AN ABSTRACT OF THE THESIS OF

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E. M. Taylor

The northern part of the Southeast Three Sisters quadrangle straddles the crest of the central High Cascades of Oregon. The area is covered by Pleistocene and Holocene volcanic and volcaniclastic rocks that were extruded from a number of composite cones, shield volcanoes, and cinder cones. The principal eruptive centers include Sphinx Butte, The Wife, The Husband, and South Sister volcanoes. Sphinx Butte, The Wife, and The Husband are typical High Cascade shield and composite volcanoes whose compositions are limited to basalt and basaltic andesite. South Sister is a complex composite volcano composed of a diverse assemblage of rocks. In contrast with earlier studies, the present investigation finds that South Sister is not a simple accumulation of andesite and dacite lavas; nor does the eruptive sequence display obvious evolutionary trends or late stage divergence to basalt and rhyolite. Rather, the field relations indicate that magmas of diverse composition have been extruded from South Sister vents throughout the lifespan of this volcano. The compositional variation at South Sister is atypical of the Oregon High Cascade platform. This variation, however, represents part

of a continued pattern of late Pliocene and Pleistocene magmatic diversity in a local region that includes Middle Sister, South Sister, and Broken Top volcanoes. Regional and local geologic constraints combined with chemical and petrographic criteria indicate that a local subcrustal process probably produced the magmas extruded from South Sister, whereas a regional subcrustal process probably produced the magmas extruded from Sphinx Butte, The Wife, and The Husband.

All of the volcanoes in the field area are probably less than 720,000 years old. Sphinx Butte, The Wife, and The Husband are older than South Sister and have been subjected to at least two glaciations. Late Pleistocene glaciers covered all but the upper ridges and summit of South Sister; however, evidence for multiple glaciation is obscure and it is possible that the bulk of South Sister is younger than the second-to-last Pleistocene glaciation. Glaciated andesite lavas at the summit of South Sister are capped by a veneer of basaltic andesite lavas. The basaltic andesite lavas were extruded prior to 6840 yrs. B.P., but are probably of late Pleistocene rather than Holocene age. At some time between 12,000 and 2300 yrs. B.P., basaltic andesite lavas and cinders were extruded from the Le Conte vent at the southwest base of South Sister. The Le Conte lavas may bear only a spatial relation to South Sister. Between 2300 and 1900 yrs. B.P., a series of rhyodacite domes and block flows were extruded from flank vents on South Sister. Future eruptive activity is likely at this volcano.

Geology of the Northern Part of the Southeast Three Sisters Quadrangle, Oregon

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INTRODUCTION

Purpose of Study

A complete understanding of the natural history of the earth must include knowledge of the origin and evolution of the igneous rocks. To facilitate this understanding we must study present day igneous environments as a basis for the interpretation of past igneous activity. The major facts come from the rocks themselves, geophysical evidence, and experimental petrologic evidence. The last two categories of information are only useful in terms of the first. Detailed field observations are a necessary prerequisite to any comprehensive understanding of igneous processes. "The days are past when study of random samples of rock of unknown structural and time relationship can be of much real value to petrology" (MacDonald and Katsura, 1964).

The Oregon High Cascades offer an outstanding opportunity for the study of recent calc-alkaline volcanism within the contiguous United States. Structural deformation has not masked the basic field relations and Pleistocene glaciers have dissected the pile in various localities, providing excellent three-dimensional views. Yet there is a paucity of detailed field data upon which to build an understanding of the geologic history of the range.

This study was undertaken to determine the volcanic stratigraphy, distribution of lithologies, history of volcanism, and major element geochemistry of rocks in the vicinity of the South Sister Volcano, Oregon. Major emphasis was directed toward field mapping on a 1:24,000 scale with supporting petrographic and chemical work. I hope that my data and map will provide a solid foundation for further, advanced studies on the origin and evolution of the Cascade Range.

Location and Access

The thesis area is approximately 30 miles west of Bend, Oregon and encompasses the South Sister Volcano and the slopes to the west (Figure 1). The area includes most of the northern one-half of the S.E. Three Sisters 7½-minute quadrangle and is bounded by 44°3' and 44°07'30" north latitude and by 121°45' and 121°52'30" west longitude.

The entire field area lies within the Three Sisters Wilderness area; therefore, access is by foot only. To the south, entrance can be gained on a trailhead at Devils Lake, on Century Drive. To the west, several trails in the vicinity of McKenzie Bridge allow access to the western slopes. In addition, the northeast flank of the South Sister can be approached on a trail from Pole Creek Spring. The Oregon Skyline Trail and several older unmaintained trails provide additional access to most of the area.

Previous Studies

The South Sister and the surrounding area have been the focus of very few previous studies. One of the earliest investigators was Hodge (1925) and he hypothesized that the South and Middle Sisters were constructed within a large caldera whose rim was defined by North Sister, Little Brother, The Husband, The Wife, Devils Hill, and Broken Top. Williams (1944) effectively demonstrated that these peaks were

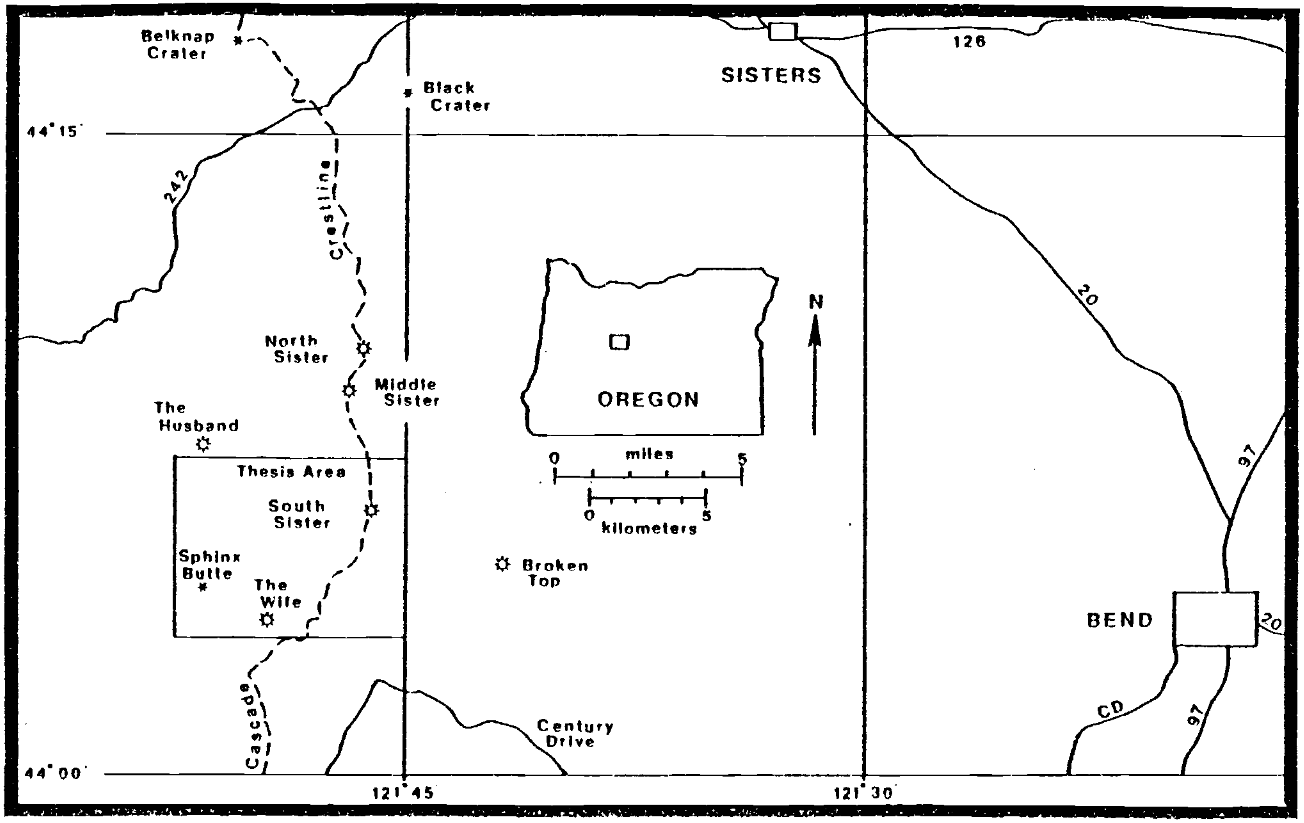


Figure 1. Index Map showing location of thesis area.

individual volcanoes and that no such caldera was present. Although his study included a large area of the central Oregon High Cascades and was limited to six weeks in the field, Williams (1944) was able to produce general descriptions of the rocks and major volcanic centers, a reconnaissance geologic map of the Three Sisters area, and a reasonably accurate account of the volcanic history of the region. The present study adds to his body of observations, modifies the details of his volcanic history, and offers a different interpretation of the development of the South Sister.

McBirney (1968; 1978) has proposed a generalized model for the development of the large Cascade stratovolcanoes. His discussion of the South Sister, however, appears to be based on a limited amount of field data and his interpretations contrast with those presented in this paper.

Taylor has mapped the southeast flank of the South Sister (unpublished data) and the 7½-minute quadrangle that borders the thesis area on the east (Taylor, 1978). Consequently, his observations and conclusions provide a local framework for the interpretations presented in this paper.

REGIONAL GEOLOGY and VOLCANIC HISTORY

The Cascade volcanic province extends from southern British Columbia to northern California (Figure 2) and is physiographically subdivided into two groups; the Western Cascades and the High Cascades (Callaghan, 1933; Peck and others, 1964).

The Western Cascades are a thick sequence of gently folded basalts, andesites, and rhyolites of late Eocene to early Pliocene age (Peck and others, 1964). The strata have been deeply eroded and the present topography bears no relation to the positions of old volcanic centers. Locally the rocks have been intruded by Eocene to late Miocene epizonal plutons (Buddington and Callaghan, 1936; Peck and others, 1964; Hopson and others, 1965).

The High Cascades rest unconformably on the Western Cascades and are of late Pliocene to Holocene age. Pleistocene glaciers have modified the topography but the rocks are undeformed and the landscape is constructional. Intrusive rocks occur only as dikes and plugs of eroded volcanic centers. In Oregon and southern Washington the High Cascades are chiefly a platform of coalescing basalt and basaltic andesite shield volcanoes (Williams, 1944, 1957; Taylor, 1978, 1980; Hammond, 1979). Large andesite or basaltic andesite stratovolcanoes mark the crest of the range but andesite constitutes only a small proportion of the total rock volume (Thayer, 1937; McBirney, 1978).

The rocks of the Oregon High Cascades record only the latest episode in a long history of volcanism in the state. The pre-Cenozoic volcanic record is poorly preserved, but the Cenozoic record is well documented. Throughout the Cenozoic, volcanism played a major role in

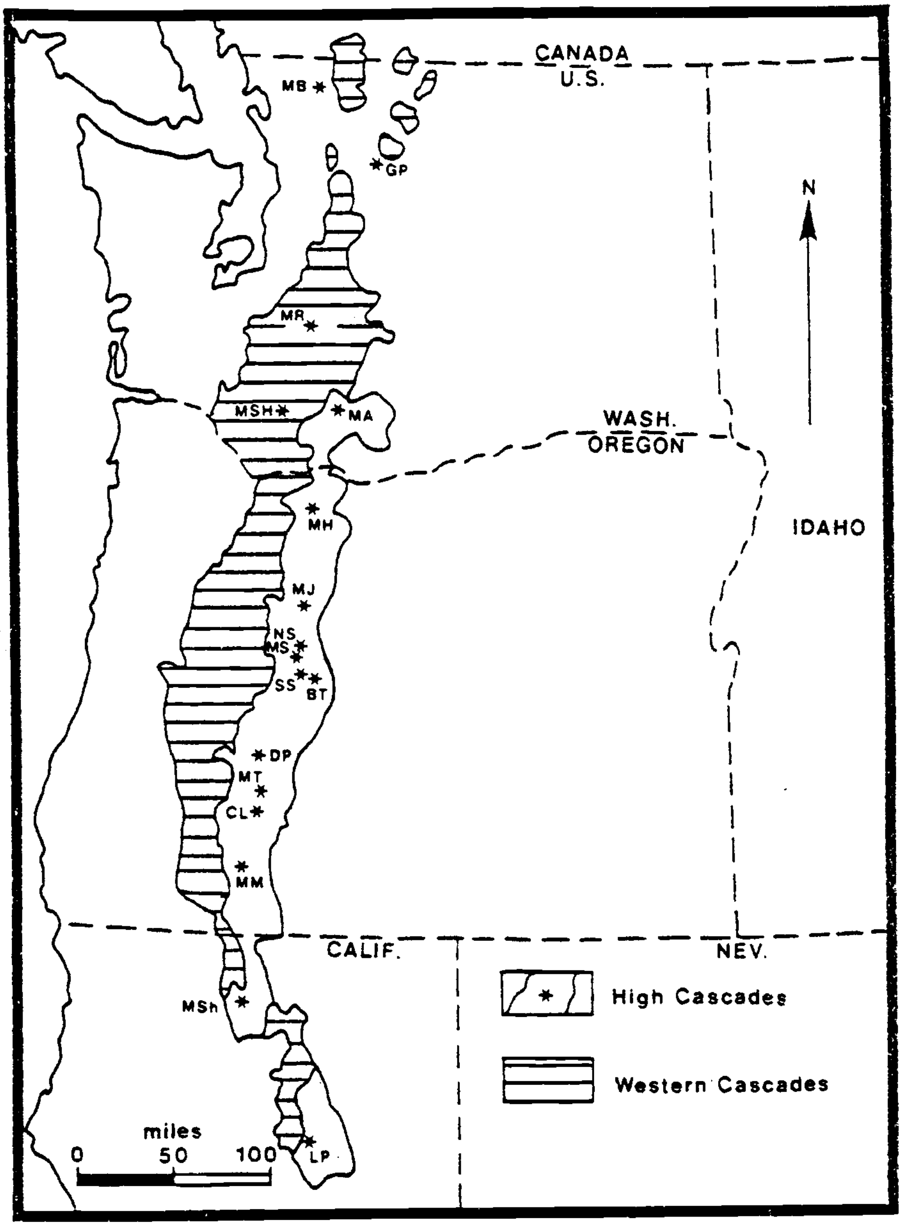


Figure 2. Cascade volcanic province. BT: Broken Top. CL: Crater Lake (Mt. Mazama). DP: Diamond Peak. GP: Glacier Peak. LP: Lassen Peak. MA: Mt. Adams. MB: Mt. Baker. MH: Mt. Hood. MJ: Mt. Jefferson. MM: Mt. McLoughlin. MR: Mt. Rainier. MS: Middle Sister. MSH: Mt. St. Helens. MSh: Mt. Shasta. MT: Mt. Thielsen. NS: North Sister. SS: South Sister. Modified from Figure 2 of Hammond (1979).

the development of the Oregon landscape.

Early and Middle Cenozoic

In Paleocene times volcanic activity was rare throughout the Pacific Northwest. During the Eocene epoch, however, volcanism was common in many areas of the northwest United States (Armstrong, 1978). During the early Eocene submarine eruptions of tholeiitic and alkalic basalts were widespread along the axes of the Puget-Willamette Trough and Coast Ranges in Oregon and Washington (Snavely and others, 1968). Eocene volcanism in north-central Oregon produced a diverse assemblage of calc-alkaline rocks now known as the Clarno Formation. Throughout most of the Eocene, marine sediments were being deposited in the area occupied by the present-day Cascades, but toward the end of this epoch the andesitic rocks of the Colestin Formation were extruded to form the base of the Western Cascades.

By early or middle Oligocene times a belt of calc-alkaline vents was established along the trend of the present-day Cascades (Armstrong, 1978). These vents were active through late Oligocene and early Miocene times and produced the thick accumulations of the Little Butte Volcanic Series of the Western Cascades (Peck and others, 1964). The andesite and dacite volcaniclastic deposits of the John Day Formation of north-central Oregon were deposited during this same time interval. Robinson and Brem (1981) suggest that the deposits of the John Day Formation are chiefly downwind accumulations of debris from Western Cascade volcanoes.

In middle Miocene times, basaltic volcanism, associated with crustal extension, became the dominant form of igneous activity in eastern

Oregon; calc-alkaline volcanism was chiefly confined to a belt coinciding with the present Western Cascades (Lipman and others, 1972; Christiansen and Lipman, 1972). Voluminous eruptive activity characterized both of these provinces. Most of the Columbia River Basalt Group and a large part of the Oregon Western Cascade sequence (the Sardine Formation) were probably extruded during a period between 13 and 16 m.y. B.P. (McBirney and others, 1974).

Late Cenozoic

The geologic literature contains many discrepancies concerning the stratigraphic, structural, and chronologic relations of the late Cenozoic sequence in the Oregon Cascades. Various authors subdivide the rock sequence on the basis of different criteria and interpret the structural history in different ways (Thayer, 1937; Williams, 1957; Peck and others, 1964; McBirney and others, 1974; Sutter, 1978; Taylor, 1978; Hammond, 1979). Nonetheless, a thread of consistency occurs in many of the accounts.

During late Miocene and early Pliocene times, a broad calc-alkaline volcanic field covered the region now occupied by the central High Cascades, the east half of the Western Cascades, and the Deschutes Basin. The compositions of lavas and volcaniclastic debris in this field ranged from basalt to rhyodacite. After early Pliocene times, however, basalt and basaltic andesite became the dominant extrusive products and volcanism was largely restricted to a narrow belt coincident with the High Cascades. Several authors have correlated this magmatic change to a change in structural regime (Thayer, 1937; Taylor, 1978, 1980; Hammond, 1979). Within the High Cascades, north-south alignments of vents occur on a regional and local scale. Taylor (1978) and Hammond (1979) have suggested that these alignments are controlled by a series of subsurface faults that trend north-south. Taylor (1978, 1980) has proposed that a complex north-south graben system was formed between 4 and 5 m.y. ago along the axis of the High Cascades; subsidence of this system coincided with the change from andesitic to basaltic volcanism. Although basaltic volcanism has characterized most of the central High Cascades of Oregon since late Pliocene times, intermediate and silicic volcanism has persisted in a localized region in the vicinity of South Sister, Middle Sister, and Broken Top volcanoes (Taylor, 1978; 1980).

LITHOLOGY AND STRATIGRAPHY

Rock Classification

At present different authors apply names to extrusive rocks on the basis of widely different criteria. Chayes (1969) has aptly illustrated this point in a discussion of the usages of the term "andesite". The International Union of Geologic Sciences has recommended that volcanic rocks be classified on the basis of modal mineralogy (Streckeisen, 1979). I found this to be impractical in the present study because of the fine-grained or glassy nature of the rocks from my field area. However, chemical analyses for the major oxides were performed on all samples for which thin sections were prepared. Therefore, I have adopted a chemical classification that is currently being used by E. M. Taylor for High Cascade volcanic rocks. The following definitions (Taylor, 1978) will be used throughout:

Basalt:	48-53 weight percent silica
Basaltic andesite:	53-58 weight percent silica
Andesite:	58-63 weight percent silica
Dacite:	63-68 weight percent silica
Rhyodacite:	> 68 weight percent silica

All values are H_2O-free. Although rocks with greater than 73 percent silica occur in the thesis area all contain less than four percent K_2O and thus are referred to as rhyodacites rather than rhyolites.

The above classification parallels historic usage. Several authors have used similar schemes with respect to other calc-alkaline suites (e.g., Taylor, 1968) and in conjunction with other Cascade studies (e.g., Williams, 1944; Peck and others, 1964; Greene, 1968; Wise, 1969;

White and McBirney, 1978).

Representation of Mapped Units

Mapped volcanic deposits are referred to by symbolic names (Taylor, 1978) which convey four categories of information: age, composition, occurrence, and unit number. Mapped nonvolcanic deposits are generally referred to by age and occurrence only. Combinations of the symbols listed below provide succinct, informative unit names. Thus, PsRdLa3 refers to the third-numbered unit of Pleistocene rhyodacite lava and HoAl refers to undifferentiated Holocene alluvium.

Age

- Ho: Holocene units.
- Ps: Pleistocene units.

Composition

- Bs: Basalt.
- BA: Basaltic andesite.
- An: Andesite.
- Da: Dacite.
- Rd: Rhyodacite.

Occurrence of Volcanic Deposits

- La: Lavas. Includes single flows, composite flows, and volcanic domes.
- Pc: Coarse pyroclastic deposits. Includes pumice ramparts adjacent to volcanic domes, and scoria and agglomerate of cinder cones and composite volcanoes.
- Id: Intrusive dikes.
- Ip: Intrusive plugs.

Occurrence of Nonvolcanic Deposits

- Al: Alluvium. Includes stream and lake deposits (clay, silt, sand, and gravel) and well-sorted glacial outwash.
- Gd: Glacial drift. Includes terminal, lateral, and ground moraines and poorly-sorted outwash adjacent to moraines.
- Ta: Talus aprons and blockfields.
- Sn: Glacial ice and "permanent" snowfields.

Field Descriptions and Age Relations

During the following discussion only salient features of the stratigraphy are noted. Detailed field and petrographic descriptions of individual units are given in Appendix 1.

During the field season I used a portable magnetometer to measure the paleomagnetic polarities of most rock units within the thesis area. All tested rocks were found to be normally polarized. Because no magnetic reversals were found, all rocks in the field area are probably less than 720,000 years old (McDougall, 1979). McBirney (1968) has previously suggested that the entire South Sister rock sequence is normally polarized but Williams (1944) believed Sphinx Butte, The Husband, and The Wife to be largely, if not completely, Pliocene in age. My data indicate that in addition to South Sister, the Sphinx, Husband, and Wife were probably constructed during the latter half of the Pleistocene epoch. Armstrong and others (1975) report a whole rock K-Ar date of 0.04 $\pm$ 0.1 m.y. for a normally polarized basaltic andesite from the saddle on the south ridge of The Husband volcano.

The stratigraphic position of the Brunhes-Matuyama boundary is not known but it is probably no more than several miles west of the field area. The High Cascade-Western Cascade contact is approximately seven miles west of the field area (Williams, 1957; Taylor, 1968). One of the earliest High Cascade lavas exposed along this contact is an intracanyon basalt flow that now forms Foley Ridge in the McKenzie River Canyon. This flow has a K-Ar whole rock date of 2.8 m.y. (E. M. Taylor, personal communication). Within the central Oregon High Cascades the oldest rock has been dated at 3.9 m.y. (Taylor, 1980). Therefore, the volcanic section described in this paper represents only the upper part of the High Cascade platform.

The oldest rocks in the field area are a series of medium to dark gray olivine-bearing basalt lavas (PsBsLal) that crop out near the confluence of Mesa and James Creeks and Mesa and Separation Creeks. Olivine phenocrysts vary from two to three percent and are accompanied by equal or subordinate amounts of plagioclase. The source of these lavas is uncertain but most have westward dips of less than five degrees and it is probable that some were derived from The Husband or The Wife.

Most of the remaining rocks within the map area were extruded from one of five volcanoes: Sphinx Butte, The Wife, The Husband, Middle Sister, and South Sister. Relative ages can be inferred on the basis of stratigraphic relations and degree of incision by Pleistocene glaciers.

The central conduits and internal structures of Sphinx Butte, The Wife, and The Husband have been exposed by Pleistocene glaciers. In contrast, Middle Sister and South Sister have been only moderately incised by Pleistocene glaciers. Part of the central conduit of Middle Sister has been exposed and can be seen on the glaciated northeast face of the peak (E. M. Taylor, personal communication). The central conduit of South Sister is not exposed. A few dikes are exposed on South Sister, but these are chiefly restricted to the cirque walls on the upper flanks of the mountain. Lavas from the South and Middle Sisters (PsBALa5, PsDaLal) have spread westward to cover flows derived, in part, from The Husband, The Wife, and Sphinx Butte. Therefore, The Husband, The Wife, and Sphinx Butte are older than the Middle and South Sisters.

Sphinx Butte is a small, broad-based, basaltic andesite shield volcano typical of those that constitute the bulk of the High Cascade platform (Taylor, 1980). The Wife and The Husband are much larger basalt and basaltic andesite shield volcanoes. Their respective bases measure at least five and ten miles across; large composite structures rest upon these shield foundations. Upper level flows from Sphinx Butte (PsBALa4) lap up against the west flank of The Wife and indicate that Sphinx Butte is younger than The Wife. I could make no correlations across the glacial canyon that separates Sphinx Butte and The Wife from The Husband; however, The Husband appears to be more deeply eroded than The Wife and on this basis can probably be regarded as older than The Wife and Sphinx Butte. Because absolute age determinations are not available it is difficult to assess how closely these centers were related in time.

A glaciated South Sister dacite flow (PsDaLa1) occupies part of the canyon floor between Sphinx Butte and The Husband. Lavas that were extruded from Sphinx Butte (PsBALa4), The Husband (PsBALa2; PsBALa3), and The Wife (PsBsLa2) are exposed as subhorizontally layered flows in the steep canyon walls adjacent to the dacite flow; however, the base of the dacite is from 600 to 1000 feet below the level of most of the canyon-wall flows. Originally these canyon-wall flows probably formed sheet-like surfaces across large parts of the valley now occupied by the dacite. The morphology of the canyon near the terminus of the dacite flow suggests that the pre-dacite surface was carved during an earlier glacial advance. To account for the present rock configurations I propose that the following sequence of events occurred:

1) Fluid, laterally extensive basalt and basaltic andesite flows were extruded from the shield volcanoes of The Husband, The Wife, and Sphinx Butte during the late Pleistocene. Activity

at these peaks may or may not have overlapped in time.

2) During one or more glacial advances an ancestral canyon was carved into the surface formed by the above-mentioned flows.

3) A dacite lava was extruded from the South Sister and flowed into the upper part of the canyon formed in step 2 above.

4) During one or more glacial advances the upper surface of the dacite flow was removed and the canyon was modified to its present form.

On the basis of this reasoning it is likely that Sphinx Butte, The Wife, and The Husband have been subjected to the last two Pleistocene glaciations. I found no hyaloclastites and recognized no tuyas or ice-chilled flow margins on these three volcanoes.

The monotonous sequences of basalt and basaltic andesite extruded by The Husband, The Wife, and Sphinx Butte are in sharp contrast to the varied eruptive products of the Middle and South Sisters. Middle Sister lavas vary in composition from basalt to rhyodacite (Taylor, 1980). South Sister lavas include basaltic andesite, andesite, dacite, and rhyodacite; basalts are conspicuously absent.

Although eruptions have occurred at South Sister during the Holocene, both Middle Sister and South Sister were active late in the Pleistocene. For example, well-preserved marginal levees can be seen on a glaciated dacite flow (PsDaLa7) that was extruded from a vent on the south flank of Middle Sister, at approximately 8300 feet elevation (Figure 3). It seems unlikely that this flow was subjected to more than one glaciation. Similarly, the summit lavas of South Sister were probably extruded late in the Pleistocene. Immediately north of the field area, between Chambers Lake and Diller Glacier, glaciated basalt porphyry lavas of the Middle Sister overlie glaciated dacite lava (PsDaLa4) of the South Sister. Elsewhere the stratigraphic relations are less clear but considerable overlap in lifespan has probably occurred between these two volcanoes.

The Husband

The Husband (Figure 4) was a large volcano and probably rivaled North Sister in size during its prime. All that remains today is a broad shield base, remnants of a composite cone, and an unusually large north-south elongate plug. Only the south flank of The Husband lies within the field area; however, the remainder of the mountain is composed of rocks which are identical in mineralogy and chemistry to these south flank lavas (E. M. Taylor, personal communication).

Within the field area I have mapped a succession of three flow units on the south flank of The Husband. Lavas in the uppermost unit have southerly dips and are probably derived from The Husband. The lower two units contain subhorizontal lavas, but flow directions could not be determined and the lateral extent of these lavas is not known; therefore, they cannot be unambiguously assigned to The Husband. Collectively, these three units overlie a series of basalt lavas (PsBsLa1) that, in part, may be derived from The Husband.

The lowermost mapped unit on the south flank of The Husband is composed of fine-grained, sparsely porphyritic, olivine- and orthopyroxene-bearing basaltic andesite lavas (PsBALa2). Good cross-sectional exposures occur in the bed of Honey Creek on the steep canyon walls to the southeast of Honey Lake. These flows have ropy surfaces and vary from two to ten feet thick. No intervening soil horizons were found.

Figure 3. Glaciated dacite flow (PsDaLa7) on south flank of Middle Sister. Vent is visible in upper right hand corner of photograph. Note well-preserved marginal levees and bifurcation of flow in foreground where lava flowed around andesite dome (PsAnLa5).

Figure 4. The Husband Volcano. View from north flank of South Sister.

Abundant smooth-walled, spherical-to-oblate vesicles are found throughout but increase in abundance toward the top and bottom of each flow. Subequal amounts of olivine and othopyroxene phenocrysts constitute less than two percent of the rock volume. On the basis of the above features I propose that these flows were a closely related series of fluid, gas-rich lavas which were extruded over a relatively short time interval.

A thick flow of light gray, fine-grained, platy, basaltic andesite lava (PsBALa3) overlies the preceding unit. Good exposures can be found in the vicinity of Honey Lakes. The rock breaks into plates which vary from one-eighth to four inches thick and weathers to a light gray sand. Samples appear aphyric at arm's length but small phenocrysts of olivine and plagioclase are commonly present and may total up to two and one percent respectively.

The uppermost mapped unit on the south flank of The Husband consists of a monotonous sequence of olivine-bearing basalt lavas (PsBsLa4). The most accessible exposures occur in the northwest part of the map area along the Foley Ridge Trail. Most of these lavas are light to dark gray block flows that contain less than five percent olivine and less than three percent plagioclase phenocrysts.

The Wife

I did not map The Wife as part of my thesis but I did reconnoiter the area late in the summer of 1980. The following discussion is based on the field notes and sketch map (Figure 5) from this preliminary survey.

The Wife consists of a broad-based shield volcano surmounted by

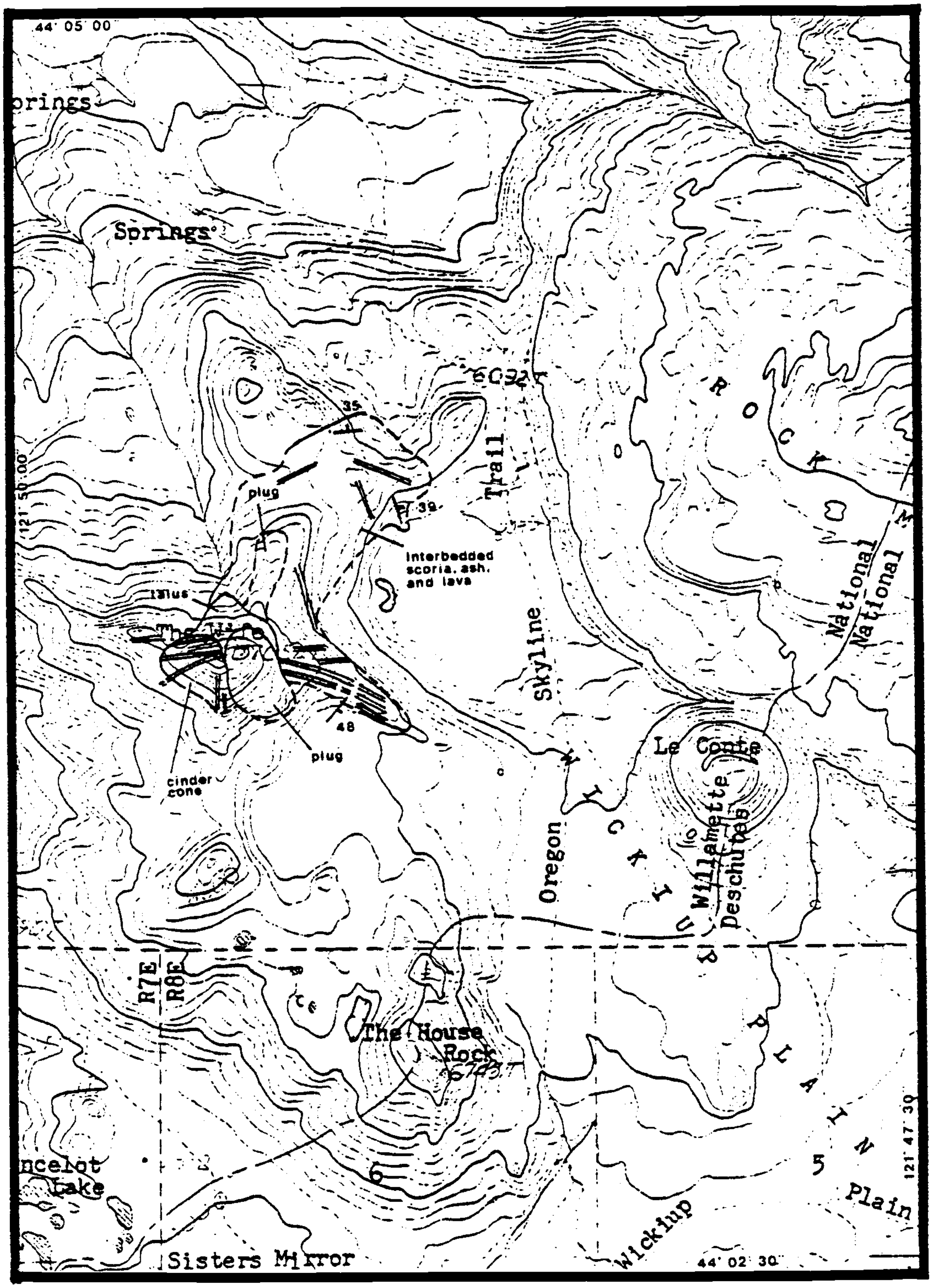


Figure 5. Geologic sketch map of The Wife.

remnants of a large composite cone. The shield base is composed of many subhorizontal basalt and basaltic andesite lavas; these are similar in texture and composition to the lavas of Sphinx Butte and The Husband. The composite cone is composed of moderate- to steeply-dipping beds of scoria and ash, and interbeds of thin mafic lavas. The radius of the composite cone, measured along the ridge that trends northeast from the summit, is approximately 3500 feet. Smaller remnants of the cone are preserved on the east and southeast flanks of The Wife.

A steep-walled plug occupies the east half of the summit of The Wife. An extension of this plug is exposed at the north base of the summit. The west half of the summit of The Wife is the remnant of a cinder cone that was constructed near the vent. The cone is cut by many steeply-inclined east-west dikes which probably fed many of the flows on the surrounding flanks.

Sphinx Butte

Sphinx Butte (Figure 6) is a small basaltic andesite shield volcano whose internal structure has been magnificently exposed by Pleistocene glaciers. A dark gray to black, irregularly jointed plug (PsBAIp4) fills the central vent and is bordered on the west by the remains of a small cinder cone (PsBAPc4). Dikes are rare and only one (PsBAId4) was large enough to be mapped. The plug and cinder cone are enclosed by a succession of thin, gently inclined lavas (PsBALa4). Several of these flows were traced to the west margin of the field area and it is likely that they extend at least several more miles in this direction. The west flank of The Wife formed a barrier that restricted the eastward advance of Sphinx Butte lavas.

Figure 6. Sphinx Butte Volcano. Irregular mass of central conduit plug is exposed in center.

Sphinx Butte lavas and scoria contain two to five percent olivine, up to two percent plagioclase, and less than one percent clinopyroxene phenocrysts. In the plug rocks, however, olivine totals ten percent and is the only porphyritic phase; it is rounded and resorbed and has commonly undergone deuteric alteration to bowlingite and granular opaque oxides.

Several Sphinx Butte flows have coarse-grained groundmass constituents, diktytaxitic textures, and vesicle linings of cristobalite and hematite. These flows are thin, gently inclined, and laterally extensive. An abundant supply of gas probably decreased the viscosity of these lavas yet facilitated the growth of larger groundmass crystals. The diktytaxitic textures and precipitates of ferric iron and silica were produced as gas continued to evolve during late stages of consolidation.

My field descriptions and a limited number of chemical analyses (1501, 1503, 1513, 1523) suggest that the lavas, scoria, and plug rocks of Sphinx Butte are of uniform chemical composition. On this basis it seems probable that a single magmatic event was responsible for the growth of this volcano.

Middle Sister

Glaciated Middle Sister lavas crop out between Separation Creek and the north margin of the map area. From oldest to youngest these include (a) olivine-bearing basalt porphyry lavas (PsBsLa5) that contain up to fifty percent plagioclase and five percent olivine phenocrysts, (b) a thick flow of platy andesite (PsAnLa4) and a steep-sided dome (PsAnLa5) of vitreous, flow-banded andesite, and (c) a vitrophyric dacite lava (PsDaLa7). The dacite lava was extruded from a vent on the south flank of the Middle Sister and flowed downslope as a single stream until its advance to the south was blocked by the andesite dome. At this point the stream bifurcated but both forks continued to flow for short distances around the east and west margins of the dome (Figure 3). The congealed west fork now projects as a narrow arm into the north part of the thesis area where it overlies the Middle Sister basalt and andesite lavas described in (a) and (b) above. Only the very tip of the east fork lava rock extends into the map area.

Middle Sister basalt porphyry lavas (PsBsLa5) overlie a series of orthopyroxene- and clinopyroxene-bearing basaltic andesite lavas (PsBALa5) that crop out on the slopes to the east and south of Separation Creek Meadow. On the basis of field relations I could not determine whether these basaltic andesites were derived from Middle Sister or South Sister vents; however, on the basis of mineralogy, texture, and chemical composition they cannot be distinguished from South Sister basaltic andesites (PsBALa6) that crop out less than one mile to the east, on the south bank of Separation Creek. It is possible, but by no means certain, that these two groups of lavas are equivalent and once formed a continuous outcrop across Separation Creek and the area now covered by Middle Sister basalts (PsBsLa5), andesites (PsAnLa4) and dacites (PsDaLa7).

South Sister

South Sister is a complex composite volcano composed of basaltic andesite, andesite, dacite, and rhyodacite lavas and pyroclastic deposits. A typical basaltic andesite lava is a light gray olivine- and clinopyroxene-bearing block flow that contains between ten and twenty percent phenocrysts. On steep slopes this flow may consist of a thin, dense interior sandwiched between thick upper and lower surfaces of red and black scoria. As a source vent is approached, pyroclastic debris becomes more common between flows and rock color grades to dark gray or black as glass increases in abundance.

South Sister andesite and dacite lavas are thick, two-pyroxene flows that have light to dark gray platy interiors and dark gray to black vitrophyric margins. Phenocryst contents commonly vary from ten to twenty percent. I found it difficult to distinguish between these two rock types in the field, but the glassy margins of dacite lavas were commonly columnar-jointed, whereas the glassy margins of andesite lavas tended to be blocky. Andesite pyroclastic debris separates andesite flows (PsAnLa2) in the cirque walls of Prouty Glacier and crops out at the surface (PsAnPc2) in the col between the summit of South Sister and the prominence that lies 2,000 feet to the southeast. I found few other occurrences of andesite or dacite tephra on the flanks of South Sister. One occurrence was found in the upper reaches of Hinton Creek near 6800 feet elevation. At this locality a thin bed of dacite pumice and scoria separates two dacite flows. At most other localities I found the basal contacts of andesite or dacite flows obscured by the platy talus aprons that inevitably accompanied these flows. This relation probably accounts for the scarcity of exposed andesite or dacite pyroclastic deposits.

Recent South Sister rhyodacite lavas occur as steep-sided, biscuit-shaped domes (e.g., HoRdLa1) or thick pressure-ridged block flows (e.g., HoRdLa2). Both kinds contain dense interiors of red or gray, vitreous, flow-banded lava or black obsidian, and blocky crusts of gray, vitreous, partly inflated lava. Spherulitic interiors are common. Adjacent to these lavas, the ground is covered by crumble breccias. Explosive outbursts commonly accompanied or preceded extrusion of South Sister rhyodacite lavas. Pyroclastic debris from these explosions accumulated as pumice ramparts adjacent to vents, and as thin, widespread blankets of pumice and ash. The exposed interiors of glaciated rhyodacites are similar to the interiors of recent rhyodacite lavas.

Lavas of the compositional groups described above are complexly interbedded from the lower flanks to the summit of South Sister Volcano (see map). For example, basaltic andesite lavas crop out at low (PsBALa5, PsBALa6), intermediate (PsBALa7, PsBALa8), and high (PsBALa8) stratigraphic levels on the north and west flanks of the mountain. At each level these mafic lavas are overlain or underlain by andesite or dacite lavas. At the northwest base of South Sister, basaltic andesite lavas of PsBALa6 are overlain by dacite lavas of PsDaLa4 which in turn are overlain by basaltic andesite lavas of PsBALa8. On the north and west flanks of South Sister, basaltic andesite lavas of PsBALa8 overlie (a) andesite lavas of PsAnLa2, near the snout of Lost Creek Glacier, (b) andesite lavas of PsAnLa2, between Prouty and Skinner Glaciers, (c) dacite lavas of PsDaLa2, between Carver Lake and Chambers Lakes, (d) dacite lavas of PsDaLa3, on the ridge between Carver and Skinner Glaciers, and (e) dacite lavas of PsDaLa4, at the base of Skinner Glacier. On the upper north flank of South Sister, basaltic andesite lavas and scoria of PsBALa8 are overlain by andesite lavas of PsAnLa3, which are overlain in turn by basaltic andesite summit flows (PsBALa9).

Andesite, dacite, and rhyodacite lavas are interbedded on the east and south flanks of South Sister. For example, between Rock Mesa and Clark Glacier, glaciated dacite flows (PsDaLa6) overlie the glaciated remnants of two rhyodacite lavas (PsRdLa2, PsRdLa3). These dacites and rhyodacites are overlain by rhyodacite tephra (HoRdPc2) from Rock Mesa (HoRdLa2; C-14, 2300 yrs. B.P.). E. M. Taylor has mapped rock relations of similar complexity at the east base (1978) and on the southeast flank (unpublished data) of South Sister.

More than a dozen rhyodacite domes and block flows were extruded from vents on the east and south flanks of South Sister between 1900 and 2300 yrs. B.P. (Taylor, 1978). These include Rock Mesa (HoRdLa2), the Newberry flow (HoRdLa1 of Taylor, 1978), the Devils Hill chain of domes (HoRdLa3 of Taylor, 1978), and the Goose Creek chain of domes (Figure 7; HoRdLa2 of Taylor, 1978). A third chain of Holocene domes (HoRdLa1) crops out on the northeast flank of South Sister between Carver Lake and Carver Glacier, and is aligned N.5W. The Devils Hill chain is aligned N.3W.; the Goose Creek chain, N.10W. (Taylor, 1978). North-south alignments of closely related vents are common throughout the Oregon High Cascades. Taylor (1978) and Hammond (1979) have suggested that these alignments may be related to a system of north-south-trending faults that underlie the High Cascades. I did not recognize any faults at the surface within the thesis area.

The vents beneath Le Conte cinder cone, Rock Mesa, and a rhyodacite dome (PsRdLa4) between Rock Mesa and Lewis Glacier appear to be radially aligned with respect to South Sister. No fracture is visible at the surface but the alignment may mark the position of an underlying fracture produced by tumescence during a South Sister eruption. Alternatively, this alignment may be fortuitous.

Pleistocene rhyodacite lavas are also common on the flanks of South Sister; like their Holocene counterparts, these were probably extruded from flank vents. Examples include a large dome complex one mile northwest of Prouty Glacier (PsRdLa1), several lavas between Rock Mesa and Lewis Glacier (PsRdLa2, PsRdLa3, PsRdLa4), and an extensive flow between Lewis Glacier and Moraine Lake (mapped by E. M. Taylor, unpublished). On the southeast flank of South Sister, Taylor (1978) has identified a glaciated chain of rhyodacite domes (his PsRdLa9, PsRdLa10) that underlies the Devils Hill chain of Holocene domes; one of these is Devils Hill. Glaciated rhyodacite lavas also crop out on Kaleetan Butte, between Rock Mesa and Devils Hill. All of these Pleistocene rhyodacite lavas are partly covered by andesites and dacites from South Sister vents.

I found several xenoliths of rhyodacite (e.g., sample 1718b, Appendix 2) in a dacite flow (PsDaLa3) on the north flank of South Sister. E. M. Taylor (personal communication) has found andesite, dacite, and rhyodacite accessory ejecta in tephra from Rock Mesa. These occurrences indicate that andesite, dacite, and rhyodacite lavas or subvolcanic intrusions occur at some level in the subsurface beneath South Sister.

The precise eruptive sequence of South Sister volcano is not known but the variety of rock types and the complexity of the field relations belie a simple eruptive history. The main conclusion that I draw from the field relations is that magmas of diverse composition were extruded from South Sister vents throughout the eruptive history of this volcano. Andesite, dacite, and rhyodacite lavas and pyroclastic deposits are uncommon throughout the central Oregon High Cascades; however, Taylor (1978; 1980) has demonstrated that extrusion of silicic, intermediate, and mafic magma occurred throughout the Quaternary in a localized area that includes South Sister, Middle Sister, and Broken Top volcanoes. The growth of South Sister was a continuation of this pattern of local magmatic diversity.

McBirney (1968) reported that the main mass of South Sister is composed of siliceous andesites or dacites. By his account, the growth of the main andesite-dacite cone was preceded by eruptions of rhyolite and followed by eruptions of basalt and rhyolite (basaltic andesites and rhyodacites in this paper). On this basis he classified South Sister as a "divergent" Cascade volcano. McBirney (1968) defines divergent volcanoes as those whose rocks are "...varied and become increasingly divergent with time." The present study confirms the occurrence of varied rock types at South Sister but shows that the stratigraphy and eruptive sequence are more complex than portrayed by McBirney. In another paper, McBirney (1978) cites a pattern of growth for the large Cascade volcanoes "...in which compositions evolve through andesite and then diverge into more or less contemporaneous basalt and rhyolite in the late stages of activity." South Sister does not conform to this pattern.

Williams (1944; 1957) reported that South Sister is composed of three parts: a basal shield volcano of basalt, a composite cone of andesite and dacite, and two summit cones of Recent olivine-basalt lavas and scoria. I have already illustrated that South Sister is not a uniform mass of andesite and dacite and I will discuss Williams' interpretation of the summit sequence in the next section. The main arguments that he advances to support the presence of a shield base beneath South Sister are (a) the occurrence of westward-dipping mafic lavas at the base of the west flank of the mountain (my PsBsLa3 and PsBALal), and (b) the presence of basal shields beneath other High Cascade volcanoes (e.g., North Sister, The Husband, The Wife). No firm evidence exists, however, to show that the precursor of South Sister was a shield volcano. Taylor (1978) has mapped a series of basaltic andesite lavas (his PsBALal) that underlie South Sister andesites (his PsAnLal) at the base of the east flank of South Sister. None of these correlates in mineralogy or chemical composition to the basalts and basaltic andesites at the base of the west flank of South Sister.

Summit Sequence

Viewed from the west (Figure 8), South Sister has a highly symmetric profile and appears to have undergone only minor incision by Pleistocene glaciers. Viewed from the north (Figure 9) and east (Figure 10), however, the profile is less symmetric and the flanks appear to be more deeply gouged. Nevertheless, the summit retains a symmetric outline that probably reflects its relative youth.

The summit of South Sister consists of three units (Figures 11 and 12). The lowermost unit is composed of thin basaltic andesite lavas that are separated by red scoria and pyroclastic debris (PsBALa8). These lavas make up most of the exposed bedrock on the north flank of the mountain. The sequence has been deeply incised by the precursors of Prouty and Skinner Glaciers (Figure 9); most of the unit below 8400 feet is glacially striated.

Directly overlying the preceding unit is a unit comprised of several thick andesite lavas and associated scoria (PsAnLa3). These

Figure 7. Rhyodacite lavas of Goose Creek chain and Devils Hill chain of domes. Lewis Glacier in foreground.

Figure 8. View of the west flank of South Sister. Lost Creek Glacier on left, Clark Glacier on right.

Figure 9. View of the north flank of South Sister. Bachelor Butte in background.

Figure 10. View of Prouty Glacier on the east flank of South Sister. Pleistocene glacial moraine in foreground.

Figure 11. North flank summit sequence, South Sister. Inclined layers of basaltic andesite scoria and lava (PsBALa8) are overlain by several thick andesite lavas (PsAnLa3). Veneer of basaltic andesite lava (PsBALa9) caps the sequence. Prouty Glacier on left, Skinner Glacier on right.

Figure 12. West flank summit sequence, South Sister. Interbedded basaltic andesite scoria (red) and lava (PsBALa8) overlain by several thick, light gray andesite lavas (PsAnLa3). Sequence capped by veneer of dark gray basaltic andesite lava (PsBALa9). Lost Creek Glacier in foreground.

rocks are not glacially striated on the ridge between Eugene and Lost Creek Glaciers; however, they are striated on the ridge between Clark and Lost Creek Glaciers, below 8200 feet elevation.

The uppermost summit unit at South Sister consists of several thin basaltic andesite (PsBALa9) lavas that veneer the surface of the previously described andesites. These basaltic andesite lavas were extruded from a summit crater that measures 1200 feet in diameter. An agglutinated crust of bombs and spatter caps the sequence. The flows are well-preserved on the west and south flanks of the mountain, but are abruptly truncated at the north and east rim of the crater. The truncated margins project skyward away from the crater (Figure 13). Distal parts of the summit lavas are preserved on the southeast flank of the 10,039 foot elevation prominance that lies east of the 10,358 foot summit of South Sister (Figure 14). These flows were once continuous across the col that now separates the summit from the prominence; eroded flow remnants now litter the surface of the col. The remnant of an old andesite pyroclastic cone (PsAnPc2) crops out at the surface on the col. This cone of pumice and scoria was a zone of weakness that allowed Lewis and Prouty Glaciers, or their Pleistocene equivalents, to undercut the ridge that supported the summit lavas.

Williams (1944) describes the prominence to the east of the summit of South Sister as the remnant of a lava and scoria cone composed of olivine-rich basalt and cut by narrow dikes. He also describes the summit of South Sister as a cone of Recent olivine-rich basalt and scoria. I found that the upper surface of the southeast flank of the prominence is composed of basaltic andesite lavas (PsBALa9) that contain sparse olivine. These flows are underlain by altered andesite

Figure 13. Skyward-projecting, truncated east margin of summit basaltic andesite lava (PsBALa9), South Sister. Bachelor Butte in background.

Figure 14. Summit and east prominence, South Sister. View of south flank. Upper, dark gray lavas on prominence are distal parts of summit lavas (PsBALa9) which were originally continuous across the col that now separates the summit from the prominence.

lavas (PsAnLa2). The andesite and basaltic andesite lavas have eastward dips. I did not observe any dikes. Thus no remnant cone of olivine-basalt occurs at this locality. The few basaltic andesite flows that do occur on the southeast flank of the prominence can be projected back to the truncated margins of the summit lavas on the east rim of the summit crater.

Sparse fragments of Mazama pumice (6840 ± 50 C-14 yrs. B.P.; weighted mean of five carbon samples; Charles Bacon, personal communication) and Rock Mesa tephra (2300 yrs. B.P.) mantle the upper surface of the basaltic andesite summit lavas. These lavas are not glacially striated, but the preserved parts of the flows lie on ridges that were not covered by Pleistocene glaciers. On the basis of the erosion that has occurred between the summit and the prominence to the east, I believe that the summit lavas were extruded late in the Pleistocene rather than early in the Holocene. The evidence is equivocal, however, and the only firm conclusion to be made is that the summit lavas were extruded prior to 6640 yrs. B.P.

Comments on an Unusual South Sister Unit

A brecciated, highly inflated dacite lava (PsDaLa3) is exposed at the base of the north flank of South Sister on the ridge between Carver and Skinner Glaciers. The lava is chiefly composed of a chaotic assortment of bright orange to reddish-brown pumice (Figure 15). Individual pumice fragments may be angular, spherical, or ellipsoidal, but all have coarse, uneven surfaces. The fragments commonly include lenses and ribbons of dense, gray or black, vitreous dacite. Vitreous dacite also occurs as isolated blocks, lenses, or pods that are surrounded by pumice fragments. Small rhyodacite xenoliths are common throughout. In an up-slope direction, the orange, pumiceous breccia grades into a gray, partly inflated breccia which is overlain by a platy dacite lava (PsDaLa5).

At scattered localities in the pumiceous breccia, thin ribbons and lenses of dense, black glass are intercalated with lenses and bands of red pumice to form undulated bodies of ribboned rock (Figure 16). These ribboned bodies vary from one-half to two feet in thickness, but are not laterally extensive; they occur at various levels in the rock mass. Close inspection of ribboned rock shows that the glass forms an anastomosing network that encloses pods and lenses of pumice (Figure 17). In some parts of the rock, glass is less abundant, the glass network is less continuous, and the pumice appears to enclose lenses and ribbons of glass (Figure 18). In thin section, the border between pumice and black glass appears to be gradational (Figure 19). The black glass commonly has a scalloped outer margin and is highly charged with tiny grains of magnetite that render it opaque. This opaque glass grades outward to a brown, partly inflated, translucent glass which grades, in turn, into a reddish-brown, pumiceous glass. The transitional glass is studded with dendritic magnetite but the pumiceous glass is clear. The texture of the transitional glass is similar to the groundmass texture of the gray brecciated part of the unit. The phenocryst assemblage in the opaque glass is identical to the assemblages in the pumiceous glass and the gray breccia. In the pumiceous glass, however, individual crystals are commonly broken and iron-bearing minerals are oxidized.

Six samples from this unit and one from the overlying dacite lava were analyzed chemically (Table I). Samples 1567 and 1622 are gray

Figure 15. Chaotic assortment of reddish-brown pumice of PsDaLa3. Enclosed block of vitreous dacite.

Figure 16. Ribboned glass and pumice of PsDaLa3. Middle Sister in background.

Figure 17. Pods and lenses of pumice enclosed in an anastomosing network of opaque glass in PsDaLa3. Sample 1619.

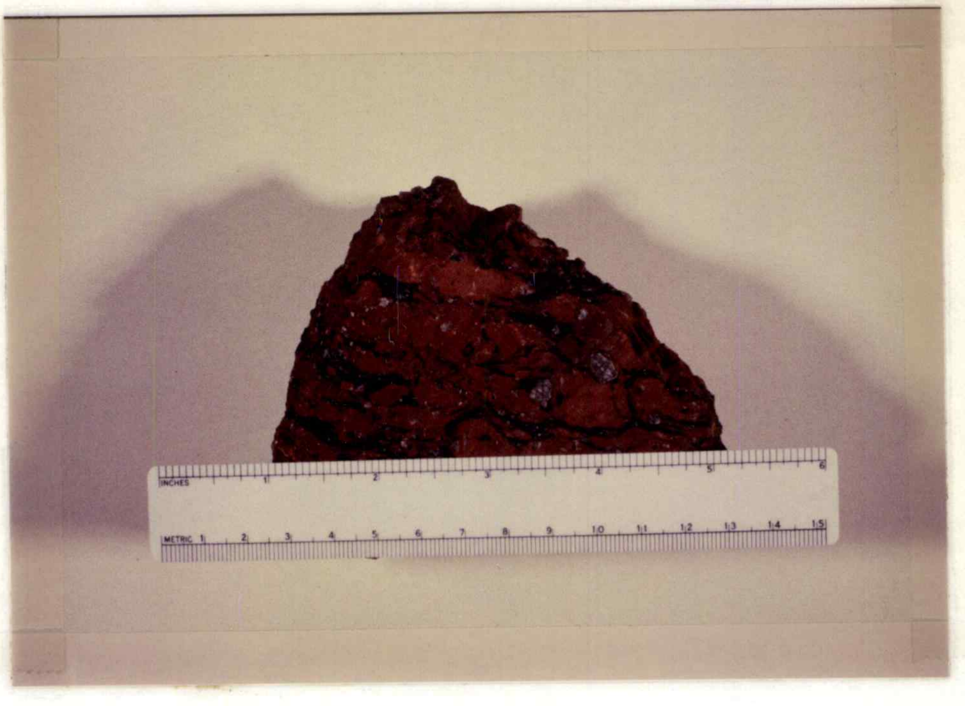


Figure 18. Pods and lenses of opaque glass in an anastomosing network of pumiceous glass in PsDaLa3. Sample 1620.

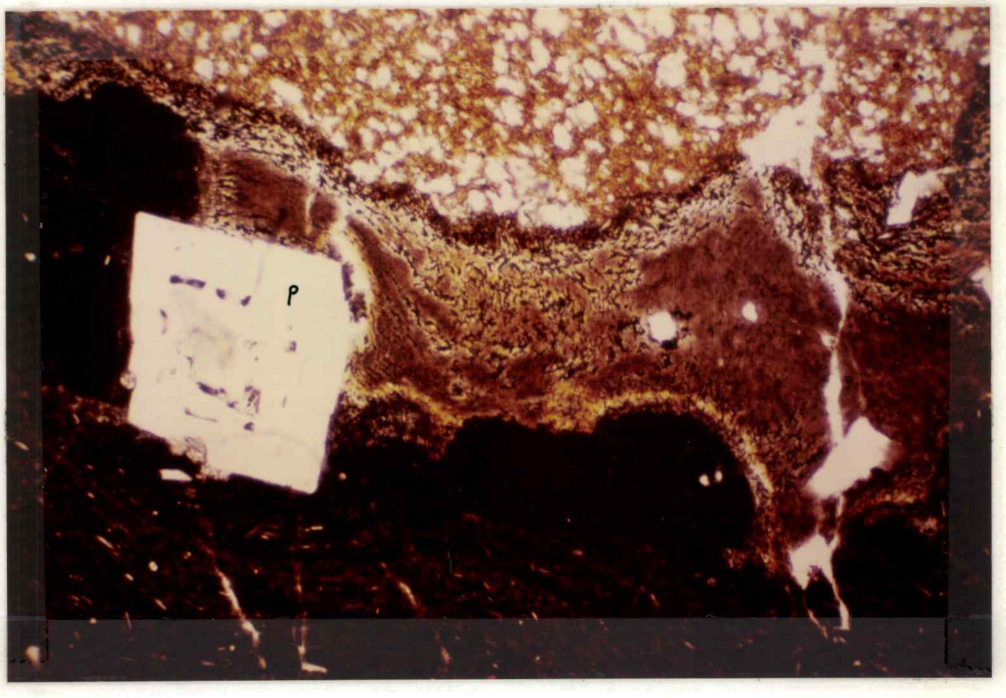


Figure 19. Photomicrograph showing nature of transition between opaque glass and pumiceous glass in PsDaLa3. Sequence from top to bottom: pumiceous glass, transitional glass, opaque glass. P, plagioclase. Plane light. Sample 1619.

Table I. Chemical analyses of rocks from PsDaLa3 and PsDaLa5.

Sample	1567	1619	1620	1622	1718	1718b	1575
SiO2	66.2	65.1	64.4	65.3	64.5	75.5	65.8
TiO2	0.96	0.97	1.01	0.95	1.03	0.10	0.96
Al2O3	16.1	16.9	16.7	15.8	16.0	13.6	16.0
FeO*	4.3	4.8	5.0	4.3	4.9	1.2	4.2
MgO	1.7	1.5	1.5	1.4	1.4	—	1.3
CaO	3.4	3.5	3.9	3.4	3.7	0.9	3.4
Na2O	5.1	4.9	5.0	5.1	5.4	4.8	5.3
K2O	2.51	2.44	2.41	2.36	2.48	3.53	2.49
Total	100.27	100.11	99.92	98.61	99.41	99.63	99.45

1567, 1622: Gray breccias from upper part of PsDaLa3.
1619, 1620: Mixed pumice and opaque glass from ribboned bodies of PsDaLa3.
1718: Opaque glass from a large pod in PsDaLa3.
1718b: A rhyodacite xenolith that was included in the margin of the glass pod that contained 1718.
1575: Dense, black glass from the margin of PsDaLa5.

breccias from the upper part of the unit; 1619 and 1620 are mixed pumice and opaque glass from ribboned bodies; 1718 is opaque glass from a large pod that was enclosed by a mass of pumiceous breccia; 1718b is a rhyodacite xenolith that was included in the margin of the pod that contained 1718; 1575 is dense, black glass from the margin of the overlying dacite lava. Except for the rhyodacite, the compositions of the samples from the dacite breccia are relatively uniform and the composition of any given sample is similar to that of the opaque glass (1718). Assuming that the glass represents the composition of the original magma, it seems likely that all parts of this unit were derived from a common liquid.

The inflated texture and brecciated character of these rocks indicate that a volatile phase played an important role in their development. However, the rocks contain only a small proportion of fine-grained particles and these appear to be abraded fragments from the margins of pumice lumps. Glass shards or devitrified remnants of glass shards were not found. No stratification was observed in the unit and no compaction textures were observed in outcrop or in thin section. Ribbons, lenses, and pods of opaque glass occur randomly throughout the unit. These features are inconsistant with an ash-fall or ash-flow mode of origin and indicate that the eruption was not particularly violent.

I propose that this unit is an accumulation of spatter and pumice formed by fountaining of gas-rich dacite lava. Lava fountains are commonly formed during the extrusion of basalt magma, but I could find no accounts in the literature describing the occurrence of silicic lava fountains. Under the proper conditions, however, fountains could be produced during the extrusion of silicic magma.

McBirney (1973) and Williams and McBirney (1979) have shown that the violence of an eruption is governed by the rate and degree of gas expansion in a column of rising magma. Exsolution and expansion of gas is largely controlled by the viscosity of the magma. If the viscosity is low, then gas can exsolve and expand freely. This results in low residual pressures and relatively nonviolent eruptions. Under these conditions fluid magma will be disrupted into spatter, vesiculating clots of molten glass, and pumice. If the viscosity is high, then exsolution and expansion of gas is retarded. This results in high residual pressures and violent eruptions. The viscosity of a magma is proportional to silica content and inversely proportional to temperature, pressure, and volatile content.

The degree of vesiculation in PsDaLa3 indicates that a substantial amount of dissolved gas was present at the time of extrusion. Total phenocryst content in this unit varies from four to five percent and the crystals are uniformly small. This implies that the temperature of the extruded magma was not much lower than the liquidus temperature. These features are consistent with rapid rise of the magma from depth with little or no intervening storage time at shallow crustal levels. High temperature and gas content would be preserved by rapid ascent and would tend to maintain a low viscosity.

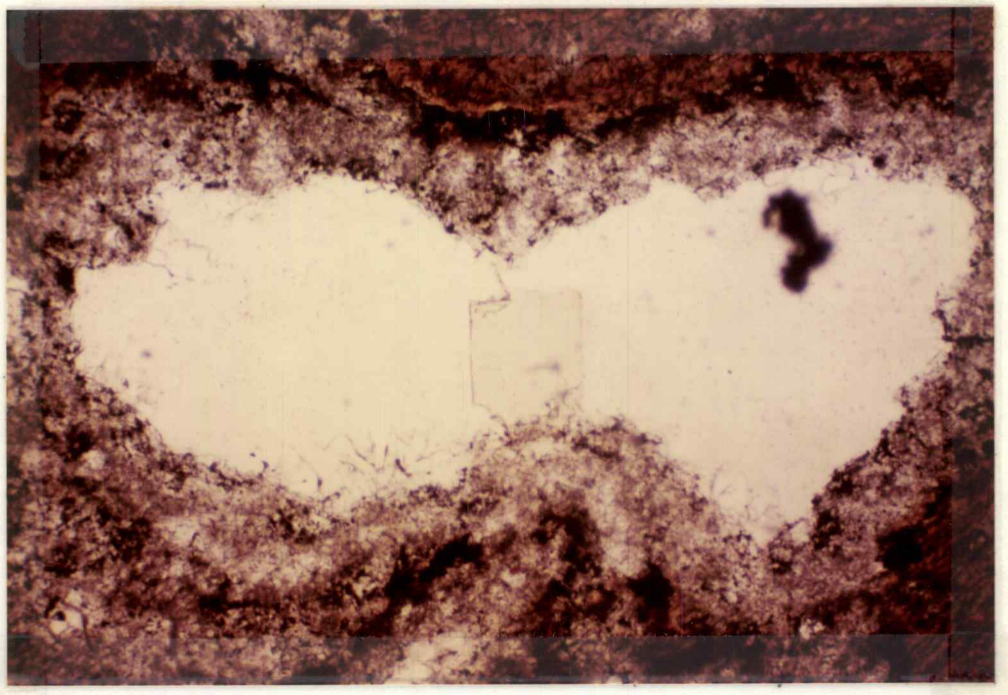
The lack of similar deposits on the South Sister or in other dacite and andesite volcanic fields may simply reflect the low probability of maintaining low viscosities in dacite and andesite magmas in the upper crust because even a slight decrease in temperature or volatile content will have a large effect on the viscosity of intermediate magmas.

As previously mentioned, the orange, pumiceous breccia of PsDaLa3 grades up to a gray, partly inflated breccia which is overlain by a platy dacite lava (PsDaLa5). The chemistry (Table I), phenocryst assemblage, phenocryst proportions, and total phenocryst content of the platy dacite are nearly identical to that of the underlying breccia. Perhaps the platy dacite lava represents a late stage extrusion of the same magma, now degassed, that produced the orange and gray breccias.

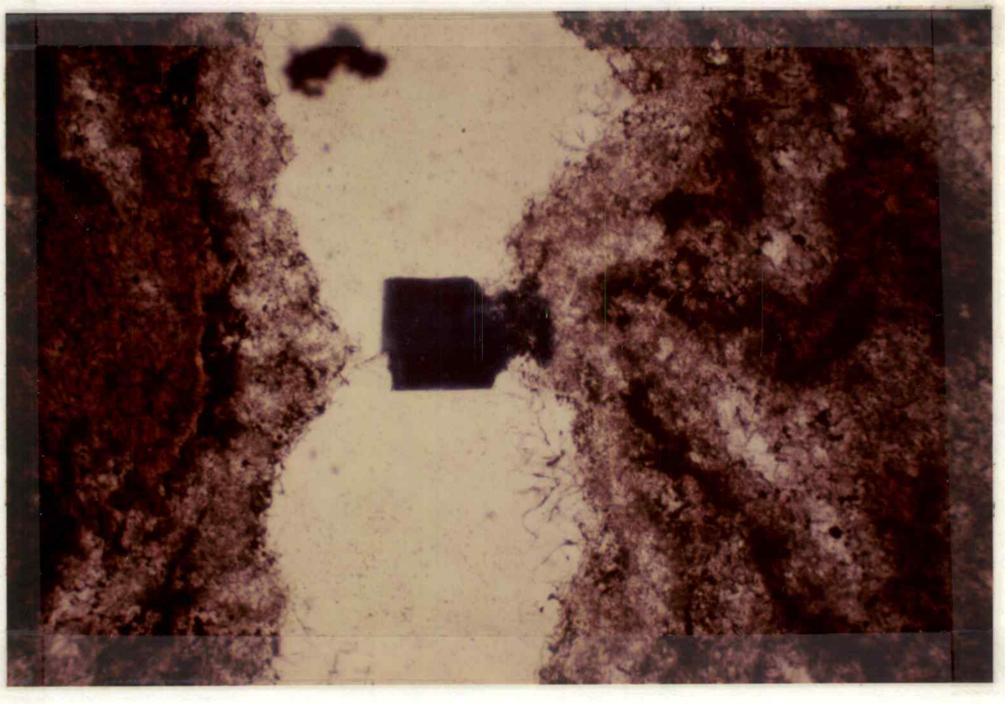
An occurrence of the mineral osumilite was found in one of the rhyodacite xenoliths (sample 1718b) from the brecciated unit described above. The mineral occurs as disseminated anhedral grains in the devitrified biotite-bearing groundmass and as euhedral crystals in cavities. Crystals are black in hand specimen. In thin section (Figure 20), osumilite is uniaxial positive and exhibits a marked colorless-to-deep blue pleochroism. The mineral was named by Miyashiro (1956) who first described its physical and chemical properties. It is closely related to cordierite and has a chemical composition of (K, Na, Ca) $(Mg, Fe^{+2})_2$ $(Al, Fe^{+3}, Fe^{+2})_3$ $(Si, Al)_{12}O_{30}\cdot H_2O$. Miyashiro reported occurrences of osumilite in biotite-bearing rhyodacites from the Japan volcanic arc. He believed the mineral to be relatively common but suspected that it was generally mistaken for cordierite. E. M. Taylor (personal communication) has found osumilite in a rhyodacite lava near the base of the northwest flank of Middle Sister. I am aware of no other reported occurrences of osumilite in the Oregon Cascades.

Pleistocene Glaciation

Late Pleistocene glaciers covered the entire landscape within the thesis area except the upper ridges and summit of South Sister.



(a)



(b)

Figure 20. (a) Photomicrograph of a clear, euhedral osumilite crystal in a small cavity in a rhyodacite xenolith. Plane light. Sample 1718b. (b) Same view photographed after a 90° rotation on microscope stage. Note intense blue pleochroism.

According to Crandell (1965) a continuous ice cap covered most of the Oregon High Cascade platform during the last Pleistocene glaciation. Scott (1977) recognized three major periods of glaciation in the Mount Jefferson area: the Cabot Creek, Jack Creek, and Abbot Butte glaciations. The Cabot Creek glaciation occurred between 12,000 and 25,000 yrs. B.P. Scott (1977) tentatively assigns an age of 40,000 to 80,000 or 120,000 to 200,000 yrs. B.P. to the Jack Creek glaciation, and an age of 200,000 to 900,000 yrs. B.P. to the Abbot Butte glaciation. Corresponding glaciations probably occurred in the thesis area but I could make no direct correlations.

The older volcanoes in the west part of the thesis area have probably been subjected to at least two glaciations, as discussed in the introductory comments of the Field Descriptions and Age Relations section. However, evidence of multiple glaciation is obscure on South Sister because most of the erosional debris from glaciers originating on this mountain was deposited beyond the limits of the field area. Terminal and lateral moraines deposited by glaciers from South Sister crop out several miles to the northeast of the field area (E. M. Taylor, unpublished map). These moraines were probably deposited during the Suttle Lake advance of the Cabot Creek glaciation. No older moraines from South Sister glaciers are exposed in this area (E. M. Taylor, personal communication) but they may occur beneath the late Pleistocene volcanic cover that mantles the region. Alternatively, South Sister may not have been a source area for older glaciers because the entire mountain may be younger than the Jack Creek glaciation (i.e., 40,000 yrs. B.P.). In this case, however, one would expect to find abundant ash deposits preserved to the east and northeast of South Sister. No such ash deposits occur in these areas (E. M. Taylor, personal communication). No deposits produced by subglacial eruptions (e.g., hyaloclastites) were recognized in the thesis area.

Holocene Glaciation

Large parts of the South Sister are mantled by Neoglacial moraines. Mazama ash (6640 yrs. B.P.) was not found on any of these deposits. I found Rock Mesa tephra (2300 yrs. B.P.) on the surfaces of stabilized Neoglacial moraines (HoGd1) at the north base of South Sister, but not on the surfaces of steep-sided Neoglacial moraines (HoGd2) near the termini of present glaciers. The advances recorded by these two moraine sets probably correlate to the two post-Altithermal advances (2700 yrs. B.P. and 130 yrs. B.P., Porter and Denton, 1967) that occurred in most northern hemisphere alpine regions. Several authors have reported two sets of Neoglacial moraines at other Cascade peaks (Miller, 1969; Scott, 1977; Taylor, 1978; Dethier, 1980).

SUMMARY OF PETROGRAPHIC FEATURES

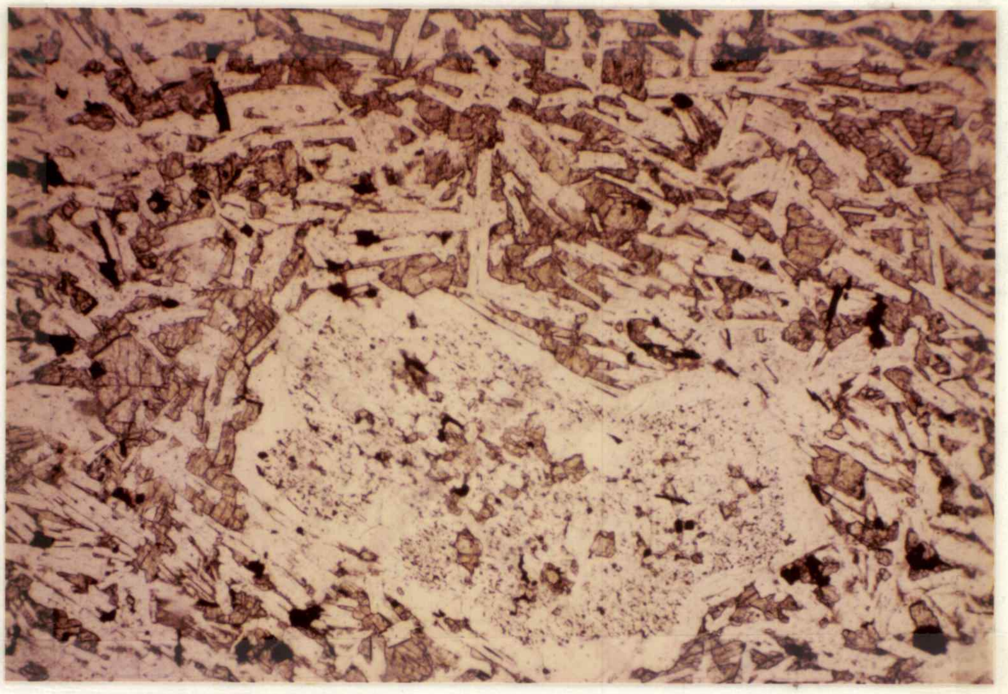
Generalized petrographic characteristics of the major rock groups in the thesis area are listed below. Petrographic descriptions of individual units are given in Appendix 1. References to rocks from Sphinx Butte, The Wife, and The Husband include rocks of similar composition and texture, but of unknown source vent, that occur in the west half of the thesis area.

Basalts of Sphinx Butte, The Wife, and The Husband

The basalts in this group are homogeneous in composition. Silica content ranges from 51 to 54 and averages 52 percent. Phenocrysts generally total less than five percent and are limited to olivine (one to four percent) and plagioclase (zero to five percent, but commonly less than two percent). Plagioclase is normal or normal-oscillatory zoned; typical compositions range from An 68-50, in the core, to An 50-46 at the margin. The cores of larger grains may be as calcic as An 70 or 72 and are commonly patchy zoned. Groundmass textures are intergranular, intersertal, or subophitic (Figure 21); constituents include plagioclase, clinopyroxene, and granular magnetite. The composition of groundmass plagioclase lies between An 46 and 56.

Basaltic Andesites of Sphinx Butte, The Wife, and The Husband

Samples of basaltic andesite from Sphinx Butte, The Wife, and The Husband fall into a low silica group (53-54 percent) and a high silica group (56-57 percent). The gap in silica content between these groups



(a)

(b)

Figure 21. (a) Photomicrograph showing subophitic texture in basalt lava of PsBsLa3. Note large patchy zoned plagioclase phenocryst. Plane light. Sample 1660. (b) Crossed nicols.

may be the result of incomplete sampling. The low silica basaltic andesites are identical in petrography to the basalts discussed above. In the high silica basaltic andesites olivine may total up to two percent, but plagioclase and clinopyroxene are uncommon as phenocrysts. Olivine is commonly corroded and some grains are jacketed by minute laths of orthopyroxene (Figure 22). The groundmass is pilotaxitic or intergranular and contains plagioclase, clinopyroxene, orthopyroxene, and magnetite. Plagioclase compositions range from An 42 to An 63.

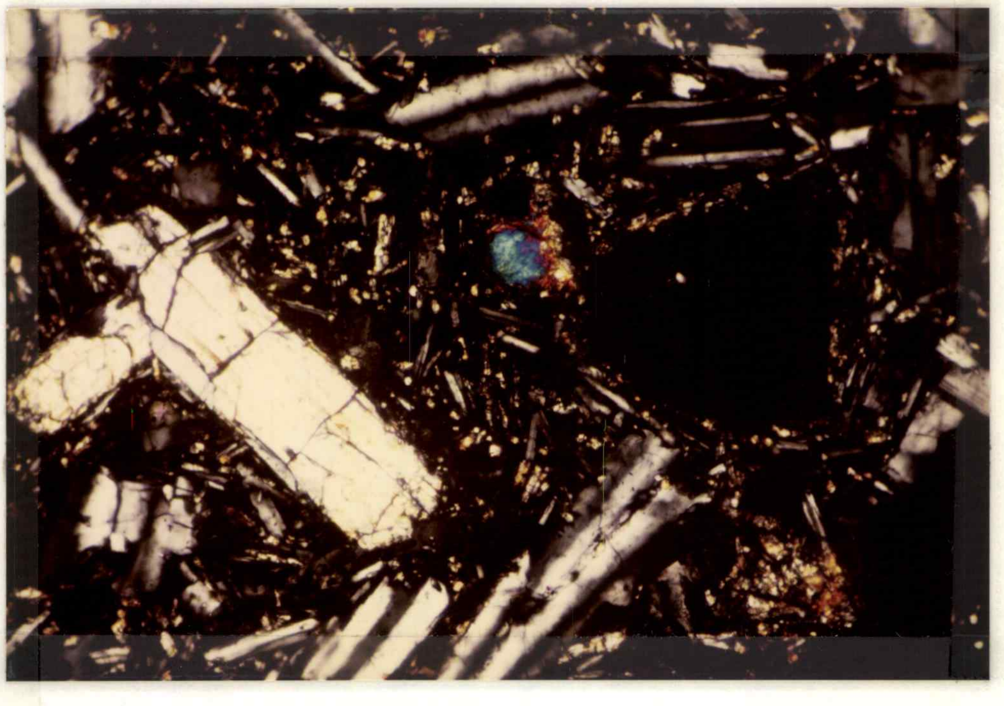
South Sister Basaltic Andesites

Silica in South Sister basaltic andesites ranges from 56 to 58 and averages 57 percent. Phenocrysts include plagioclase (1-34, but average 15 percent), clinopyroxene (up to five percent), and olivine (up to two percent). Orthopyroxene is present from trace amount to two percent and magnetite generally totals less than one percent. Plagioclase is normal-oscillatory zoned and has compositions that extend from An 65 in the core, to An 40 at the margin. Larger grains have patchy zoned cores. Olivine is rounded or embayed (Figure 23) and is commonly rimmed by granular magnetite. Inclusions of magnetite are common in clinopyroxene phenocrysts. Plagioclase, clinopyroxene, and magnetite are the chief groundmass constituents. Glass is locally abundant and apatite is a common accessory. Groundmass textures are intergranular, pilotaxitic, or hyalopilitic.

South Sister Andesites and Dacites

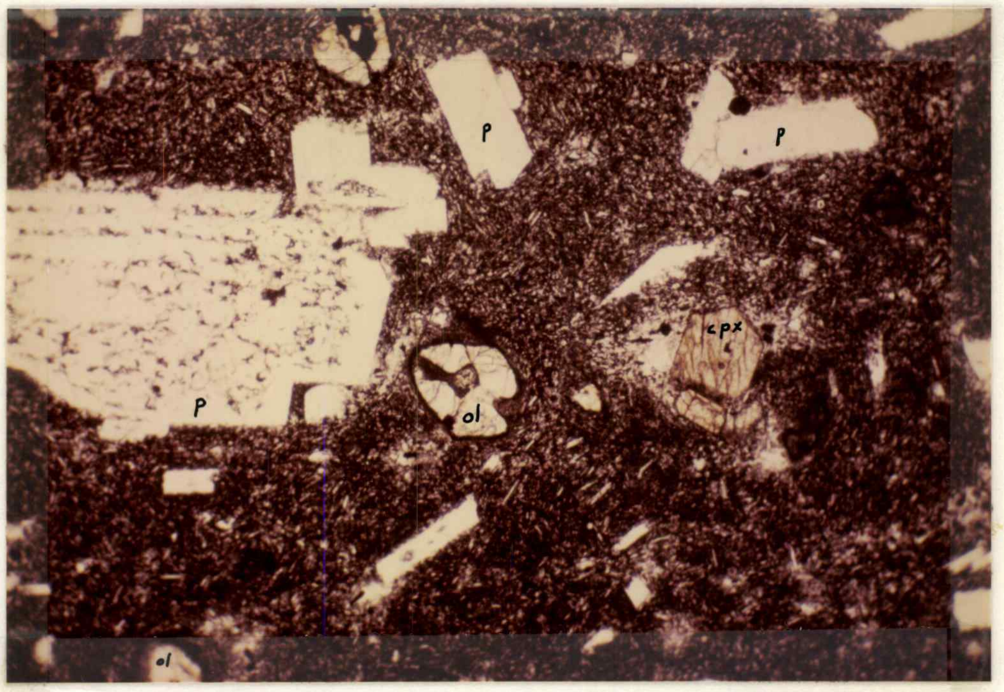
South Sister andesites and dacites have silica contents that lie

(a)

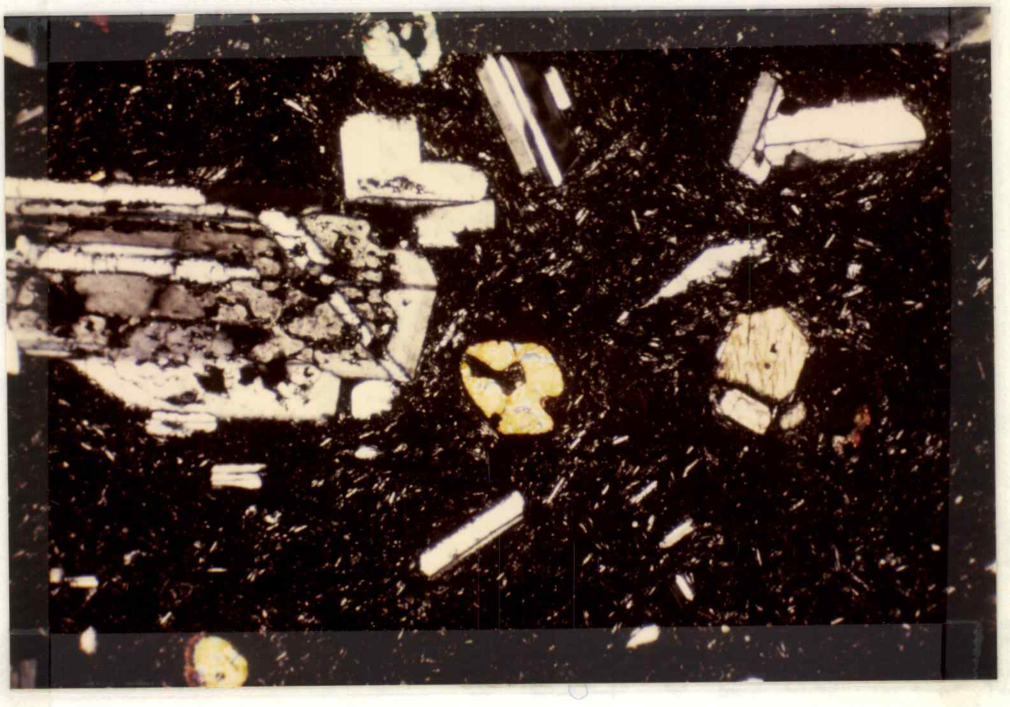


(b)

Figure 22. (a) Photomicrograph of olivine (ol) and orthopyroxene (opx) phenocrysts in high silica basaltic andesite lava of PsBALa2. Plane light. Sample 1541. (b) Crossed nicols.



(a)



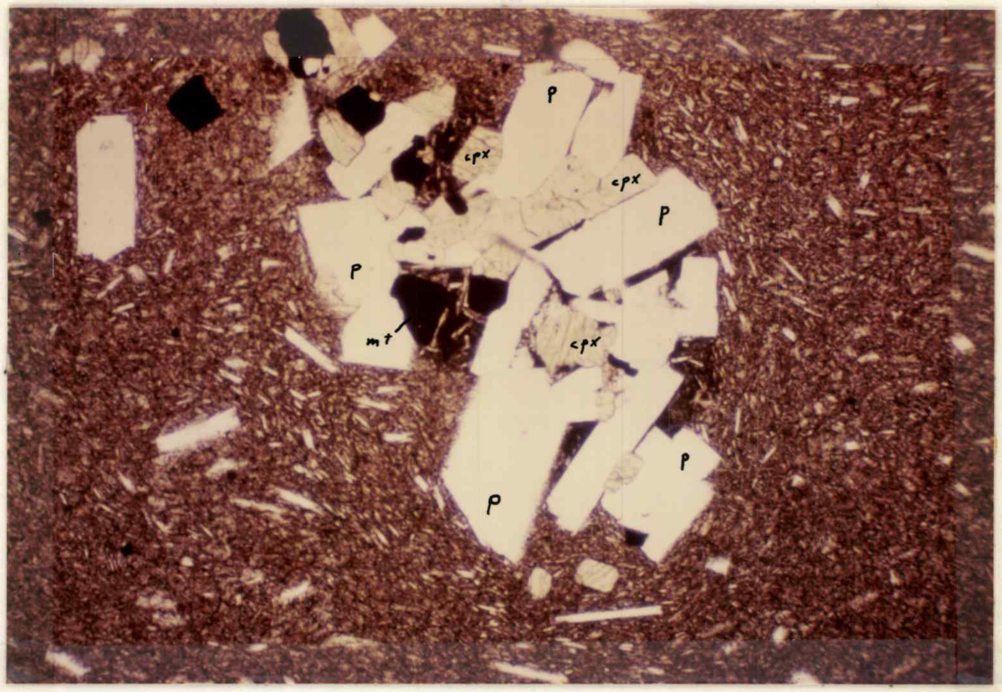
(b)

Figure 23. (a) Photomicrograph of rounded and embayed olivine (ol) phenocryst (center) in South Sister basaltic andesite lava (PsBALa8). Rimmed by granular magnetite. Accompanied by plagioclase (p) and clinopyroxene (cpx). Plane light. Sample 1559. (b) Crossed nicols.

between 60 and 68 percent. The average value is 64 percent. Phenocrysts and glomerocrysts (Figure 24) include plagioclase (2-20 percent, but average 13 percent), clinopyroxene (up to three percent), orthopyroxene (up to two percent), and magnetite (up to one percent). Clinopyroxene exceeds orthopyroxene by a factor of two or three to one. Plagioclase is normal-oscillatory zoned; composition ranges from An 55 in the cores, to An 35 at the margins. Larger phenocrysts are commonly patchy zoned. A few hornblende phenocrysts occur in some of the silicic dacites. Magnetite inclusions are common in clinopyroxene and orthopyroxene phenocrysts. Groundmass textures are pilotaxitic, fluidal, or hyalopilitic. Groundmass constituents include plagioclase, glass, pyroxene, and magnetite dust. Apatite is common as an inclusion in plagioclase phenocrysts. Zircon is a rare accessory.

Olivine "xenocrysts" and basaltic andesite xenoliths were found to occur in several South Sister andesite and dacite lavas (PsAnLal, PsDaLa2, PsDaLa4). Olivine xenocrysts occur as individual grains or aggregates in the groundmass of the host rock. The xenocrysts are less than four millimeters in diameter, they have rounded (Figure 25) or ragged (Figure 26) margins, and they are commonly rimmed by small tangential laths of orthopyroxene. Basaltic andesite xenoliths occur as fine-grained aggregates of plagioclase and clinopyroxene; glass and microphenocrysts of olivine may be present. All of the xenoliths that I observed were less than six millimeters in diameter. Some had sharp margins, others were partly assimilated.

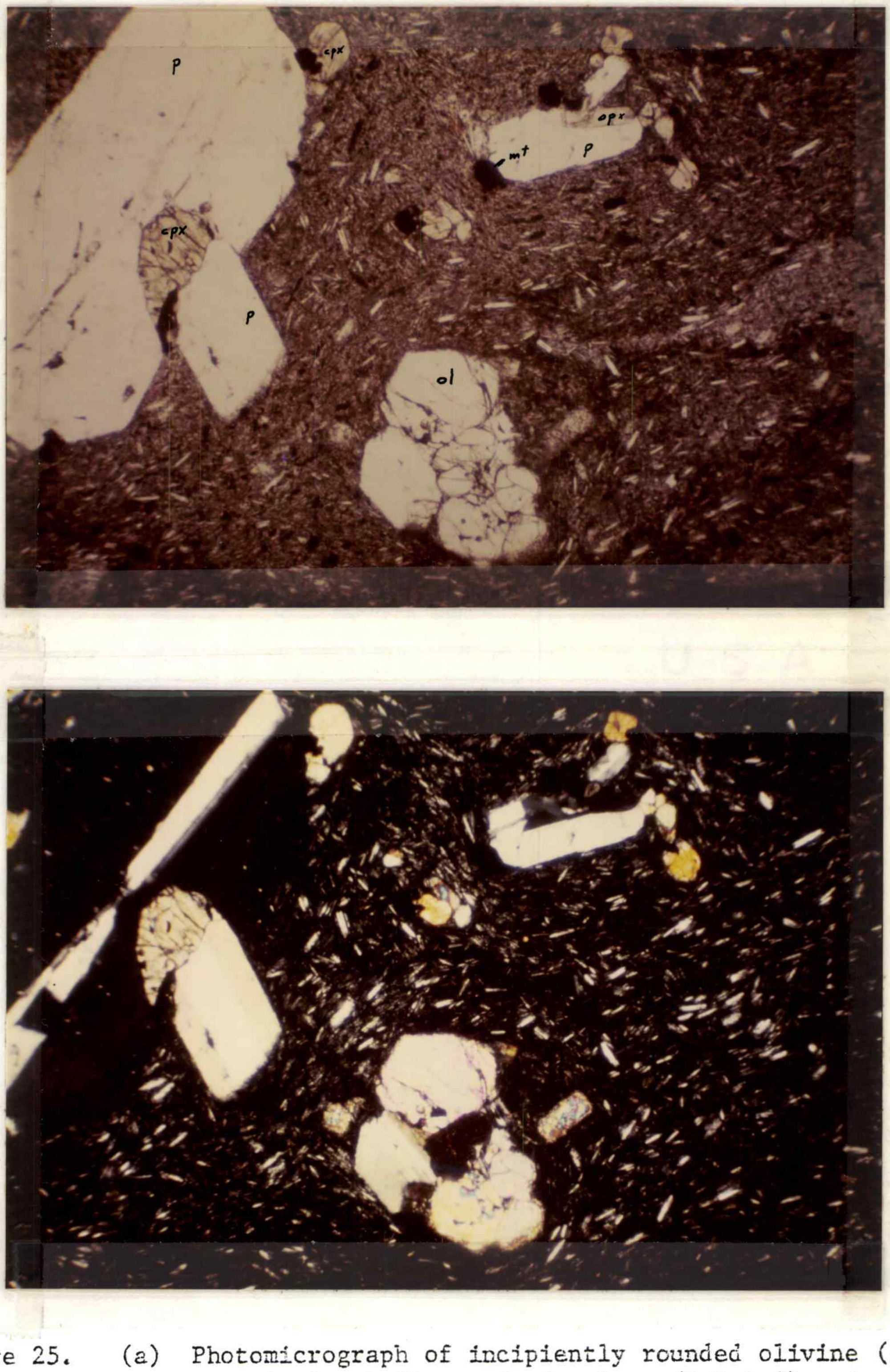
Sample 1586 (PsDaLa5) is unusual because it contains phenocrysts of hornblende, orthopyroxene, clinopyroxene, and olivine, yet the rock has a silica content of 68 percent. Hornblende occurs as sparse,



(a)

(b)

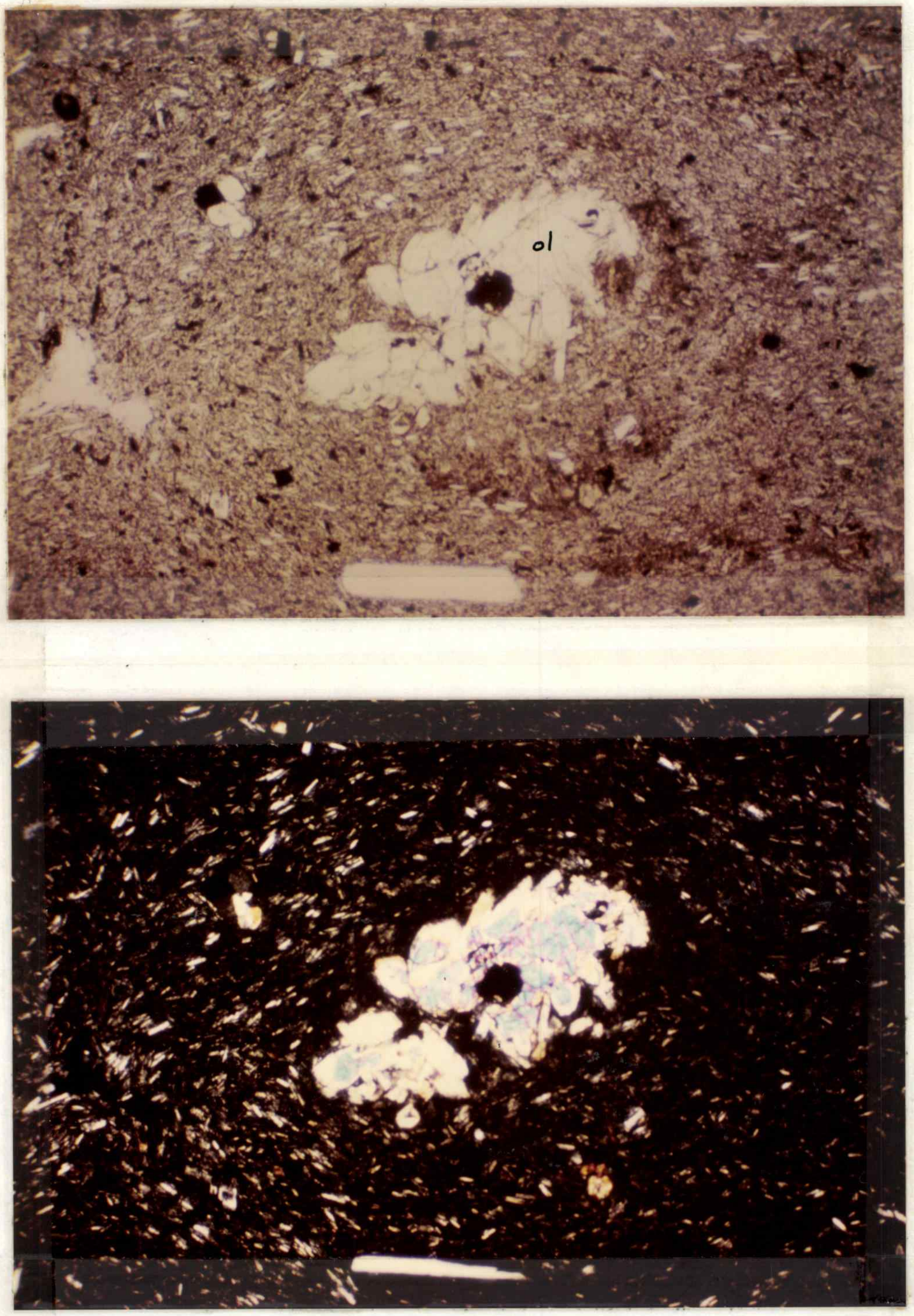
Figure 24. (a) Photomicrograph of plagioclase (p)-clinopyroxene (cpx)-magnetite (mt) glomerocryst in South Sister andesite lava (PsAnLa3). Plane light. Sample 1631. (b) Crossed nicols.



(a)

(b)

Figure 25. (a) Photomicrograph of incipiently rounded olivine (ol) xenocryst in South Sister dacite lava (PsDaLa4). Accompanied by plagioclase (p), clinopyroxene (cpx), orthopyroxene (opx), and magnetite (mt). Plane light. Sample 1586. (b) Crossed nicols.



(a)

(b)

Figure 26. (a) Photomicrograph showing ragged margin of olivine (ol) xenocryst in South Sister dacite lava (PsDaLa4). Note reaction rim of orthopyroxene. Plane light. Sample 1586. (b) Crossed nicols.

euhedral to anhedral crystals that are oxidized and rimmed by granular magnetite (Figure 27). Olivine occurs as rounded or ragged grains (Figures 25 and 26). Several of the plagioclase phenocrysts in sample 1586 have resorbed internal margins, but show euhedral exterior margins (Figure 28).

Sample 1558 (PsDaLa2) contains olivine xenocrysts and basaltic andesite xenoliths. One olivine-bearing xenolith fills an embayment in a plagioclase phenocryst (Figure 29). The plagioclase-xenolith contact is irregular in shape, but the plagioclase crystal is oscillatory zoned parallel to the contact. This texture suggests that the plagioclase phenocryst was resorbed by a basaltic andesite liquid.

The basaltic andesite xenoliths in South Sister dacites and andesites probably represent mechanically entrained rock fragments. The origin of the olivine xenocrysts is enigmatic. The bulk composition of dacite and andesite is not compatible with primary precipitation of olivine, yet it is difficult to imagine how individual grains of olivine could be mechanically assimilated into an intermediate liquid. Perhaps these olivine crystals are the disaggregated remnants of coarse-grained, olivine-rich, plutonic rocks.

South Sister Rhyodacites

Silica in South Sister rhyodacites ranges from 72 to 75 and averages 73 percent. Phenocrysts include plagioclase (one to seven percent) and orthopyroxene (up to one percent). Clinopyroxene, magnetite, and hornblende are present in trace amounts. Plagioclase is patchy or oscillatory zoned and has an average composition of An 45. Rounded and

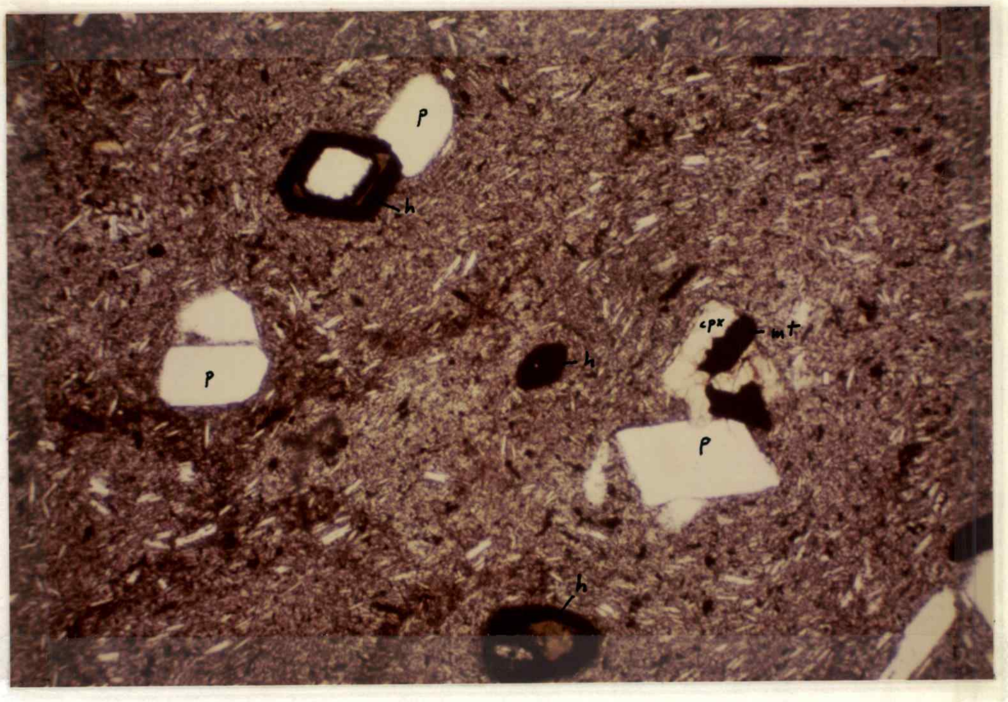


Figure 27. Photomicrograph of oxidized hornblende (h) phenocrysts in South Sister dacite lava (PsDaLa4). Rim of granular magnetite. Accompanied by plagioclase (p), clinopyroxene (cpx), and magnetite (mt). Plane light. Sample 1586.

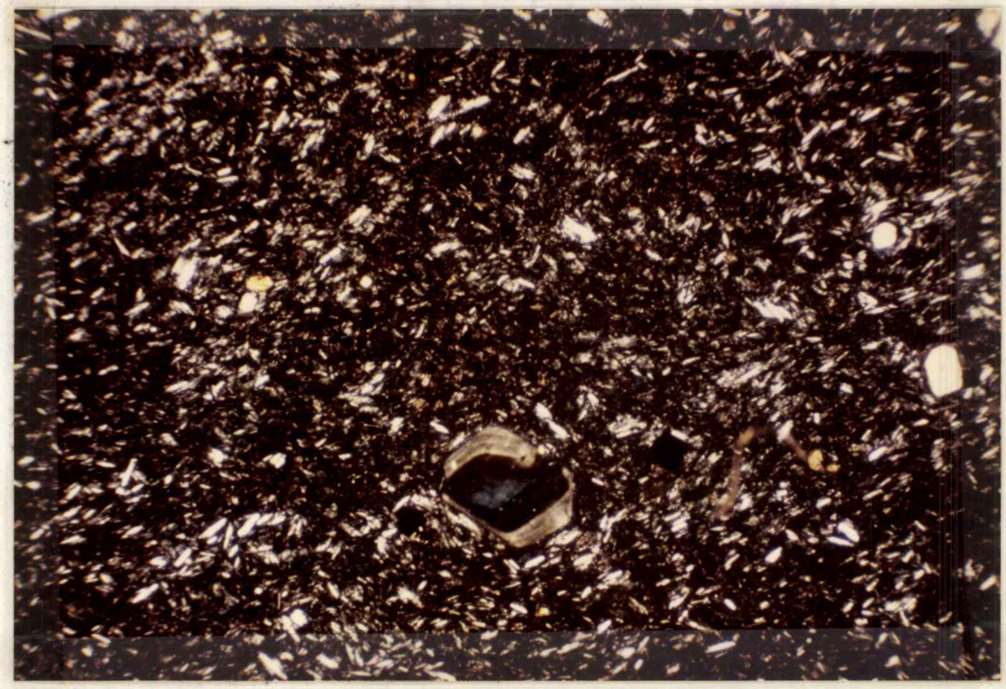


Figure 28. Photomicrograph of plagioclase phenocryst that has resorbed internal and euhedral external margins. From South Sister dacite lava (PsDaLa4). Plane light. Sample 1586.

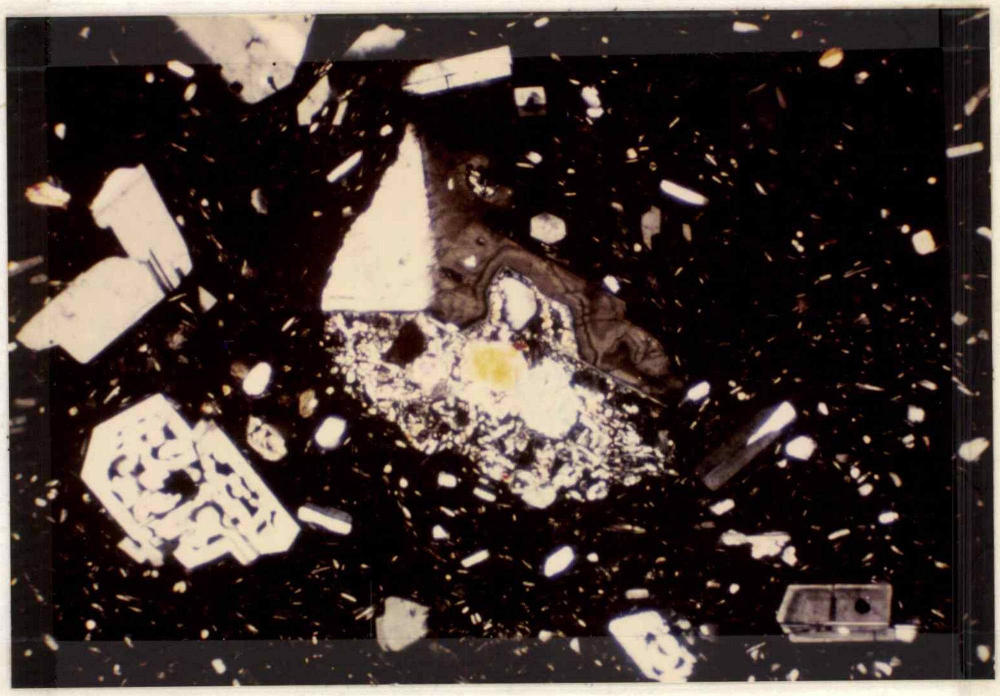


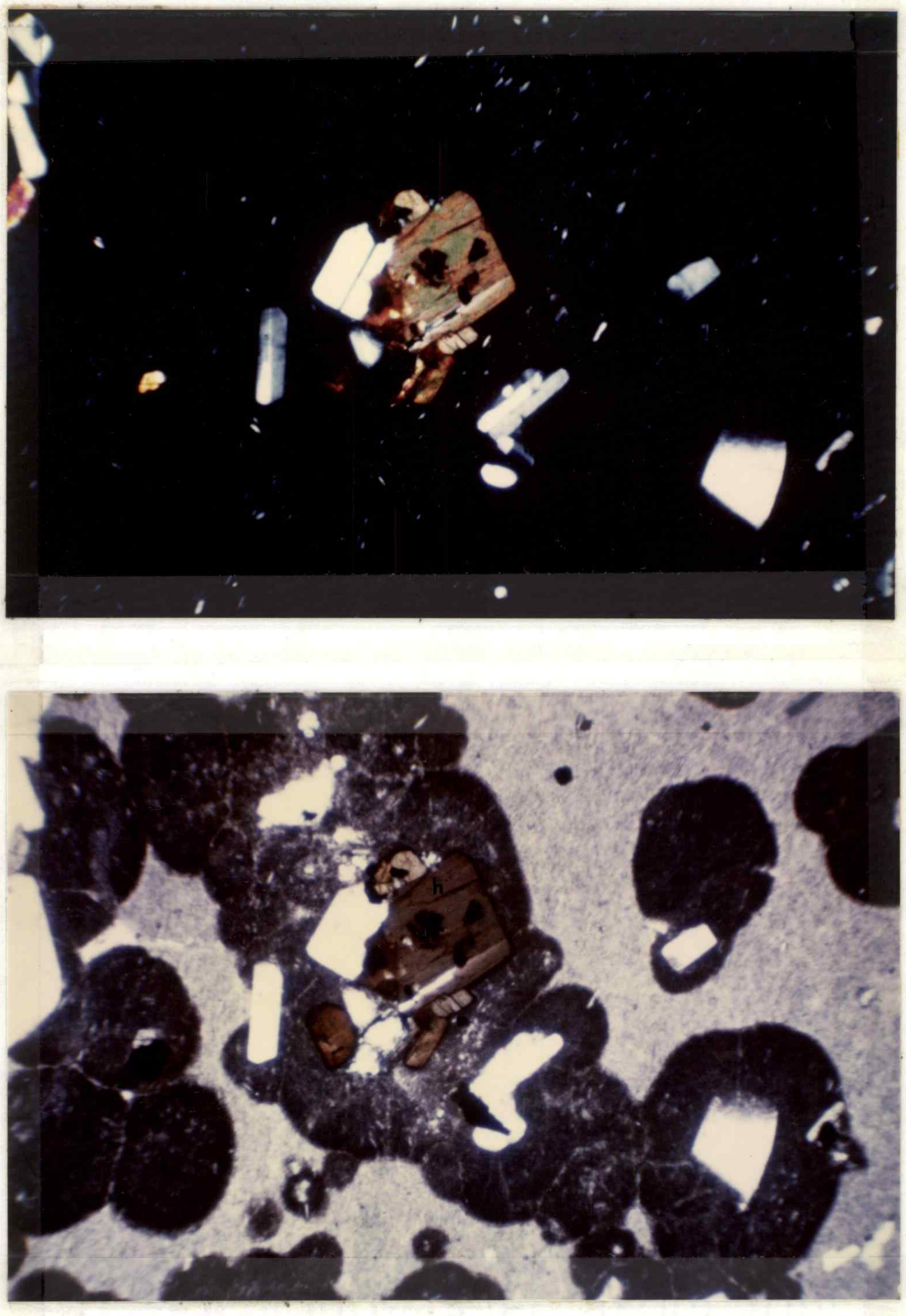
Figure 29. Photomicrograph of basaltic andesite xenolith in South Sister dacite lava (PsDaLa2). Note oscillatory zoning in plagioclase along the plagioclase-xenolith contact. Crossed nicols. Sample 1558.

resorbed crystals are common. Hornblende is typically oxidized to oxyhornblende and rimmed by granular magnetite (Figure 30). The groundmass is fluidal or hyalopilitic and contains glass, plagioclase, and sparse magnetite dust.

Discussion

South Sister rocks form a petrographic series that ranges in composition from basaltic andesite to rhyodacite. Although gaps in silica content are present, the petrographic features of each major rock type are gradational within and between compositional groups. The major features of this series can be summarized as follows:

1) Total phenocryst content is generally high and commonly exceeds ten percent.
2) Plagioclase is the dominant porphyritic phase.
3) As silica increases, the An content of plagioclase decreases. Plagioclase is normal-oscillatory zoned in basaltic andesites, andesites, and dacites, and oscillatory zoned in rhyodacites. Patchy zoning is common throughout, especially in the cores of large phenocrysts.
4) Clinopyroxene is the dominant ferromagnesian phenocryst in basaltic andesites, andesites, and dacites. Orthopyroxene dominates in rhyodacites.
5) Except as noted above, olivine occurs in basaltic andesites only. It is corroded, embayed, and uniformly small. As silica increases, orthopyroxene increases at the expense of olivine until olivine no longer occurs as a phase, at



(a)

(b)

Figure 30. (a) Photomicrograph of oxyhornblende (h) phenocrysts in South Sister rhyodacite lava (PsRdLa2). Rims of granular magnetite. Note incipient development of spherulites in vitreous groundmass. Plane light. Sample 1668.
(b) Crossed nicols.

approximately 58 percent silica.

6) Magnetite microphenocrysts are common throughout the series but are most abundant in the andesites and dacites. Except in rhyodacites, magnetite is a ubiquitous groundmass constituent. Magnetite inclusions are common in pyroxene phenocrysts.

7) Trace amounts of hornblende phenocrysts occur in silicic dacites and rhyodacites.

The basalts and basaltic andesites of Sphinx Butte, The Wife, and The Husband comprise a second petrographic series. These rocks are characterized as follows:

1) Total phenocryst content is generally low and rarely exceeds five percent.

2) Olivine is the dominant porphyritic phase.

3) Plagioclase is normal-oscillatory zoned and has a wide compositional range from core to margin. Cores of larger crystals are commonly patchy zoned.

4) Clinopyroxene and orthopyroxene are uncommon as phenocrysts.

5) Olivine phenocrysts exhibit a reaction relation with orthopyroxene in silicic basaltic andesites.

6) Magnetite occurs as a groundmass constituent but is rare as a microphenocryst.

Although both series contain high silica basaltic andesites, each remains distinct within this compositional range. The most noticable differences are (a) the high phenocryst content of South Sister basaltic andesites, (b) the occurrence of plagioclase, clinopyroxene, and magnetite phenocrysts in South Sister basaltic andesites, and (c) the inclusion of magnetite in pyroxenes of South Sister basaltic andesites.

PETROLOGY

Analytical Techniques

Specimens selected for chemical analysis were prepared and analyzed according to a standard laboratory procedure. At least one-half kg of each sample was ground to a fine sand. Splits of approximately ten grams were then pulverized in a tungsten-carbide ball mill to a uniformly fine powder. From this powder, three-gram splits were mixed in a ratio of 1:3 with lithium metaborate, fused at 1000 degrees Centigrade for one hour, and quenched to a homogeneous glass. The glass was then analyzed by x-ray fluorescence spectrometry for Si, Ti, Al, Fe, Ca, and K. Subsequently, the glass was pulverized to a fine powder in a ball mill. One-tenth gram splits of this powder were then dissolved in 200 ml of 0.5 N HNO_3. This solution was analyzed by atomic absorption spectrophotometry for Mg and Na. All determinations were calibrated to a set of laboratory standards. Oxygen was calculated by stoichiometry and all iron is reported as FeO (hereafter referred to as FeO*). Accuracy of the results is estimated to be within 0.5, 0.05, 0.5, 0.1, 0.1, 0.1, 0.1, and 0.05 weight percent for the respective oxides of Si, Ti, Al, Fe, Mg, Ca, Na, and K (E. M. Taylor, personal communication).

Characterization of the Suite

On a plot of total alkalies versus silica (Figure 31) rocks from the thesis area fall within the subalkaline field of Irvine and Baragar (1971). These rocks can be further characterized as calc-alkaline on an AFM diagram (Figure 32). Four data clusters can be recognized on

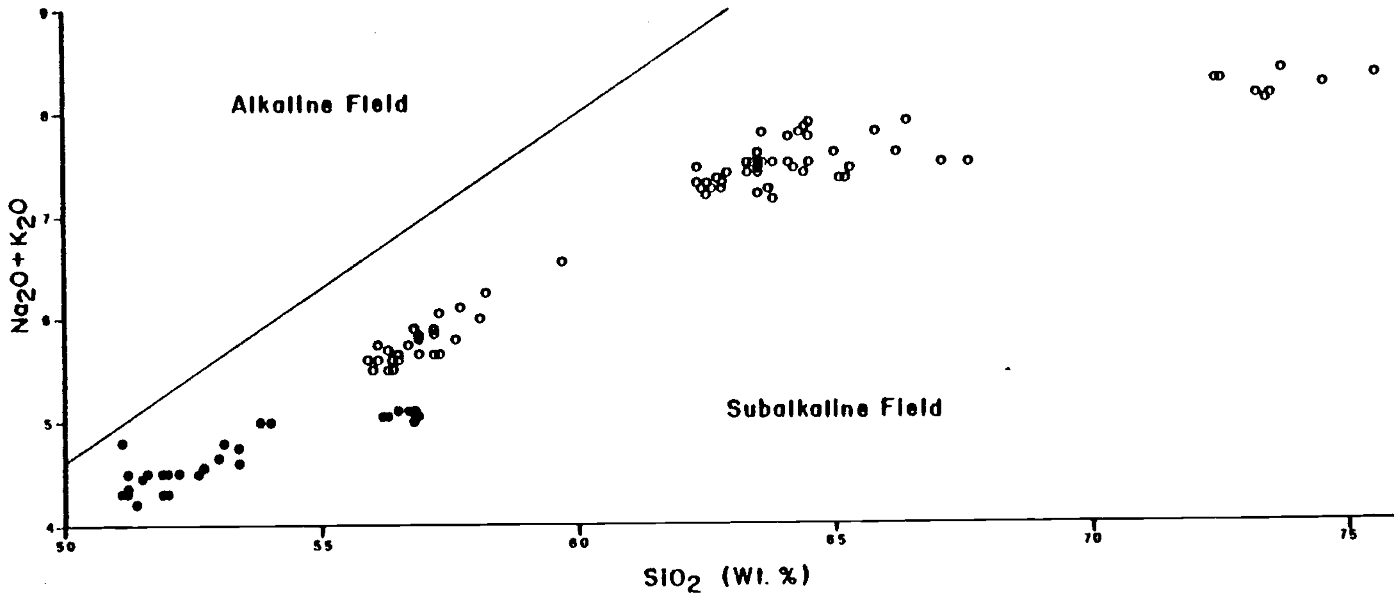


Figure 31. Total alkalies vs silica. Open circles: South Sister rocks. Solid circles: rocks from Sphinx Butte, The Wife, and The Husband. Coincident data points are not shown. Alkaline-subalkaline field boundary after Irvine and Baragar (1971).

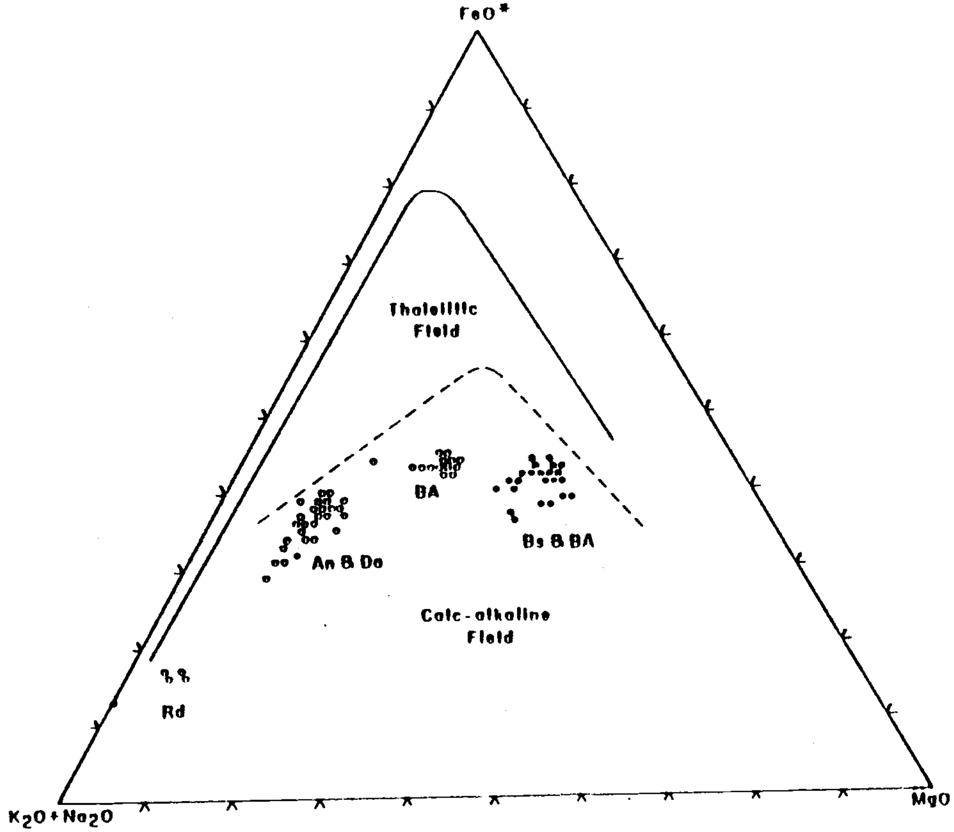


Figure 32. AFM diagram. Symbols are the same as those in Figure 26. Bs: basalt. BA: basaltic andesite. An: andesite. Da: dacite. Rd: rhyodacite. Dashed line separates tholeiitic and calc-alkaline fields, after Irvine and Baragar (1971). Solid line is Skaergaard trend, after Wager and Brown (1967).

the AFM diagram:

1) Basalts and basaltic andesites from Sphinx Butte, The Wife, and The Husband.

2) South Sister basaltic andesites.

3) South Sister andesites and dacites.

4) South Sister rhyodacites.

South Sister rocks define a curvilinear but discontinuous trend toward alkali enrichment.

A plot of alkalies and lime versus silica (Figure 33) shows an alkali-lime index of 58.3 for South Sister rocks. This places the suite within the calc-alkalic field of Peacock (1931). My data are not sufficient to determine an alkali-lime index for non-South Sister rocks but, as a group, these rocks appear to be more calcic than the South Sister suite. Williams (1942) reported alkali-lime indices of 62.0, 63.7, 63.9, and 63.2 for rocks from Crater Lake, Mount Shasta, the Mount Lassen region, and Mount St. Helens, respectively; Greene (1968) reported an index of 61.0 for Mount Jefferson area rocks.

Figures 34-36 show silica variation diagrams for each of the major oxides. Four data clusters can be recognized:

1) Basalts and low silica basaltic andesites from Sphinx Butte, The Wife, and The Husband.

2) High silica basaltic andesites.

3) South Sister andesites and dacites.

4) South Sister rhyodacites.

The TiO_2 and MgO plots show a subdivision of high silica basaltic andesites into South Sister and non-South Sister rocks; similar subdivisions are less readily visible on the FeO*, CaO, and Na_2O plots.

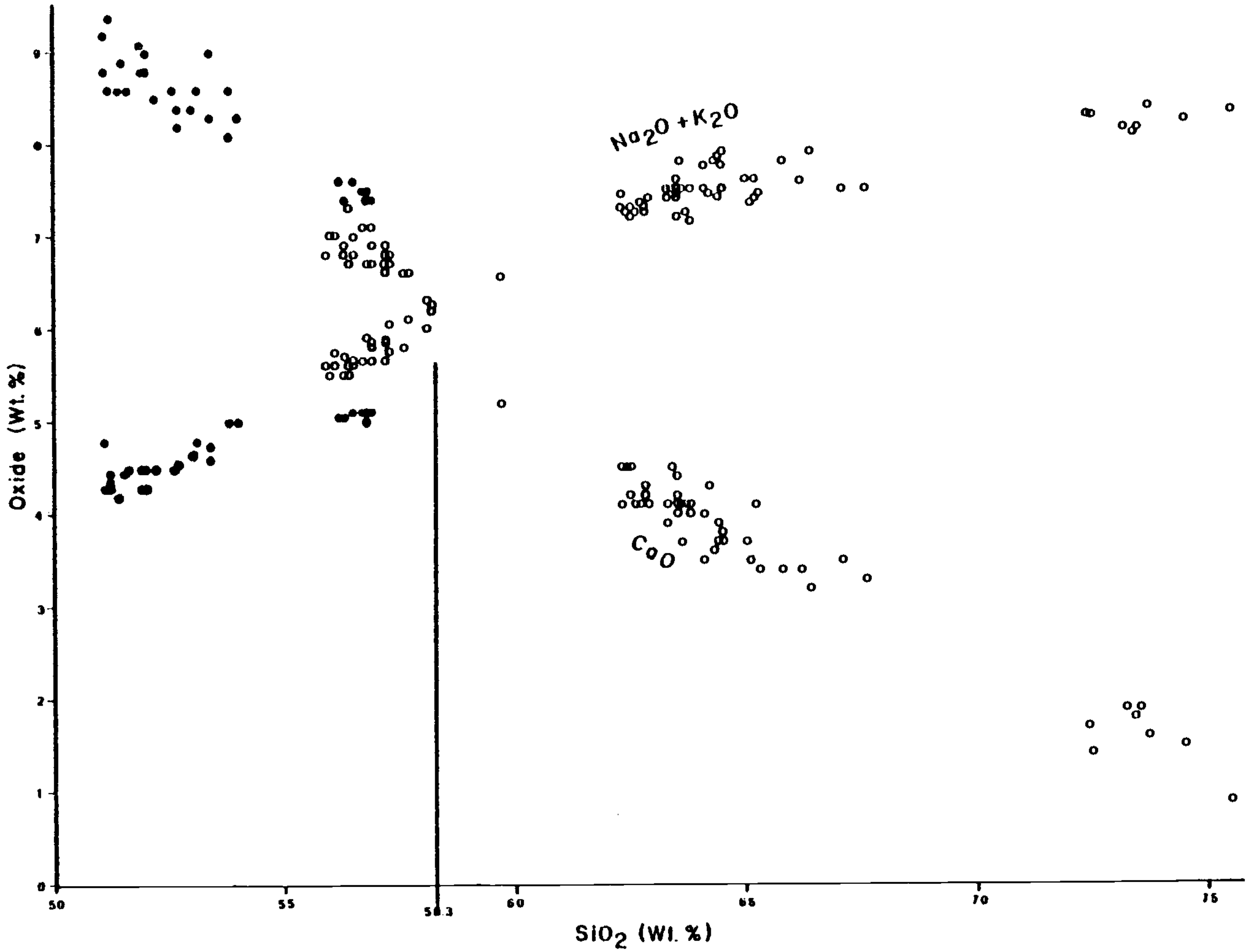


Figure 33. Total alkalies and lime vs silica. Symbols are the same as those in Figure 26. Alkali-lime index equals 58.3, after Peacock (1931).

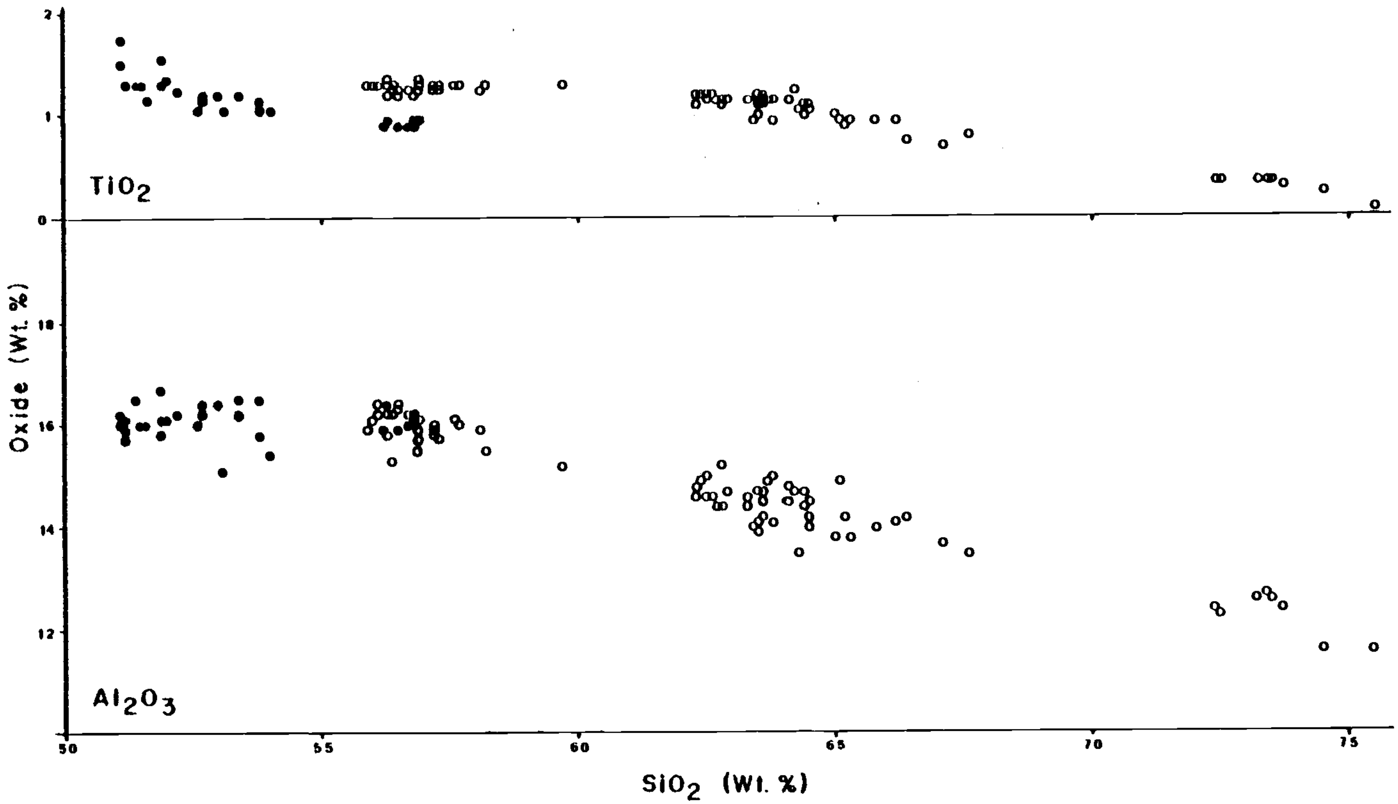


Figure 34. Silica variation diagram. TiO_2 and Al_2O_3 vs SiO_2. Symbols are the same as those in Figure 26.

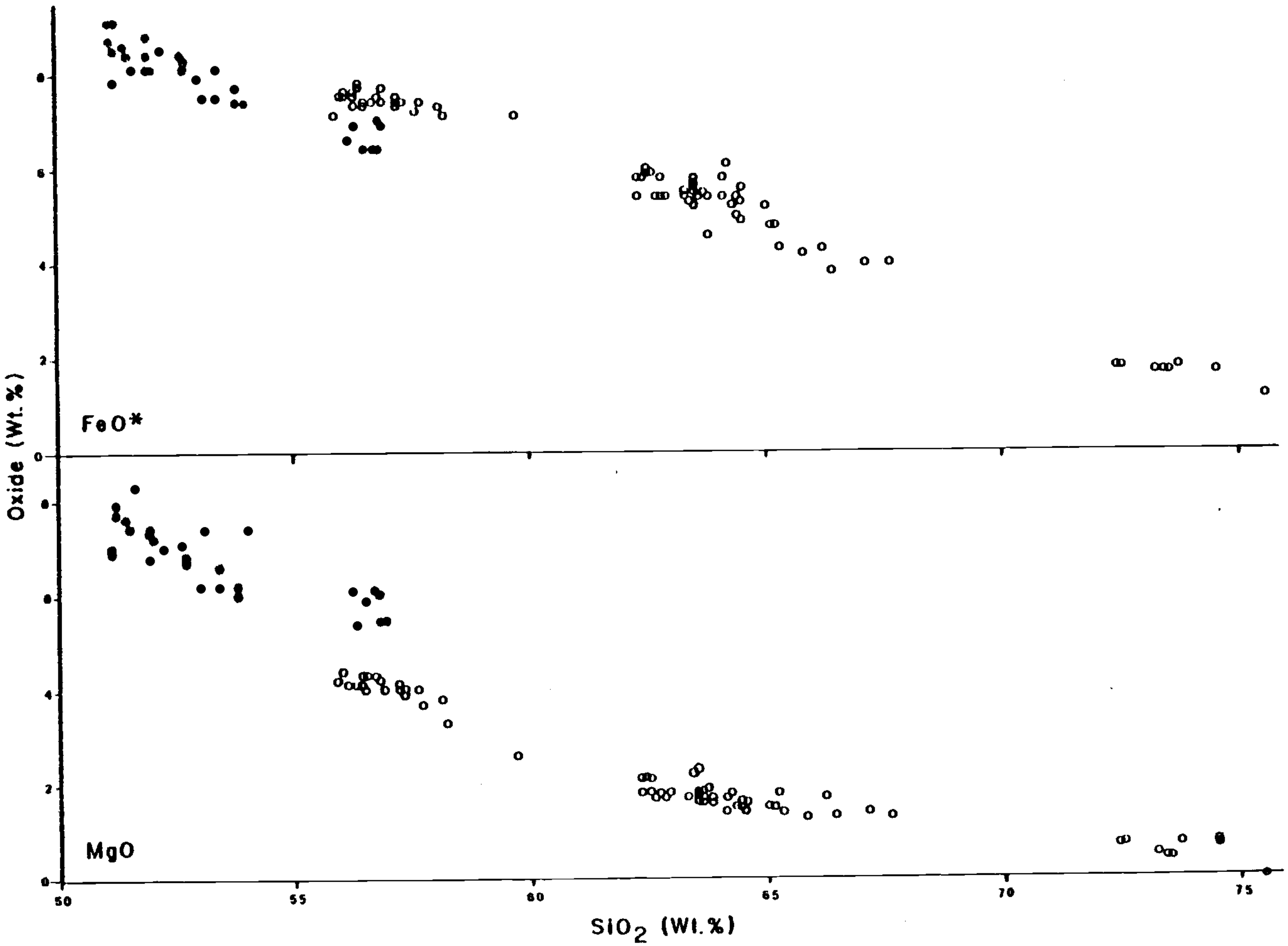


Figure 35. Silica variation diagram. FeO* and MgO vs SiO_2. Symbols are the same as those in Figure 26.

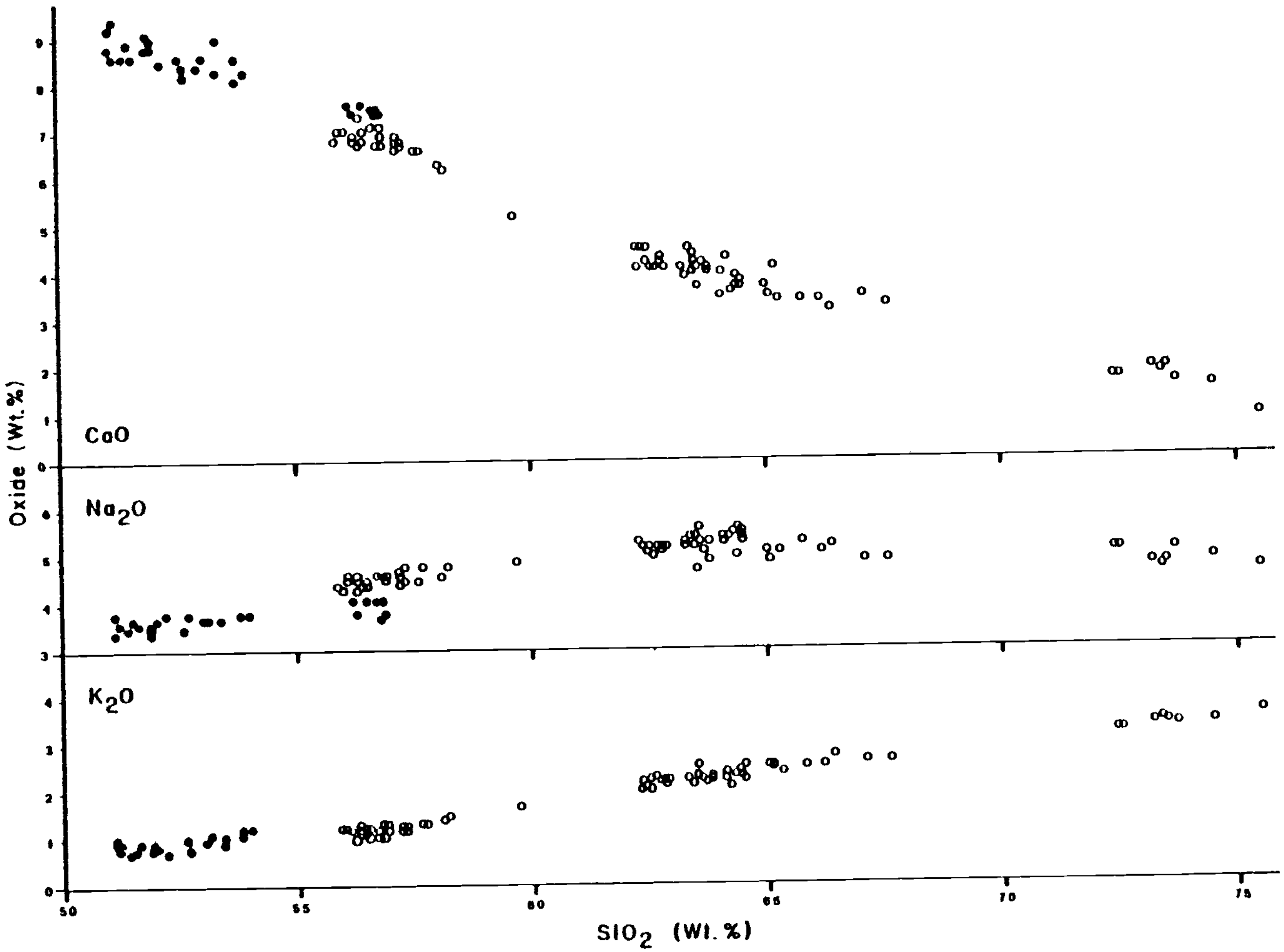


Figure 36. Silica variation diagram. CaO, Na_2O, and K_2O vs SiO_2. Symbols are the same as those in Figure 26.

On the basis of the above discussion, I propose that South Sister rocks form a suite that is chemically distinct from a second suite composed of rocks from the mafic shield and composite volcanoes in the thesis area. These suites correspond to the previously delineated petrographic suites.

Most of the basalts and low-silica basaltic andesites from Sphinx Butte, The Wife, and The Husband plot within the tholeiitic field of MacDonald and Katsura (1964) on a total alkalies versus silica diagram (Figure 37), but the data points cluster near the field boundary. According to Kuno's (1960, 1968) petrographic, chemical, and emperical criteria (Figure 38), these rocks are transitional between tholeiites and alkalic basalts and should be classified as high-alumina basalts.

Petrogenesis

Hypotheses that are proposed to explain the origin of the volcanic rocks within the thesis area must account for several features of the regional and local geology. Regional features to be considered include the following:

1) The central High Cascades of Oregon are chiefly composed of basalt and basaltic andesite shield volcanoes (Taylor, 1980). In exceptional cases, andesite may occur at one of these mafic centers (e.g., Collier Cone).
2) Since late Pliocene times mafic volcanism has been common throughout the central High Cascades of Oregon but intermediate and silicic volcanism has been localized in the vicinity of South Sister, Middle Sister, and Broken Top

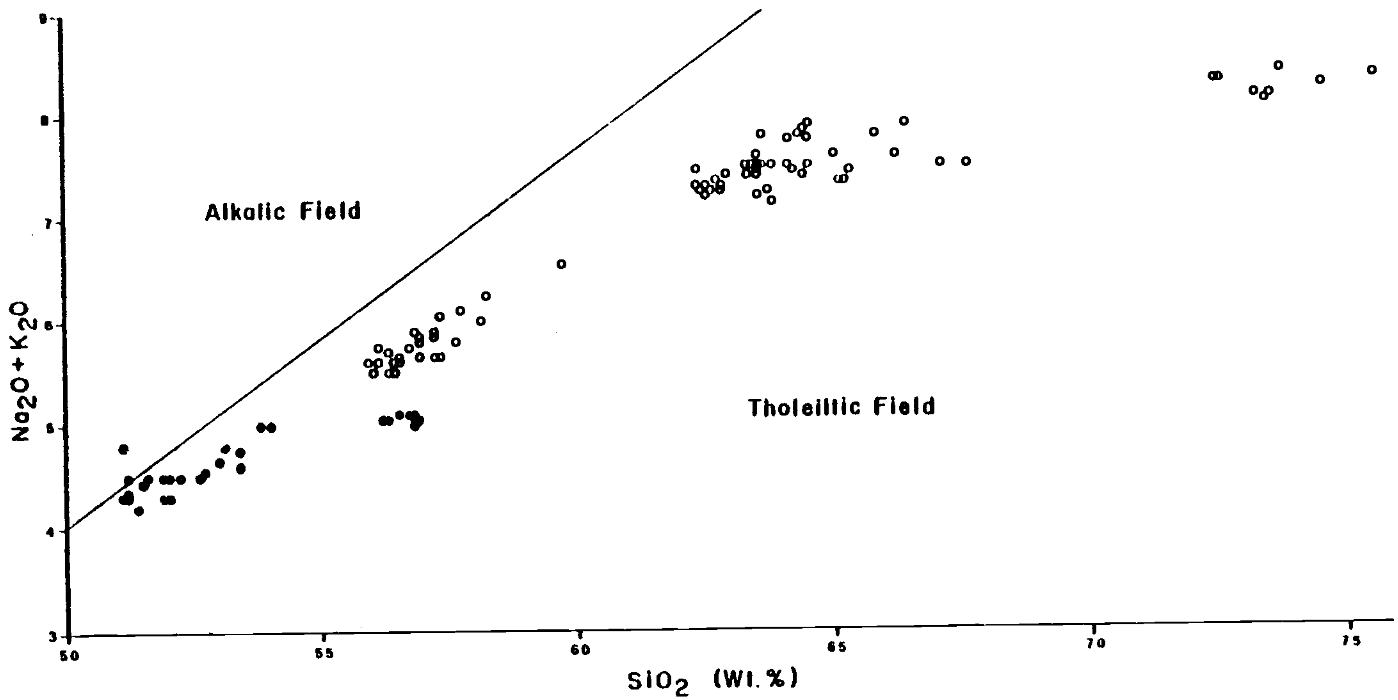


Figure 37. Total alkalies vs silica. Symbols are the same as those in Figure 26. Alkalic-tholeiitic field boundary after MacDonald and Katsura (1964).

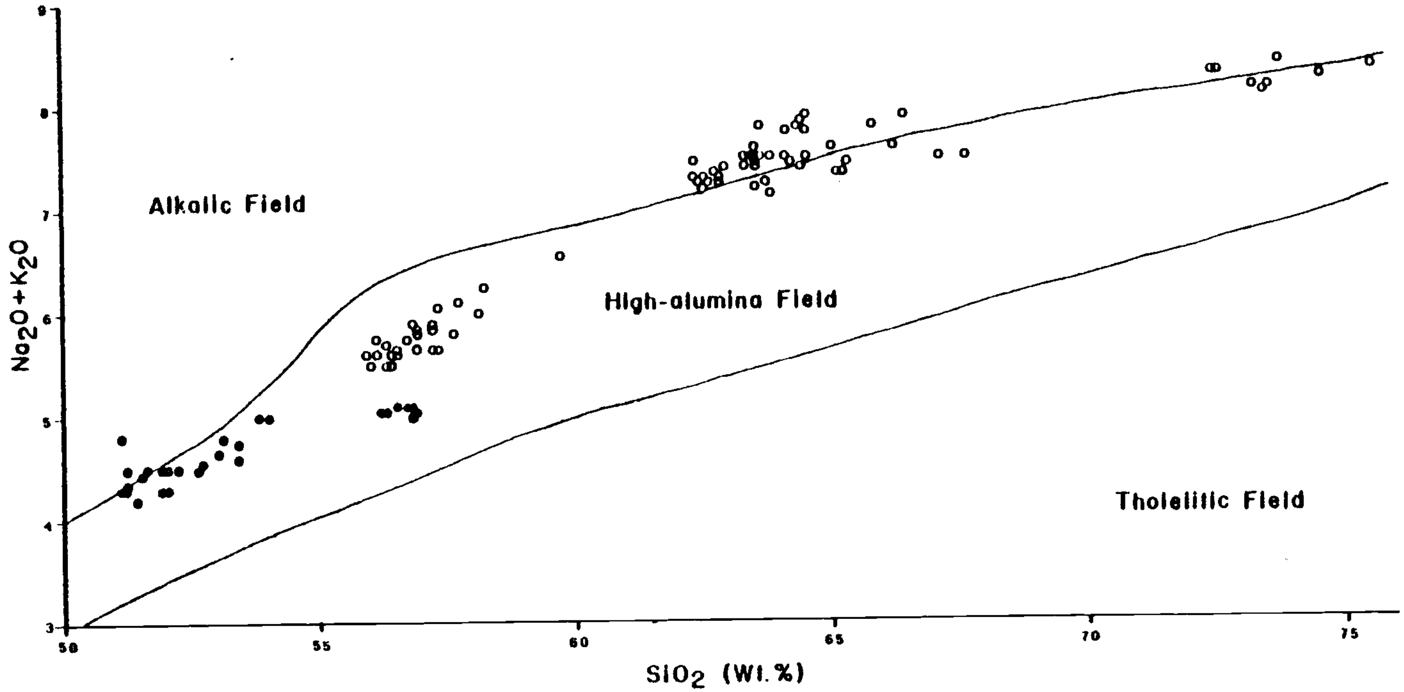


Figure 38. Total alkalies vs silica. Symbols are the same as those in Figure 26. Field boundaries after Kuno (1968).

volcanoes (Taylor, 1978, 1980).

Local features to be considered are listed below:

1) On the basis of silica content, South Sister rocks fall into three compositional groups: basaltic andesites, silicic andesites and dacites, and rhyodacites. Rocks that are transitional between these groups are rare (e.g., see Figures 34-36).

2) The South Sister has extruded magmas of diverse composition throughout its eruptive history.

3) South Sister rocks are chemically and petrographically distinct from rocks of Sphinx Butte, The Wife, and The Husband.

The above features argue against a genetic relation between high-alumina basalt magmas of the High Cascade platform, such as those extruded from The Husband, The Wife, and Sphinx Butte, and the intermediate and silicic magmas that were extruded from South Sister. For instance, if fractional crystallization of high-alumina basalt produced the South Sister suite it would be fortuitous if intermediate and silicic rocks were not found throughout the central High Cascades of Oregon. High-alumina basalts are ubiquitous throughout the platform, yet intermediate and silicic rocks are limited to an area around Middle Sister, South Sister, and Broken Top volcanoes. Andesites, dacites, and rhyodacites are even lacking at large, long-lived volcanoes such as The Husband, The Wife, North Sister, and Mount Washington. These same features argue against partial melting of the same source material to produce high-alumina basalt and The South Sister suite. The least siliceous rocks at South Sister are high-silica basaltic andesites, yet, as shown in the previous sections, these are petrographically and chemically distinct from the high-silica basaltic andesites of The Husband, The Wife, and Sphinx Butte. On the basis of the above discussion I hypothesize that magmas extruded from South Sister were derived from a different source than basalt and basaltic andesite magmas extruded from adjoining parts of the High Cascade platform. More sophisticated geochemical studies will be needed to test this hypothesis.

The diversity of rock compositions at South Sister Volcano may be the product of a variety of subcrustal processes. Most of these cannot be evaluated using the data from this thesis. Chayes (1964) has pointed out that "...the Harker diagram is of little use in discriminating between the effects of nearly all the processes thought to be of major importance in the differentiation of volcanic rocks." Thus, the chemical trends of the South Sister suite could be the result of partial melting, magma mixing, contamination, gas transfer, a variety of fractional crystallization schemes, or any combination of the above. Several observations, however, may provide some insight into the origin of South Sister magmas.

1) Of the rocks analyzed at South Sister, early and late representatives of any compositional group display little variation in major element chemistry or petrography.
2) The eruptive sequence at South Sister did not appear to follow any systematic or evolutionary progression such as extrusion of mafic, followed by progressively more silicic magmas.
3) Gaps are present on the silica variation diagrams even though many rocks were analyzed. The data cluster around three compositional groups: basaltic andesites, silicic andesites and dacites, and rhyodacites.

Chayes (1964) has concluded that if large numbers of analyses are available, then gaps in silica variation diagrams strongly imply the existence of more than one parent magma. On the basis of my observations I propose that separate processes have given rise to three different magma compositions at various times during the growth of South Sister. These processes may or may not be related. Further studies are needed to test these proposals.

Le Conte Crater is the only exception that I am aware of to statement number one, above. Le Conte Crater is a small Holocene cinder cone at the southwest base of South Sister. Basaltic andesite lavas from the Le Conte vent inundated a small area surrounding the cone before spreading to the north and south. North of the cone, Le Conte lavas (HoBALal) are partly buried beneath the main mass of Rock Mesa; south of the cone, they are mantled by Rock Mesa tephra. I did not examine thin sections of lava from the Le Conte cone; however, I observed approximately four percent olivine and one percent plagioclase phenocrysts in hand specimens. This phenocryst assemblage is similar to those of basaltic andesites from Sphinx Butte, The Wife, and The Husband; it is dissimilar to the phenocryst assemblage of South Sister basaltic andesites. In Table II, ten analyses of Le Conte lavas (provided by E. M. Taylor) are compared to the average analysis of South Sister basaltic andesites and the average analysis for high silica basaltic andesites from Sphinx Butte, The Wife, and The Husband. Except for TiO_2 and FeO*, oxide values for Le Conte lavas are similar to values for rocks from Sphinx Butte, The Wife, and The Husband and dissimilar to values for rocks from South Sister.

It follows from my previous discussions that the magmatic processes that produced South Sister lavas operated on a local scale, whereas

Table II. Chemical analyses of rocks from Le Conte Crater and average analyses of basaltic andesites from the field area.

Sample	417	418	421	422	426	433	434
SiO2	56.2	56.3	56.4	52.6	55.9	55.5	55.0
TiO2	1.40	1.33	1.40	1.58	1.26	1.34	1.35
Al2O3	15.4	15.5	15.7	16.7	16.3	15.5	15.3
FeO*	8.7	8.2	8.6	9.1	8.3	8.5	8.7
MgO	5.7	5.8	5.7	6.5	6.0	6.5	6.5
CaO	7.4	7.2	7.5	8.4	7.7	7.6	7.8
Na2O	3.6	3.8	3.0	3.6	3.7	3.6	3.6
K2O	1.29	1.33	1.12	1.10	1.00	1.08	1.05
Total	99.69	99.46	99.42	99.58	100.16	99.62	99.30

Sample	451	453	454	A	B	C
SiO2	55.8	55.6	55.9	55.8	56.8	56.6
TiO2	1.35	1.34	1.34	1.35	1.28	0.93
Al2O3	16.4	15.5	15.4	15.7	18.0	18.0
FeO*	8.2	8.3	8.5	8.4	7.4	6.7
MgO	5.8	5.8	6.2	6.0	4.1	5.8
CaO	7.4	7.8	7.9	7.6	6.8	7.5
Na2O	3.8	3.6	3.6	3.6	4.5	4.0
K2O	1.10	1.15	1.05	1.13	1.22	1.12
Total	99.85	99.89	99.09	99.58	100.10	100.65

A: Average analysis of Le Conte lava, excluding sample 422.
B: Average South Sister basaltic andesite. Samples 708, 1557, 1559, 1560, 1568, 1569, 1571, 1573, 1584, 1594, 1599, 1607, 1609, 1614, 1617, 1621, 1623, 1632, 1634, 1650, 1652, 1653, 1708, 1709, 1712, 1719.
C: Average high silica basaltic andesite from Sphinx Butte, The Wife, and The Husband. Samples 1524, 1529, 1531, 1532, 1534, 1541, 1698.

1 Analyses of Le Conte lavas provided by E. M. Taylor.

those that produced the rocks of Sphinx Butte, The Wife, and The Husband operated on a regional scale. If so, it is likely that some overlap has occurred in the spatial distributions of rocks derived from each process. For example, if the processes occurred at different levels in the mantle, the resultant magmas could use the same conduit systems at higher levels in the crust. This could only occur in regions where there was subcrustal overlap in the distribution of the two processes. I hypothesize that such a scenario has occurred in the case of Le Conte Crater. Many basalt and basaltic andesite lavas similar to the Le Conte lavas have been extruded during the Holocene from vents in the central High Cascades of Oregon. Examples include Belknap Crater, Yapoah Cone, and Twin Craters, near McKenzie Pass, and the Lost Creek cones and Nash Crater cones, near Santiam Pass. These extrusions represent a continuation of the mafic volcanism that has characterized the central High Cascades of Oregon since Pliocene times (Taylor, 1978, 1980). Le Conte Crater may be related to these Holocene cones and shield volcanoes and may bear only a spatial relation to South Sister. Further petrographic and chemical studies will be needed to test this hypothesis.

SUMMARY AND CONCLUSIONS

All of the volcanoes within the field area are probably less than 720,000 years old. Sphinx Butte, The Wife, and The Husband are older than Middle Sister and South Sister and have probably been subjected to a minimum of two glaciations. Sphinx Butte is younger than The Wife; The Wife is probably younger than The Husband. Middle Sister and South Sister were active late in the Pleistocene. Evidence for multiple Pleistocene glaciation of South Sister is obscure and it is possible that the bulk of the mountain is younger than the second-to-last Pleistocene glaciation. The basaltic andesite summit lavas at South Sister were extruded prior to 6640 yrs. B.P., but are probably of late Pleistocene rather than Holocene age. The basaltic andesite cinders and lavas of Le Conte Crater were extruded after the recession of the last Pleistocene glaciers, approximately 12,000 yrs. B.P., but prior to 2300 yrs. B.P. Silicic flank eruptions have occurred on South Sister between 2300 and 1900 yrs. B.P.

Sphinx Butte, The Wife, and The Husband are basalt and basaltic andesite shield and composite volcanoes typical of those that constitute the bulk of the High Cascade platform. In contrast, South Sister is a complex composite volcano composed of basaltic andesite, andesite, dacite, and rhyodacite. Field relations indicate that magmas of diverse composition were extruded from South Sister vents throughout the eruptive history of this volcano. The diverse magmatic activity at South Sister was simply a continuation of a pattern of localized magmatic diversity. This localized diversity has persisted throughout the late Pliocene and Quaternary in an isolated area of the High Cascade platform in the vicinity of Middle Sister, South Sister and Broken Top volcanoes.

South Sister rocks are petrographically and chemically distinct from the rocks of Sphinx Butte, The Wife, and The Husband. Regional and local geologic features indicate that magmas extruded from South Sister were probably derived from a different source than magmas extruded from Sphinx Butte, The Wife, and The Husband. The magmatic processes that produced South Sister rocks operated on a local scale, whereas those that produced the basalts and basaltic andesites of Sphinx Butte, The Wife, and The Husband, operated on a regional scale.

Early and late representatives of any compositional group at South Sister display little variation in major element chemistry or petrographic characteristics. No systematic or evolutionary progression could be discerned. Even though many rocks were analyzed, three distinct clusters occur on silica variation diagrams. These features suggest that three separate, but possibly related, subcrustal processes have operated intermittently throughout the growth of South Sister to give rise to three types of magmas: basaltic andesites, andesites and silicic dacites, and rhyodacites. Basaltic andesite lavas extruded from the Le Conte cinder cone may bear no genetic relation to South Sister basaltic andesites even though the Le Conte cone is situated at the base of South Sister.

Eruptions at South Sister have occurred during the late Pleistocene and Holocene epochs. Many Holocene extrusions have also occurred in adjacent areas of the High Cascade platform. It seems likely that such activity will persist into the future.

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APPENDICES

APPENDIX 1

Petrography and Descriptions of Mapped Units

Descriptions of mapped units are listed below in consecutively numbered age-composition groups. Symbols used in unit names are defined in the Lithology and Stratigraphy section under Representation of Mapped Units. Samples that were examined in thin section and chemically analyzed are listed by number in the pertinent unit descriptions and sample localities are plotted by number on the geologic map. All chemical analyses are consecutively listed by sample number in Appendix 2.

Except where noted, phenocryst proportions were measured in thin section using standard point-counting procedures and are reported as volume percent of the total rock, excluding pore space. Plagioclase composition was determined by measuring extinction angles according to the Carlsbad-albite, a-normal, and Michel-Levy methods, in that order of preference. Criteria discussed by Tobi (1961) were used to distinguish between the various kinds of plagioclase twins in sections normal to (010). A chart prepared by Tobi (1963) was used to convert extinction angles to mole percent anorthite (An).

Groundmass constituents are listed in order of decreasing abundance.

Units of Holocene Nonvolcanic Deposits

HoAl — Detrital deposits of streams and lakes. Includes well-sorted glacial outwash adjacent to terminal moraines.

HoTa — Talus aprons and blockfields.

HoGd1 Neoglacial moraines overlain by tephra from the 2300 yrs. B.P. Rock Mesa (HoRdLa2) eruption.

HoGd2 Neoglacial moraines not overlain by Rock Mesa tephra.

Units of Holocene Basaltic Andesite

HoBALa1 Olivine-bearing basaltic andesite lava from Le Conte cone. Dark gray to black. Scoriaceous, blocky, pressure-ridged surface. Distal part of flow crops out in bed of Mesa Creek, proximal part overlain by Rock Mesa lava (HoRdLa2). Phenocrysts of olivine (4%; up to 2.0 mm) and plagioclase (1%; up to 1.0 mm). Not examined in thin section. See Table II for chemical analyses.

Units of Holocene Rhyodacite

HoRdLa1 Orthopyroxene-bearing rhyodacite lavas from chain of domes on east margin of Carver Glacier. Silica 73%. Four domes, aligned N.5W. over 0.9 miles. Gray, vitreous, flow-banded interiors, spherulitic in part. Surface and marginal breccias of light gray, vitreous, partly inflated blocks. Phenocrysts of plagioclase (6-10%; An 49-45, oscillatory and patchy zoned; rounded, resorbed, and embayed; commonly contain apatite inclusions; up to 3.0 mm) and orthopyroxene (less than 1%; up to 1.2 mm). Trace amounts of clinopyroxene, oxyhornblende, and magnetite (all less than 0.5 mm). Fluidal or hyalopilitic groundmass; abundant plagioclase microlites, minor magnetite dust. Overlies till of Neoglacial moraines (HoGd2) and glaciated South Sister dacite (PsDaLa2). Probably equivalent to Goose Creek chain of domes (HoRdLa2 of E. M. Taylor, 1978) on southeast flank of South Sister. Samples 1561, 1562, 1563.

HoRdLa2
HoRdPc2 Orthopyroxene-bearing rhyodacite lavas and pumice deposits from Rock Mesa vent. Lava measures 1 3/4 by 1 1/3 miles. Gray, inflated crust; interior of dense obsidian; blocky pressure-ridged surface. Phenocrysts of plagioclase (15%; up to 3.0 mm) and orthopyroxene (1%; up to 1.0 mm). C-14 date, 2300 yrs. B.P. Not analyzed or examined in thin section.

Units of Pleistocene Basalt

PsBsLa1 Glaciated olivine-bearing basalt lavas between Honey Lake and Sphinx Butte. Silica 51-53%. Phenocrysts of Plagioclase (up to 3.0%; An 69-49, normal-oscillatory zoned, patchy zoned cores in larger grains, less than 2.0 mm) and olivine (2-3%; commonly oxidized; less than 1.2 mm). Trace amounts of clinopyroxene. Intergranular or intersertal groundmass contains plagioclase, clinopyroxene, and granular magnetite. Scattered anhedral flakes of orange-brown pleochroic biotite (?) in samples 1507 and 1553. Normal paleomagnetic polarity. Overlain by South Sister dacite lava (PsDaLa1). Samples 1507, 1535, 1543, 1552, 1553.

PsBsLa2 Olivine-bearing basalt lavas between Mesa Creek and The Wife. Silica 52-53%. Medium to dark gray, vesicular block flows. Glaciated. Phenocrysts of olivine (4%; commonly Fe-stained and surrounded by blebs of secondary magnetite; up to 2.5 mm) and plagioclase (trace; An 66). Groundmass intergranular or subophitic; plagioclase, clinopyroxene, and magnetite. Normal paleomagnetic polarity. Samples 1509, 1516.

PsBsLa3 Glaciated olivine-bearing basalt lavas between Pacific Crest Trail and James Creek Shelter, and Dew Lake and Rock Mesa. Silica 51-52%. Phenocrysts of plagioclase (up to 5, but generally less than 2%; An 68-46, normal-oscillatory zoned; cores up to An 72 in large patchy zoned crystals; up to 0.5 mm) and olivine (1-3%; oxidized; up to 1.4 mm). Trace clinopyroxene. Pilotaxitic, intergranular, or subophitic groundmass contains plagioclase (An 56-46, normal zoned), clinopyroxene, and magnetite. Cristobalite lines some vesicles. Normal paleomagnetic polarity. Overlain by South Sister dacite lavas (PsDaLa1, PsDaLa6). Overlies lavas of PsBALa1. Samples 1637, 1658, 1660, 1661, 1694, 1696, 1704.

PsBsLa4 Glaciated olivine-bearing basalt lavas from The Husband. Crop out between Foley Ridge Trail and Separation Creek Meadow. Silica 52-53%. Phenocrysts of plagioclase (average 3%; An 68-46, normal oscillatory zoned; An 70, patchy zoned cores in large crystals; up to 1.3 mm) and olivine (2-3%; commonly iddingsitized along grain and fracture margins; up to 4.0 mm). Trace clinopyroxene. Groundmass intergranular or pilotaxitic; contains plagioclase, clinopyroxene, magnetite, and trace apatite. Normal paleomagnetic polarity. Overlies lavas of PsBALa3. Samples 1527, 1537, 1539.

PsBsLa5 Olivine-bearing basalt porphyry lavas of Middle Sister. Crop out between Pacific Crest Trail and Separation Creek. Dark gray to black flows, some with ropy surfaces. Phenocrysts of plagioclase (up to 50%; 2.0-4.0 mm) and olivine (5%; up to 3.0 mm). Overlain by Middle Sister andesite (PsAnLa4) and dacite (PsDaLa7) lavas. Not analyzed or examined in thin section.

Units of Pleistocene Basaltic Andesite

PsBALa1 Olivine-bearing basaltic andesite lavas between James Creek Shelter and Indian Holes, and Dew Lake and Mesa Creek. Silica 53-57%. Light to dark gray. Glaciated. Phenocrysts of plagioclase (5-6%; An 68-32, normal and normal-oscillatory zoned; less than 1.5 mm) and olivine (2%; oxidized; up to 1.5 mm), except for aphyric flow on east wall of Indian Holes (sample location 1547). Intergranular groundmass contains granular clinopyroxene, orthopyroxene (sample 1547 only), and magnetite. Minor cristobalite in cavities. Normal paleomagnetic polarity. Overlain by South Sister dacite (PsDaLa1). Samples 1547, 1655, 1698.

PsBALa2 Orthopyroxene- and olivine-bearing basaltic andesite lavas between Honey Lakes and Indian Holes. Silica 56-57%. Dark gray to black, vesicular; ropy surfaces. Glaciated. Microphenocrysts of olivine and orthopyroxene (less than 1% each; average 0.1 mm). Hyaloophitic groundmass; Tachylyte crowded with microlitic plagioclase (An 58-42, normal-oscillatory zoned), clinopyroxene, orthopyroxene, and magnetite dust. Normal paleomagnetic polarity. Overlain by lavas of PsBALa3. Samples 1534, 1541.

PsBALa3 Glaciated olivine-bearing basaltic andesite lava near Honey Lakes. Silica 56-57%. Light gray, platy. Olivine phenocrysts (2%; average 0.2 mm) commonly corroded, rimmed by granular clinopyroxene, orthopyroxene, and magnetite. Trace plagioclase and clinopyroxene. Pilotaxitic groundmass contains plagioclase (An 63-43, normal zoned), clinopyroxene (granular aggregates and subhedral prisms), orthopyroxene, magnetite, apatite, and cristobalite. Normal magnetic polarity. Overlain by Husband basalt lavas (PsBsLa4). Samples 1524, 1529, 1531, 1532.

PsBALa4
PsBAPc4
PsBAId4
PsBAIp4 Olivine-bearing basaltic andesite lavas, pyroclastic deposits, dikes, and plug rocks of Sphinx Butte volcano. Silica 53-54%. Glaciated. Dikes not sampled. Thin (5-10 ft), medium to dark gray flows contain phenocrysts of olivine (2-5%; commonly corroded, riddled with granular or vermicular magnetite), plagioclase (less than 2%; An 72-44, normal zoned; up to 1.5 mm). Groundmass intergranular, contains plagioclase (An 58-45, normal zoned), clinopyroxene, and granular magnetite. Vesicles of some flows lined with cristobalite and hematite. Normal magnetic polarity. Analyses 1501, 1503. Cinders not analyzed or examined in thin section, but mineralogy of hand specimens similar to lavas. Plug rocks contain phenocrysts of olivine (10%; corroded, embayed, jacketed by orthopyroxene; deutericly altered to bowlingite and magnetite). Intergranular groundmass contains plagioclase (An 61-45, normal zoned), clinopyroxene, orthopyroxene, and magnetite. Normal magnetite polarity. Samples 1513, 1523.

PsBALa5 Glaciated two-pyroxene basaltic andesite lavas between Separation Creek Meadow and Pacific Crest Trail. Silica 56-58%. Phenocrysts of plagioclase (13-35%; An 64-41, normal-oscillatory zoned), patchy zoned cores in large crystals; up to 3.2 mm), clinopyroxene (2-5%; rimmed by granular clinopyroxene in some flows; up to 3.0 mm), orthopyroxene (0.5-2%; average 0.5 mm), and olivine (less than 1%; rimmed by clinopyroxene and magnetite, 0.2-0.5 mm). Microphenocrysts of magnetite (less than 1%; up to 0.3 mm). Glomerocrysts of plagioclase + clinopyroxene ± orthopyroxene + magnetite. Intergranular or hyalopilitic groundmass. Accessory apatite. Normal paleomagnetic polarity. Overlain by Middle Sister basalt lavas (PsBsLa5). Samples 1557, 1634, 1650, 1652, 1653, 1708, 1709.

PsBALa6 Glaciated olivine- and clinopyroxene-bearing basaltic andesite lavas of South Sister. Silica 57-58%. Crop out at northwest base of South Sister between Separation Creek and Lost Creek Glacier. Light gray, blocky to platy. Phenocrysts of plagioclase (up to 15%; An 78-55, normal-oscillatory and patchy zoned; up to 3.2 mm), olivine (up to 2%; rounded; less than 0.4 mm), and clinopyroxene (less than 1%; up to 0.8 mm). Trace orthopyroxene. Magnetite microphenocrysts, less than 1%, up to 0.2 mm. Intergranular groundmass contains plagioclase, clinopyroxene, and magnetite dust. Similar to flows of PsBALa5 that crop out one mile to the east. Samples 1599, 1614.

PsBALa7 Glaciated olivine- and clinopyroxene-bearing basaltic andesite lava on west slope of South Sister between 7200 and 7400 feet elevation. Silica 56%. Light gray, blocky. Phenocrysts of plagioclase (8%; An 58-37, normal-oscillatory and patchy zoned; up to 2.0 mm), clinopyroxene (2%; up to 0.6 mm), olivine (1%; rounded, rimmed by granular magnetite; up to 0.6 mm), and magnetite (less than 1%; up to 0.2 mm). Intergranular groundmass. Overlain by till of Neoglacial moraine (HoGd2). Sample 1632.

PsBALa8 Olivine- and clinopyroxene-bearing basaltic andesite lavas of South Sister. Silica 56-58%. Lavas crop out on north flank down to 7500 feet elevation and in cirque walls of Skinner, Eugene, and Lost Creek Glaciers. Glacially striated below approximately 8600 feet elevation. Light gray interiors, red scoriaceous surfaces. Thick interbeds of red and black cinders on cliffs in cirque walls. Overlain by lavas of PsAnLa4. Phenocrysts of plagioclase (8-34%, average 18%; An 60-42, normal-oscillatory zoned, larger phenocrysts patchy zoned; apatite inclusions; up to 4.0 mm), clinopyroxene (2%; some with magnetite inclusions; up to 1.0 mm), olivine (1-2%; rounded or embayed, surrounded by granular pyroxene and magnetite; average 0.1 mm), and magnetite (up to 0.5%; less than 0.3 mm). Trace orthopyroxene. Pilotaxitic, hyalopilitic, or intergranular groundmass; glass up to 10%; plagioclase, granular clinopyroxene, and magnetite dust. Samples 1559, 1560, 1568, 1569, 1571, 1573, 1584, 1594, 1607, 1609, 1617, 1621, 1623, 1719.

PsBALa9 PsBAId9 Clinopyroxene- and olivine-bearing basaltic andesite summit lavas and related dikes of South Sister. Silica 57%. Medium to dark gray, weathers reddish-brown. Thin flows separated by red and black scoria, bombs, and spatter. Thin dikes in cirque walls of Skinner, Lost Creek, and Lewis Glaciers. Phenocrysts of plagioclase (28%; An 60-36, normal-oscillatory and patchy zoned; up to 3.5 mm), clinopyroxene (2%; up to 1.5 mm), olivine and orthopyroxene (both less than 1%; olivine corroded; both up to 0.5 mm). Trace amounts of magnetite microphenocrysts (up to 0.2 mm). Intersertal groundmass; tachylyte crowded with plagioclase, clinopyroxene, and magnetite dust. Overlies lavas of PsAnLa4. Samples 708, 1712.

Units of Pleistocene Andesite

PsAnLa1 Glaciated two-pyroxene andesite lavas on lower northwest flank of South Sister. Silica 62%. Gray platy interiors, vitreous margins. Phenocrysts of plagioclase (6-10%; normal-oscillatory zoned cores, An 62-45; normal zoned rims, An 45-27; larger phenocrysts patchy zoned; up to 3.0 mm), clinopyroxene (1%; commonly rimmed by granular clinopyroxene; up to 1.2 mm), orthopyroxene and olivine (both less than 1%; up to 0.4 mm). Glomerocrysts of plagioclase and clinopyroxene ± orthopyroxene + magnetite (2.0-5.0 mm diameters). Magnetite inclusions occur in plagioclase, clinopyroxene, and orthopyroxene. Pilotaxitic or hyalopilitic groundmass contains plagioclase, clinopyroxene, and magnetite dust; up to 40% glass. Overlain by lavas of PsAnLa3 and PsBALa8. Samples 1616, 1629, 1633. Thin section of sample 1633 contains one olivine xenocryst (0.3 mm diameter with ragged margins); almost wholly replaced by orthopyroxene.

PsAnLa2
PsAnPc2 Glaciated two-pyroxene andesite lavas and pyroclastic deposits on east flank of South Sister at top and base of Prouty Glacier. Silica 60%. Lavas medium to dark gray, altered reddish-brown near top of southwest cirque wall. Platy with vitreous margins on lower slopes. Pyroclastic deposit (not sampled) composed of light gray to black pumice, cinders and blocks; crops out on col between summit of South Sister and 10,037 foot prominence to the east. Phenocrysts and glomerocrysts of plagioclase (10-25%; An 49-36, normal-oscillatory zoned; commonly contain apatite inclusions; up to 3.0 mm), clinopyroxene (3%; up to 1.3 mm), orthopyroxene (1.5%; less than 1.0 mm), and magnetite (less than 1%; up to 0.4 mm). Clinopyroxene and orthopyroxene rimmed and riddled by magnetite in altered samples. Hyalopilitic or pilotaxitic groundmass contains plagioclase, pyroxene, magnetite, and up to 10% glass. Overlain by lavas of PsAnLa3, PsBALa8, PsBALa9. Samples 707, 1578, 1715.

PsAnLa3 Two-pyroxene andesite lavas near summit of South Sister. Silica 63%. Glaciated on west flank below 8200 feet elevation. Gray, platy interiors; black, vitreous margins. Phenocyrsts and glomerocrysts of plagioclase (5-20%, average 11%; An 53-36, normal oscillatory zoned; some larger phenocrysts patchy zoned in cores; up to 3.5 mm), clinopyroxene (1-3%; up to 2.0 mm), othopyroxene (trace - 1%; up to 0.6 mm), and magnetite (up to 1%; up to 0.4 mm). Apatite inclusions in plagioclase. Groundmass pilotaxitic, fluidal, or hyalopilitic, plagioclase, glass, pyroxene, granular magnetite. Overlain by basaltic andesite lavas of PsBALa9. Samples 1631, 1710, 1711, 1720, 1721.

PsAnLa4 Glaciated platy andesite lava between western Chambers Lake and Pacific Crest Trail. Phenocrysts of plagioclase (5%; up to 2.0 mm) and clinopyroxene (2%; up to 1.0 mm). Not analyzed or examined in thin section. Similar in appearance and mineralogy to South Sister andesites. May be derived from same vent that extruded andesite dome (PsAnLa5) to the east. Overlies Middle Sister basalt lavas of PsBsLa5.

PsAnLa5 Glaciated andesite lava of dome between western Chambers Lake and Pacific Crest Trail. Light gray, vitreous to holocrystalline, flow-banded to platy. Phenocrysts of plagioclase (5%; up to 3.0 mm) and clinopyroxene (2%; up to 2.0 mm). Not analyzed or examined in thin section.

Units of Pleistocene Dacite

PsDaLa1 Glaciated clinopyroxene-bearing dacite lava between Pacific Crest Trail and confluence of James and Mesa Creeks. Silica 64%. Light gray, platy interior; black, vitreous, columnar-jointed margins. Columns 5 to 6-sided, commonly in fans and rosettes. Flow up to 300 feet thick between Sphinx Butte and James Creek. Phenocrysts of plagioclase (2-3%; An 52-48, indistinctly normal-oscillatory zoned; up to 3.0 mm), clinopyroxene (1%; commonly with narrow rim of granular clinopyroxene; up to 1.6 mm), orthopyroxene, and magnetite (both less than 1%; up to 0.8 and 0.3 mm, respectively). Pilotaxitic, fluidal, or hyalopilitic groundmass; plagioclase, glass, pyroxene, and magnetite dust. Samples 1505, 1545, and 1690 contain trace amounts of hornblende replaced by granular magnetite (?). Overlies basalt and basaltic andesite lavas of PsBsLa3 and PsBALa1 between Pacific Crest Trail and bluffs west of James Creek Shelter. Overlies basalt lavas of PsBsLa1 near confluence of James and Mesa Creeks. Samples 1505, 1506, 1545, 1654, 1690, 1702, 1703.

PsDaLa2 Glaciated clinopyroxene-bearing dacite lavas between Carver and Chambers Lakes. Silica 64-68%. Gray, platy interiors; black, vitrophyric margins. Phenocrysts and glomerocrysts of plagioclase (6-19%; An 55-40, normal-oscillatory zoned; larger phenocrysts patchy zoned; up to 4.0 mm), clinopyroxene (1-3%; up to 1.0 mm), magnetite (up to 1%; up to 0.4 mm), and orthopyroxene (less than 1%; up to 2.0 mm). Groundmass is fluidal or pilotaxitic and contains plagioclase, glass, granular pyroxene, and magnetic dust. Samples 1558, 1566, 1716. Sample 1566 contains several hornblende phenocrysts that have been pseudomorphed by granular magnetite (?). Sample 1716 (silica 65.2%) contains a rounded olivine xenocryst (0.3 mm diameter). Sample 1558 contains several basaltic andesite (?) micro-xenoliths (up to 3.0 mm). Some are partly assimilated. One olivine-bearing xenocryst fills an embayment in a resorbed plagioclase phenocryst. Sample 1558 also contains a coarse-grained xenolith composed of plagioclase and olivine; at the xenolith-dacite interface olivine is rimmed by orthopyroxene and plagioclase is rounded.

PsDaLa3 Glaciated clinopyroxene-bearing dacite lava between Carver and Skinner Glaciers. Silica 64-66%. Composed of reddish-brown, pumiceous lava that contains lenses and thin, elongate ribbons of dense, black glass. Subhorizontal, alternately layered, ribboned, and pumiceous glass are common. Brecciated in part. Grades upslope to gray, brecciated, partly inflated lava. Phenocryst assemblages are virtually identical in all parts of unit. Phenocrysts of plagioclase

(3-4%; An 52-42, normal and normal-oscillatory zoned; up to 2.0 mm), clinopyroxene (1%; up to 1.2 mm), orthopyroxene, and magnetite (both less than 1%; up to 0.4 mm). Pyroxenes and magnetite are oxidized in vesicular parts of unit. Red pumiceous and black glassy lava are gradational in thin section. Red pumiceous part composed of clear glass filmed by red iron-oxides. Black glassy part composed of opaque glass charged with magnetite dust. Opaque glass commonly exhibits scalloped outer margin. Transitional zone contains brown translucent glass with dentritic magnetite. Groundmass fluidal or hyalopititic in dense glass. Groundmass of gray, brecciated, partly inflated lava contains brown translucent glass charged with magnetite dust. Rhyodacite xenoliths are common. Samples 1567, 1619, 1620, 1622, 1718. Samples 1567 and 1622 are from gray, partly inflated part of unit. Sample 1718 is from pod of dense black glass. Samples 1619 and 1620 are mixed pumiceous and black glassy lava. A large pinkish-gray aphyric rhyodacite xenonlith (sample 1718b) was extracted from the margin of sample 1718b. The groundmass consists of flow-banded, partly devitrified glass that contains feldspar, tridymite, and flow-aligned biotite. The mineral osumilite is present as euhedral, clear- to blue-pleochroic crystals in cavities and as disseminated anhedral grains in the groundmass.

PsDaLa4 Glaciated clinopyroxene-bearing dacite lavas at base of Skinner and Eugene Glaciers. Silica 65-68%. Gray, platy interiors; black, vitrophyric margins. Phenocrysts and glomerocrysts of plagioclase (5-9%; An 57-33, normal-oscillatory zoned; larger crystals patchy zoned; up to 3.0 mm), clinopyroxene (1%; up to 1.2 mm), orthopyroxene and magnetite (both less than 1%; up to 0.4 mm). Apatite inclusions in plagioclase. Groundmass is pilotaxitic, fluidal, or hyalopilitic and contains plagioclase, glass, pyroxene, magnetite, and trace amounts of zircon. Overlies basaltic andesite lavas of PsBALa6 at northwest base of South Sister. Samples 1586, 1714. Sample 1714 (silica 65.0%) contains micro-xenoliths of basaltic andesite and xenocrysts of olivine (ragged borders; rimmed by orthopyroxene). Sample 1586 (silica 67.6) contains trace amounts of hornblende (rimmed or completely replaced by granular magnetite), several olivine xenocrysts (rimmed by orthopyroxene), and a few plagioclase phenocrysts that have resorbed internal margins (as defined by compositional zones) and euhedral exterior margins.

PsDaLa5 Glaciated clinopyroxene-bearing dacite lava at base of Skinner Glacier. Silica 66%. Gray, platy interor; black vitreous margins. Phenocrysts of plagioclase (5%; An 52, oscillatory zoned; up to 3.0 mm), clinopyroxene (1%; up to 0.8 mm), orthopyroxene and magnetite (both less than 1%; up to 0.4 mm). Groundmass of sample from margin is hyalopilitic; contains plagioclase, glass, and magnetite dust. Overlies lava of PsDaLa3. Sample 1575.

PsDaLa6 Glaciated two-pyroxene dacite lavas on southwest flank of South Sister. Gray, platy interiors; black, vitreous, blocky, or columnar-jointed margins. Silica 63-66%. Phenocrysts and glomerocrysts of plagioclase (12-20%; An 54-46, normal-oscillatory zoned; some larger crystals patchy zoned; up to 3.0 mm), clinopyroxene (2-3%, up to 0.6 mm), orthopyroxene (1%; up to 0.5 mm), and magnetite (less than 1%; up to 0.3 mm). Apatite inclusions in some plagioclase. Groundmass is pilotaxitic, fluidal, or hyalopilitic and contains plagioclase, glass, granular clinopyroxene, and magnetite dust. Overlies PsDaLa1 at west base of South Sister. Overlies PsRdLa2 and PsRdLa3 at south base of South Sister. Samples 1636, 1638, 1639, 1640, 1642, 1644, 1645, 1646, 1659, 1670, 11678, 1679, 1682, 1705, 1706.

PsDaLa7 Glaciated clinopyroxene-bearing dacite lava between Chambers Lakes and Pacific Crest Trail. From vent at 8300 feet elevation on south flank of Middle Sister. Gray, platy interior; black, vitrophyric, columnar-jointed margins. Overlies lavas of PsAnLa4, PsAnLa5, and PsBsLa5. Not analyzed or examined in thin section.

Units of Pleistocene Rhyodacite

PsRdLa1 Glaciated rhyodacite dome north of Carver Lake. Silica 73%. Aphyric. Black, brown, and red flow-banded margins. Densely spherulitic in places. Gray platy interior. Analyzed and described by E. M. Taylor (1978; his PsRdLa1). Overlain by dacite lavas of PsDaLa2.

PsRdLa2 Glaciated orthopyroxene-bearing lava between Rock Mesa and Clark Glacier. Silica 72-74%. Gray, spherulitic base of devitrified glass. Light gray, partly inflated crust. Phenocrysts of plagioclase (7-10%; An 42-37, normal-oscillatory zoned; up to 3.5 mm), orthopyroxene (up to 1%; less than 2.0 mm), magnetite (less than 1%; up to 0.3 mm), clinopyroxene, and oxyhornblende (both in trace amounts; up to 0.3 and 1.5 mm, respectively). Hornblende commonly rimmed by granular magnetite. Apatite common as inclusion in plagioclase. Groundmass is fluidal or hyalopilitic; constituents are glass, plagioclase, granular pyroxene, and minor magnetite dust. Cristobalite occurs as vesicle lining. Spherulites cut across fluidal texture and appear to be local centers of devitrification. Overlain by dacite lavas of PsDaLa6 and rhyodacite pumice of HoRdPc2. Samples 1668, 1669, 1686.

PsRdLa3 Glaciated rhyodacite lava between Rock Mesa and Clark Glacier. Silica 74%. Light gray, vesicular and spherulitic to dense, black, vitreous lava. Phenocrysts of plagioclase (1%; An 46, indistinct oscillatory zones; commonly rounded; up to 1.0 mm), clinopyroxene, orthopyroxene (both in trace amounts; up to 0.4 mm), and magnetite (trace; up to 0.1 mm). Fluidal groundmass composed of glass, plagioclase, unidentifiable crystallites, and minor amounts of magnetite dust. Overlain by dacite lavas of PsDaLa6. May be the interior part of a remnant dome that includes PsRdLa2. Sample 1673.

APPENDIX 2

Chemical Analyses of Rocks From S.E. Three Sisters Quadrangle

Sample	707	708	1501	1503	1505	1506	1507
SiO2	59.7	56.8	54.0	53.4	64.3	64.2	51.1
TiO2	1.30	1.22	1.05	1.19	1.03	1.24	1.48
Al2O3	17.2	18.1	17.4	18.2	15.5	16.7	18.0
FeO*	7.1	7.5	7.4	7.5	5.2	6.1	9.1
MgO	2.6	4.2	7.4	6.2	1.5	1.8	7.0
CaO	5.2	6.7	8.3	9.0	3.6	4.3	8.8
Na2O	4.9	4.6	3.8	3.7	5.5	5.4	3.8
K2O	1.64	1.28	1.21	1.05	2.28	2.06	0.99
Total	99.64	100.40	100.56	100.24	98.91	101.80	100.27

Sample	1509	1513	1516	1523	1524	1527	1529
SiO2	51.6	53.1	52.6	53.8	56.2	52.2	56.5
TiO2	1.14	1.07	1.03	1.07	0.91	1.27	0.90
Al2O3	18.0	17.6	18.0	17.8	17.9	18.2	17.9
FeO*	8.1	7.5	8.4	7.4	6.6	8.5	6.4
MgO	8.3	7.4	7.1	6.2	6.1	7.0	5.9
CaO	8.6	8.6	8.6	8.1	7.6	8.5	7.6
Na2O	3.6	3.7	3.5	3.8	4.1	3.8	4.1
K2O	0.91	1.12	0.99	1.21	0.94	0.70	1.01
Total	100.25	100.09	100.22	99.38	100.35	100.17	100.31

Sample	1531	1532	1534	1535	1537	1539	1541
SiO2	56.7	56.8	56.3	51.1	52.7	52.7	56.8
TiO2	0.91	0.90	0.95	1.75	1.22	1.15	0.94
Al2O3	18.0	18.2	18.4	18.2	18.2	18.4	18.0
FeO*	6.4	6.4	6.9	8.7	8.3	8.1	7.0
MgO	6.1	6.0	5.4	6.9	6.7	6.8	5.5
CaO	7.5	7.5	7.4	9.2	8.2	8.4	7.4
Na2O	4.1	4.1	3.8	3.4	3.8	3.8	3.7
K2O	1.02	1.01	1.26	0.89	0.74	0.76	1.32
Total	100.73	100.91	100.41	100.14	99.86	100.11	100.66

Sample	1543	1545	1547	1552	1553	1557	1558
SiO2	51.9	64.5	53.8	53.0	51.2	55.9	67.1
TiO2	1.32	1.10	1.14	1.20	1.31	1.28	0.69
Al2O3	18.1	16.5	18.5	18.4	17.9	17.9	15.7
FeO*	8.4	5.6	7.7	7.9	7.8	7.1	4.0
MgO	7.3	1.6	6.0	6.2	7.7	4.2	1.4
CaO	8.8	3.8	8.6	8.4	9.4	6.8	3.5
Na2O	3.5	5.3	3.9	3.7	3.6	4.4	4.9
K2O	0.79	2.22	1.09	0.94	0.87	1.21	2.60
Total	100.11	100.62	100.73	99.74	99.78	98.79	99.89

Sample	1559	1560	1561	1562	1563	1566	1567
SiO2	57.6	56.7	73.2	73.5	73.4	63.8	66.2
TiO2	1.29	1.27	0.33	0.33	0.33	0.93	0.96
Al2O3	18.1	18.2	14.6	14.6	14.7	17.0	16.1
FeO*	7.2	7.4	1.7	1.7	1.7	4.6	4.3
MgO	4.0	4.3	0.5	0.4	0.4	1.6	1.7
CaO	6.6	7.1	1.9	1.9	1.8	4.1	3.4
Na2O	4.5	4.6	4.8	4.8	4.7	4.9	5.1
K2O	1.32	1.16	3.33	3.37	3.39	2.25	2.51
Total	100.61	100.73	100.36	100.60	100.42	99.18	100.27

Sample	1568	1569	1571	1573	1575	1578	1584
SiO2	56.9	56.1	56.5	56.3	65.8	63.5	57.2
TiO2	1.29	1.28	1.27	1.29	0.96	1.18	1.31
Al2O3	18.1	18.2	18.4	18.2	16.0	16.1	17.9
FeO*	7.4	7.5	7.4	7.5	4.2	5.5	7.4
MgO	4.1	4.2	4.0	4.1	1.3	1.7	4.0
CaO	6.9	7.0	7.0	6.9	3.4	4.1	6.6
Na2O	4.5	4.6	4.5	4.5	5.3	5.2	4.4
K2O	1.16	1.14	1.16	1.19	2.49	2.23	1.25
Total	100.35	100.02	100.23	99.98	99.45	99.51	100.06

Sample	1586	1594	1599	1607	1609	1614	1616
SiO2	67.6	56.3	57.7	58.2	57.3	57.2	62.3
TiO2	0.81	1.36	1.29	1.29	1.27	1.28	1.20
Al2O3	15.5	17.8	18.0	17.5	17.7	17.8	16.6
FeO*	4.0	7.6	7.4	7.1	7.4	7.5	5.8
MgO	1.3	4.2	3.7	3.3	4.0	4.1	2.1
CaO	3.3	6.8	6.6	6.2	6.8	6.9	4.5
Na2O	4.9	4.6	4.8	4.8	4.5	4.7	5.3
K2O	2.58	1.12	1.32	1.44	1.23	1.18	2.01
Total	99.99	99.78	100.81	99.83	100.20	100.66	99.81

Sample	1617	1619	1620	1621	1622	1623	1629
SiO2	56.9	65.1	64.4	57.3	65.3	57.2	62.5
TiO2	1.27	0.97	1.01	1.29	0.95	1.28	1.21
Al2O3	17.7	16.9	16.7	17.7	15.8	18.0	17.0
FeO*	7.4	4.8	5.0	7.4	4.3	7.4	5.9
MgO	4.0	1.5	1.5	3.9	1.4	4.0	2.1
CaO	6.7	3.5	3.9	6.7	3.4	6.8	4.5
Na2O	4.6	4.9	5.0	4.8	5.1	4.6	5.2
K2O	1.27	2.44	2.41	1.25	2.36	1.23	2.01
Total	99.84	100.11	99.92	100.34	98.61	100.51	100.42

Sample	1631	1632	1633	1634	1636	1637	1638
SiO2	62.9	56.1	62.4	58.1	62.6	51.9	63.7
TiO2	1.13	1.28	1.19	1.27	1.18	1.54	1.16
Al2O3	16.7	18.4	16.9	17.9	16.6	18.7	16.9
FeO*	5.4	7.6	5.8	7.3	5.9	8.1	5.5
MgO	1.8	4.1	2.1	3.8	1.7	6.8	1.9
CaO	4.1	7.0	4.5	6.3	4.1	9.1	4.2
Na2O	5.2	4.5	5.2	4.6	5.0	3.6	5.1
K2O	2.18	1.12	2.04	1.38	2.23	0.91	2.15
Total	99.41	100.10	100.13	100.65	99.31	100.65	100.61

Sample	1639	1640	1642	1644	1645	1646	1650
SiO2	64.1	63.5	66.4	62.8	62.3	63.8	57.2
TiO2	1.13	1.09	0.77	1.14	1.12	1.13	1.23
Al2O3	16.5	16.7	16.2	17.2	16.8	16.1	17.9
FeO*	5.3	5.2	3.8	5.8	5.4	5.4	7.3
MgO	1.7	1.8	1.3	1.7	1.8	1.7	4.1
CaO	4.0	4.0	3.2	4.2	4.1	4.0	6.7
Na2O	5.3	5.4	5.2	5.1	5.3	5.3	4.6
K2O	2.22	2.19	2.69	2.14	2.14	2.22	1.25
Total	100.25	99.88	99.56	100.08	98.96	99.65	100.28

Sample	1652	1653	1654	1655	1658	1659	1660
SiO2	56.3	56.5	64.1	53.4	52.0	63.3	51.5
TiO2	1.22	1.21	1.16	1.19	1.34	1.14	1.32
Al2O3	17.8	18.3	16.8	18.5	18.1	16.4	18.0
FeO*	7.3	7.3	5.8	8.1	8.1	5.4	8.4
MgO	4.1	4.3	1.4	6.6	7.2	1.8	7.4
CaO	6.8	6.8	3.5	8.3	8.8	4.1	8.9
Na2O	4.3	4.4	5.4	3.7	3.7	5.2	3.7
K2O	1.19	1.19	2.36	0.88	0.82	2.20	0.73
Total	99.01	100.00	100.52	100.67	100.06	99.54	99.95

Sample	1661	1668	1669	1670	1673	1678	1679
SiO2	51.2	72.5	72.4	62.7	74.5	63.6	62.5
TiO2	1.32	0.33	0.33	1.13	0.26	1.13	1.17
Al2O3	17.7	14.3	14.4	16.4	13.6	16.5	16.6
FeO*	8.5	1.8	1.8	5.4	1.7	5.4	6.0
MgO	7.7	0.7	0.7	1.8	0.7	1.7	1.8
CaO	8.6	1.7	1.7	4.1	1.5	4.1	4.2
Na2O	3.6	5.1	5.1	5.2	4.9	5.3	5.1
K2O	0.74	3.19	3.21	2.15	3.34	2.20	2.18
Total	99.36	99.62	99.64	98.88	100.50	99.93	99.55

Sample	1682	1686	1690	1694	1696	1698	1702
SiO2	62.8	73.7	64.5	51.4	51.2	56.9	64.4
TiO2	1.12	0.32	1.09	1.31	1.32	0.97	1.09
Al2O3	16.4	14.4	16.2	18.5	18.1	17.9	16.4
FeO*	5.4	1.8	5.3	8.6	9.1	6.9	5.4
MgO	1.7	0.7	1.4	7.6	7.9	5.5	1.6
CaO	4.3	1.6	3.7	8.6	8.6	7.4	3.7
Na2O	5.2	5.1	5.5	3.5	3.6	3.8	5.6
K2O	2.12	3.30	2.25	0.72	0.72	1.29	2.26
Total	99.04	100.92	99.94	100.23	100.54	100.66	100.45

Sample	1703	1704	1705	1706	1708	1709	1710
SiO2	63.6	52.0	63.5	63.6	56.0	56.4	63.5
TiO2	1.09	1.35	1.18	1.15	1.29	1.28	1.00
Al2O3	16.2	17.3	16.7	16.7	18.1	18.2	15.9
FeO*	5.4	9.0	5.8	5.5	7.5	7.8	5.6
MgO	1.6	7.6	1.8	1.8	4.4	4.1	2.3
CaO	3.7	9.0	4.1	4.1	7.0	6.7	4.4
Na2O	5.6	3.5	5.3	5.3	4.3	4.4	4.7
K2O	2.22	0.78	2.19	2.19	1.20	1.20	2.50
Total	99.41	100.53	100.57	100.34	99.79	100.08	99.90

Sample	1711	1712	1714	1715	1716	1718	1718b
SiO2	63.3	56.4	65.0	63.5	65.2	64.5	75.5
TiO2	1.15	1.27	1.00	1.15	0.90	1.03	0.10
Al2O3	16.6	17.3	15.8	16.1	16.2	16.0	13.6
FeO*	5.5	7.7	5.2	5.7	4.8	4.9	1.2
MgO	1.7	4.3	1.5	1.6	1.8	1.4	--
CaO	3.9	7.3	3.7	4.2	4.1	3.7	0.9
Na2O	5.3	4.4	5.1	5.2	4.9	5.4	4.8
K2O	2.19	1.09	2.49	2.20	2.49	2.48	3.53
Total	99.64	99.76	99.79	99.65	100.39	99.41	99.63

Sample	1719	1720	1721
SiO2	56.9	63.3	63.4
TiO2	1.37	0.86	0.95
Al2O3	17.5	16.5	16.0
FeO*	7.7	5.0	5.3
MgO	4.0	2.1	2.2
CaO	7.1	4.2	4.5
Na2O	4.6	5.3	5.4
K2O	1.20	2.27	2.11
Total	100.37	99.53	99.86