine and plagioclase in nearly equal proportions are fairly common. Orthopyroxene is rare. Labradorite phenocrysts make up 40 percent of the rock. They are zoned from approximately An 60 in the cores to near An 40 on the rims.

Over 53 percent of the rock is groundmass. It is composed of plagioclase (29 percent), pyroxene (18 percent), and ore (5 percent)

Figure 24. Cumulate olivine as inclusions in clinopyroxene.

Figure 25. Texture of Brown Mountain lava showing rare olivine phenocryst.

set in a microcrystaline matrix (1 percent). Both pyroxenes are present in nearly equal amounts.

Sample LS-82 was taken in section 33, to the southeast of the Frey Lake lava previously described. Although similar in hand specimen, it is more basic than LS-28 and is an olivine-pyroxene bearing basaltic andesite.

The most abundant mafic phenocryst is olivine (7 percent). The subhedral grains are commonly 0.25 to 0.5 mm in size with a thick, red-brown alteration zone at their rims. The mineral appears much fresher when found in granular form, eithor as separate grains, as inclusions, or in clusters with plagioclase and pyroxene. Olivine crystals contain many small ore grains, some appear to be chrome spinel.

Clinopyroxene (2 percent) and plagioclase (34 percent) also occur as phenocrysts. The plagioclase laths are commonly 1 mm in length and are zoned from calcic labradorite (An 67) to andesine. Orthopyroxene is present in minor amounts and is found as intermediate sized grains, some of which are coated with clinopyroxene.

The groundmass constitutes 57 percent of the rock. Granular pyroxene accounts for 42 percent of the groundmass material or 24 percent of the total bulk. Groundmass plagioclase represents 27 percent and ore 5 percent, with microcrystaline material making up less than one percent of the bulk.

Sample BL-9, from the top of Robinson Butte, is associated with the late stage cinder cone on top. The rock has a large proportion of mafic phenocrysts (11 percent), which may be due to cumulate enrichment and give the rock a basaltic composition. This lava may not, therefore, be representative of Robinson Butte as a whole. Only one other Robinson Butte sample was sectioned and although it was taken from the north flank of the butte and is from the older north vent, it also seemed to be enriched in mafic phenocrysts.

Olivine makes up 5 percent of sample BL-9 and clinopyroxene 6 percent. Olivine is strongly stained along fractures and rims but is otherwise little altered. Grain sise ranges from less than 0.25 mm to more than 2 mm. Both large and small grains are found in phenocryst clusters and in the groundmass. The largest grains contain chrome spinel inclusions, commonly grouped near the centers of crystals. When in contact with the groundmass, olivine is rimmed with granular clinopyroxene.

Clinopyroxene occurs as euhedral to subhedral phenocrysts over 3 mm in length and as granular material in the groundmass. Most large crystals are found in clusters with plagioclase and granular olivine. The latter two minerals commonly occur as inclusions in the clinopyroxene. Often, pyroxene crystals are twinned and some show faint, broad oscillatory zoning in basal sections, similar to that shown in figure 20.

Several large phenocrysts contain olivine inclusions which go to extinction together, again suggesting that a former olivine crystal has largely been converted to pyroxene. No orthopyroxene was found.

Brown Mountain Lava

The blocky flows which cover most of Brown Mountain are amoung the youngest flows in the Cascades. Sample BL-4 is one of the latest of these lavas. It erupted from the northwest base of the summit cinder cone.

The rock is dark grey, fine-grained, and looks very much like a basalt but is in fact a silicic andesite at 59 percent silica. The dark color is a result of a dark, glassy base which makes up 67 percent of the rock, (**figure 25**). The base, in thin section, is a light brown glass which contains small crystalites of pyroxene and plagioclase. Crystals of orthopyroxene (6 percent) and labradorite (27 percent, An 55) are considered groundmass since they form laths less than 0.5 mm in length.

The lack of mafic phenocrysts attests to the silicic nature of the rock. An occasional phenocryst of plagioclase (1 mm in size) which show resorption and a few rare olivines are found but the rock is essentially non-porphyritic.

All of the Brown Mountain lavas studied were of this same character, glassy and non-porphyritic. In places, especially on the east side, schlieren are very noticeable on weathered surfaces of blocks. Fresh surfaces do not show these lighter bands to such a degree. As seen under the microscope, this feature could be explained by the mixing of two separate portions of the magma which had different degrees of crystalization in the groundmass or by segregation of a filter-press liquid.

NOMENCLATURE

The chemical compositions of the lavas sampled range from basalt to silicic andesite. Silica values range from 52 to 61 percent. Rocks were named on the basis of a combination of factors which would prove both reasonable and workable. These factors are: 1) natural discontinuities in the compositional sequence of lavas, 2) petrographic changes, 3) cation norm values, and 4) a desire to conform as closely as possible to rock terms now in use in the literature.

Because of the limited number of chemical analyses, many workers in the past have distinguished andesites from basalts by the disappearance of olivine in the more silicic rocks. On this basis, some basalts may have silica values above 58 percent. More commonly, however, the term andesite refers to orogenic lavas which have silica values ranging between 53 and 63 percent.

Basalts

Rocks in this study are considered basalts if the normative value of the anorthite component of total plagioclase exceeds 50 percent. This break is near the silica value of 53 percent and fortuitously falls on a natural break in the compositional sequence of lavas studied. Other means used to characterize basalts are a normative quartz value of less than 2.5 and a color index greater than 30.

Andesites

For convenience, and to conform to recent usage, andesites are commonly divided into two groups called basaltic andesites and silicic andesites. Basaltic andesites are those lavas which have a silica content between 53 and 58 percent and which may or not contain olivine phenocrysts. The normative anorthite content of these lavas is less than 50 percent, normative quartz is between 2.5 and 10 percent, and the color index is between 20 and 30.

Silicic andesites are lavas which normally contain no olivine. They are characterized by a silica value above 58 percent, normative quartz above 10 percent, and a color index of less than 20. There is no natural discontinuity between basaltic andesites and silicic andesites, nor between silicic andesites and dacites.

These divisions are fundamentally the same as those used by Greene (1968) for the Mt. Jefferson area and by Wise (1969) for the Mt. Hood area. Other commonly used terms are "low-silica andesite" and "olivine andesite" which are essentially basaltic andesite. The terms "high-silica andesite" and "pyroxene andesite" are comparable to silicic andesite.

VOLUME RELATIONSHIPS

It is important to know the abundance of the different lava types, but since limits on the thicknesses and the area covered by older flows could vary greatly, only crude estimates are possible. Consequently, volume estimates are presented only for the major rock types which post-date the Heppsie Andesite. As a starting assumption, the upper surface of the Heppsie Andesite is believed to lie at an average elevation of 3000 feet when extended beneath the High Cascades. Since on the western edge of the thesis area these older lavas dip between 5 and 10 degrees to the northeast, some mechanism is assumed, such as repeated faulting or lessning of dip, to keep the formation near this elevation. The area used in the calculations is a 12 by 7.5 mile north-south strip which lies directly west of the Lake O' Woods fault and runs the length of the thesis area.

Plio-Cascades and Olivine Basalts

Pliocene and Pleistocene basalts and basaltic andesites which erupted before the Fish Lake series have an estimated average upper surface elevation of 5000 feet. The calculated volume of these lavas (with average dimensions of 12 miles long, 7.5 miles wide, and 2000 feet thick) is 35 cubic miles. The high-phosphorus basaltic andesites comprise one-third to one-half of this volume with the younger olivine basalts making up the remainder.

Fish Lake Series

The volume of the Fish Lake series in the strip area is estimated to be nearly 6 cubic miles. This is the sum of a calculated northern and southern portion. That portion of the series north of route 140 is about 2 cubic miles. The average dimensions are 7 miles long, 3 wide, and 500 feet thick. These numbers take into account the high basement (6000 feet) of olivine basalt at the north end and the thinning of the Fish Lake lavas near route 140.

The volume of the southern portion of this series is estimated to be 4 cubic miles. The top of the older olivine basalts is believed to stay near 5000 feet elevation from route 140 to the south edge of the map. Near the south edge, the Fish Lake series appears to thin once again. The average dimensions used for calculating this volume are 4 miles long, 5 miles wide, and 1000 feet thick. The silicic andesite differentiates were found to occur only southeast of Brown Mountain and probably add less than 0.5 cubic mile to the volume of the series.

Late Pleistocene and Recent Lavas

The volume of Mt. McLoughlin, before glaciation, was computed from the equation for the volume of a simple cone, $V=\pi R^2H/3$, where R is the radius and H the height of the cone. With an estimated elevation of 3500 feet above the surrounding terrain and a radius of 1.5 miles, the volume is close to 1.8 cubic miles. Even when the flows around the base are added, the volume is still less than 2 cubic miles. The size of Mt. McLoughlin may seem insignificant when compared with volumes of Mt. Hood (about 10 mi^3), Mt. Rainier (about 30 mi^3), and Mt. Shasta (more than 50 mi^3). Mt. McLoughlin is comparable to one of the Three Sisters in volume.

My interpretation of Mt. McLoughlin's beginning, shown in cross section BB', plate 1, is that the older units beneath the mountain form a high base at 6500 feet elevation. Included with these older units could be a pre-stage-one buildup of McLoughlin lavas to form a shield "platform" before stage one pyroclastic rocks were laid down. Although this is known to have occurred at other Cascade volcanoes, there is no evidence to support this interpretation at Mt. McLoughlin.

If the original base were at 6500 feet elevation, the stage one pyroclasic cone would not be near enough to the surface to be exposed by erosion. However, if large sections of the cone were raised several hundred feet by stage two injections of lava, they could form outcrops now seen in the cirque headwalls. An alternate explanation of why stage one pyroclastic rocks are found at such a high elevation would assume that explosive activity continued well into stage two but the cone was reinforced by hidden lava flows to enable it to grow to great height.

The volume of Robinson Butte is estimated to be 0.5 cubic mile. The Recent silicic andesite flows covering Brown Mountain have an estimated average thickness of 250 feet and cover more than 13 square miles. This amounts to another half cubic mile. Other late Quaternary flows on the flanks of Mt. McLoughlin are less than 0.1 cubic mile in volume. Therefore, all late Pleistocene and Holocene volcanism in the mapped area totals three to four cubic miles.

The estimated break-down of the volume by rock type for the High Cascades in the thesis area is as follows:

Plio-Cascades basaltic andesite	15 mi^3
Olivine basalt (very speculative)	20 mi^3
Basaltic andesite	9 mi^3
Silicic andesite	1 mi^3

ANALYSING TECHNIQUES

Major oxide contents were determined on 35 samples using the X-ray fluorescence (XRF) method described by Norrish and Hutton (1968). A general description of the method is as follows: A rock sample is crushed and powdered using equipment which minimizes contamination. Two glass discs are made from each sample using a fusion-stamping process. The discs contain a mixture of precisely weighed portions of rock powder, lanthanum tetraborate flux, and sodium nitrate. Discs of known mixtures, standards, and unknown samples are subjected to x-rays from a specific source tube which cause the disc surface to fluoresce.

An analysing crystal disperses the resulting fluorescence and a flow timer counts the number of photons of a specific (small band width) energy received during a known time interval. The number of counts recorded for an unknown is more-or-less directly proportional to the amount of the oxide in the sample as compared to a known sample.

Oxide percentages are computed from nominal values which are fed into a computer "matrix" program. This program is designed to sort out the effects that one oxide has on the determination of the other oxides. As the final step, the percentages of the oxides from the two discs are averaged. Details of the proceedure are contained in the reference given above.

Table 1 lists the ten major and minor oxides determined for each sample. Also listed is the x-ray source tube, analysing crystal, counting time in seconds, the one-sigma counting error, estimated actual error, and the actual error in percentage of the oxide weight.

Sodium abundances were determined using the instrumental neutron activation analysis (INAA) technique described by Gordon, et al., (1968). In this method, the sample is first irradiated and the resultant x-ray emissions are counted and compared to a known standard much as in the XRF method.

The errors listed take in the actual counting error, which is a relationship between the counting peak height and the level of background, and also electronic errors which are inherent in the system.

The final estimated limits of error, columns f and g, are found by comparing both sample discs for all 35 samples and listing the maximum difference found for each oxide. Most of the additional error between counting error and total estimated error is considered to result from the weighing of the components, differences in batches of flux, and unresolved discrepancies in the computer "matrix" corrections.

Table 1

a	b	c	d	e	f	g
Oxide	Type x-ray source tube	Analysing crystal	counting time in seconds	one sigma counting error	limit of error in total oxide wt.	limit of error as % total oxide wt.
SiO_2	Cr	PET	10	.20	.40	1
TiO_2	Cr	PET	20	.01	.03	4
Al_2O_3	Cr	PET	10	.10	.20	1
MgO	Cr	ADP	2 counts @ 100	.20	.20	4
Fe_2O_3*	W	LiF (200)	30	.05	.20	3
MnO**	W	LiF (200)	30	.01	.01	10
CaO	Cr	PET	20	.03	.20	3
Na_2O	Germanium detector	INAA method	40	.07	--	--
K_2O	Cr	PET	20	.02	.05	5
P_2O_5	Cr	PET	10	.01	.02	5

* Total iron calculated as Fe_2O_3

** Mno abundances are so low (.09 to .17 % of total rock wt.) that the final error was essentially limited by the method of analysis and the total error can be represented by the statistical counting error.

LiF (200) - fluorescence was detected using the (200) face of LiF crystal

PEACOCK INDEX

The alkali-lime index proposed by Peacock (1931) is the silica value for which CaO equals total alkalies when values are plotted for a suite of rocks. This index is not readily obtained from the plots of McLoughlin area lavas since none of the rocks are rich enough in silica to make the trends on plots of $K_2O + Na_2O$ / CaO against SiO_2 go above unity, (figure 24). The plots do show a vague trend which would put the Peacock Index for the Fish Lake series between 61 and 62. If this projected value is valid for the rocks of the Mt. McLoughlin area, the suite is calc-alkaline to calcic in nature and is similar in chemical and mineralogical composition to the rest of the High Cascades and to other continental margin orogenic andesites.

The lavas of Mt. McLoughlin vary less than do the lavas of the Fish Lake series so that the index for Mt. McLoughlin alone could not be determined. Mt. McLoughlin lavas are slightly richer in CaO and poorer in alkalies than are the Fish Lake series. These values group in a position on the variation diagram which indicates that the index might be 62 or higher. This is the same value as found at Crater Lake, higher than that for the Modoc lavas (60.5), but less than that for Mt. Shasta (63.7).

The Peacock Index is not widely used today. It was initiated as a means of arbitrarily comparing and classifying rock suites by using this slight difference in their compositions. More recently, Dickinson and Hatherton (1967) have raised the possibility that differences in the alkali content (specifically K_2O) are related to depth of magma

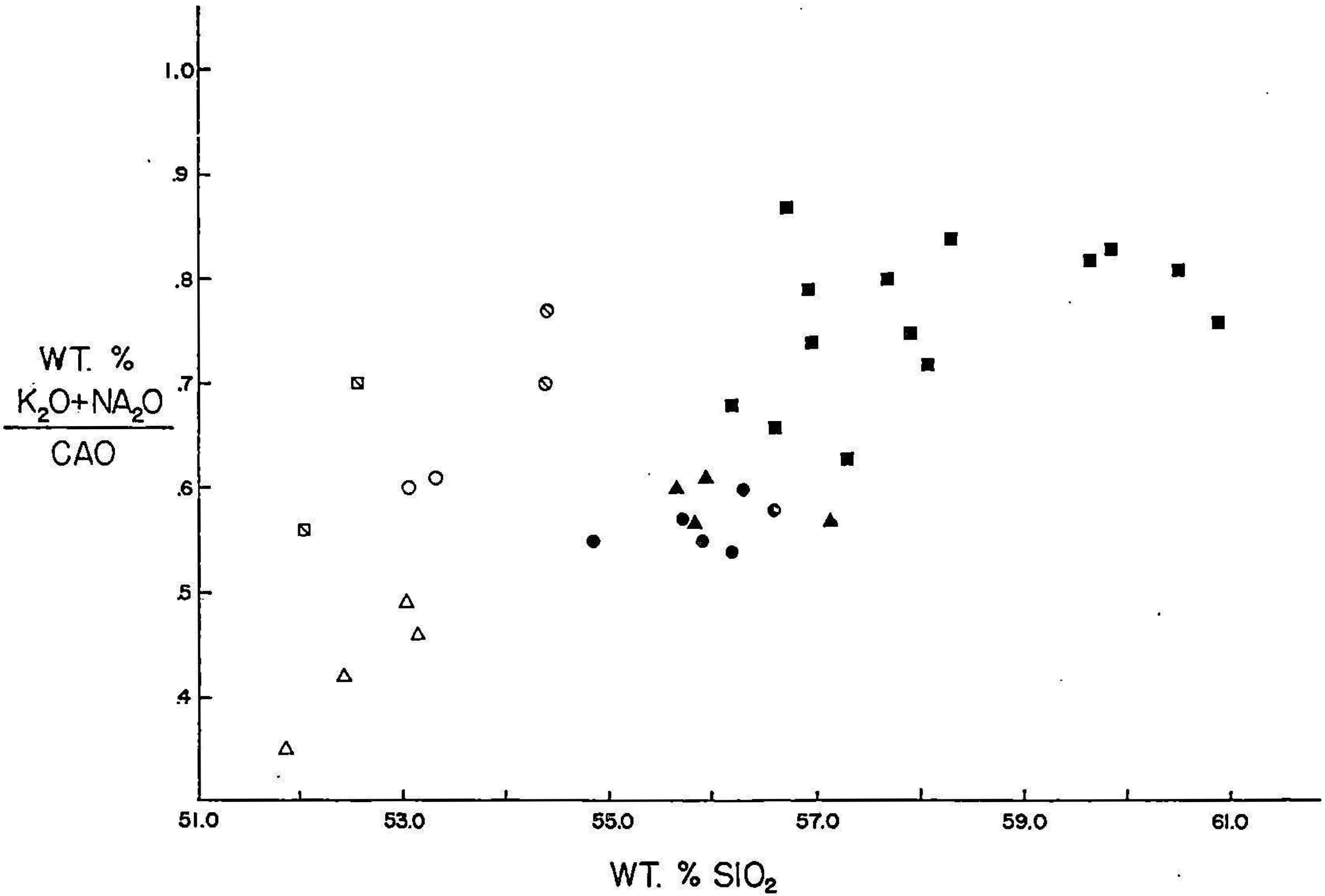

Figure 26. Closed circles, main-cone lavas of Mt. McLoughlin; closed triangles, flank lavas; closed squares, Fish Lake series. Other symbols, figure 29, page 100.

generation. This difference is maintained as the magma works its way to the surface and can can be seen in variations of surface lavas.

If this hypothesis is valid, the Peacock Index, or a modification of it, could take on genetic significance. Relative depths of origin of the primary magma could possibly be determined between rock suites and between individual series within a rock suite.

ROCK COMPOSITIONS

Western Cascades

No lavas from the fourth member of the Wasson Formation were chemically analysed but because they are dark and contain olivine they are probably basalts or basaltic andesites. Some of the agglomerates may be andesitic but they are so strongly weathered that it is difficult to assess their former rock type. If the chemical character of these rocks is consistent with that of other rocks of the Western Cascades sampled by Peck and others (1964), they are slightly more alkaline than High Cascade rocks. Peck reported the Peacock Index to be near 60 for the Western Cascade series of lavas.

Two samples of Heppsie Andesite were analysed. They are listed in table 2, page 106. Analysis 1 is of the medium grey type of rock and analysis 2 is of the light grey type. The two chemical compositions are essentially the same in silica, but there are differences in MgO, total Fe, CaO, and Al_2O_3. Little Butte Forest Camp near the west end of Fish Lake is located on an eroded Heppsie Andesite vent in which the two lithologies are intermingled within a 10 meter radius, suggesting that they share a common time and space relationship.

Plio-Cascades

Plio-Cascade lavas are mapped separately from Heppsie Andesites Because of the angular unconformity between them, and their differences in composition. Again, only two samples from this unit were analysed but petrographic features of other samples indicate that the two are representative of the group.

Plio-Cascade lavas are transitional between basalts and andesites. Their low average silica value (52 percent) and the presence of normative olivine put them in the basalt field, but their color index is slightly less than 30 and the normative An content is less than 50 percent which is in the andesite field.

The transitional nature of the lavas could not be a result of a slight concentration of mafic phenocrysts in a magma which would otherwise be a High Cascade basaltic andesite. Besides having a substantial age difference, the high relative values for K_2O and P_2O_5 indicate that phenocrysts enrichment did not occur and that the lavas have a composition distinct from and not genetically related to the High Cascade lavas.

The Plio-Cascade lavas are more alkaline in nature than are the High Cascade lavas. The K_2O level of the two samples, figure 33, is almost twice as high when comparing rocks of equal silica values. It is uncertain whether sodium really shows this same contrast. Sample LS-4 shows a high sodium level but LS-24 does not. Because it is so difficult to obtain fresh samples of Plio-Cascade lavas, it is probable that a substantial amount of sodium was leached out of LS-24 during the intense weathering of the unit.

The most important difference between Plio-Cascade lavas and High Cascade lavas is the high phosphorus content of the Plio-Cascades, (figure 34, page 105). The P_2O_5 content is nearly 0.5 percent, twice the level of other lavas analysed.

When studying the North Santiam district, Thayer (1937) listed three chemical analyses in which the P_2O_5 content is near 0.5 percent; all three are labeled Outerson basalts. Outerson lavas were given a Pliocene age since they unconformably lie between the Miocene Sardine lavas and the Plio(?)-Pleistocene lavas of the High Cascades.

Perhaps there is an extensive high phosphorus rock unit which lies between the Western Cascades and the High Cascades. It may not be continuous or have uniformly high phosphorus levels, but if these characteristics are indeed distinctive throughout the Cascades, this unit will be a valuable stratigraphic marker. Most of the high-phosphorus lavas should be easily found by looking at rock thin sections and noting the relative abundance of apatite needles.

<u>Plio-Peistocene Olivine Basalts</u>

The basalts in the Mt. McLoughlin area are typical of the high-alumina lavas of orogenic regions, and similar to those which have been reported from other parts of the Cascades, for example the Santiam basalts of Thayer. They are compositionally similar and at times texturally similar to the diktytaxitic olivine basalts found east of the Cascades.

Kuno (1960) was the first to separate and name high-alumina basalts as a distinct basalt type. It has been noted that they are commonly associated with orogenic andesites. Some workers have argued that high-alumina basalts are the parent magma from which andesites are derived through the process of crystal fractionation.

In the Mt. McLoughlin area, few olivine basalts are exposed at the surface. Most are assumed to pre-date the Fish Lake lavas. Two olivine basalts were analysed, LS-45 and LS-56. They are listed in table 2 as analyses 5 and 6.

Fish Lake Series

The Fish Lake series is best exposed on the south side of Brown Mountain. The flows stairstep up to the east toward the former vents which are located immediately west of Lake O' Woods. The ten analysed samples, labeled I through X, show a gradual change in major element composition. The earliest flows have a silica value of 56 percent, a basaltic andesite; the latest flows reach a maximum value of 61 percent, a silicic andesite.

Harker diagrams for Fe, Mn, Ti, and Mg show linear depletion trends with increasing silica. This fact along with petrographic and field evidence indicates that differentiation of the initial magma has occurred. Since the lavas progressively become more crystaline and contain numerous phenocryst clusters, it is believed that crystal fractionation is the main process working to cause differentiation.

Although not as linear as those previously mentioned, Ca also shows a depletion trend while the alkalies show enrichment. There is a strange character to the trends of the alkalies. Although both K_2O and Na_2O increase, the most siliceous lavas start to show a decrease in these components. The K_2O diagram, figure 33, displays this "hook" most prominently.

Published data from other Cascade volcanoes were plotted on a similar diagram. The K_2O values for Mt. Shasta, Crater Lake, the Three Sisters, Mt. Hood, and Mt. Rainier produce a scatter in the silicic andesite field. The K_2O values of rocks from the Mt. Jefferson area show the same hooked pattern as the Fish Lake series and at the same K_2O and SiO_2 levels.

Not all of the lavas mapped as Fish Lake series belong to a sequence which has differentiated. Rye Spur volcano due east of Mt. McLoughlin is composed of lavas which did not. The lavas from this volcano are basaltic andesites which are rich in glomerophenocrysts but the groundmass is fine-grained and dark grey in all the lavas. Two other volcanoes to the north of Rye Spur show the same constructional form, the same stage of erosion, and are also bisected by north-south faults with the east side down. These cones were not visited and the composition of their lavas are unknown.

Mt. McLoughlin Lavas

After the faulting of the now extinct Fish Lake volcanoes, or perhaps commencing with it, Mt. McLoughlin and its associated vents began to erupt. The general chemical nature of the lavas is the same as for other High Cascade centers. On both the NCK and AMF diagrams, figures 27 and 28, Mt. McLoughlin lavas plot near the basic ends of the other suites. Lavas of the Fish Lake series which have differentiated overlap the basaltic andesite field of the Mt. McLoughlin lavas and the silicic andesite field of the Mt. Rainier lavas.

Mt. McLoughlin has erupted both coarse- and fine-grained lavas almost simultaneously at different stages of its growth. Both types vary only slightly in composition. All are basaltic andesites which are almost identical in major element chemistry to the initial lavas of the Fish Lake series.

When Mt. McLoughlin lavas are plotted on silica variation diagrams, the coarse- and fine-grained types form separate groupings. The groupings are close together but seem to be mutually exclusive. The silica values for the two groups are the same, varying between 55 and 57 percent, but all other major oxides are lower in the coarse-grained lavas except CaO, Na_2O, and Al_2O_3, which are higher, (see figures 29 through 34).

Most of the differences in major oxide components between the two lava types can be explained be their obvious contrasting crystalline texture. Since the coarse-grained lavas are very porphyritic with plagioclase, an enrichment in this phase can raise the values for CaO, Na_2O, and Al_2O_3. The other components are then lowered slightly by the dilution effect of the added plagioclase. This effect can be confirmed by computing a 15 percent by weight enrichment in labradorite crystals of composition An 65.

This method does not explain all of the differences in the oxide values. The concentrations of K_2O and P_2O_5 are lower than can be expected from the dilution effect described above. Since these two oxides are not removed by any phenocryst phase present in the lava, they are being lost through some other differentiation process or were deficient in the original magma.

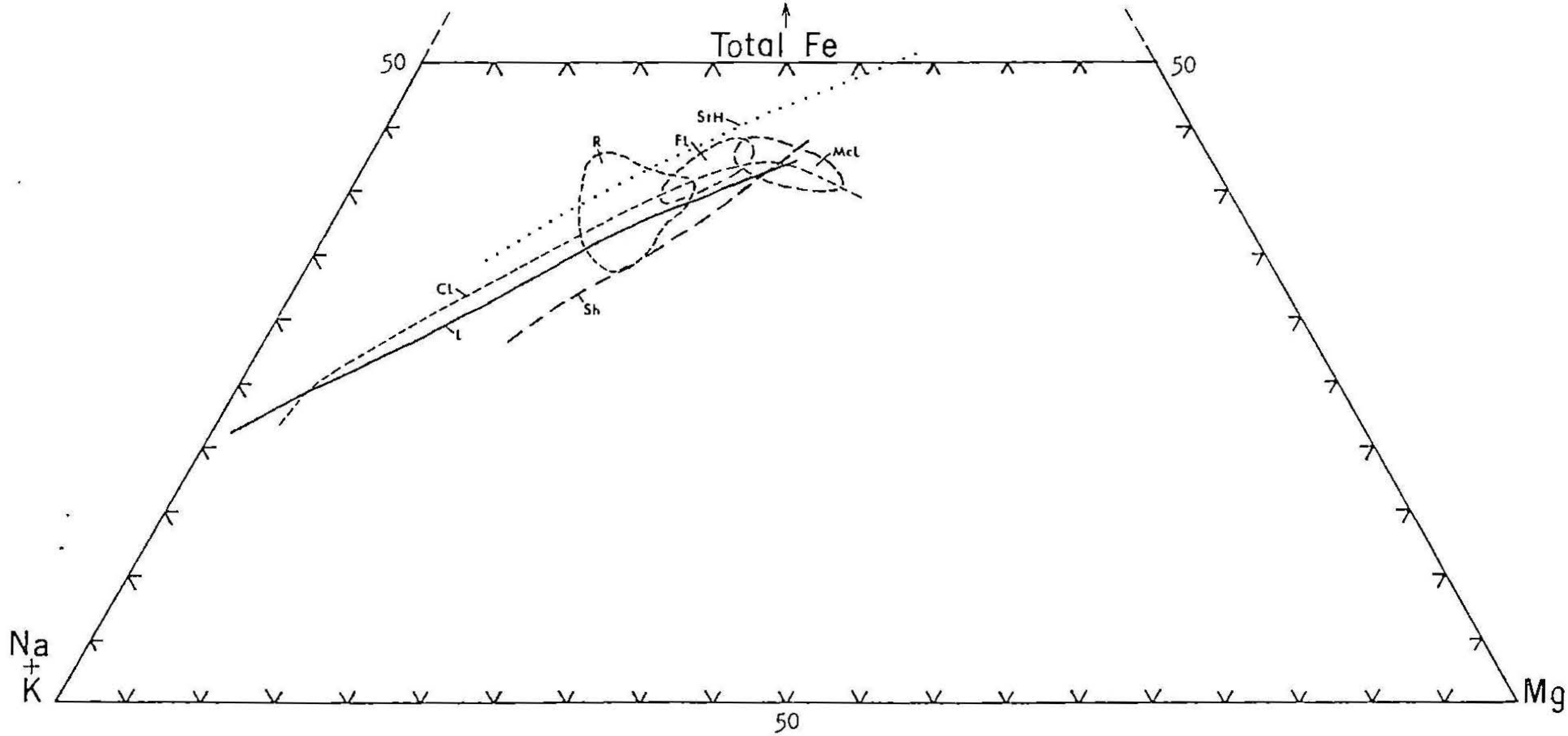

Figure 27. AMF diagram of rock suites from the Cascade Range. R-Mount Rainier, StH-Mount St. Helens, CL-Crater Lake, McL-Mount McLoughlin, FL-Fish Lake series, Sh-Mount Shasta, L-Mount Lassen.

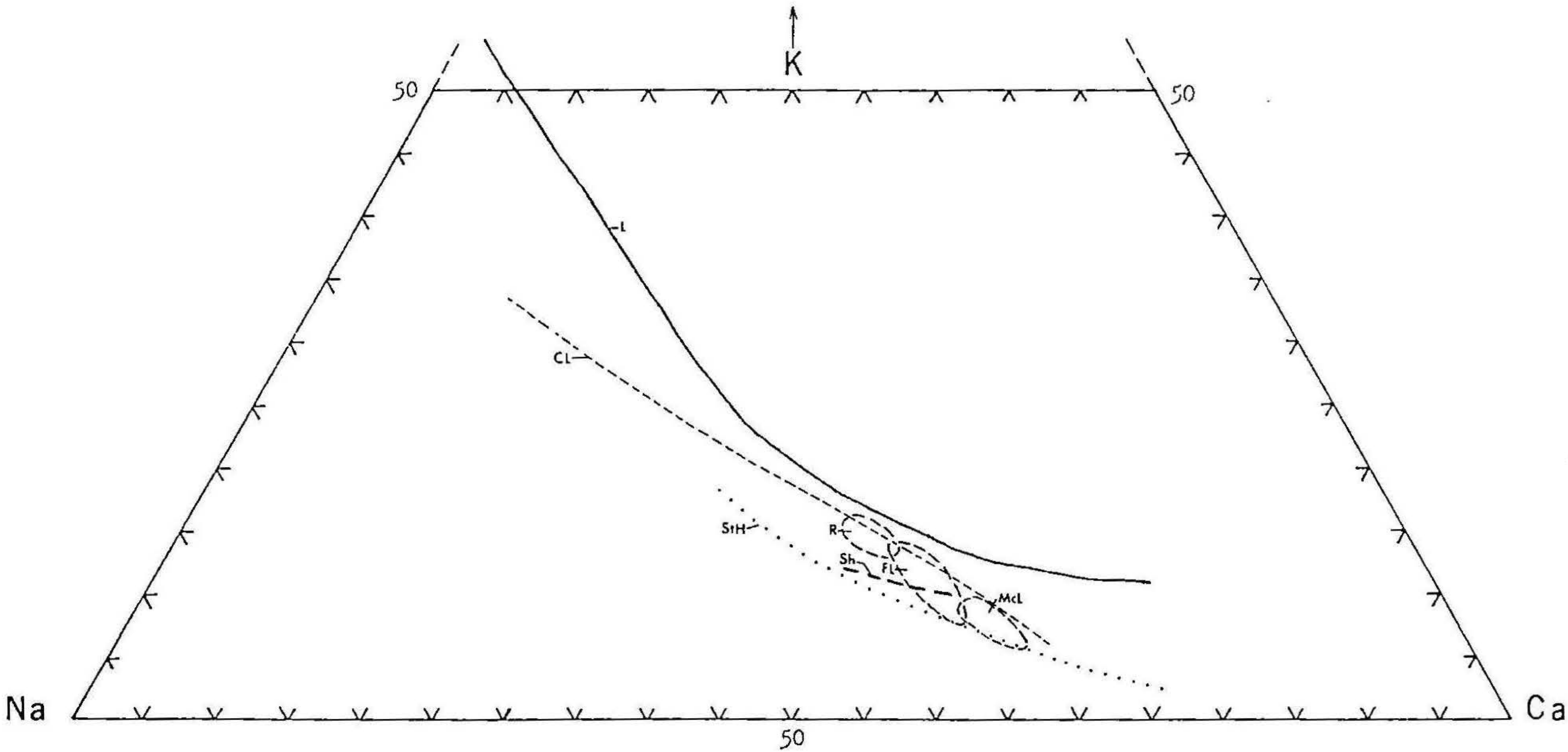

Figure 28. NCK diagram of rock suites from the Cascade Range. Symbols same as in figure 27.

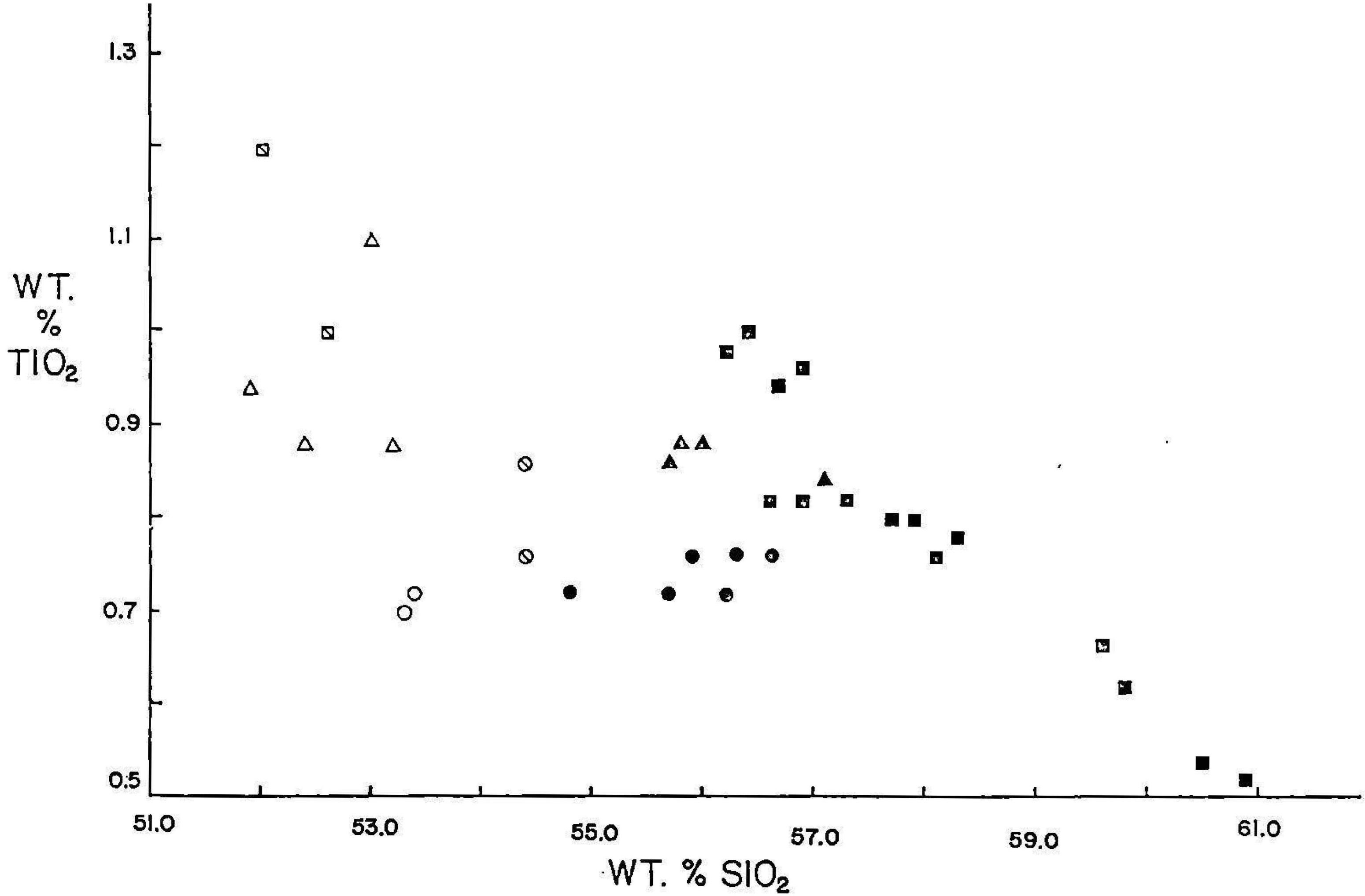

Figure 29. Closed circles, main-cone lavas; open circles, lavas suspected of phanocryst enrichment; closed triangles, fine-grained flank lavas; open triangles, olivine basalts and cumulate lavas; closed squares, Fish Lake series and Brown Mountain lava; slashed squares, Plio-Cascades; slashed circles, Heppsie Andesites.

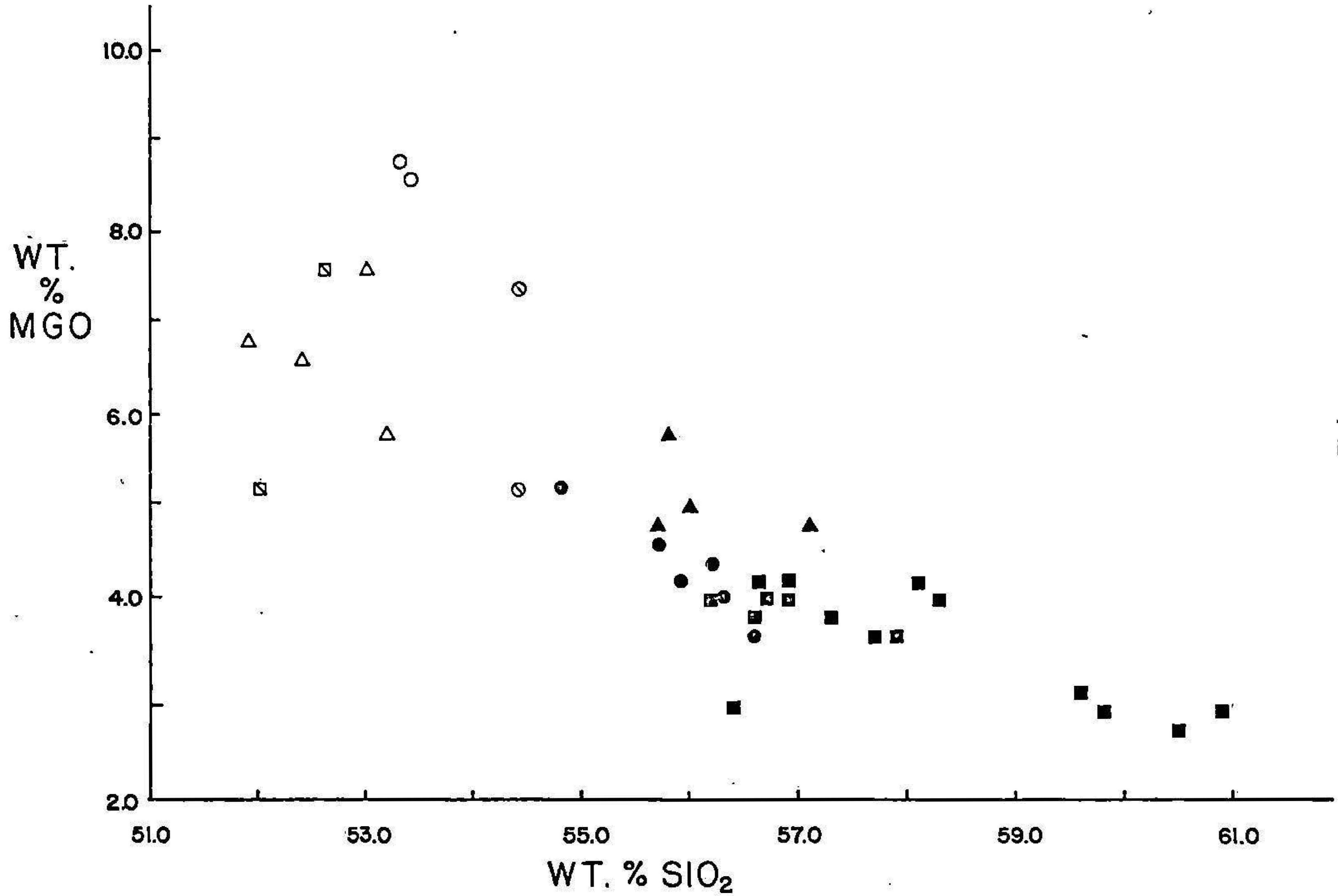

Figure 30. Symbols are the same as in figure 29.

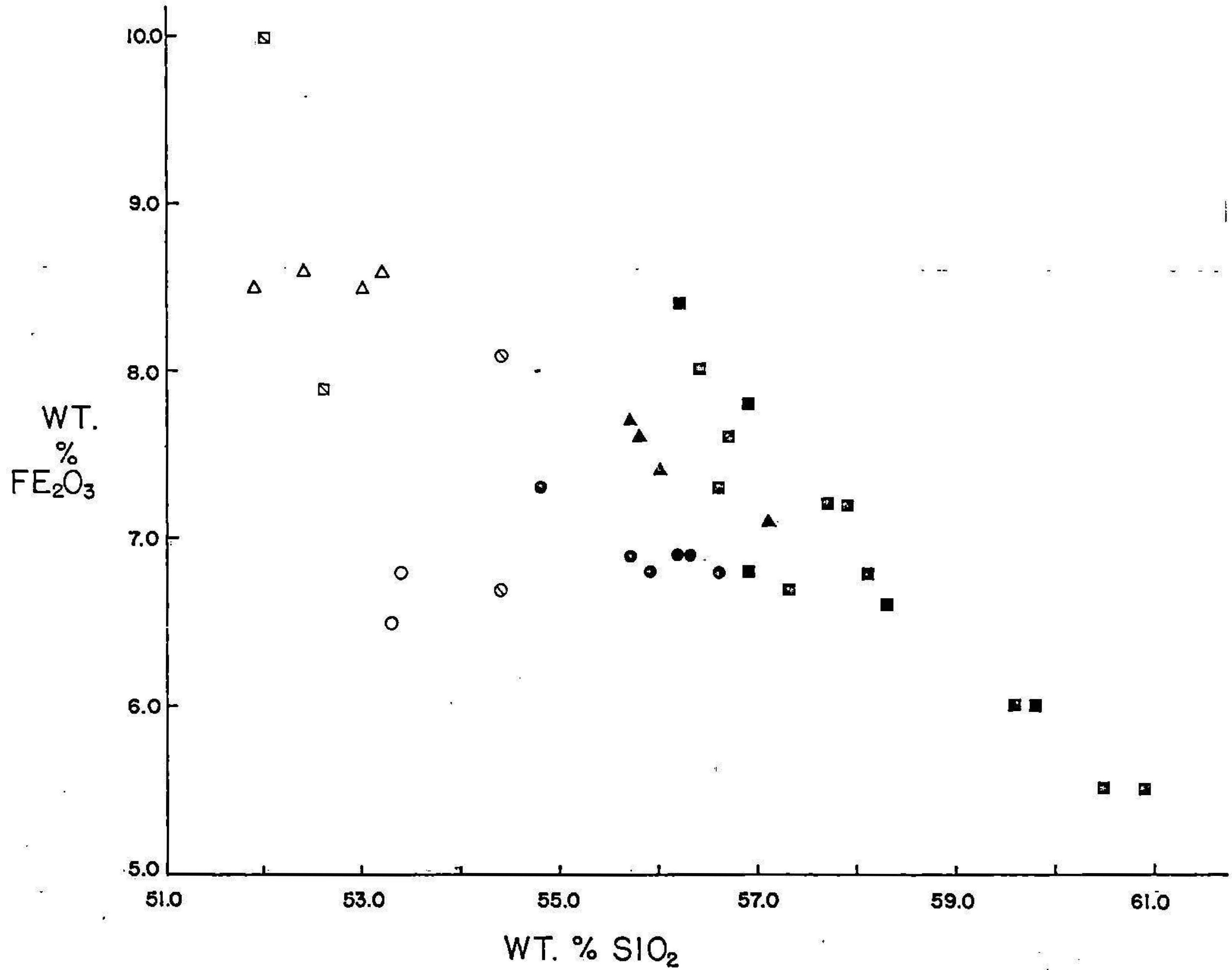

Figure 31. Symbols are the same as in figure 29.

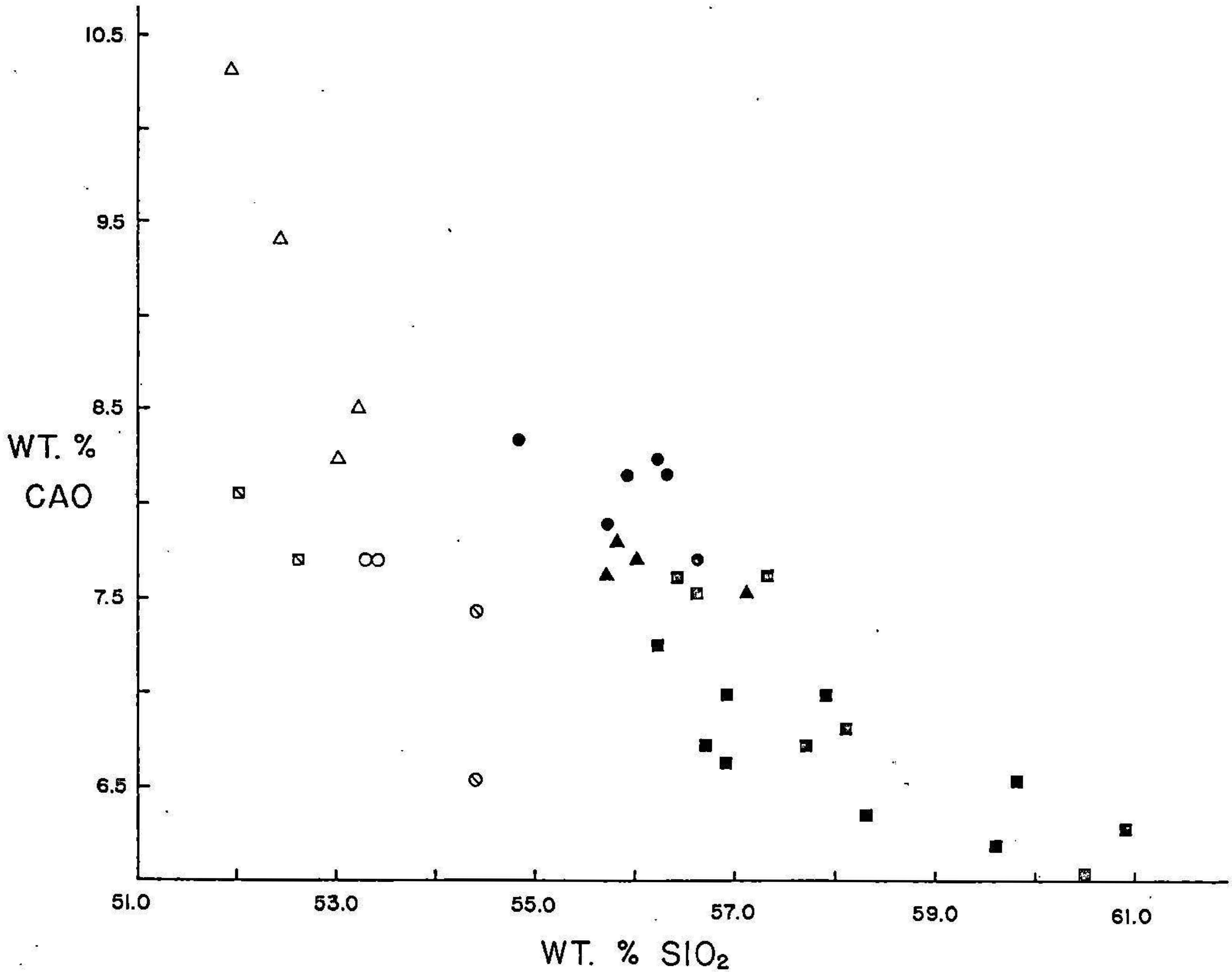

Figure 32. Symbols are the same as in figure 29.

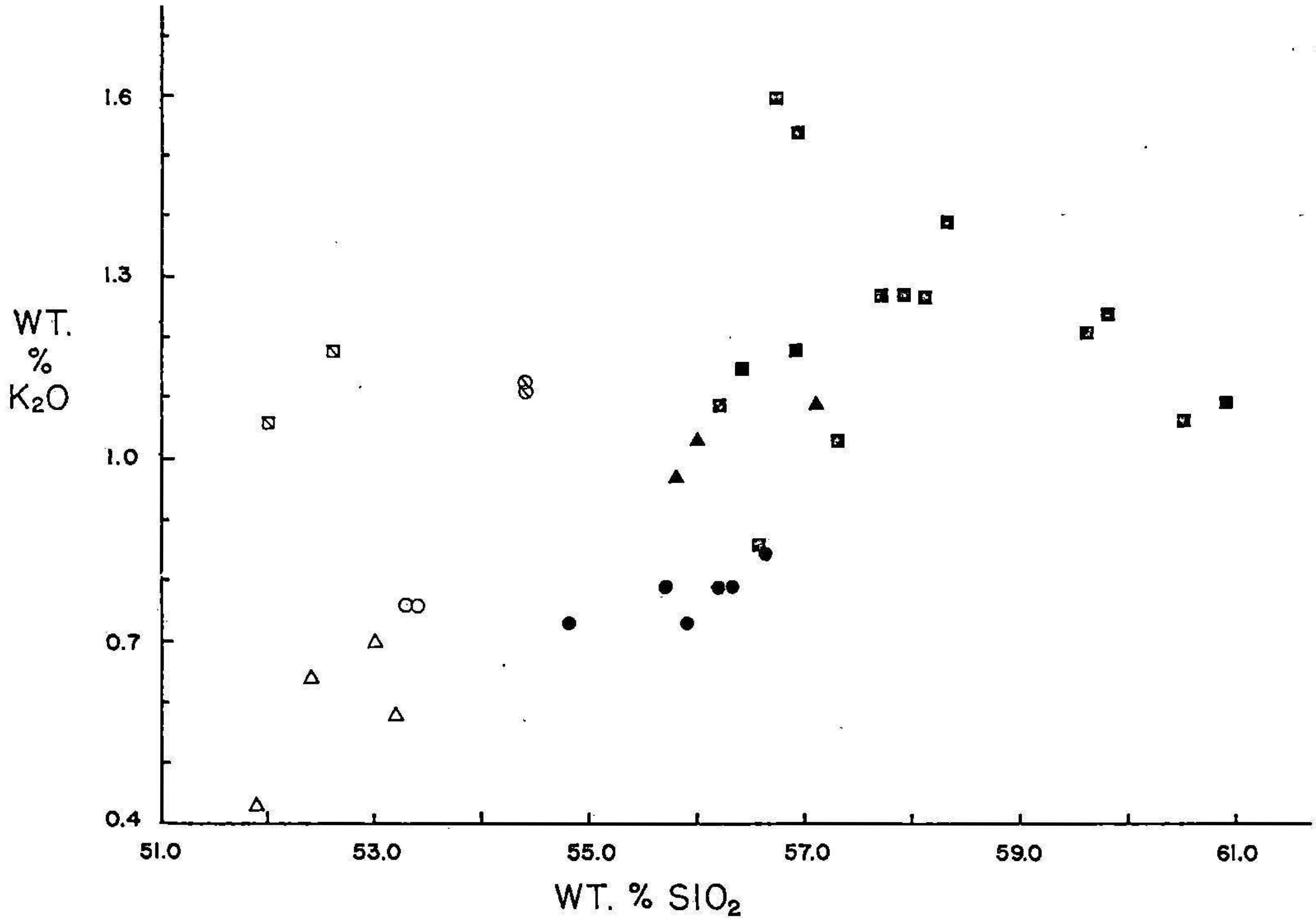

Figure 33. Symbols are the same as in figure 29.

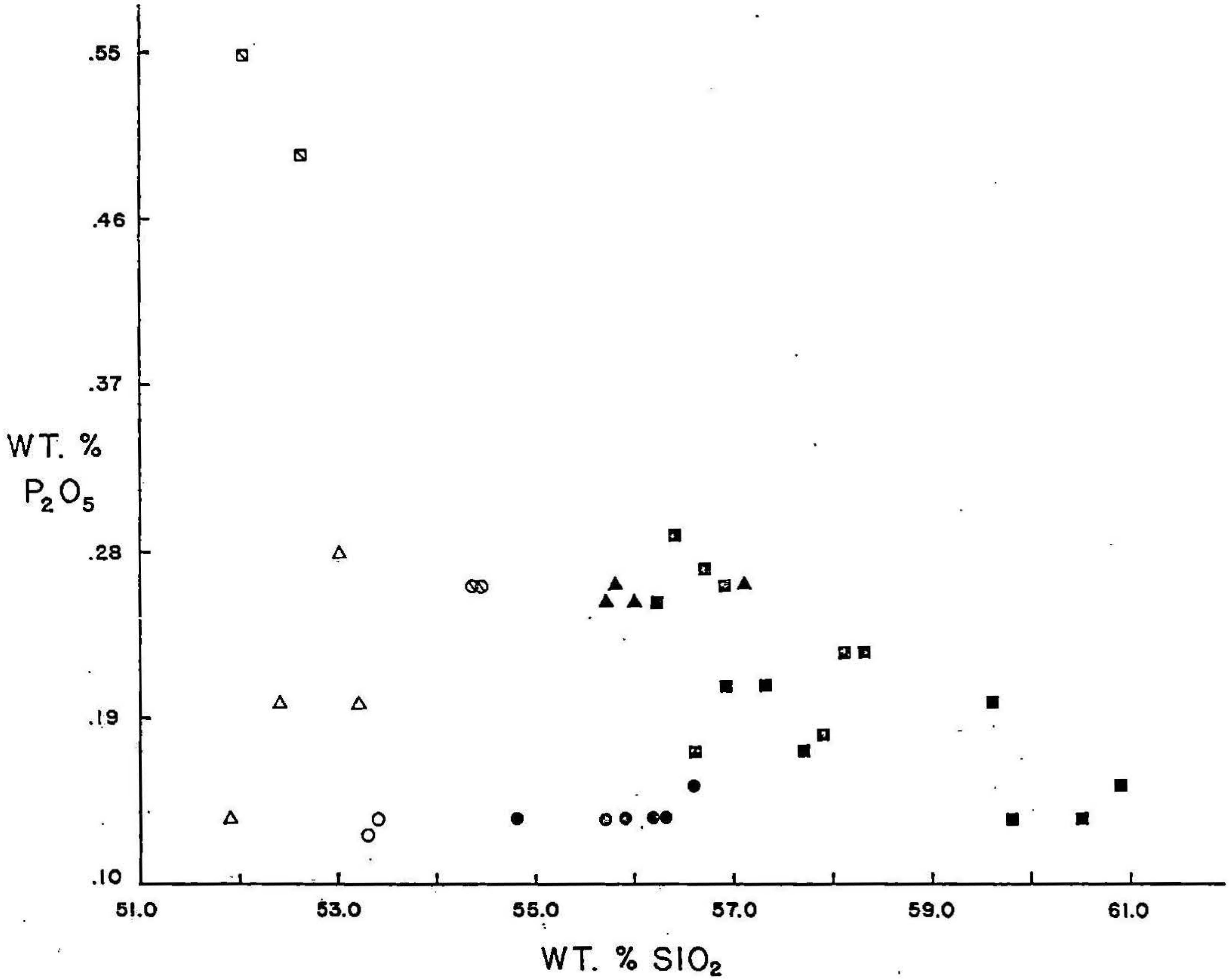

Figure 34. Symbols are the same as in figure 29.

Table 2. Chemical analyses and norms of Heppsie andesites, Plio-Cascades, and olivine basalts.

Sample No.	1 LS-2	2 LS-58	3 LS-4	4 LS-24	5 LS-45	6 LS-56
SiO_2	54.42	54.39	52.55	52.03	53.03	52.43
TiO_2	0.76	0.87	1.00	1.21	1.09	0.88
Al_2O_3	17.97	18.57	17.72	18.14	17.29	18.13
Fe total as Fe_2O_3	6.74	8.13	7.93	9.97	8.48	8.64
MnO	0.10	0.14	0.15	0.17	0.14	0.15
MgO	7.42	5.10	7.58	5.26	7.58	6.34
CaO	6.52	7.41	7.69	8.10	8.23	9.45
Na_2O	3.90	4.06	4.20	3.47	3.31	3.38
K_2O	1.12	1.13	1.18	1.07	0.71	0.63
P_2O_5	0.26	0.26	0.50	0.55	0.28	0.20
Total	99.21	100.06	100.50	99.97	100.14	100.43
Catanorms*						
Ol	-	-	13.7	0.1	-	2.6
Qz	0.1	0.6	-	-	0.4	-
Or	6.6	6.7	6.8	6.4	4.2	3.7
Plag	62.9	65.4	62.6	62.6	59.7	62.5
Di	1.9	4.8	7.0	4.7	7.0	10.5
Hy	26.0	19.8	6.4	22.1	25.5	17.9
Ap	0.5	0.5	1.0	1.2	0.6	0.4
Il	1.1	1.2	1.4	1.7	1.5	1.2
Mt	0.9	1.1	1.1	1.4	1.2	1.2
% plag An	44.6	44.4	40.8	49.7	50.4	51.7
Color Index	29.9	26.9	29.6	29.9	35.2	33.4

1. Heppsie andesite, light-grey type. Eroded knob along Forest Service road 3634G, near center of sec. 20, SW base of Mt. McLoughlin.

2. Heppsie andesite, medium-grey type. Eroded knob near junction of F.S. roads 3650 and 356, near center of sec. 19, SW of Mt. McLoughlin

3. Plio-Cascades olivine andesite. Eroded plug at Rye Flat, sec. 27, south base of Mt. McLoughlin.

4. Plio-Cascades olivine andesite. Lava float east of Rye Flat, near south edge of sec. 28, along F.S. road 3634B.

5. Olivine basalt. NW flank of Mt. McLoughlin, end of unmarked fire road, NE$\frac{1}{4}$, sec. 4.

6. Olivine basalt. Lava float in glacial debris along Twin Ponds trail, SW$\frac{1}{4}$, sec. 26, north base of Mt. McLoughlin.

* Fe^3/Fe^2 used to compute norms was 0.15.

Table 3. Chemical analyses and norms of Fish Lake series andesites.

Sample No.	7 I	8 IX	9 LS-81	10 LS-75	11 II
SiO_2	56.18	56.38	56.59	56.70	56.91
TiO_2	0.98	1.00	0.83	0.95	0.97
Al_2O_3	18.06	18.04	18.72	17.50	17.14
Fe total as Fe_2O_3	8.43	7.98	7.33	7.61	7.81
MnO	0.14	0.14	0.12	0.12	0.14
MgO	3.95	3.01	3.85	3.92	4.10
CaO	7.22	7.65	7.56	6.75	6.97
Na_2O	3.85	3.96	4.13	4.27	3.97
K_2O	1.09	1.16	0.84	1.61	1.53
P_2O_5	0.25	0.29	0.17	0.27	0.26
Total	100.15	99.61	100.14	99.70	99.80
Catanorms					
Ol	-	-	-	-	-
Qz	5.3	6.0	5.0	3.6	5.0
Or	6.5	6.9	5.0	9.6	9.1
Plag	63.7	64.4	67.2	62.4	60.4
Di	4.4	6.5	5.1	6.3	6.8
Hy	17.1	13.0	15.3	15.1	15.7
Ap	0.5	0.6	0.4	0.6	0.5
Il	1.4	1.4	1.2	1.3	1.4
Mt	1.2	1.1	1.0	1.1	1.1
% Plag An	45.4	44.1	44.8	38.3	40.7
Color Index	24.1	22.0	22.6	23.8	25.0

7. Glassy olivine andesite. Lava at junction of Forest Service roads 3705 and 3706, sec. 16, east of Robinson Butte.

8. Olivine andesite. Lava in road cut along F.S. road 3640, west edge of sec. 10, between Brown Mountain and Lake O' Woods.

9. Olivine andesite from Rye Spur volcano. Lava on east side of Billie Creek on F.S. road 3633, NW$\frac{1}{4}$, sec. 21.

10. Olivine-pyroxene andesite. Lava along unmaintained logging road, NW$\frac{1}{4}$, sec. 31, NW base of Mt. McLoughlin.

11. Glassy olivine andesite. Lava along F.S. road 3705, south side of Beaver Dam Creek, SW$\frac{1}{4}$, sec. 14, SW of Brown Mountain.

Table 4. Chemical analyses of Fish Lake series andesites, continued.

Sample No.	12 VI	13 III	14 BL-23	15 BL-8	16 X
SiO_2	56.93	57.68	57.90	58.07	58.29
TiO_2	0.83	0.81	0.80	0.77	0.79
Al_2O_3	18.48	18.05	17.91	17.46	17.50
Fe total as Fe_2O_3	6.82	7.20	7.16	6.78	6.64
MnO	0.12	0.12	0.12	0.11	0.11
MgO	3.94	3.60	3.57	4.28	4.08
CaO	6.63	6.69	6.98	6.85	6.35
Na_2O	3.71	4.06	3.96	3.68	3.94
K_2O	1.19	1.28	1.27	1.28	1.39
P_2O_5	0.21	0.17	0.18	0.23	0.23
Total	98.86	99.66	99.85	99.51	99.32
Catanorms					
Ol	-	-	-	-	-
Qz	7.5	6.7	7.2	8.3	7.8
Or	7.1	7.6	7.5	7.6	8.3
Plag	64.5	64.1	63.3	60.9	62.8
Di	1.0	3.9	4.9	4.1	3.3
Hy	17.3	15.2	14.6	16.6	16.3
Ap	0.5	0.4	0.4	0.5	0.5
Il	1.2	1.1	1.1	1.1	1.1
Mt	1.0	1.0	1.0	0.9	0.9
% plag An	47.6	42.8	43.5	45.3	42.3
Color Index	20.5	21.2	21.6	22.7	21.6

12. Olivine andesite. Lava float along F.S. road 3774, south of Little Butte Creek, south edge of sec. 20, south of Brown Mountain.

13. Olivine-pyroxene andesite. Lava along F.S. road 3774, at boundary between sec. 19 and 24, south of Brown Mountain.

14. Olivine bearing pyroxene andesite. Lava at junction of F.S. roads 3774 and 3640, sec. 21, SE side of Brown Mountain.

15. Pyroxene andesite. Lava on east side of F.S. road 3640, at boundary between sec. 9 and 16, east of Brown Mountain.

16. Olivine bearing pyroxene andesite. Lava in road cut along F.S. road 3640, SE$\frac{1}{4}$, sec. 4, NE side of Brown Mountain.

Table 5. Chemical analyses of Fish Lake series andesites, continued.

Sample No.	17 V	18 VIII	19 VII
SiO_2	59.62	60.49	60.88
TiO_2	0.67	0.55	0.53
Al_2O_3	17.96	18.53	18.43
Fe total as Fe_2O_3	5.98	5.52	5.49
MnO	0.09	0.09	0.09
MgO	3.18	2.88	2.91
CaO	6.20	6.04	6.28
Na_2O	3.89	3.82	3.70
K_2O	1.21	1.05	1.08
P_2O_5	0.20	0.14	0.15
Total	99.00	99.11	99.54
Catanorms			
Ol	-	-	-
Qz	11.3	13.5	13.9
Or	7.2	6.3	6.4
Plag	63.8	64.2	64.0
Di	1.2	-	-
Hy	14.3	13.7	13.7
Ap	0.4	0.3	0.3
Il	1.0	0.8	0.8
Mt	0.8	0.8	0.8
% plag An	44.5	45.9	47.6
Color Index	17.3	15.2	15.2

17. Pyroxene andesite. Lava on boundary between sec. 19 and 30, along Forest Service road 3774, south of Brown Mountain.

18. Pyroxene andesite. Lava in road cut along F.S. road 3774, south central portion of sec. 29, south of Brown Mountain.

19. Pyroxene andesite. Lava in road cut along F.S. road 3774, at boundary between sec. 28 and 29, SW of Brown Mountain.

Table 6. Chemical analyses and norms of Mt. McLoughlin main-cone andesites.

Sample No.	20 LS-71	21 LS-7	22 21F	23 LS-80	24 LS-68	25 LS-14
SiO_2	54.84	55.73	55.90	56.19	56.29	56.59
TiO_2	0.73	0.72	0.76	0.72	0.77	0.76
Al_2O_3	19.13	18.98	19.13	19.04	19.31	19.43
Fe total as Fe_2O_3	7.32	6.92	6.83	6.92	6.85	6.75
MnO	0.12	0.11	0.11	0.12	0.11	0.11
MgO	5.13	4.62	4.18	4.36	3.96	3.65
CaO	8.35	7.92	8.20	8.27	8.16	7.69
Na_2O	3.88	3.76	3.80	3.69	3.86	3.63
K_2O	0.73	0.79	0.74	0.78	0.79	0.86
P_2O_5	0.14	0.14	0.14	0.14	0.14	0.15
Total	100.37	99.69	99.79	100.23	100.24	99.62
Catanorms						
Ol	-	-	-	-	-	-
Qz	1.9	4.5	5.0	5.3	5.2	7.2
Or	4.3	4.7	4.4	4.6	4.7	5.1
Plag	67.0	66.5	67.3	66.1	67.6	67.3
Di	6.3	4.7	5.5	5.6	5.2	2.4
Hy	18.3	17.4	15.6	16.2	15.1	15.7
Ap	0.3	0.3	0.3	0.3	0.3	0.3
Il	1.0	1.0	1.1	1.0	1.1	1.1
Mt	1.0	0.9	0.9	0.9	0.9	0.9
% Plag An	48.4	49.1	49.1	50.0	48.8	51.2
Color Index	26.6	24.0	23.1	23.7	22.3	20.1

20. Olivine-pyroxene andesite. Post-glacial coulee flow, SW$\frac{1}{4}$, sec. 12, NE flank of Mt. McLoughlin.

21. Olivine-pyroxene andesite. Black, glassy lava near the top of Mt. McLoughlin.

22. Olivine-pyroxene andesite. Twenty-first flow from the top of head-wall of the NE cirque, near boundary between sec. 13 and 14.

23. Olivine-pyroxene andesite. Squaw Tip lava in cut on F.S. road 356I, on north side of outcrop area, SW$\frac{1}{4}$, sec. 8, post-glacial.

24. Olivine-pyroxene andesite. Post-glacial coulee flow, SE$\frac{1}{4}$, sec. 1, NE flank of Mt. McLoughlin.

25. Olivine-pyroxene andesite. Top of South Squaw Tip, sec. 15, west flank of Mt. McLoughlin.

Table 7. Chemical analyses and norms of Mt. McLoughlin flank andesites and Brown Mountain andesite.

Sample No.	26 LS-28	27 LS-39	28 LS-26	29 LS-85	30 LS-65	31 BL-4
SiO_2	55.66	55.78	55.97	57.13	57.30	59.82
TiO_2	0.86	0.89	0.88	0.85	0.82	0.62
Al_2O_3	18.33	17.59	17.69	17.46	18.80	18.29
Fe total as Fe_2O_3	7.67	7.55	7.44	7.05	6.73	5.96
MnO	0.12	0.13	0.12	0.13	0.12	0.10
MgO	4.85	5.76	5.06	4.81	3.71	3.07
CaO	7.61	7.76	7.70	7.50	7.63	6.50
Na_2O	3.62	3.50	3.68	3.22	3.76	4.14
K_2O	0.94	0.96	1.04	1.08	1.03	1.24
P_2O_5	0.25	0.26	0.25	0.26	0.21	0.14
Total	99.91	100.18	99.83	99.46	100.11	99.88
Catanorms						
Ol	-	-	-	-	-	-
Qz	4.8	4.5	4.7	8.6	7.2	9.7
Or	5.6	5.7	6.2	6.5	6.1	7.3
Plag	63.7	60.8	61.9	59.6	65.3	65.0
Di	4.1	5.9	6.3	4.5	4.1	2.9
Hy	19.0	20.4	18.2	18.2	14.8	13.0
Ap	0.5	0.5	0.5	0.6	0.4	0.3
Il	1.2	1.2	1.2	1.2	1.2	0.9
Mt	1.1	1.0	1.0	1.0	0.9	0.8
% plag An	48.8	48.4	46.5	50.9	48.2	42.7
Color Index	25.4	28.5	26.7	24.9	21.0	17.6

26. Olivine-pyroxene andesite. Lava along trail up east side of Mt. McLoughlin, NW¼, sec. 20, about ½ mile from parking lot.

27. Olivine andesite. Fine-grained stage two lava in road cut along F.S. road 3650, SW¼, sec. 21, SW flank of Mt. McLoughlin.

28. Olivine andesite. Fine-grained stage three lava on west side of Cascade Canal, along old Fourmile Lake road, SE¼, sec. 30.

29. Olivine andesite. Fine-grained stage three lava on north side of cinder cone along Butte Falls road, SW¼, sec. 36, NW base of Mt. McLoughlin.

30. Olivine-pyroxene andesite. Dense, grey lava in escarpment south of Summit Lake, NW¼, sec. 6, north base of Mt. McLoughlin.

31. Silicic andesite. Post-glacial lava erupted from the NW base of the summit cinder cone of Brown Mountain.

Table 8. Chemical analyses and norms of Mt. McLoughlin and Robinson Butte andesites suspected of phenocryst enrichment.

Sample No.	32 BL-9	33 LS-82	34 LS-3	35 LS-6
SiO_2	51.88	53.15	53.36	53.31
TiO_2	0.95	0.88	0.72	0.71
Al_2O_3	17.79	18.33	18.49	18.31
Fe total as Fe_2O_3	8.55	8.62	6.82	6.53
MnO	0.14	0.14	0.11	0.11
MgO	6.78	5.77	8.60	8.87
CaO	10.34	8.56	7.73	7.72
Na_2O	3.19	3.24	3.81	3.97
K_2O	0.42	0.57	0.77	0.75
P_2O_5	0.14	0.20	0.14	0.13
Total	100.18	99.46	100.55	100.41
Catanorms				
Ol	2.7	-	13.2	10.6
Qz	-	2.5	-	-
Or	2.5	3.4	5.0	4.3
Plag	61.5	63.5	64.0	63.9
Di	13.9	6.0	4.8	5.9
Hy	16.6	21.8	10.8	13.1
Ap	0.3	0.4	0.3	0.3
Il	1.3	1.2	1.0	1.0
Mt	1.2	1.2	0.9	0.9
% plag An	53.5	53.7	47.6	45.6
Color Index	35.7	30.2	30.7	31.5

32. Olivine-pyroxene basalt. Lava float on top of Robinson Butte.

33. Olivine-pyroxene andesite. Lava in road cut along F.S. road 3661, just south of boundary between sec. 28 and 33, NW¼, sec. 33, on ridge NW of Lake O' Woods.

34. Olivine-pyroxene andesite. Coarse-grained stage three flow erupted on the SW flank of Mt. McLoughlin, near Rye Spring, NW¼, sec. 27.

35. Olivine-pyroxene andesite. Light-grey lava found at the summit of Mt. McLoughlin.

Table 9. Chemical analyses for olivine, orthopyroxene, and clinopyroxenes from Three Mt. McLoughlin andesites.

	36	37	38	39	40	41
Sample No.	LS-6	LS-6	LS-28	LS-71	LS-71	LS-26
Mineral	OPX	CPX	CPX	CPX	OL	OL
SiO_2	53.35	50.75	49.92	50.18	38.57	38.47
TiO_2	0.24	0.58	0.66	0.58	-	-
Al_2O_3	2.08	2.90	3.62	3.86	0.21	0.22
FeO	14.67	7.43	7.56	7.66	18.86	17.11
MnO	0.47	0.36	0.33	0.35	0.40	0.42
MgO	27.36	15.57	15.16	15.42	41.70	43.49
CaO	1.64	20.21	20.47	21.02	0.19	0.18
Na_2O	-	0.47	0.48	0.49	-	-
Molecular weight %						
CaO	3.21	42.44	43.17	43.43	-	-
MgO	74.45	45.43	44.43	44.27	79.46	81.59
FeO	22.34	12.13	12.40	12.30	20.54	18.41

Table 10. Chemical analyses of pyroxenes from Crater Lake rocks.

	42	43	44	45	46	47
Sample No.	AC-1	C3-3B	HP-2	AC-1	C3-3B	HP-2
Mineral	OPX	OPX	OPX	CPX	CPX	CPX
SiO_2	52.10	52.34	53.17	51.48	50.14	50.81
TiO_2	0.14	0.24	0.27	0.37	0.45	0.56
Al_2O_3	0.48	1.10	1.51	1.39	3.50	2.46
FeO	22.25	18.93	13.29	9.02	7.31	7.66
MnO	0.90	0.37	0.25	0.39	0.16	0.12
MgO	21.95	24.35	28.42	14.54	14.94	15.67
CaO	1.11	1.28	1.42	21.25	21.34	20.75
Na_2O	-	-	-	0.26	0.23	0.31
Molecular weight %						
CaO	2.3	2.6	2.8	43.8	44.6	42.8
MgO	62.3	67.8	77.0	41.7	43.4	44.9
FeO	35.4	29.6	20.2	14.5	11.9	12.3

42. Pumiceous andesite tuff. Friable air-fall deposits just north of junction of Annie Creek and Munson Creek.

43. Pumiceous andesite tuff. Friable air-fall deposits on north ridge of Cloud Cap.

44. Hillman Peak andesite.

Samples LS-26, LS-39, and LS-85 are dark, fine-grained flank lavas which are believed to represent in composition the parental magma of Mt. McLoughlin. Grouped with these samples are two coarse-grained lavas which also erupted on the flanks, LS-28 and LS-65. The plots for sample LS-28 do not show the effects of plagioclase enrichment or loss of K_2O and P_2O_5. Sample LS-65 seems to be intermediate between the two lava types, showing a slight plagioclase enrichment and a slight loss of potassium and phosphorus.

The most important textural change in the parental magma as it rises from its source to the low-pressure, low-temperature environment near the earth's surface is the rapid crystalization of plagioclase and to a lesser extent, pyroxene. Figure 35 shows the melting characteristics of a high-alumina basalt under wet, intermediate pressure conditions. If it can be assumed that a basaltic andesite will melt in a similar manner, this graph shows why large phenocrysts of plagioclase and pyroxene can be expected in lavas which have stewed in a magma chamber. Once these two phases become stable and are given the opportunity to grow in a magma chamber, they do so very rapidly. The presence of large, strongly zoned phenocrysts in the coarse-grained lavas support this claim. The large olivine phenocrysts present in these lavas are usually not actively growing. They are high temperature relicts which usually have reaction rims of pyroxene and are never found in the groundmass.

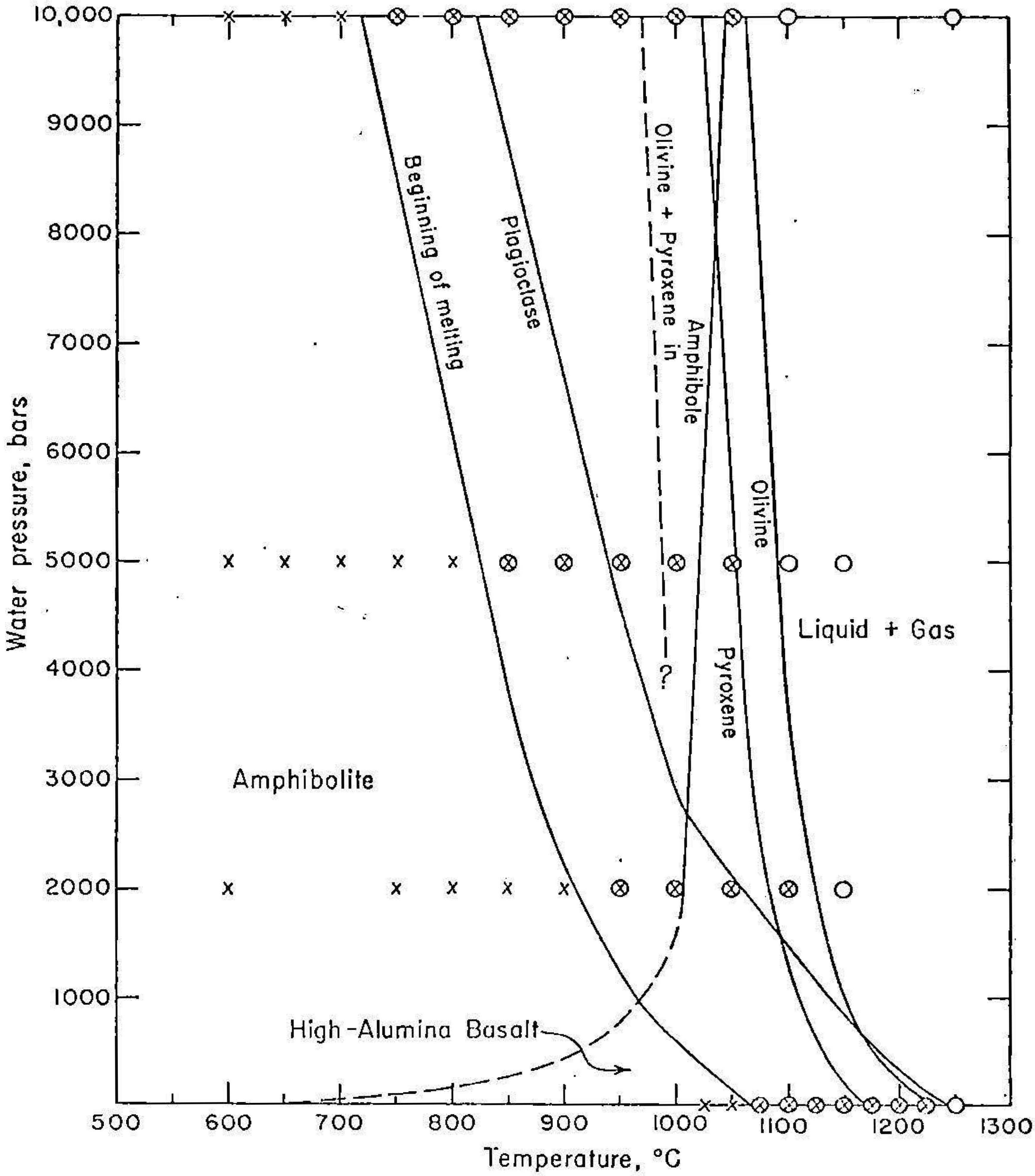

Figure 35. Pressure-temperature diagram of a natural high-alumina basalt-water system, (Yoder and Tilley, 1962).

The coarse-grained lavas of the main cone include LS-7, LS-14, LS-68, LS-71, LS-80, 21F, and two special cases, LS-3 and LS-6. The latter is one of the last flows to erupt from the central vent and LS-3 is a Holocene flow located at the southwest base of the mountain. These two samples plot very close together on all of the Harker diagrams. They are 4 percentage points higher in MgO and 2 points lower in silica than in the other coarse-grained lavas, (open circles, figures 29 through 34). The norm values given in table 8 indicate that there has been a 15 percent enrichment in olivine. The petrography of LS-6 confirms the existence of mafic phenocryst accumulation, but it is of clinopyroxene, (8 percent mode). Details of the petrography, however, reveal that many large grains of pyroxene have grown around olivine cumulate material and has almost entirely replaced it. Only slight accumulations above the other lavas can be detected in LS-3.

In sample LS-71 there is a noticable modal concentration of large olivines. This enrichment is also apparent in the lower silica and higher MgO level of the sample. The level of olivine, Fo 80, accumulation is computed to be about 2 to 3 percent.

Brown Mountain Lava

Brown Mountain lava is the only silicic andesite in the mapped area which has erupted since the Fish Lake volcanoes ceased their activity. This lava is not like the former Fish Lake differentiates in texture. Brown Mountain flows are post-glacial lavas which have the dark color and the blocky flow surface texture of the fine-grained flank lavas of Mt. McLoughlin. These lavas are also the only non-porphyritic lavas in the area.

These two facts point to the probable origin of the lavas, which is that Brown Mountain lavas are a result of the filter-pressing of porphyritic olivine andesite similar to the flank lavas on Mt. McLoughlin.

Petrographic evidence supporting this premise is the occassional appearance of patchy-zoned plagioclase phenocrysts and the rare ocurrance of a fresh olivine grain in a lava which is a silicic andesite. The sample plots on the variation diagrams with the Fish Lake series differentiates. This is to be expected since the initial lavas for both groups were the same.

PETROLOGY AND PETROGENESIS

Parental Magma

A basaltic andesite is the most likely parental magma not only in the Mt. McLoughlin area but for the whole High Cascade subprovince. The evidence for this is of several types:

1) Even though the parental magma type may not be the dominant lava at the surface, one would expect that occasionally some of this magma will find its way to the surface in an undifferentiated form. Features of a parental magma would include recurring eruptions and an aphyric texture in lava flows. Especially important is the lack of plagioclase phenocrysts. Their presence would indicate that the magma had started to change under low pressure fractionation conditions.

There are lavas of three different ages around the base of Mt. McLoughlin that fulfill these requirements. They are all fine-grained; they have the same chemical composition; and they are a recurring rock type.

2) If basaltic andesite was derived by near-surface fractionation of an olivine basalt, one would expect to find basalts as a recuurring rock type. There are no known, fine-grained, high-alumina basalts that are definately the same age as Mt. McLoughlin.

3) The initial lavas of the Fish Lake series also started out with the same bulk chemistry as Mt. McLoughlin lavas and then differentiated to silicic andesites.

4) The large composite cones of the High Cascades are dominated by silicic andesite but most of them have at least small exposures of olivine andesite. Mt. Rainier and Mt. Baker are commonly said to be comprised solely of silicic andesites. This is not true. Both centers are reported in the literature to have olivine andesites, (Fiske and others, 1953; Coombs 1939). Unfortunately only silicic andesites were chosen by the workers for analysis. Many of the olivine andesites of the various centers are dark, fine-grained, and occur more than once in the eruptive sequence.

5) A parental magma would be expected to be the dominant rock type at all centers which did not differentiate. Even though olivine basalts and silicic andesites are locally voluminous, the most abundant lava in the High Cascades since the Fish Lake series began has been basaltic andesite.

6) When Mt. McLoughlin lavas are plotted on a high water pressure forsterite-diopside-quartz diagram, they lie on the invariant point for liquids co-existing with olivine and pyroxene, (figure 36). Kushiro (1969) deduced this diagram from the results of experimental runs at P_{H2O}= 20 kilobars. Yoder (1969) later showed the implications of this system as it relates to the calc-alkaline lavas.

The first melt of an olivine normative basalt, or even of an olivine plus two pyroxene peridotite (lierzolite) under these conditions would be at the high-temperature invariant point. This implies that basaltic andesites are primary magmas at high pressures when water is present.

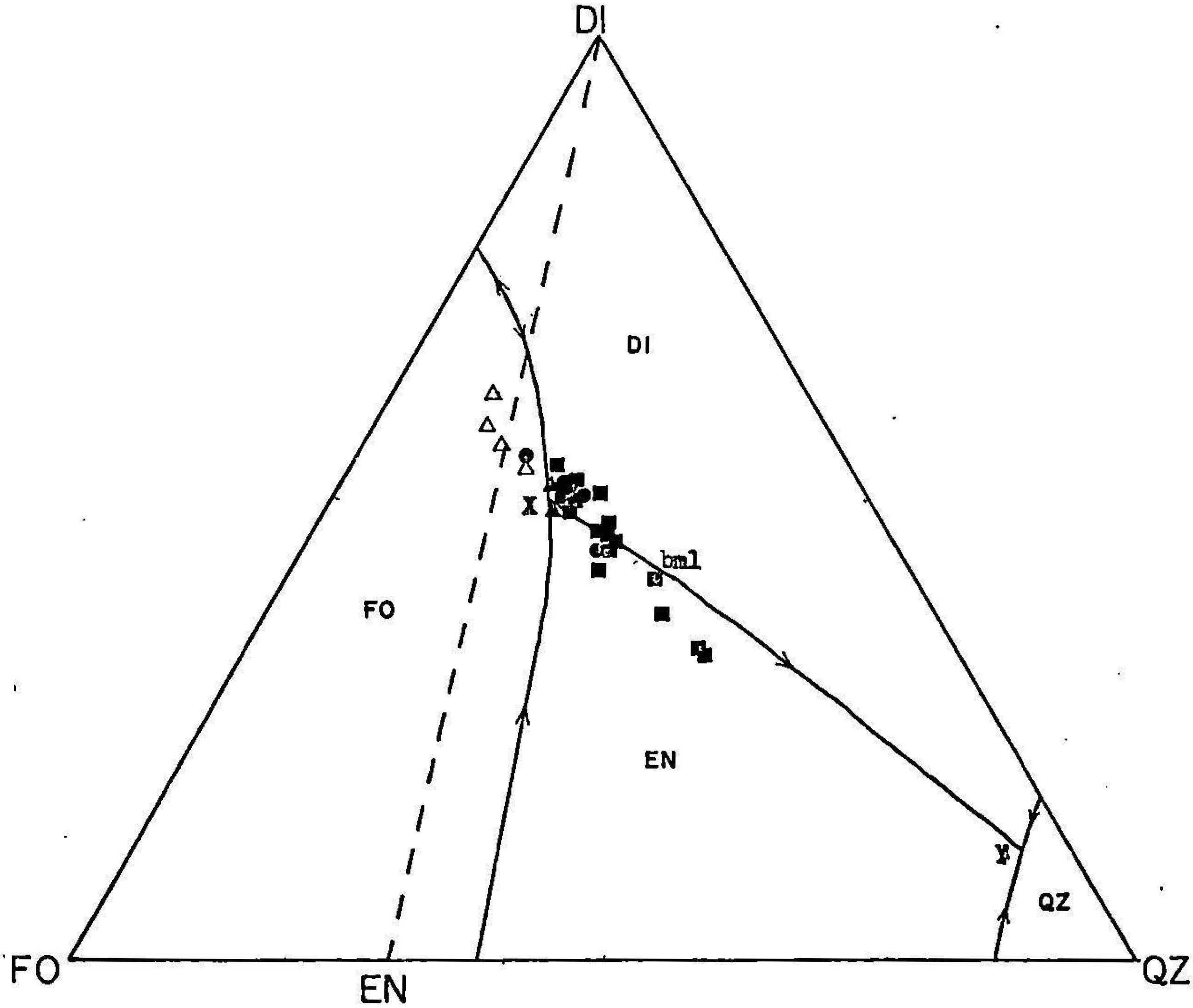

Figure 36. Fo-Di-Qz diagram at 20 kilobars wet, adapted from Kushiro (1969). Circles, coarse-grained Mt. McLoughlin lavas; solid triangles, fine-grained flank lavas; open triangles, basalts and basic cumulate lavas; squares, Fish Lake lavas and Brown Mountain lava (bml).

By making adjustments of the partial pressure of water, this diagram can explain the common association of andesites and high-alumina basalts. If the partial pressure of water is low, the invariant point shifts toward basaltic compositions and to higher temperatures.

According to the flow lines, silicic andesites would plot along the join XY as olivine and pyroxene are subtracted from the liquid. This is also the case indicated by the plots of the Fish Lake lava series. Their trend is subparallel to the XY flow line which proceeds toward silica enrichment.

Differentiation

One of the factors that must contribute to the differentiation of a magma is the development of a large magma chamber. In such a chamber, crystal fractionation could be the major process in the differentiation of calc-alkaline lavas. Therefore, an efficient magma chamber would be one that is able to separate phenocrysts from the liquid effectively, eithor by crystal settling, depostion from a down-going convection current, filter-pressing, or some other unknown method.

Several aspects of a differentiating calc-alkaline volcano can be justifiably proposed from the chemical, petrographic, and field evidence. These include the following:

1) A magma chamber should be large and shaped in such a way that early formed phenocrysts can effectively separate and be left behind when the magma erupts. If convection currents are needed to

separate the crystals, then a large spheroidal or cylindrical shape may be needed as opposed to an irregular system of anastomosing dikes and sills.

2) The magma chamber should be located at an optimum depth such that it is not so shallow that it cools rapidly forming an intrusive plug, but not so deep that convection currents can not operate.

3) Volatile pressure is fairly high but it is variable. This can produce the high anorthite content and oscillatory and patchy zoning seen in the plagioclases. High volatile pressure, especially in an andesite melt which is more viscous than basalt, can produce explosive eruptions, such as those which have occurred on Mt. McLoughlin.

4) The appearance of olivine, pyroxene, and calcic plagioclase in glomerophyric clusters indicates that these phases can be concentrated and separated. This can cause the magma to change toward silicic andesite, a rock type that predominates in the large, composite volcanoes of the Cascades. At Mt. McLoughlin, the mineral clusters were not effectively separated from the liquid.

<u>Conclusion</u>

In the past, most workers in the High Cascades have concentrated their attention on the large volcanic centers of the range. These centers usually have large volumes of silicic andesite with subordinate dacites, rhyolites, and basaltic andesites. Even as early as 1937 Thayer states, "Overemphasis has apparently been placed on andesites in the High Cascades . . The evidence that great quantities of basaltic lavas were erupted while the large andesite peaks were being built is indisputable . . " Of course, in Thayer's frame of reference andesites are silicic andesites and basaltic lavas are basaltic andesites.

At Mt. Hood, the dominant lava is a silicic andesite which Wise (1969) concluded must have been the primary magma. Although olivine andesites are found in the deepest exposure on Mt. Hood which are chemically and mineralogically similar to a Holocene flank lava, he states that they are not genetically related to the silicic andesites.

In his study of Mt. Jefferson, Greene (1968) found that basaltic andesites dominate all other lavas in volume. He deduced that a magma with 53 to 56 percent silica was the parental magma of that volcano. The presence of Recent intracanyon flows which have the same chemical composition as the most common type of older lavas convinced Greene that this must be a reappearance of undifferentiated parental magma. Mt. Jefferson is a large center which apparently did not differentiate its lavas efficiently or possibly had just started to do so when the system stopped.

The same is true of Mt. McLoughlin. The lavas of the main cone have abundant crystal clusters, but they were not effectively separated before eruption. Even though the coarse-grained lavas have the general appearance of a silicic andesite, the lavas retain the bulk composition of the initial fine-grained magma, namely a basaltic andesite.

APPENDIX

ROAD LOG ALONG ROUTE 140

From mile post 19 to 35.2

M.P.	Description
19.0	Road cut showing Wasson tuff overlying a red flow breccia unit of the Roxy Formation. The ash dips to the northeast. A dike cuts the ash, trending approximately NE, on the east end of the cut. The ash is rich in lithic fragments. The breccia is well cemented, perhaps silicified.
19.5	Note the cliff-forming units high on the north side of the highway. The top units are Heppsie Andesite flows.
19.7	Outcrop of red agglomerate and flow breccia. Where dense rock is found, it is a dark, green-black holocrystaline basalt. A series of these flow breccias comprise the cliff outcrops much higher above the road. This particular outcrop may be a slump block since the subdued topography indicates that Wasson ash should be here. Colluvium has been covering the ash since the last stop.
21.8	First of a succession of roadcuts which expose along a 0.7 mile section the flow breccias of the fourth member of the Wasson. It is described by Wells as "flow agglomerate ranging from red flow breccia to scoriaceous and vesicular flows."
21.9	The flows are cut by a vertical dike which is oriented almost parallel to the highway. Although the scoriaceous tops and bottoms of the flows undulate, the attitude of the flows can clearly be seen to dip eastward.
22.9	More scoriaceous and vesicular lava. Some of the vesicles have been filled, forming amygdules.
23.1	Roadcut in dark, olivine basalt which may be the dense phase of the altered, vesicular rock at the last stop. It looks very much like the dike rock at MP 21.9.
24.5	Grizzly road branches off to the right (south). The roadcut shows more dark rock grading into a red, scoriaceous flow breccia. Near The east end of the cut, there are two blocks several meters wide which were caught up in the flow. They are similar to Wasson tuff. One block has cobbles which contain crystals of hornblende up to 1 cm in length.

M.P.	Description
25.0	Two more flows which have breccia on the top and the bottom. The top of the lower flow developed a soil horizon which smoothed over the irregular surface. The top flow baked the soil to a bright red-orange.
25.2	East end of exposure is cut by a dike two meters wide.
25.6	This is the last roadcut of flows and agglomerates until MP 26.7 where it may be repeated. A fault crosses the road in the subdued area east of the cut. The west block is downdropped approximately 2000 feet. The red agglomerate-flow breccia member of the Wasson seems to be very thick in the highway section. This is not due to repetition by faulting. Several vents on both sides of the highway have been mapped as possible sources for this member. If these vents are the primary sources, the member would be expected to thicken toward them. In mapping this member in the type section, Wells has it thickest around Little Butte Creek, but a few miles to the north and the south it thins and is not mapped further.
25.8	Red, brown and grey pyroclastic rocks of the Wasson tuff.
26.0	A 20 foot high roadcut of a light grey pyroclastic flow containing pumice and lithic fragments.
26.3	A thin, white ash bed is off-set about 2 meters, west side down.
26.7	Last of the ash and into a red agglomerate flow unit. This unit may be a repeated fourth member flow or possibly an irregular contact with dark Heppsie Andesit flows.
27.0	Heppsie Andesite with several large blocks of dark, green-black basalt inclusions. Overlying this flow is a flow of the younger Plio-Cascades unit which has very similar lithology when fresh.
27.3	Red agglomerate. This may be the fourth member or a scoriaceous flow of Heppsie andesite.
27.5	Heppsie Andesite flow showing lots of basal scoria overlying an essentially flat lying lens of water-lain sediments.
27.6	Basaltic andesites of Plio-Cascades unit.
27.9	Butte Falls road to the left (north).

M.P. Description

28.3 Road to right to Big Elk Guard Station, Robinson Butte, and Little Butte Forest Camp.

29.1 Road north to Rye Spring and Rye Flat.

29.9 **Road south to Doe Point Forest Camp.** Roadcut shows spheroidally weathered Plio-Cascade rocks.

30.4 Road to right goes in to Fish Lake Resort. Next roadcut is through a rubbly flow of dark, fine-grained, olivine andesite which erupted on the south flank of Mt. McLoughlin. A stage two flow.

For approximately the next mile, fresh , blocky lava flows can be seen on both sides of the road. These are post-glacial (stage three) olivine andesites which were erupted on the south flank of Mt. McLoughlin.

32.5 Summit

32.7 First roadcut through Brown Mountain lava. The flows look like stage three flank lavas from Mt. McLoughlin but they contain no olivine and are chemically silicic andesites.

33.8 The easternmost roadcut through Brown Mountain lava. Rock type changes to coarse-grained andesites which were erupted on the ridge to the southeast of Mt. McLoughlin.

35.2 Deep roadcut in spheroidally weathered rock. The rock may be Plio-Cascades ar early Quaternary olivine basalt.

Age of Mt. McLoughlin

The ages of the high peaks of the Cascade Range have never been well resolved. Most High Cascade lavas are too young to be dated using the K/A method and too old to be dated using the C_{14} method, even if charcoal inclusions could be found. The peaks must be older than the close of the last major glaciation 15,000 years ago because the former glaciers have left large cirques and till deposits. The peaks are younger than the earth's last major magnetic reversal approximately 700,000 years ago; all of the rocks of the high peaks tested for natural remnant magnetism, including Mt. McLoughlin, have normal magnetism. That is, rocks cooled in the earth's magnetic field which had the same polarity that it has today.

The last period of reversed polarity, the Matuyama reversed epoch, lasted from 2.34 million years ago (MYA) to 0.69 MYA. Except for a possible reversal of short duration 30,000 to 20,000 YA, the Brunhes epoch, 0.69 MYA to present, has been normal. (Cox, 1969). This short reversal has not been recognized in the Cascades.

According to E.M. Taylor (oral communication, 1973) even the deeply buried rocks of the High Cascades near the Three Sisters have normal remnant magnetism. These rocks are exposed in deeply glaciated valleys and form the base on which the Three Sisters grew. The high, composite cones are considerably younger than these basal rocks, but at the present time, there is no way of knowing how much younger they are.

PLEISTOCENE GLACIATION

During the maximum ice advances during Pleistocene time, there was an ice cap on the high, narrow plateau area of the High Cascades. This fact was first recognized in the early 1900's but not widely appreciated, perhaps because of the lack of published glacial studies in the Oregon Cascades.

Evidence for this ice cap can easily be seen on topographic maps of the area between Mt. McLoughlin and Crater Lake. The ice cap formed along the crest of the range and upon melting left a large humucky area of moderate relief and poor drainage. Leading out of the area to the east and west are U-shaped glacially scoured valleys. There are no individual catchment basins or cirques that could have accumulated snow to feed these valley glaciers. They must have been fed by the overflow from the ice cap.

Mt. McLoughlin was the southern limit of the ice cap in Oregon. The average elevation of the Cascade crest between Mt. McLoughlin and the Klamath River in California was below 5600 feet and too low to support an ice cap.

Two cirque-fed glaciers flowed north and northeast from Mt. McLoughlin and coalesced with ice moving south from the ice cap into the Fourmile Lake basin. Most of this ice was then diverted west, down the south fork of Fourbit Creek. Although a small portion of the ice probably flowed down Billie Creek on the east side, no moraines could be discerned on aerial photographs.

Some of the ice in the northeast cirque overflowed its edge and left three lobe-shaped end moraines south of Frey Lake. It is in the middle lobe that a post-glacial block lava flow erupted and contributed to the formation of an unusual geomorphic feature. The dark blocks from this flow are creeping downhill and feeding a blockstream in a small drainage depression. From the other side of the drainage, weathered buff-colored Frey Lake lava blocks are being fed into the blockstream. This results in a sharp color line which runs down the center of the blockstream and can be clearly seen on the ground and on aerial photographs. Blockstreams also occur on the west slope of the mountain where they are fed by the block lava which was erupted from North and South Squaw Tip.

During maximum glaciation, a small glacier started to develope a cirque on the northwest side of Mt. McLoughlin. Two well-defined troughs between North Squaw Tip and the north cirque are a result of this action. Ice flowed down the mountain for more than a mile and deposited a great volume of huge blocks below the 5600 foot level. Movement probably continued for some time after the main glacier melted. The huge field of blocks may have moved as a rock glacier. The surface of the field has no matrix but it shows strongly ridged and convex toes which are characteristic of rock glaciers. Below the surface, there may be an accumulation of fine material which may have provided a matrix so that true solifluction movement could occur.

The glacial features on the north side of Mt. McLoughlin shown on plate 2 were transferred from aerial photograghs (scale, 1:13,000; dated 1969) onto an enlarged fifteen minute topographic map (1:32,000) using a stereo-plotter.

Gary Carver (1973, unpublished thesis) studied the glacial stratigraphy of the Mountain Lakes Wilderness area located to the southeast of Mt. McLoughlin. Although no tills in the area were dated radiometricly, Carver has compared the drifts in the area with those from the Washington Cascades and the Sierra Nevada to show approximate age correlations, (table 11).

Obscure glacial moraine features are located in sections 3 and 34 on the northwest flank of Mt. McLoughlin. They may be Varney Creek age or older, even though in his table, Carver tentatively has the age of Mt. McLoughlin younger than the Varney Creek till. The prominent glacial features on Mt. McLoughlin are assumed to be no older than the last major glaciation and would therefore correlate with the Waban drift. Carver reports that a drift of Zephyr Lake age (which may be a late Waban drift) is found four kilometers down the north slope of the mountain, or three kilometers beyond the cirque thresholds, and ended below the 1900 meter level.

Neoglacial-I till is said to show up well on Mt. McLoughlin. It is found on the north slope to within two kilometers of Fourmile Lake and ends at an elevation slightly less than 2000 meters. After the Mazama ash was deposited (c. 7000 YA), the glaciers were confined to their pre-existing cirques. Such features as fossil rock glaciers and block streams are assumed to have been active during the Neoglacial-I and -II episodes. Protalus ramparts and rock glaciers in and around the present cirque basin are still active today.

Table 11. Comparison of Quaternary glacial successions in the Sierra Nevada and Cascade Range, after Carver (1973).

Cascade Range Southern Oregon	Sierra Nevada California	Appoximate Age
Neoglacial II	Matthes Till	
	unnamed till	500
Neoglacial I (McL till)	Recess Peak Till	2000
Mazama Ash	Mazama Ash	6700
Zephyr Lake drift	Hilgard Till	9400
Waban drift	Tioga Till	13,000
	Tenaya Till	
Varney Creek drift	Tahoe Till	
	- basalt -	90,000
Moss Creek till	Mono Basin Till	
Winema till	Casa Diablo Till	240,000
	Bishop Tuff	700,000
older tills	Sherwin Till	

Table 12. Trace element data (INAA) for Mt. McLoughlin area rocks.

	LS-6	LS-56	LS-3	LS-4	BL-9
Na %	2.94 ±.03	2.51 ±.03	2.83 ±.03	3.11 ±.04	2.36 ±.03
Cs			0.31 ±.04		
Ba	260 ±43		235 ±35	386 ±61	
La	6.22 ±.16	9.02 ±.20	7.12 ±.12	18.08 ±.35	8.74 ±.18
Ce	14.5 ±.3	19.0 ±.6	14.7 ±.3	39.7 ±.5	19.6 ±.5
Sm	2.28 ±.03	3.18 ±.03	2.35 ±.02	5.23 ±.06	3.08 ±.04
Eu	0.91 ±.02	1.11 ±.03	0.89 ±.02	1.50 ±.03	1.10 ±.02
Tb	0.40 ±.02	0.55 ±.03	0.27 ±.02	0.63 ±.02	0.48 ±.03
Yb	1.0 ±.1	2.0 ±.1	1.0 ±.1	2.1 ±.1	2.0 ±.1
Lu	0.16 ±.02	0.29 ±.02	0.18 ±.1	0.27 ±.02	0.31 ±.02
Th	0.96 ±.04	1.23 ±.08	1.02 ±.04	1.21 ±.07	0.94 ±.08
Zr				332 ±50	
Hf	1.55 ±.06	1.85 ±.11	1.77 ±.05	2.82 ±.08	1.91 ±.09
Co	23.2 ±.3	32.7 ±.4	23.0 ±.2	21.6 ±.2	32.0 ±.3
Sc	19.8 ±.2	27.0 ±.3	19.4 ±.2	21.6 ±.2	32.6 ±.3
Cr	35 ± 1	180 ± 2	25 ± 1	32 ± 1	178 ± 2

All abundances in ppm except as indicated.

Table 13. Trace element data (INAA) for Mt. McLoughlin area rocks.

	BL-4	LS-2	LS-75	LS-26	LS-81
Na %	3.07 ±.04	2.89 ±.03	3.17 ±.04	2.73 ±.03	3.07 ±.04
Cs	0.78 ±.04		0.53 ±.05	0.67 ±.05	0.34 ±.08
Ba	376 ±38		429 ±71	40 ±10	
La	11.42 ±.25	11.29 ±.21	18.57 ±.34	14.24 ±.25	9.10 ±.21
Ce	23.2 ±.3	22.9 ±.5	40.7 ±.5	28.3 ±.4	18.4 ±.4
Sm	2.83 ±.04	3.36 ±.04	5.21 ±.06	3.79 ±.04	3.10 ±.04
Eu	0.90 ±.02	1.16 ±.03	1.42 ±.02	1.20 ±.02	1.03 ±.02
Tb	0.36 ±.02	0.48 ±.02	0.74 ±.02	0.52 ±.02	0.38 ±.02
Yb	1.1 ±.1	1.1 ±.1	2.7 ±.1	1.5 ±.1	1.1 ±.1
Lu	0.20 ±.02	0.18 ±.02	0.48 ±.02	0.26 ±.02	0.18 ±.02
Th	2.77 ±.05	1.48 ±.07	3.69 ±.08	1.54 ±.06	1.22 ±.06
Zr			230 ±38		
Hf	2.21 ±.05	2.34 ±.08	3.26 ±.07	2.95 ±.08	1.75 ±.06
Co	17.0 ±.2	21.7 ±.3	24.0 ±.3	23.7 ±.3	22.1 ±.2
Sc	13.6 ±.1	17.1 ±.2	17.6 ±.2	19.9 ±.2	19.4 ±.2
Cr	32 ± 1	73 ± 1	76 ± 1	95 ± 1	33 ± 1

Table 14. Trace element data (INAA) for Mt. McLoughlin area rocks.

	LS-71	W-1-1*	BCR-1*	AGV-1*
Na %	2.88 ±.03	1.65 ±.02	2.45 ±.03	3.22 ±.04
Cs		1.00 ±.13		1.15 ±.10
Ba		170 ±20	652 ±35	1213 ±33
La	6.10 ±.16	10.33 ±.24	24.27 ±.44	37.50 ±.53
Ce		23.4 ±.5	54.1 ±.7	74.1 ±.7
Sm	2.13 ±.03	3.55 ±.04	7.10 ±.08	6.07 ±.07
Eu		1.09 ±.03	1.95 ±.04	1.71 ±.04
Tb		0.66 ±.04	1.07 ±.04	0.70 ±.03
Yb		2.2 ±.1	3.6 ±.2	2.0 ±.1
Lu	0.17 ±.02	0.32 ±.02	0.55 ±.03	0.35 ±.02
Th		2.41 ±.07	6.63 ±.11	7.19 ±.10
Zr				536 ±53
Hf		2.39 ±.10	4.96 ±.12	4.76 ±.09
Co		43.2 ±.5	35.4 ±.4	14.7 ±.2
Sc		38.0 ±.4	34.6 ±.4	12.8 ±.1
Cr		121 ± 2	8 ± 1	10 ± 1

* Standard rocks which were tested with the unknowns.

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