LAVA CAVES

(92)

9 - UPPER McKENZIE PITS
9 - SANTIAM PIT
12 - SAND MT. CHIMNEYS
20 - LITTLE BELKNAP
25 SIMS BUTTE
31 - YAPOAH CRATER

RECENT VULCANISM BETWEEN THREE FINGERED JACK AND NORTH SISTER, OREGON CASCADE RANGE

By

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To the Resident Instructional Staff:

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INTRODUCTION

On the crest of the Cascade Range of Oregon between the Pleistocene volcanoes known as Three Fingered Jack and North Sister, an impressive array of cinder cones stands in the midst of Recent basaltic lava fields whose total area exceeds 85 square miles. Howel Williams (1944) has written that this region "offers the traveler unobstructed views of one of the most imposing sheets of recent lava in the United States." It is possible to see nearly all of these interesting features during a single circuit of the McKenzie Pass (242), Clear Lake (126), and Santiam Pass (20) Highways. Location of highways and distribution of principal cones and flows are presented in Fig. 1.

The purpose of this report is twofold:

1. To outline chemical variations within and between the Recent lavas and to examine the relationships between these variations and the eruptive history, mineralogy, and geographic position of the flows.
2. To synthesize these relationships and to draw conclusions from them regarding the pre-eruptive history of the lavas.

Although each major lava field is closely approached by a highway, several flows and many cones, vents, and other volcanic features have not been described. The best published works are reconnaissance studies by Williams (1944, 1957).

This report summarizes results of an extensive survey in which the Recent lavas and cones were mapped and sampled. Three summer seasons, from 1961 to 1963, were spent in the study area. In the field, geological features were located on stereo-pairs of aerial photographs of 1:50,000 and 1:12,000 scale (series VRI, U.S. Geological Survey, 1957, and series EGI, U.S. Forest Service, 1959), then transferred to U.S. Geological Survey advance topographic

Recent Lava Flows And Cinder Cones
Between Three Fingered Jack And North Sister

Oregon Cascade Range

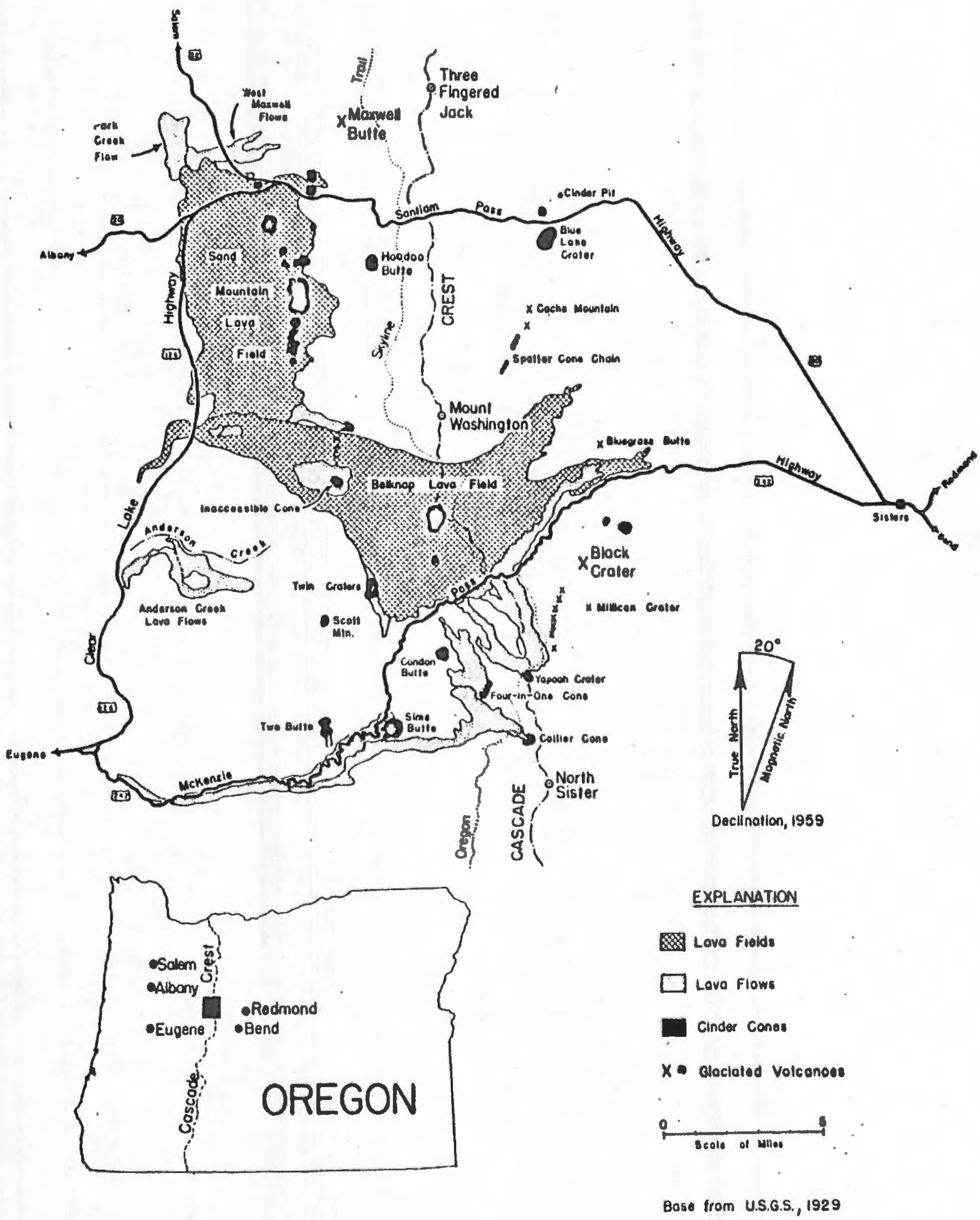

Fig. 1.--Index Map

prints of 1:24,000 scale. So many distinctive land forms appear on the photographs and on the topographic prints that locations of geological features can be transferred precisely from one to the other by inspection.

North and south geographic limits of the study area were placed along straight east-west lines through Three Fingered Jack and North Sister, respectively; east and west boundaries were drawn coincident with the east and west borders of the High Cascades as outlined by Williams (1957). The temporal range of geologic events extends from the end of the last major glacial episode to the present. It is believed that all exposed eruptive units, so defined, are included in this report.

An attempt was made in the field to unravel the eruptive history of the lava flows and lava fields with the aid of surficial flow features, stratigraphic relationships, and radiocarbon dates. Patterns of lava levees, lava gutters, and pressure ridges were determined from aerial photographs and were used to outline directions of flow within complex lava fields. Direction of flow was assumed to be parallel to the lava levees and gutters, transverse to arcuate pressure ridges, and downslope. Stratigraphic superposition of lava units was observed in the field and was often confirmed by laborious excavation of lava margins. While charcoal was found to be common in soil beneath the lava flows, only charcoal which was clearly formed from wood by hot lava or cinders was submitted for radiocarbon analysis.

HISTORY OF VOLCANIC ACTIVITY

Interpretation of the history of Recent volcanic activity between Three Fingered Jack and North Sister is based upon radiocarbon age determinations and field evidence in the form of physiographic relationships, glacial records, flow features, and stratigraphic superposition. Petrographic and chemical characteristics of the rocks are omitted in this section for two reasons:

1. Significant lithologic variations are difficult to recognize in the field. With few exceptions, the lavas are monotonously uniform, black glassy basalts containing phenocrysts of plagioclase and olivine.

2. Interpretation of eruptive history should not be strongly influenced by lithologic features of the lavas if valid unbiased correlations are to be recognized between history and lithology.

Descriptions of the eruptive units are presented here in convenient geographic subdivisions, arranged in general west-to-east sequence.

Sand Mountain Lava Field and Associated Cones

Within the High Cascades there are many volcanic mountains arranged in nearly perfect linear or arcuate patterns (Williams, 1957). Few such patterns are as easily recognized as the north-south chain of 22 cinder cones referred to here as the Sand Mountain Alignment (Fig. 2). Inspection of Fig. 2 shows that the alignment diverges northward into two distinct branches. While caution must be exercised in tracing vent patterns over long distances, the areal distribution of cones, as displayed in Fig. 1, suggests that two linear trends intersect beneath Sand Mountain. One may extend through Nash and Little Nash Craters to Inaccessible Cone and Twin Craters. The other trend may be

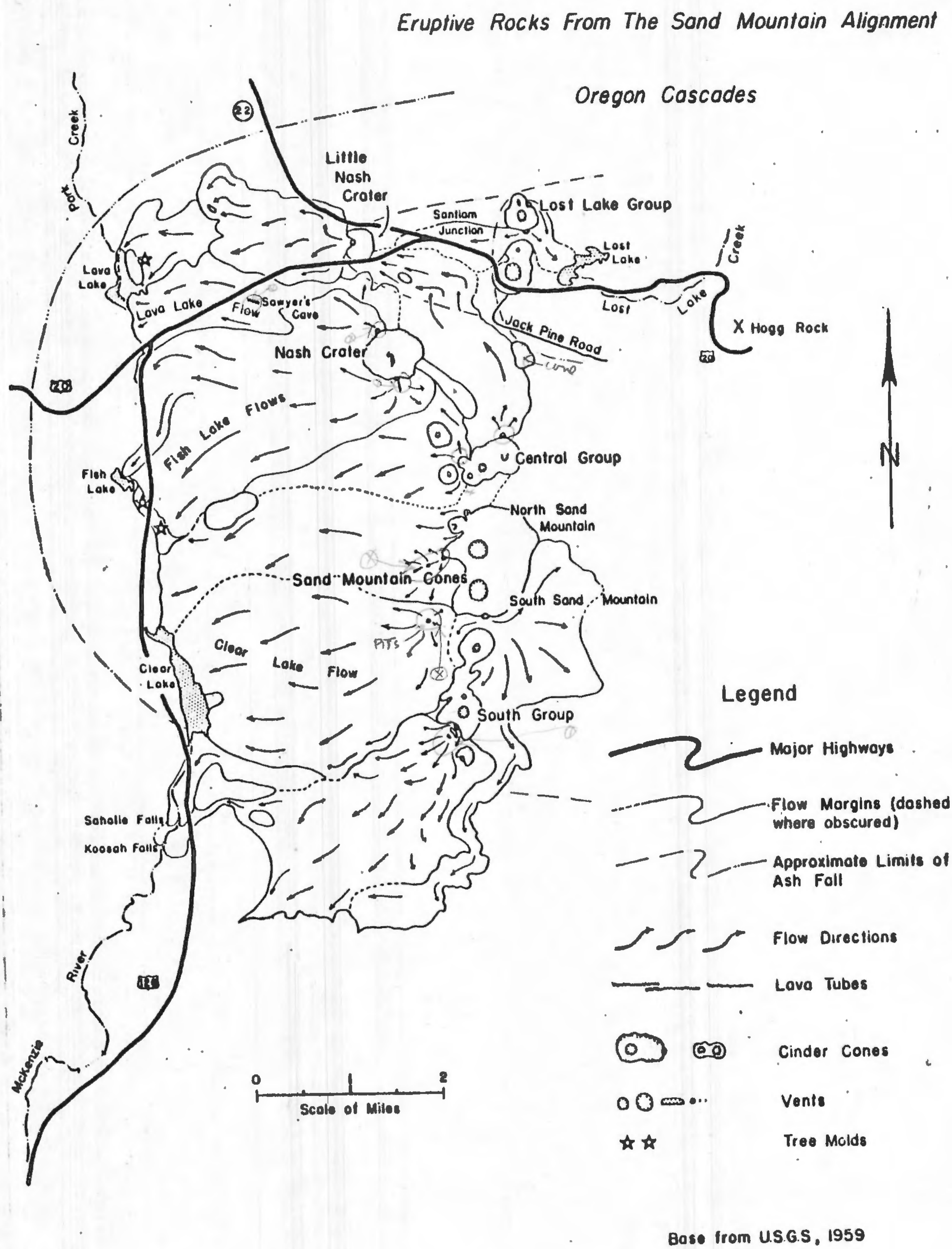

Fig. 2.--Geologic Map of the Sand Mountain Lava Field

represented by cones near Lost Lake, by cones south of Sand Mountain, and by the source vent of the Anderson Creek lava flow.

The numerous and closely spaced eruptive centers of the Sand Mountain Alignment discharged about three-fourths of a cubic mile of basalt (as calculated from topographic maps and estimates of pre-eruptive topography) and a large but unknown volume of basaltic ash. The result was an intricate accumulation of overlapping cones, flows, and sheets of ejecta, whose volcanic history is set forth below. Principal land forms are described in the following order: Little Nash Crater and Lost Lake Group to the north, Nash Crater and the Central Group farther south, Sand Mountain Cones, and the South Group (Fig. 2).

Little Nash Crater

Little Nash Crater is a basaltic cinder cone, located three-fourths of a mile west of Santiam Junction. The cone stands 450 feet above its immediate surroundings at the west end of the broad U-shaped valley occupied by Lost Lake Creek. Northeast of the cone, on the shoulder of the valley, a lateral moraine may be traced two miles to the west. A small end moraine at the northwest base of Little Nash Crater is topographically connected to the lateral moraine and is overlain by lava from the cone. Consequently, Little Nash Crater and lavas are assigned to the Recent. This is confirmed by the fact that ash from Little Nash Crater overlies lava from the Lost Lake Group, dated by radiocarbon methods as 1950 years B.P. (p. 40).

A highway cut northwest of the cone exposes weathered till of the end moraine. The till is overlain by a one-foot layer of fine black ash which, when traced southward, becomes thicker, coarser, and merges gradually into deposits of cinders from Nash Crater. Resting upon the ash layer is a four-foot bed of angular rock fragments up to one foot in diameter. The fragments are composed of the same light gray basalt and andesitic basalt which is found in the underlying till and as glaciated bedrock throughout this part of the Cascade Range (Walker, Greene, and Pattee, 1966). The layer of fragments has been recognized south, west, and north of the cone; it thins rapidly with distance and cannot be found more than one-quarter of a mile away. It is inferred that the first eruptions from the Little Nash vent were phreatic, resulting in the violent disruption of surficial till. A thick deposit of coarse cinders overlies the fragment layer and grades eastward from the cone to a thin blanket of fine ash which covers the entire Santiam Junction area.

Late in its history, the cone was breached on the west by a lava flow which extends westward for one and one-half miles, resting upon cinders from its parent cone, and upon lava from the Central Group, Nash Crater, and West Maxwell vents (to be described). The cone has been artificially quarried, exposing a complex internal structure. Persistent, inwardly dipping surfaces of uncomformity separate peripheral areas of normal, outwardly dipping cinder layers from a large central area in which stratification is crude or lacking. This suggests that the process of cone building was interrupted briefly by explosions or subsidence; in either event, the crater rim must have been alternately destroyed and then restored.

The oldest volcano exposed on the Sand Mountain Alignment probably is a small, 150-foot cinder cone located one-half of a mile southeast of Little Nash Crater. Erosion has destroyed all traces of a summit pit, and the lower forested slopes are covered by fine black ash, similar to that found beneath Little Nash cinders. The cone stands in the same glacial valley as Little Nash Crater but is too symmetrical to have been glaciated. Consequently, it is regarded as Recent, but older than the fine black ash. Another eroded cinder cone, approximately 400 feet high, lies one mile southwest of Lost Lake and has retained only a vestige of its crater rim. Any lava which might have issued from these cones is now lost to view beneath younger flows from later vents.

Lost Lake Group

A short alignment of four cinder cones forms a great ridge across the glaciated valley of Lost Lake Creek, two miles east of Santiam Junction. The name "Lost Lake Group" is taken from the lava-dammed lake nearby. The smallest cone rests upon the north valley wall, 700 feet above the lake. On the south, it overlaps the rim of a lower, but much larger cone. Consequently, both cones share a common rim which separates an elongate, shallow crater on the north from a circular, deep crater on the south. A low saddle lies between the large north cone and a centrally located third cone on which there remains only an indistinct crater. The rim of the southernmost cone rises 320 feet above the adjacent Santiam Highway and surrounds a deep crater whose floor extends to highway level.

A steeply-inclined lava flow extends from the east base of the north cone to Lost Lake, as does a much larger flow from the saddle. Irregular slabs of jagged crust can be seen protruding through a thick overburden of ash along the west shore of Lost Lake. Lava from the saddle also moved west as far as Santiam Junction, where it is deeply buried beneath ash from Little Nash Crater.

Ejecta from the Lost Lake Group is restricted on the west to the immediate vicinity of the cones. In bogs on the summit of Hogg Rock, two miles east of the Lost Lake Group, deeply weathered basaltic ash, attributed to earlier eruptions of the Sand Mountain Alignment, is overlain by a layer of fine, unweathered ash which can be traced to the Lost Lake cones. In a cut of the Jack Pine Road, about 300 yards south of its junction with the Santiam Highway, a sharp interface between underlying glacial drift and an overburden

where is Jack Pine Rd.

of coarse cinders is exposed. These cinders can be traced directly to the south cone of the Lost Lake Group. Fragments of charred limbs are abundant at the interface, and have been assigned a radiocarbon age of 1950 ± 150 years B.P. (W.S.U. 371).

Nash Crater

Nash Crater is a large cinder cone which stands upon a broad lateral moraine, one mile south of Santiam Junction. The summit contains a north-south trench-like crater 1,000 feet long with a smaller circular crater set in its west rim. A narrow ridge of six spatter cones extends from the south base of Nash Crater and each cone marks the position of a vertical conduit. The conduits are 5 to 30 feet in diameter and 30 to 40 feet in depth. They lead to a lava tube which has collapsed at the south end of the ridge. Lava from this vent area moved three miles west, where it forms the east-central shore of Fish Lake.

At the northwest base of Nash Crater is a broad depression rimmed with spatter. Approximately 100 feet farther northwest, a five-foot spatter cone surrounds a vertical conduit which is 20 feet deep. Lava gutters and inclination of the lava surface indicate that this area is the source of an extensive flow which spread westward for 2-1/2 miles, then turned south to the north shore of Fish Lake. The pattern of lava levees and gutters indicates that this lava was deflected by the margin of earlier flows from the south vent of Nash Crater. Both flow units are here given the unofficial name, Fish Lake Flows. They overlie ash from other vents on the alignment, late flows from the Central Group, and lava from the west vent of North Sand Mountain; they are overlain near their source by a thin deposit of ash from the Nash Crater summit.

The Fish Lake Flows are underlain along their north margin by an older unit which may be traced to the northeast base of Nash Crater and was probably associated with early eruptions of that volcano. This older flow moved west to the southeast shore of Lava Lake and is given the unofficial name, Lava Lake Flow. Sawyer's Cave, adjacent to the South Santiam Highway, is a lava tube within the Lava Lake Flow which is remarkable for its floor of delicate, ropy crust.

Fish Lake was dammed by a flow which is overlain by the Fish Lake Flows and which is exposed at the southeast shore of the lake. This lava can be traced along a stream channel for three-quarters of a mile to the southeast where the flow is 20 feet thick, and stream erosion has exposed a dense interior with widely spaced, irregular cooling joints. The source area of this flow is unknown, but its smooth, level, and ropy surface resembles only that of the early Central Group lavas (to be described). Horizontal tree molds are common at the base of the flow. A charred root was excavated from baked soil at the bottom of a large vertical mold, one-half of a mile southeast of Fish Lake. This material has been assigned a radiocarbon age of 3850 ± 215 years B.P. (W.S.U. - 372). Because of its unknown source, this unit will be referred to as the "flow southeast of Fish Lake."

The Central Group

The Central Group is a tight cluster of five cinder cones, three of which overlap to form an east-west volcanic ridge, one-half of a mile long and 200 feet high. The west end of the ridge contains a small circular crater, but the east end has been breached at its northern base by a great outpouring of lava. The central part of the ridge is occupied by two craters, one nested within the other. In the lava field a short distance west and northwest stand two 100-foot cones with well-preserved craters. Two additional cones occur at the northwest base of North Sand Mountain. One is 200 feet high and breached on the west; the other is only 50 feet high but contains a small summit crater.

Lava from the Central Group spread widely to the west, northwest, and north, but much of it is now covered by younger flows from Nash and Little Nash Craters. The most extensive flow breached the east cone of the Central Group ridge, poured north onto the floor of a broad, glaciated valley, and moved over the region now occupied by Santiam Junction. Throughout its length the flow displays a smooth ropy crust, quite unlike other lavas of the Sand Mountain Alignment. Several long, isolated ridges and gutters are seen in these lavas just south of the junction, where they trend westward and pass beneath a flow from Little Nash Crater. The ridges often are capped by lava crust, and their sides have been vertically striated by the foundering of adjacent blocks. These features are evidence that the Santiam Junction area was at one time a lake of lava, which formed behind an obstruction (an end moraine?) near Little Nash Crater, and which drained out to the west, probably from beneath a congealed crust. It might have reached the present site of Lava Lake, where schollendomes, tree molds, and ropy surfaces are common features along the margin of a lava flow whose source is concealed.

Additional lava issued from the west base of the Central Group ridge, undermining a small satellite cone. This lava overlies a westward extension of the east vent flows and may be much younger. Along its south margin it is in contact with an undifferentiated assemblage of lavas from the south base of the Central Group ridge and from vents west of North Sand Mountain; it is overlain by Fish Lake Flows along its north margin.

Sand Mountain Cones

Sand Mountain Cones are the two largest volcanoes on the Sand Mountain Alignment. They stand 750 feet above their surroundings and are the focal point of a deposit of basaltic ash which blankets an area of more than 100 square miles to the east and northeast. The highest points on the rims of the north and south craters lie to the northeast and rise 390 and 660 feet above their crater floors, respectively. Five miles west of the cones, fine basaltic ash is exposed in road cuts, and along the west margins of the lava field ash has been excavated from beneath the oldest flows. Even the most recent flows adjacent to the cones are thinly ash-covered. The longevity and size of these cones is probably related to their position. The point of intersection of the two distinct branches of the Sand Mountain Alignment lies beneath Sand Mountain Cones.

A large volume of blocky basalt was discharged from the base of the North Sand Mountain Cone, building a broad ridge which extends 2,000 feet to the west. A collapsed lava tube descends the western extremity of the ridge and the ridge summit is capped by a lava gutter whose walls are breached at frequent intervals. This flow moved far to the west, and may be seen on the north shore of Clear Lake. The southern contact is traced easily against the younger Clear Lake Flow (to be described), but the northern contact with Central Group lavas is obscured by ash deposits.

The extensive flow which forms the east shore of Clear Lake is referred to unofficially as the Clear Lake Flow. Lava gutters, pressure ridges, and topography of the lava field indicate that it was fed from a vent located one-half of a mile southwest of Sand Mountain Cones. Here, a circular pit, 20 feet deep and 50 feet in diameter, displays several flows in its walls and represents a collapse depression over the lava source. A smaller pit, 200 feet to the east, separates the collapse depression from an east-west spatter ridge 600 feet long. The west end of the ridge contains a shallow crater 30 feet in diameter. On the summit of the ridge are two vertical pipes, 3 and 6 feet in diameter, which are at least 40 feet deep. The south flank of South Sand Mountain is interrupted by a broad furrow which, at its base, leads to an

SAND MT. CHIMNEYS

indistinct vent and a lava gutter. Lava from this vent moved chiefly eastward and then four miles to the south, where it now lies buried beneath younger flows from Belknap Crater (Fig. 3). Proximity of the vents and similarity of blocky crusts suggest that eruption of the Clear Lake Flow and the flow from the south base of South Sand Mountain probably occurred at about the same time, but their common boundaries are obscured by ash deposits and relative age is therefore unknown.

South Group

The South Group is composed of four cinder cones arranged in a single linear trend, 1-1/2 miles long. The northernmost cinder cone of the South Group is 1,000 feet south of South Sand Mountain, is 300 feet high, and contains a circular crater 120 feet deep. Next south is a smaller cone which was built just north of an elongate northeast-trending ridge of spatter and bombs. Lava issued from the west base of this cone but has been largely buried by younger flows. The main cone of the South Group stands south of the spatter ridge and is 400 feet high. A deep summit crater is attended by a smaller counterpart on the north flank of the cone, and by a great bocca near the southwest base. Lava from the bocca spread toward the south, surrounding a small breached cone which is the southernmost cone on the alignment. This lava also spread to the southwest, where it is overlain by flows from Belknap Crater (Fig. 3), and westward to the McKenzie River, where it formed Koosah and Sahalie Falls. The Clear Lake outlet, which is the head of the McKenzie River, flows over a northwest extension of this lava. The Clear Lake flow and the flow from the south base of South Sand Mountain overlie the South Group lavas.

Several geologists (Stearns, 1928; Brown, 1941; Williams, 1957), have drawn attention to ancient trees which stand upright, bare of limbs, beneath

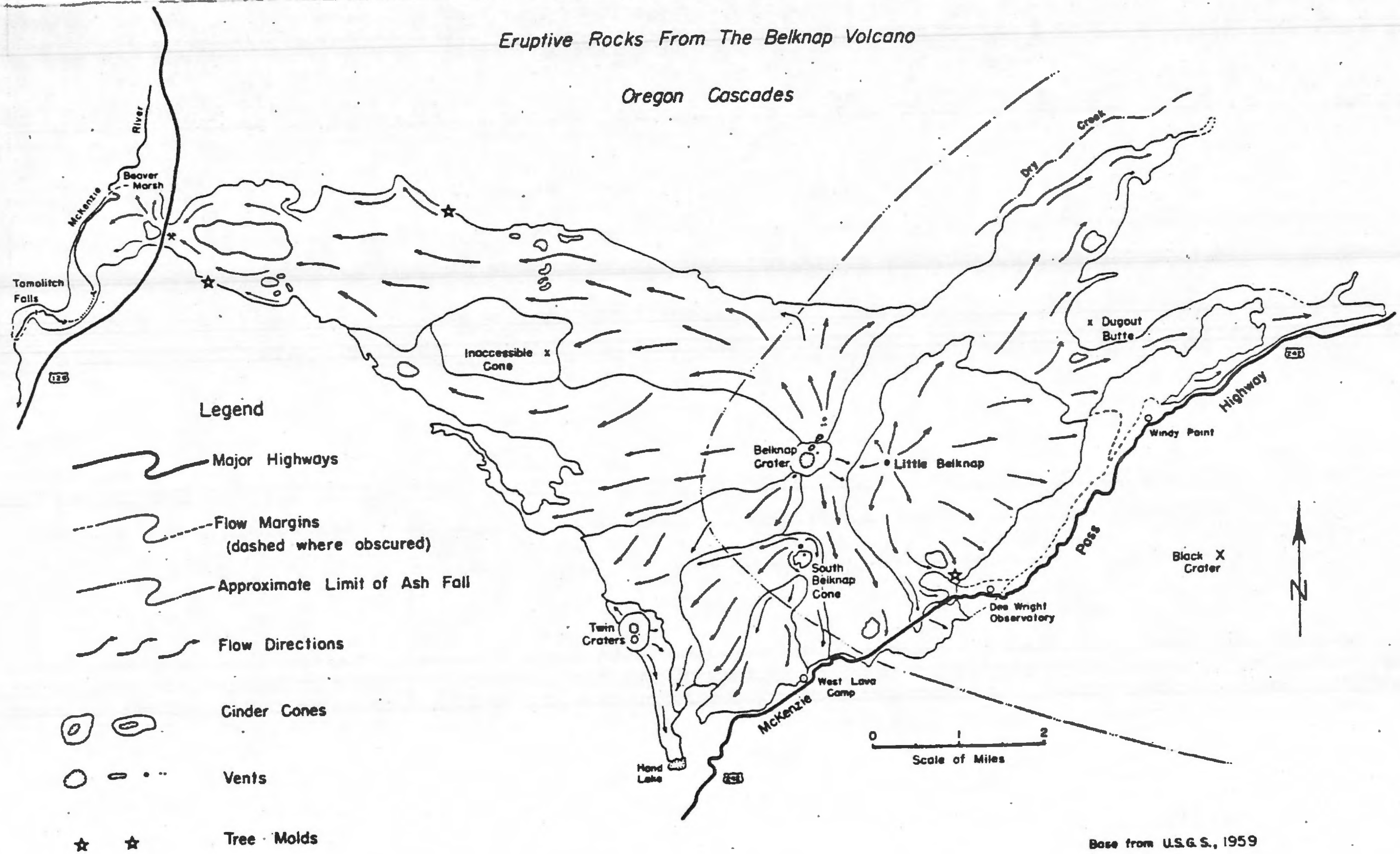

Fig. 3.--Geologic Map of the Belknap Volcano and Vicinity

the surface of Clear Lake, and have called upon a rapid rise of water behind a dam of lava to account for the inundation and preservation of a pre-existing forest. Benson (1965) reported a carbon-14 age of 3,000 years for one of these submerged trees and concluded that this must be the age of the lava which formed the dam. The lava must be much older, however, than the trees. More than a dozen submerged tree trunks, identical to others of the ancient forest, are so firmly rooted on the lava of the east shore and on the older lava of the "dam," that with a nylon rope and a shore-based winch, they can be broken off near water level. Some of these trees stand in 30 feet of water and retain an estimated 150 to 200 growth rings in sound wood. Numerous stumps can be seen at even greater depth, but it has not been demonstrated that their roots penetrate lava. Obviously, a long interval separated the emplacement of the lakeshore lava and the formation of the lake. The age of the drowned forest therefore can represent only a minimum age of the lava.

In summary, attention should be directed to the similar histories displayed by Nash Crater, the Central Group vents, and Sand Mountain Cones. At each of these eruptive centers, the major episode of cone building preceded or accompanied the appearance of early lavas. Later lavas appeared after the cones had attained their present stature, and further ejecta served only to reshape the rims and deposit a relatively thin layer of ash in the immediate surroundings.

Inaccessible Alignment

Three and one-half miles southwest of Mount Washington, a short north-south alignment of four cinder cones has been nearly buried by Belknap flows (Fig. 1). The southernmost and largest cone, unofficially named Inaccessible Cone, is 300 feet high, lies five miles from the nearest road, and is surrounded by a wide barrier of jagged lava. The cone contains a well-preserved crater and is encircled by flows which issued from numerous boccas at its base. The Belknap flows partly obscure three smaller cones which lie one mile to the north. An unnamed cone, offset near the north end of the Inaccessible Alignment, is 300 feet high and has been breached on the west and southwest by a flow of gray basalt, charged with bombs. The flow has been traced westward beneath the Sand Mountain and Belknap lava fields, and thus is older than both of them. It is probable that additional vents and a small field of lava associated with the alignment have also been covered by the younger lavas.

Twin Craters

Twin Craters is a cinder cone located at the margin of the Belknap lava field, three miles southwest of the Belknap summit (Fig. 3). The cone is 300 feet high and the north and south craters are about 200 feet deep. A small pit, 30 feet in diameter, is set into the east rim of the north crater. Fine scoria and ash accumulated in stratified deposits on the north crater rim. The south crater emitted clots of spatter which, as they fell upon the rim, split apart and disgorged tiny streams of lava. Scoria and bombs litter the glaciated landscape to the west. North of the cone, several mounds of red cinders are imperfectly exposed along the margin of Belknap lava; whether they represent separate cones or scoria-covered flow ridges is not known. Boccas exist at the north, east, and south base of the Twin Craters cone, but most of them are clustered upon the north and south flanks. The lava must have been very fluid, for some flows are only three feet thick near the vents and their upper surface is coated with minute, glassy spines. One of these flows poured south 1-1/2 miles through a narrow gap into Lake Valley where it now forms the north shore of Hand Lake. An extensive lava field may have spread into the broad glaciated valley which then existed to the north; if so, it is deeply buried beneath the Belknap volcano.

Hoodoo Butte

Hoodoo Butte is an isolated cinder cone which rises 500 feet above the eastern edge of a glaciated platform, midway between Sand Mountain Cones and Santiam Pass (Fig. 1). A small summit crater is open to the east, but it could not have been breached by lava because none has been found in association with this cone. Instead, the incomplete appearance of the crater rim is evidently a result of the very irregular topography on which the cone was built; a broad fan of cinder-talus extends from the base of the open crater to the valley below, and it appears that much of the ejecta simply fell over the east edge of the platform. Although Hoodoo Butte stood in the path of fallout from Sand Mountain Cones, most of this ash has been washed onto the surrounding lowlands. A thick stratified deposit of fine ash rests upon the coarse cinders of the crater floor.

Belknap Lava Field and Associated Cones

Of the volcanic centers discussed in this report, none poured forth a greater volume of basalt than the shield volcano which is surmounted by Belknap Crater, Little Belknap, and related vents (Fig. 3). The volume of all Belknap rocks, calculated from contour maps of the lava surface, is approximately one and one-third cubic miles. This must be regarded as a rough estimate because accurate reconstruction of the surface on which the volcano rests is precluded by the great thickness and widespread distribution of lava.

The surface of most of the mountain is covered by ropy, pahoehoe-like lavas which issued from vents marginal to a composite summit cone. The lavas eventually inundated an area of more than 37 square miles. They did not move in long, continuous streams. Instead, short channels branched and crossed one another, resulting in thin lobes with complex drainage patterns. To an observer on the ground, these lava fields are a confusing wilderness of craggy basalt. On aerial photographs, however, the lava channels can be traced to their sources and the surface of the shield can be subdivided into distinct eruptive units. In this way, the flow directions and contacts of Fig. 3 were mapped and subjected to additional field study. The following account of eruptive history is based upon areal distribution of units as interpreted from photographs and sequence of superposition as observed in the field.

The oldest exposed lavas of the Belknap shield occur on its eastern flanks. They were erupted from vents now poorly defined, which may have been buried subsequently as the summit cone reached final development. These lavas moved principally northeastward, diverging into two lobes on either side of a ridge called Dugout Butte. Both lobes descended 2,250 feet, from source to terminus. Another flow whose source vents were obscured by later growth of the summit cone covers the west-central sector of the volcano.

One mile south of the Belknap summit is a small adventive volcano referred to unofficially as the South Belknap Cone. Nearly all cinder cones which have been included in this study are associated with deposits of cinders and ash which extend beyond the immediate vicinity of the cones. If the South Belknap Cone was built after eruption of the lava just described, cinders would cover that lava near the east base of the cone. In fact, none are to be seen. This suggests that South Belknap Cone is one of the oldest exposed features on the Belknap shield.

NO TEPHRA

South Belknap Cone was breached by a flow which spread two miles to the south. Ropy surfaces and lava squeeze-ups between large rafted platforms of broken crust are common in this flow and can be seen adjacent to the McKenzie Pass Highway from West Lava Camp to a point one mile southwest. A broad alluvial fill has been deposited against the southeast flow margin. The stream channel down which the alluvium was carried can be traced to the modern position of Collier Glacier (p. 29). The channel shows abundant evidence of meltwater flooding but is now dry because it was blocked by Collier Cone and by lava from Four-in-One Cone. This blocking and the consequent cessation of alluvial deposition took place 2550 years B.P. and provides a minimum age for the lavas which breached South Belknap Cone. Subsequent lava flows emerged from a vent 300 feet northwest of South Belknap Cone. They completely surrounded the cone and moved in a double stream two miles south and southwest, covering the east and west margins of the earlier flow from the South Belknap breach.

The summit cone of the Belknap volcano rises 400 feet above its basal shield. Two craters at the top of the cone emitted ashes and coarse cinders, which accumulated as high mounds of stratified lapilli-tuff on the east rims. In the walls of the southern crater, which is about 250 feet deep and over 1,000 feet wide at the rim, thick lava flows are exposed. Some lava poured over the southwest rim and is now partly obscured by spatter. Well-formed spindle bombs, up to three feet in length, are common along the west rim of the north crater.

The distribution of ash and cinders on the rim of Belknap Crater, as described above, was caused by strong and prevailing wind transport to the east. Thin deposits of scoria are found on lava immediately west of the cone, but as the eastern slopes are approached the lavas become mantled in black ash and fine cinders. A wide area from Dry Creek on the north to Black Crater on the south was heavily blanketed and a continuous ash deposit can be traced eight miles to the east.

The next addition to the Belknap volcano took the form of quiet discharge of lava from a vent called Little Belknap, one mile east of the summit craters. So much lava issued from this one point that a subsidiary shield was formed. It is surmounted by a small but chaotic heap of cinders and blocks from which collapsed lava tubes diverge radially. One of the western tubes can be followed to its confluence with a vertical conduit which is approximately 20 feet in diameter. Lava from Little Belknap spread east to within one mile of Windy Point and southeast to the present site of Dee Wright Observatory. It rests upon the ash from Belknap Crater and is overlain by younger flows from Yapoah Cone. A tree mold was discovered in the Little Belknap lava margin adjacent to the Skyline Trail, one-quarter of a mile northwest of McKenzie Pass Highway. A charred root at the base of the mold has been given a radiocarbon age of 2880 ± 175 years B.P. (W.S.U. 364).

A peculiar and general feature of the Little Belknap lava surface is referred to here as a lava curl. It is best seen along the Skyline Trail one-half of a mile northwest of the McKenzie Pass Highway, where the lava stream diverged after passing between two prominent steptoes. As it cooled, the contracting surface warped upward to lift part of the crust, together with its still-plastic substratum, and peel it back upon itself. Thick overturned slabs can be found which are up to 10 feet wide and 50 feet long, usually parallel to the direction of flow. Except for distortion due to contraction and fragmentation, each slab matches perfectly the adjacent counterpart surface from which it was pulled. Lava curls are often valuable depositories of stratigraphic information. The blocky and sub-pahoehoe character of flow tops on Recent Cascade lavas is quite porous, preventing light ash falls from accumulating on the surface. The V-shaped cleft, formed where a slab curls away from its base, can trap such material and preserve it in proper sequence.

During a late stage in the development of the Belknap summit cone, vast quantities of lava issued from boccas on the south and north. A deep and narrow lava gutter leads to the south bocca but the actual vent is obscured by fresh-looking, iridescent cinders. Lava from this source moved three miles to the southwest, and poured across older lava from Twin Craters. The most extensive flows reached the surface through many vents at the north base of the summit cone. A broad pit, 200 feet long, was blasted through the side of the cone just above these vents, and the resulting shower of cinders and ashes largely obscures them. However, two small spatter cones can be discerned about 1,000 feet to the north. Lava from the north vents turned westward at the north base of the shield and overran lava and cinder cones of the Inaccessible Alignment. Farther west, the Belknap lava poured over flows from the south vent of South Sand Mountain and from the South Group, before finally plunging in a steep cascade into the canyon of the McKenzie River.

The McKenzie River was altered profoundly by the lava which spread across its path. A broad, swampy area known as Beaver Marsh formed upstream from the point where the river now flows onto the Belknap rocks. Where it once flowed freely through its open canyon, the river is now gradually absorbed into the buried talus along the canyon margins and into permeable zones between lava units, reappearing at Tamolitch Falls. Downstream from the falls, the flow has been reduced by erosion to a lateral terrace, perched on the west canyon wall 30 feet above the level of the river.

Tree molds were formed along the margins of the west Belknap flows. They are displayed best at the westernmost locality shown in Fig. 3. Here, several dozen molds range from one to five feet in diameter and from six to fifteen feet in depth. Most of them are vertical and widen downward. Hemi-cylindrical trenches up to 35 feet long occur where trees fell onto the pasty lava. In most areas tree molds are rare because lava must be sufficiently fluid to conform to the shape of a tree, yet must not flow or be deformed after the tree has been consumed. In the present instance, the Belknap flow spilled into a protected recession in a steep, north-facing slope which presumably was, at the time of the eruption, as moist and deeply forested as it is today. The level surface of the resulting pond is an indication of the fluidity of the lava at the time of its isolation from the active stream. A radial system of large roots which had been deeply charred was excavated from the buried soil at the base of one of these molds. Radiocarbon analysis was performed twice and the results were: 1590 ± 160 years B.P. (W.S.U. 292) and 1400 ± 100 years B.P. (W.S.U. 370). These values are within reasonable limits of analytical error.

The Belknap volcano, while different from the cones of the Sand Mountain Alignment in many important respects, shares their prolonged development over an essentially equivalent span of time. In both instances, an observer would have witnessed the accumulation of a vast pile of lava accompanied by violent eruption of ash and the building of large summit cones. After a period of quiescence (whose duration can not yet be accurately specified), he would contrast this with nearly equal volumes of lava discharged, without notable explosive action, from vents marginal to, or at some distance from, the summit cone.

Blue Lake Crater

Blue Lake can be seen from the Santiam Pass Highway, three and one-half miles east of the Cascade crest (Fig. 1). It is 0.5 miles long and 0.2 miles wide, and is set in a deep pit formed by Recent volcanic explosions of great violence. The Blue Lake eruptions resulted in at least three overlapping craters which are aligned approximately N. 25° E., and which fall within a geographic trend common to Belknap Crater and the Spatter Cone Chain to the south and the Cinder Pit (to be described) to the north. The first (and only?) published suggestion that Blue Lake might occupy a volcanic crater appeared in

1903 (Langille et al.).

The southern one-half of Blue Lake is rimmed by a crescentic ridge which, in places, stands 300 feet above the water and 150 feet above the adjacent topography. The outer slopes are covered with basaltic cinders, black bombs (some of which are six feet long), and accidental fragments of older, gray holocrystalline lavas. Inner slopes of the rim generally lead to cliffs which disappear into the water. Above lake level, the southern crater walls are composed of crudely stratified cinders and bombs with intermixed bedrock blocks. No Recent lava flows have been recognized in the Blue Lake area. If one may compare Blue Lake Crater to other Cascade craters of similar diameter (the Belknap craters, for example), the lake is probably in excess of 300 feet deep.

Some of the lakeshore cliffs might have been formed by the collapse of crater walls, but no prominent dislocations of a concentric type have been found. The north crater wall, precipitous, angular and now largely submerged, was blasted through pre-existing bedrock, fragments of which are found scattered over the nearby landscape. Consequently, it appears that Blue Lake Crater was the result of upward explosions rather than interior subsidence.

Bombs and blocks were ejected in all directions from the crater, but most of the fine scoria and ash is found to the east and southeast. A typical section taken through these deposits contains, at its base, weathered till overlain by two to three feet of fine basaltic ash. The ash is attributed to eruptions of the Sand Mountain Alignment because it can be traced discontinuously westward into the surfical mantle of ash from Sand Mountain. Capping the black ash is an accumulation of scoria, four to twelve feet in thickness, which can be traced directly to Blue Lake. Charred wood from the limb of a conifer has been excavated from the sharp interface between scoria and ash.

The radiocarbon age of this material is 3440 ± 250 years B.P. (W.S.U. 291). The eruption of Blue Lake Crater commenced, therefore, at about 1500 B.C. This date, when applied to the deposits of fine black ash, is additional evidence that the Clear Lake drowned forest (1000 B.C.) does not indicate the true age of Sand Mountain eruptions.

Spatter Cone Chain

A chain of basaltic spatter cones trends N. 23° E. for one mile between Blue Lake Crater and Mount Washington (Fig. 1). The cones are restricted to north and south segments, and the midsection of the chain is occupied by several trench-like depressions which outline a strong subsurface continuity. The northernmost vent is a circular crater, 10 feet deep, which appears to have been formed by collapse or sudden explosion, because no primary ejecta are found within or near it. About 200 feet south is the first of four spatter cones, with craters 30 to 40 feet deep, which surmount a narrow ridge of red spatter and scoria. Still farther south, a series of discontinuous trenches, averaging 10 feet in width and one foot in depth, leads to a southern line of vents. Deposits of scoria and bombs occur intermittently along the trenches. There are seven southern vents: three small craters to the north are separated by a short trench from three large craters located on a spatter ridge to the south. The central crater on this ridge contains a small crater in its north rim. A shallow trench extends about 150 feet south from the ridge.

Sims and Condon Buttes

The western one-third of McKenzie Pass Highway follows a Recent basalt flow, nine and one-half miles from source to terminus. The source cone is Sims Butte, located six and one-half miles south of the Belknap volcano (Fig. 1). The cone is 650 feet high and is broadly indented on the west side by a shallow crater, located 400 feet below the summit. Ejecta are coarse and are confined largely about the vent within a circular area of one mile radius. The limited extent and symmetrical distribution of ejecta suggest that the asymmetry of the cone is a result of lava breaching rather than prevailing wind direction.

Short flows emerged from the north base of the cone, but most of the lava issued from a west bocca, 200 feet below the shallow crater. Collapsed lava tubes can be traced downstream from this bocca for several hundred yards. At one point, where the flows are steeply inclined, a 70-foot lava tube descends beneath the crust. Two "skylights" penetrate the thin roof and collapse depressions define an inaccessible western continuation of the tube.

The extensive lava flows from Sims Butte spread onto a topographic shelf west of the cone, then poured into a deep glaciated canyon which extends west to the McKenzie River. They covered the floor of the canyon and moved westward to within one and one-half miles of the junction of Highways 126 and 242. White Branch, Obsidian, Linton, and Proxy Creeks (tributaries to the glaciated canyon) all disappear beneath this blanket of lava before reappearing in a series of large springs four miles from the highway junction. It has not been possible to trace single flow units from Sims Butte for long distances because of the overlying Collier lavas, because of the heavy forest cover, and because the Sims lava advanced as thin, overlapping sheets of limited extent. Lava tongues, only one foot thick, cover several acres along some parts of the flow margins. The best cross-sectional exposures of Sims lava are seen on the hairpin turns of the McKenzie Pass Highway, where five or more separate flows can often be counted in one 15-foot embankment. A typical flow is three to five feet thick with a thin, dense crust resting upon a base of unconsolidated rubble.

Condon Butte is three miles northeast of Sims Butte and is here considered to be genetically related to it. The cones are about the same size, equally forested, and the scoriaceous, aphyric appearance of their lavas is, for all practical purposes, identical. Condon Butte, however, did not emit a great volume of lava and as a consequence the cone is symmetrical. In the summit are two nested craters from which short, stubby flows moved down the southwest flanks.

Yapoah Cone and Related Vents

Between McKenzie Pass Highway and North Sister, the Skyline Trail (Fig. 1) leads across an alignment of six cinder cones and gas vents which is one and one-quarter miles long and trends S. 4^{o} W. At the midpoint of the alignment stands Yapoah Cone, and from its base several streams of basaltic lava extend northward, covering six square miles (Fig. 4).

Yapoah Cone rises 500 feet above its surroundings except on the south side, where it abuts against a glaciated ridge. The summit crater is about 300 feet long in a north-south direction, 100 feet wide, and mantled largely with red cinders. Stratified deposits of yellow lapilli-tuff occur on the east rim, but outer slopes of the cone are covered with black cinders. Yapoah Cone is remarkably symmetrical. This might be due to persistence of explosive activity until a late eruptive stage; all lavas adjacent to the cone are partly obscured by ash and scoria. Pyroclastic deposits resulting from Yapoah eruptions, however, are neither as thick nor so widely distributed as similar material from nearby Collier and Four-in-One cones.

Lava units from Yapoah Cone are composed of black, porous crustal blocks which become increasingly coherent downward, grading into a thin, dense base. A cross-section of this structure is exposed in highway cuts east of Dee Wright Observatory. Lava from Yapoah Cone rests upon Little Belknap lava

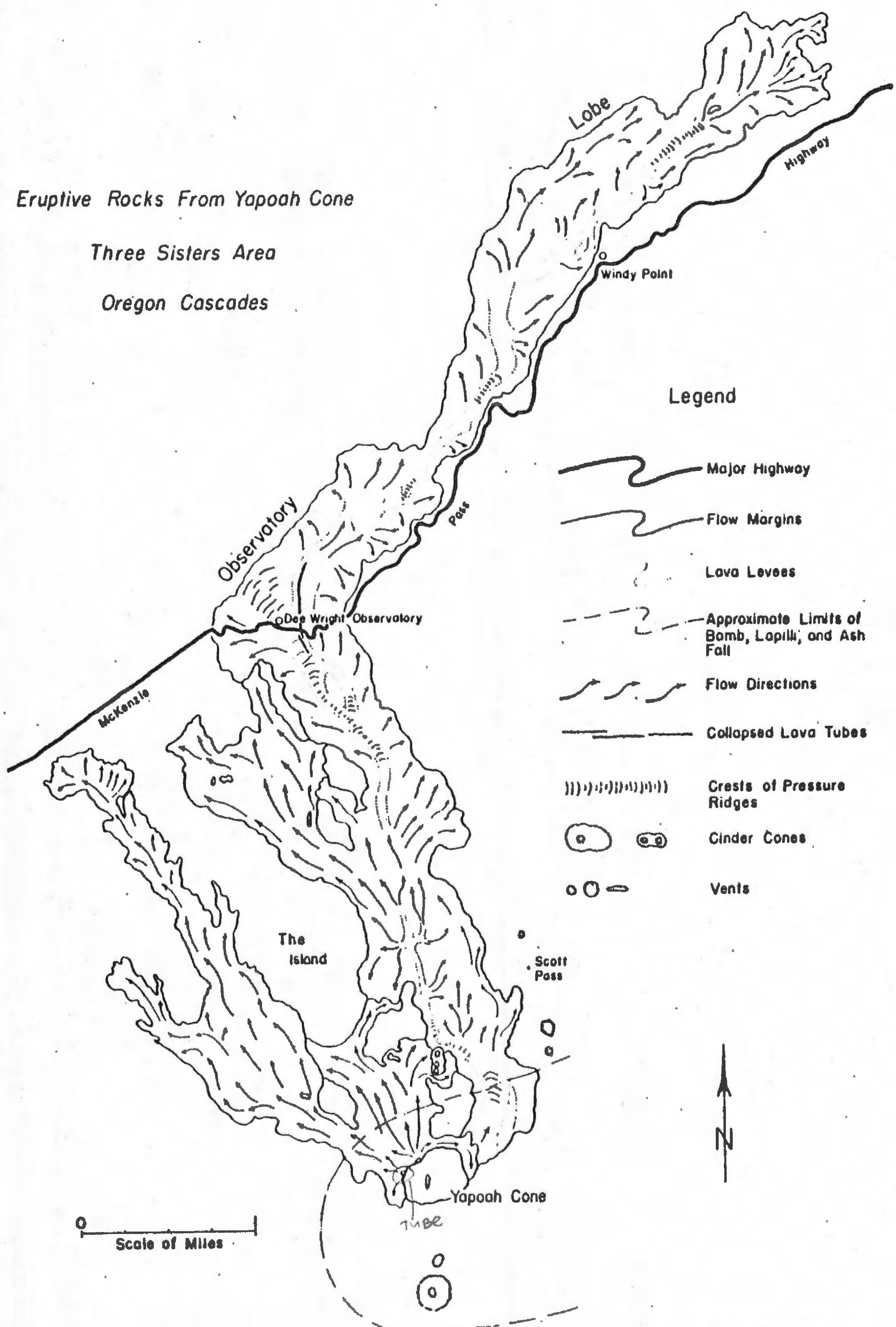

Fig. 4.--Geologic Map of Yapoah Cone and Flows

and is overlain by ashes and fine scoria from Four-in-One Cone.

An unusual type ot lava which now bears glacial striations erupted prior to Recent time from a series of vents along the Cascade crest between Black Crater and North Sister (Fig. 1). Bombs and lava were discharged simultaneously and spread down the western slopes in what might be described as an agglutinate flow. A typical unit is 30 feet thick with a 10-foot crust of red bombs and spatter, which passes gradationally into an underlying dense basalt choked with bombs. Yapoah Cone and related vents, together with Collier Cone and the Ahalapam Cinder Field (Fig. 5), rest upon the glaciated agglutinate flows. Some of these Recent and older-than-Recent eruptive features are not easily distinguished along the crest; consequently, interpretations of the volcanic history of this area have been subject to a wide variety of opinion.

Hodge (1925) named the Ahalapam Cinder Field and described it as "two rows of volcanoes having the appearance of morainal topography." Williams (1944) suggested that "ejecta from Collier and Yapoah Cones had accumulated on morainic mounds," but noted the presence of "many large bombs, several more than four feet across and a few even eight feet across, scattered among the fine scoria." The bombs were cited as evidence of eruption from local vents and most of the crest in this area was mapped as a field of Recent eruptive activity (Williams, 1957). In the opinion of the writer, however, the Ahalapam Cinder Field is a mantle of scoria which may be traced directly to the Collier vent. It was deposited upon the source of the large bombs, namely, the glacially dissected agglutinate flows. Recent eruptions between McKenzie Pass and North Sister have occurred only adjacent to Scott Pass and along the Four-in-One and Yapoah-Collier alignments, as described below.

Yapoah lava was discharged first from a bocca on the east and then from two boccas on the northwest and west sides of the cone. The first lobe,

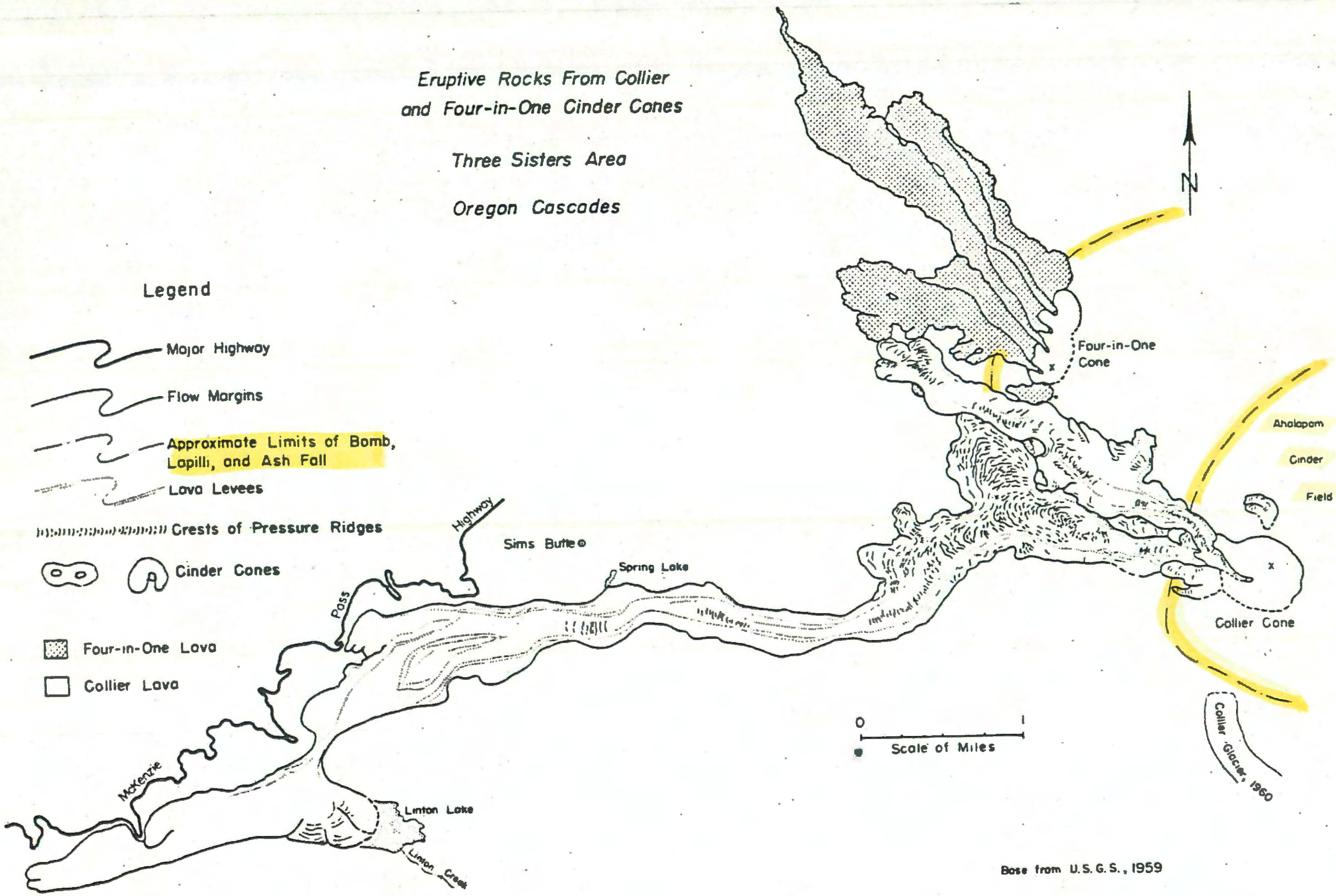

Fig. 5.--Geologic Map of Four-in-One and Collier Cones and Flows

here referred to as the Observatory Lobe, was channeled northward until it reached that part of the Cascade crest now traversed by the McKenzie Pass Highway. At this point it encountered the Little Belknap shield volcano and was deflected down the east slope of the range, eventually reaching a total length of eight and one-third miles. For a distance of one and one-half miles downstream from Yapoah Cone, the lavas of the Observatory Lobe moved in a narrow channel perched on the lobe crest, and confined by lava levees. At intervals, the levees were breached, releasing dendritic cascades which poured laterally down their flanks. At its terminal end, the channel split into three principal branches. The central and eastern branches fed the main lobe; the west branch produced a subsidiary lobe only two miles long. The remaining length of the Observatory Lobe is surmounted by a system of lava gutters which are, in some places, narrowly confined between lava levees. Upstream from such constrictions, transverse pressure ridges were formed; downstream, the lava frequently drained from beneath a congealed crust. In this way lava tubes were produced and long narrow trenches were formed where tube roofs collapsed. An excellent example of a collapsed tube is to be seen just east of the Dee Wright Observatory on both sides of McKenzie Pass Highway.

A later, centrally located lobe issued from a bocca approximately 100 feet above the northwest base of Yapoah Cone. Initially, the lava spread northward, plunged down a steep slope, and chilled to a standstill at the head of a large steptoe called "The Island." Three lava tongues extended east and west from this lobe; one moved one-half of a mile northeast, one surrounded three small spatter cones south of Yapoah Cone, and another covered the source vent of the Observatory Lobe at the east base of Yapoah Cone.

Succeeding lava flows poured from a west bocca and by-passed the central lobe, forming an extensive ribbon which ceased to move only after it had reached the base of the Belknap volcano, three miles distant. The bocca now is represented by a gutter leading to an open tube, which descends 20 feet into the flanks of the cone before it pinches out above a fill of jagged lava.

Several vents and cones of Recent age occur in the vicinity of Yapoah Cone. One-half of a mile north of Yapoah Cone, a linear cluster of three small cones was nearly engulfed by Yapoah lava. One-third of a mile south of Yapoah Cone, a gas vent was blasted through the agglutinate flows leaving a circular depression 300 feet in diameter. Immediately south of the gas vent a small, asymmetrical cinder cone was built on the margin of a precipitous ridge. The west flank of this cone rises 350 feet above nearby lowlands, while its eastern rim stands only 30 feet above the ridge top. Near Scott Pass, one mile to the northeast, a deep round pit, 400 feet in diameter, interrupts a glacially striated surface cut on red agglutinate flows. Other poorly defined gas vents exist to the north and south of Scott Pass and are located along the system of agglutinate flow fissures mentioned previously.

The vents south of Yapoah Cone and at Scott Pass are assigned on a provisional basis, to a Recent, but pre-Yapoah, eruptive episode. This activity was confined largely to the incipient Yapoah alignment, but might have also reached the surface through conduits along the older agglutinate flow fissures.

Four-in-One Cone and Related Vents

A series of 19 visible vents forms a short volcanic alignment one and one-half miles southwest of Yapoah Cone. The northern end of this alignment is marked by an elongate ridge of four coalescing cinder cones, appropriately named Four-in-One (Fig. 5). At its southern end, the alignment was inundated by lavas from Collier Cone to the southeast. Between Four-in-One Cone and the margin of Collier lava, three small vents can be seen. One is slightly offset to the east and covered with scoria; two others, which are half obscured by the Collier lobe, emitted pasty clots of black spatter and accidental fragments of underlying rocks. Midstream in the Collier lobe, one-half of a mile south of Four-in-One Cone, the summits of four cinder cones are exposed, each with a well-defined crater. The northern cone of this group was breached on its southwest flank by a lava flow which now is covered by the Collier lobe. Only the source area of the lava and its terminal extremity, one mile to the northwest, are exposed.

The eruptive history of Four-in-One Cone is not known in detail, but several major events can be inferred from the distribution of lava and the stratigraphic succession of ejecta in the cone walls. Activity developed first along a one-half mile trend of four conduits separated by a uniform interval of about 700 feet. Concurrent eruption of bombs and coarse cinders resulted in the construction of four overlapping cones which attained a height of 200 feet. Lava escaped from the southern base of the south cone, covering several acres with a thin veneer of black vitreous basalt, crowded with tiny vesicles. Late in its history of formation, the cone was enveloped in black spatter while scoria and ashes, composed chiefly of turbid brown glass, drifted east to the Cascade crest. East of the vents, the resulting deposits are more than 50 feet thick; none is found more than one-quarter of a mile west. Southward, they pass beneath Collier lavas; to the north they rest upon flows from Yapoah Cone.

A charred tree stump which was excavated from the base of a deposit of coarse cinders, 400 feet east of the south vent of Four-in-One Cone, has been given a radiocarbon age of 2550 ± 165 years B.P. (W.S.U. 365). Halos of discoloration within the cinders were observed surrounding the stump. Directly above the charcoal, the cinders were fused to a vertical column of "lava drip," presumably by combustion of organic gases.

Following the more violent stages of activity, four deep gashes were excavated in the west slope of the cone by streams of lava which eventually covered one and one-quarter square miles and reached a point two and three-quarters miles to the northwest. Counting from the north vent, the flow from the second was obscured by a subsequent flow from the third, which seems to have issued at about the same time as flows from the first and fourth vents. Because the lavas moved northwest and the ash was blown eastward, they do not in general overlap. The breaching of the cone, however, clearly involved both its reddish core and its black covering of spatter.

Surfaces on Four-in-One lava resemble those found on the Yapoah lobes, except for the prevalence of red scoria (quarried from the cone) and the lack of long continuous channels bordered by lava levees. Instead, the Four-in-One flows tend to branch repeatedly over short distances. This suggests that as the lava moved forward, it congealed quickly and succeeding lava was obliged to take a new course. Marginal lava curls were developed near the source vents.

Finally, it should be noted that fragments of quartz-rich, white vitrophyric pumice were expelled with the basaltic ejecta. The pumice is most abundant as fine ash but fragments up to six inches in diameter occur on the cone, chiefly about the north vent. Occasionally pumice is found encased within the black rind of a spindle-shaped basaltic bomb.

Collier Cone

Collier Cone stands 575 feet above its surroundings at the north-northwest base of the North Sister. Extensive deposits of ejecta and lava were formed during Collier eruptions. Black, fragmented bombs up to one foot in diameter are abundant on the cone and may be found as much as one-half of a mile west and one-fourth of a mile east of the vent. Fine-grained ejecta were driven eastward by the wind to form a square mile of alpine desolation, known as the Ahalapam Cinder Field. Vitrophyric pumice, often mixed intimately with basaltic glass, is common in deposits of Collier ash and scoria.

Collier flows afford an unusually clear record of eruptive history. An estimated 0.04 cubic miles of basaltic lava issued from the cone, producing a west lobe eight and one-half miles long and a northwest lobe three miles long (Fig. 5). The midsection of the lava streams, especially where they are steeply inclined, is occupied by long, multiple lava gutters. Several surges of lava must have poured down gutters formed previously, because two pairs of lava levees are nearly constant features of the west lobe, and three pairs often occur. These flows differ megascopically only in the size and proportion of olivine and plagioclase phenocrysts.

The initial lobe moved westward down the valley of White Branch Creek, blocking the drainage of a large spring to form Spring Lake at the base of Sims Butte. It then plunged into a glaciated canyon, damming Linton Creek to form Linton Lake. Relief of this west lobe, from source to terminus, is 4,160 feet.

A final surge of lava filled and overtopped the crater of Collier Cone, mantling its western slopes in a shroud of thin lava tongues. The northwest part of the cone must have been breached at this time because a large sector was rafted one-quarter of a mile to the northwest. As the breach widened the lava drained away, leaving a smooth coating on portions of the crater walls. The new lavas poured westward, narrowly confined between high levees. This last addition to the west lobe has been traced as far as Linton Lake, but its farthest extent has not been recognized.

Several short, broad, subsidiary lobes were formed as lava spilled out of the gutters along the upper one-third of the west lobe--probably because the narrow channel could not accommodate the large volume of lava discharged into it. Perhaps for this reason, lava burst through an opening north of the breached area to form the northwest lobe. As activity shifted to the northwest, the supply of fresh lava to the west lobe diminished, and the blocky crust was folded into transverse, arcuate pressure ridges which now occur upstream from constrictions in its course. Final motion of the west lobe consisted of draining from the steeply inclined flow near the source vent. The deep gutter thus formed is now the most accessible route to the crater floor, and is occupied by the Skyline Trail. Before the northwest lobe chilled to its present form, a minor extension moved approximately 200 feet into the upper reaches of this gutter.

A few small lava tongues emerged at the north base of Collier Cone from a vent now buried beneath scoria and ashes. The position of these flows in the eruptive history of the cone is uncertain.

At intervals throughout its length, the west lobe has been dissected by streams. In the walls of these channels, the lobe is seen to be a mass of jumbled blocks and scoria. Close to the source, however, the blocky crust is underlain by dense glassy lava cut by deep transverse fractures.

Collier Cone blocked the "Little Ice Age" advance of Collier Glacier down the slopes of North Sister. An early photograph (Campbell, 1924) shows glacial ice high on the flanks of the cone. When the ice attained a thickness of 200 feet at its terminus, meltwater was discharged into the crater, much of the floor was covered with outwash, and stream gravels were deposited for more than one mile down the west gutter. As the stream deposits near the cone are discontinuous and without interconnecting channels, the meltwater must have traversed snowfields and probably was active for only a brief time.

Eruptive Units of Questionable Recent Age

As outlined in a previous section, eruptive units of the study area are to be included in this report only if they came into existence since the last major glacial episode. Consequently, recognition of this temporal boundary is an important matter and wherever Recent age is questionable, the type of evidence on which assignment is based should be given.

Geologic maps by Williams (1944, 1957), Wells (1961), and Groh (1965), are in perfect agreement with regard to the locations of Recent basaltic cones and flows in the study area, but differ from the maps presented in this report. Discrepancies arise with respect to (1) recognition of cones and flows which have been eroded by pre-Altithermal glaciers and therefore are not Recent, (2) recognition of cones and flows which have not been glaciated but which might none-the-less be older than Recent, and (3) recognition of certain nonvolcanic land forms which were incorrectly identified on the older maps.

Land forms of group (1) are represented in Fig. 1 by the symbol "X" and are, from north to south: Maxwell Butte, which bears a mantle of glacial deposits; Cache Mountain and its subsidiary cone to the south, both of which display glacial striations on their eastern slopes; Bluegrass Butte, whose summit shows glacial striations; Black Crater, whose "crater" is a glacial cirque; Millican Crater, whose southern flanks have been modified by an east-flowing glacier; and a chain of small cinder cones and trench-like vents between Black Crater and Yapoah Cone, many of which have been deeply glaciated.

Group (2) includes Scott Mountain, Two Butte, two cinder cones on the northeast slope of Black Crater, and several features which do not appear on the older maps, namely, the Cinder Pit and Park Creek, West Maxwell, and Anderson Creek lava flows.

Scott Mountain is a shield volcano whose surface bears glacial striations, roches moutonees, and ground moraines. Upon the summit is a small cinder cone which does not appear to have been glaciated. Layered deposits of ash and lapilli-tuff are abundant near the top, where only an indistinct remnant of the crater rim has survived erosion. The flanks are composed of coarse red scoria and spindle bombs. A short blocky flow of basalt spread over the west and southwest lip of the crater but did not move beyond the cone. It is not known whether the summit cone is of Recent Age and resting upon a glaciated surface, or preglacial in age but not glacially eroded because of its high-standing, isolated position.

Two Butte is a double cinder cone located three and one-half miles south of Scott Mountain (Fig. 1). The cones are 400 feet high, are aligned north-south, and have lost their craters by erosion. Red scoria and basalt spatter are exposed near their summits, but the flanks are mantled in dense forest. Small flows of basalt can be traced south from the base of the cone to the edge of a deep glaciated canyon. Elsewhere, surrounding terrain bears glacial striations and morainal deposits. Lateral moraines, perched on the edge of the glacial canyon, suggest that the last major ice advance was confined within it and that the striations in the vicinity of Two Butte were formed during an earlier glaciation. If this is correct, Two Butte might not be Recent, even though it does not appear to have been glaciated.

Two adventive cinder cones with well-preserved summit craters stand 250 and 350 feet above the north and northeast flanks of Black Crater (Fig. 1). The coarse, red basaltic scoria and bombs on their slopes resemble ejecta from Bluegrass Butte and Millican Crater. Glacial ice, as outlined by terminal and lateral moraines, might have moved between the two adventive cones without eroding them, and, therefore, their Recent age is in doubt.

One and one-half miles north of Blue Lake Crater a diminutive cinder cone has been excavated for road metal (Fig. 1). As a result, the conduit--now occupied by a plug of basalt--has been laid bare within a shallow, cinder-covered pit. The designation "Cinder Pit," which appears on the Three Fingered

Jack, Oregon, 1:62500 topographic map (U.S. Geological Survey, 1959), is adopted here. A narrow stream of lava rests upon gray glacial deposits which, in the sides of the pit, have been oxidized to vermilion and yellow by volcanic emanations. Both the Cinder Pit and an eroded, 200-foot basaltic cone one mile to the southwest (Fig. 1) might not be Recent. A lateral moraine can be traced for three miles along the north edge of the glaciated canyon which contains Blue Lake Crater. It is therefore unlikely that the last major ice advance reached these cones.

Park Creek and West Maxwell flows (unofficial names; Fig. 1) lie northwest of the system of lateral and end moraines previously described with reference to Little Nash Crater. The last major advance of glacial ice did not reach these flows.

The Park Creek Flow is seen best at the north end of Lava Lake (Fig. 2) where a terminal, blocky lava front stands bare of vegetation. Farther north, crustal features and the outlines of lava tongues are seen only where ancient fires have limited the forest cover. From the distribution of lava, trend of visible pressure ridges, and slope of the lava surface it is inferred that the flow originated near the northwest lava margin, moved south for two miles, and forced Park Creek to undercut a high cliff in its west valley wall.

Equally vague is the eruptive history of basalt flows on the west side of Maxwell Butte (Fig. 1). Two source vents approximately two and one-third miles west of the Maxwell summit are indicated by the distribution of lava, but neither one has been located precisely nor has it been possible to trace contacts between flow units. Old forest fires have exposed slaggy crusts and numerous pressure ridges but the blocky, high-standing margin characteristic of Park Creek lava is lacking here. The thin, vesicular nature of the West Maxwell flows can be seen best in cuts of Highway 22.

The Anderson Creek Flow (Fig. 1) can be traced westward from a subdued spur two and one-third miles west of Scott Mountain Summit. One mile west of this spur, the lava poured as a cascade into the valley of Anderson Creek. Distribution of lava margins relative to surrounding topography, and patterns of lava levees and gutters suggest that this flow advanced two miles down the center of the Anderson Creek valley. A subsequent flow followed the south margin of the first flow, then was channeled west by an intervening hill and deflected northward, where it too entered the Anderson Creek valley. This second flow eventually spread westward six miles from the probable source. Its terminal lava front is obscure but can be seen beside the Clear Lake Highway.

To trace the Anderson Creek Flows one must learn to "feel" it beneath the forest floor; indeed, the very existence of fresh lava would be difficult to prove if construction of logging roads had not disclosed striking examples of lava levees and vesicular flow tops. The advanced age of this flow is inferred from the luxuriant condition of its forest cover in comparison with the cover found on other flows at similar elevations to the north and south.

Terminal moraines were deposited just east of the probable source of the Anderson Creek Flows by a system of small glaciers which descended the west slopes of Scott Mountain. No cinder cone or ejecta deposits which can be associated with the Anderson Creek Flows have been found and the true source of lava might lie buried under terminal or ground moraines.

Chronology of Eruptive Units

The chronological data presented in the preceding sections are difficult to assemble in a conventional correlation table for several reasons. Chief among these is the difference in criteria used for estimating relative age of eruptive units. Direct superposition of lavas and ash sheets, relationship to glacial features, condition of forest cover, degree of rock weathering, extent of erosion, and carbon-14 age dating have all been cited in this report. These are criteria which differ in reliability and they may indicate maximum, minimum, or radiocarbon ages. The simple format of Table 1 is therefore employed to present a sequence of the eruptive units to which a radiocarbon age has been assigned. As a supplement to Table 1, all eruptive units are listed below in the order in which they appear in preceding sections. Each unit is accompanied by a summary of the stratigraphic relationship which it bears to other units and by an assignment of maximum, minimum, or radiocarbon ages (expressions of analytical uncertainty are confined to Table 1).

TABLE 1

RADIOCARBON ERUPTIVE CHRONOLOGY

Ages in Years B.P.	Eruptive Units
1400 ± 100 (W.S.U.-270) 1590 ± 160 (W.S.U.-292)	Lava from north vent of Belknap summit cone.
1950 ± 150 (W.S.U.-371)	Cinders from south cone of Lost Lake Group.
2550 ± 165 (W.S.U.-365)	Cinders from Four-in-One cone.
2883 ± 175 (W.S.U.-364)	Little Belknap lava.
2705 ± 200 (Benson, 1965) 3200 ± 220 (Benson, 1965)	Clear Lake drowned forest.
3440 ± 250 (W.S.U.-291)	Cinders from Blue Lake Crater.
3850 ± 215 (W.S.U.-372)	Flow southeast of Fish Lake.

Little Nash Crater: Lavas younger than cone. Cinders overlie Lost Lake Group (maximum age), early Central Group lava, Lava Lake Flow, Nash Crater ash. Lavas overlie early Central Group lava, Lava Lake Flow, West Maxwell lava. Minimum age--300-400 years B.P. (living trees).

Lava Lake Flow: Overlies early Central Group (maximum age). Overlain by Fish Lake Flows (minimum age), Little Nash Crater flow.

Fish Lake Flows: Younger than bulk of Nash Crater. Overlies Lava Lake Flow, late Central Group lavas, lava from west vent of North Sand Mountain, flow southeast of Fish Lake (maximum age). Overlain by thin deposit of Nash Crater ash. Minimum age--300-400 years B.P. (living trees).

Flow southeast of Fish Lake: Overlies ash from Sand Mountain Alignment. Overlain by Fish Lake Flows. Age--3850 years B.P. (carbon-14).

Lost Lake Group: Lavas younger than bulk of cones. Lavas overlie early Central Group lavas. Overlain by cinders from Little Nash Crater. Age of cinders from south cone--1950 years B.P. (carbon-14).

Early Central Group: Lavas younger than source cone. Overlain by Little Nash Crater cone and flow, Lava Lake Flow (minimum age), Lost Lake Group, late Central Group lava. Maximum age--last glacial episode. Age by provisional correlation with flow southeast of Fish Lake--3850 years B.P. (carbon-14).

Late Central Group: Overlies early Central Group flow (maximum age). Overlain by Fish Lake Flows (minimum age).

Flow from west vent, North Sand Mountain: Overlain by Fish Lake Flows, Clear Lake Flow (minimum age). Maximum age--last glacial episode.

Clear Lake Flow: Overlies lava from west vent of North Sand Mountain, South Group Lava (maximum age). Overlain by ash from South Sand Mountain. Minimum age--3000 years B.P. (carbon-14, Clear Lake drowned forest).

Flow from south vent of South Sand Mountain: Overlies South Group lavas (maximum age). Overlain by flows from north vent of Belknap summit cone (minimum age).

South Group: Flows younger than cones. Overlain by Clear Lake Flow, flow from south vent of South Sand Mountain, flows from north vent of Belknap summit cone (minimum age). Maximum age--last glacial episode.

Flow from north cone, Inaccessible Alignment: Overlain by South Group lavas, flows from north vent of Belknap summit cone (minimum age). Maximum age--last glacial episode.

Twin Craters: Overlies early Belknap ash deposits (maximum age). Overlain by flows from south vent of Belknap summit cone (minimum age).

Hoodoo Butte: Overlain by ash from Sand Mountain Alignment (minimum age). Maximum age--last glacial episode.

Old Flows of Belknap east and west slopes: Overlain by early Belknap ash deposits (minimum age), Little Belknap lava, Observatory Lobe, west Yapoah Lobe, flows from north and south vents of Belknap summit cone, flows from vent northwest of South Belknap Cone. Maximum age--last glacial episode.

South Belknap Cone: Overlain by flows from vent northwest of cone. Cinders overlain by old flows of Belknap east slope (minimum age). Maximum age--last glacial episode.

Flows from breach of South Belknap Cone: Lava younger than cone (maximum age). Overlain by flows from vent northwest of cone (minimum age).

Flows from vent northwest of South Belknap Cone: Overlie old flows of Belknap east slope, flows from south vent of Belknap summit (maximum age), flows from breach of South Belknap Cone, South Belknap Cone. Minimum age--100 years (first recorded human history of region).

Little Belknap Flows: Overlie old flows of Belknap east slope, early Belknap ash deposits. Overlain by later Belknap ash deposits, Observatory Lobe. Age--2880 years B.P. (carbon-14).

Flows from north vent of Belknap summit cone: Overlie lava from South

Group, lava from south base of South Sand Mountain, cones and flows of Inaccessible Alignment, old flows of Belknap east and west slopes, early Belknap ash deposits. Overlain by late Belknap ash deposits. Age--1500 years B.P. (carbon-14).

Flows from south vent of Belknap summit cone: Overlie old flows of Belknap east and west slopes (maximum age), twin Craters lava. Overlain by flows from vent northwest of South Belknap Cone (minimum age).

Blue Lake Crater: Cinders overlie ash from Sand Mountain Alignment. Age--3440 B.P. (carbon-14).

Spatter Cone Chain: Overlies ash from Sand Mountain Alignment (maximum age). Minimum age--300-400 years (living trees).

Sims Butte: Lavas younger than cone. Lavas and cinders overlain by Collier west lobe (minimum age). Maximum age--last glacial episode.

Condon Butte: Cinders overlain by Four-in-One flows (minimum age). Maximum age--last glacial episode.

Yapoah Cone: Lavas and cone apparently coeval. Lavas overlie Little Belknap flows (maximum age), old flows of Belknap east slope. Overlain by cinders from Four-in-One Cone (minimum age).

Four-in-One Cone: Lavas younger than cone. Lavas overlie Condon cinders, Yapoah lava. Cinders overlain by Collier northwest lobe. Age--2550 years B.P. (carbon-14).

Collier Cone: Most lavas apparently coeval with cone. Lavas overlie Sims lava, Four-in-One cinders (maximum age). Minimum age--300-400 years B.P. (living trees).

Scott Mountain, Two Butte, cinder cones on northeast side of Black Crater, Cinder Pit, Park Creek Flow, West Maxwell Flows, Anderson Creek Flow: Insufficient stratigraphic information; units might not be Recent.

ANALYTICAL STUDIES

Purpose

Several types of chemical and mineralogical analyses have been performed upon the Recent basalts whose eruptive history has been outlined. The purpose of these analyses was threefold: (1) To provide a reliable basis for classification of rocks that appear homogeneous to the field worker; (2) to determine the degree to which chemical and mineralogical inhomogeneity exists within eruptive units; (3) to search for significant patterns in variations of chemical and mineralogical composition, both within and between eruptive units.

Procedure

Ideally, samples for the purposes stated should be obtained at intersections of a close-set grid, distributed over the lava fields. For a clear representation of variations in mineralogical and chemical composition throughout the eruptive history, a prohibitively large number of such samples would be required. In practice, therefore, an intensive effort was made to obtain several samples from all distinct units. The number of samples collected during traverses across the lava fields was dictated by personal stamina; accessibility to lava margins largely governed the traverse locations. Where lava flows are confined to long, continuous channels, a linear system of equally spaced sampling points was established in the central gutters, parallel to their length. Two samples were taken at most collecting sites. A large glassy specimen was selected for petrographic study of phenocrysts and a dozen small chips from nearby blocks were combined for chemical analysis. Fragments of red scoria which might have been quarried from cones were avoided. About one pound of fine cinders was collected from most cone rims, and a vertical sequence of several samples was obtained from two ash deposits. Locations of the 261 samples collected are given in the appendices.

For petrographic classification, phenocrysts are used here in preference to the groundmass. Vertical sequences of samples from Yapoah and Collier lavas were examined in thin section, and the abundance, size, and composition of phenocrysts were not observed to change in any regular way with vertical position. The distribution of phenocrysts in high vertical faces of fractured lava was studied in the field on many occasions; vertical layering of phenocrysts was never detected. On the other hand, groundmass color, vesicularity, crystallinity, and grain size in lavas of the study area are variable within wide limits and are clearly related to conditions of cooling. Flows which exceed 10 feet in thickness are generally lighter in color, more dense, less glassy, and coarser in the interior than at the top or bottom. Thinner flows tend to be black and glassy throughout. The composition and proportion of phenocrysts must therefore be independent of the cooling history of the lava and should constitute a more valid basis for classification than would be provided by features of the groundmass.

With few exceptions, phenocrysts are so dispersed in the lavas that several thin sections of each sample would be required to provide significant estimates of phenocryst abundance and composition. The obvious impracticability in applying this approach to all samples was circumvented by field and laboratory study with hand lens and binocular microscope. In this way, each sample was classed into one of six groups, based upon the abundance, size, and mineralogy of phenocrysts present. Six lava flows were then selected to represent the six groups and several samples from each of these flows were thin-sectioned and subjected to petrographic study. Selection of samples was governed largely by proximity to highways; they should be readily accessible to interested persons.

Plagioclase and olivine compositions were estimated by universal stage techniques, using the Rittmann zone method as described in Emmons (1943, p. 118-122), and by direct conoscopic measurement of 2V in olivine. The determinative curve of Kerr (1959, p. 258) was used for maximum extinction in the zone normal to 010 of plagioclase and the curve of Deer, Howie, and Zussman (1962, Vol. 1, p. 22) was used for olivine. Discrepancies between axial angles measured over different bisectrices of olivine, similar to the discrepancies noted by Wyllie (1959), were observed wherever acute and obtuse orientations could be obtained in the same thin section. According to Wyllie (1959) this is due to uncorrected refractions by stage elements at high angles of tilt, resulting in an estimate of 2V which is several degrees less than the true value. The olivines encountered in this study all contain between 75 and 95 per cent of the forsterite molecule (85 to 95 degrees 2V), and it was observed that the uniform addition of 3 degrees to both acute and obtuse axial angles removed all discrepancies. Accordingly, a positive correction of 3 degrees was applied, following the conventional conversion of 2H to 2V (Emmons, 1943). Proportions of phenocrysts were visually estimated. Results of petrographic studies are presented in the following section.

Because it was not economically possible to obtain complete chemical analyses of a large number of samples, a method was devised for the rapid determination of silica in all samples. Silica was selected as the best indicator of chemical variation and as a measure of rock affinity because it is the most abundant component oxide and an important parameter in chemical classifications of igneous rocks. A novel approach to silica analysis of fine grained igneous rocks which utilizes the dependence of refractive index of a fused sample upon its silica content was first suggested by Mathews (1951). This technique was modified by the present writer into a form specifically applicable to basalt, as described below.

All of the chips from a composite rock sample were crushed in a percussion mortar until 50 grams of powder passed a 200-mesh screen. A 0.6- to 0.8-gram pile of each powdered sample was then formed on the polished surface of a 20-pound steel block with the aid of a plastic template. Each pile was converted to a hemispherical bead of glass in the arc of a 70-ampere welder, using copper-sheathed carbon electrodes. The beads were next mounted on standard microslides bearing inscribed sample numbers. Each slide was then placed in a simple hand-held jig for grinding. One stage of coarse grinding on a lap wheel, followed by one stage of fine grinding on a glass plate, produced a bead with a plane facet of 1 square centimeter, suitable for final polishing with 1-micron alumina on a felt-covered lap. Beads were processed in sets of 25, one set requiring approximately five hours. The polished facet of each bead was presented to the upper prism of an Abbe-type refractometer with an intervening film of alphachloronaphthalene. Refractive index was read to one in the third decimal place. Twenty-five complete determinations were conveniently performed in a single day.

To evaluate the degree of reproducibility attained by this procedure, 12 powdered samples representing a wide range of composition were each analyzed three times. In addition, six separate lots of powder were prepared from a single hand specimen and each of these was analyzed in duplicate. The identity of the 48 resulting beads was retained by an assistant during the runs. In all instances, replicate determinations of refractive index were in agreement to within plus or minus one in the third decimal place. The value of the refractive index of a fused rock sample is therefore characteristic and highly reproducible.

Refractive index of fused rock is principally, but not totally, dependent upon silica content. If other oxides should vary in weight per cent relative to each other, the refractive index may fail to accurately register variations in the amount of silica. This failure should be more pronounced in glass of lower silica content and is, in fact, revealed by the curves of Huber and Rinehart (1966). In addition, the silica content-refractive index relationship should not be linear as assumed by Kittleman (1963), because in most suites of genetically related volcanic rocks, variations in silica are attended by variations in the amounts of other oxides relative to each other. In particular, as silica increases, soda and potash increase while iron oxides, lime, and magnesia decrease. Silica and alkalies added to commercial glass lower its refractive index while iron, lime, and magnesia raise it (Morey, 1954). A conventional rectangular plot of silica content against refractive index of fused rock should therefore present a curve convex toward the origin, and again this is revealed by the data of Huber and Rinehart (1966).

The above considerations suggest that indiscriminate application of the method of silica determination by refractive index of fused rock to a wide variety of lithologic types, especially low silica types, is hazardous, even though reproducibility is high. For this reason, 26 samples of Recent basalt from the area under study, representing a broad range in composition, were analyzed by standard wet-chemical methods for weight per cent silica. The analyses were performed by L. L. Hoagland in the laboratories of the Oregon State Department of Geology and Mineral Industries. The results appear in Fig. 6 and were used as a working basis for all fused rock determinations reported herein. The small degree of scatter shows, without recourse to a formal

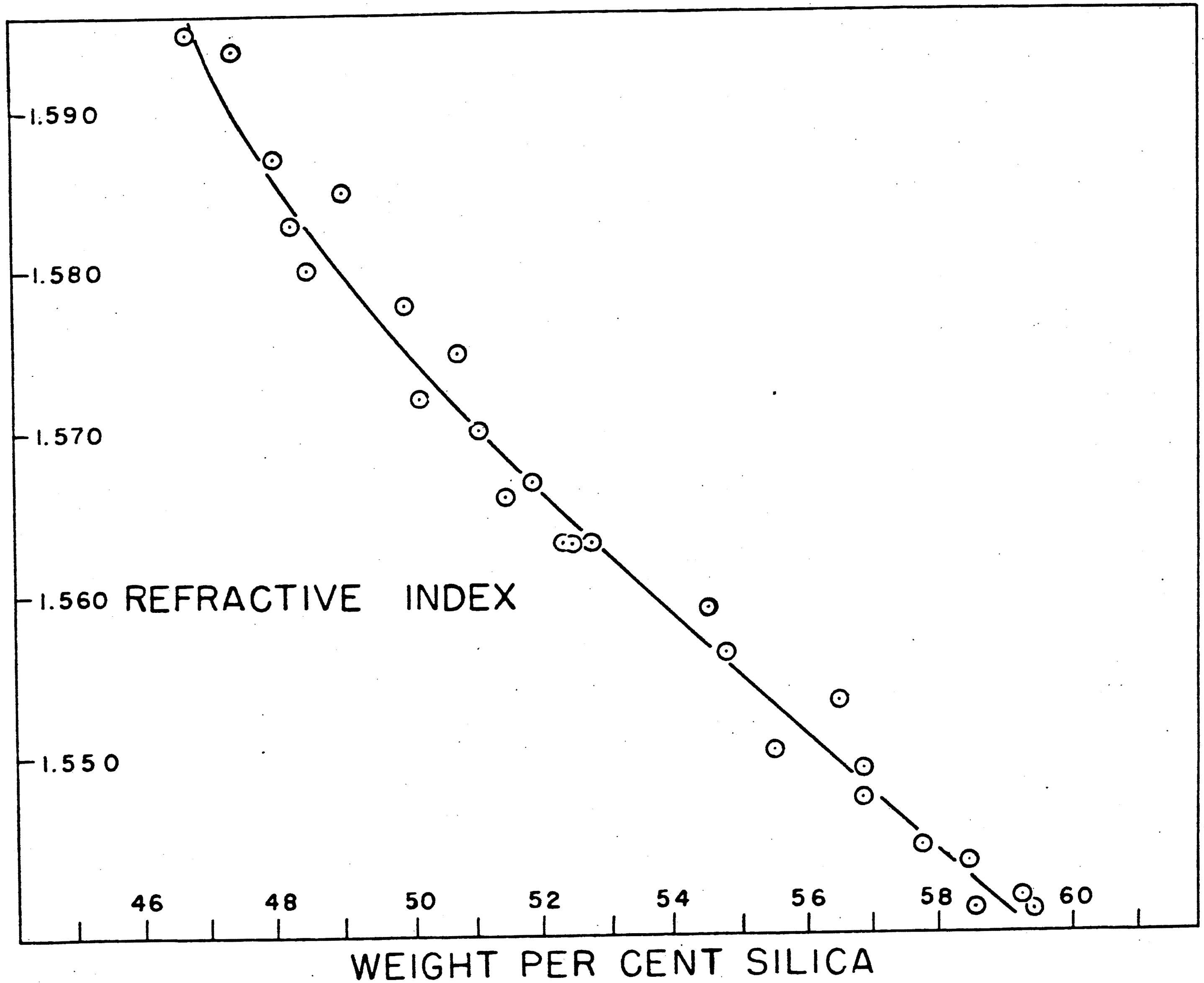

Fig. 6.--Refractive Index and Silica Content of Fused Basaltic Rocks

statistical evaluation of precision, that the likelihood of an error of more than 1 per cent silica by weight is very low.

Eleven of the above samples were also analyzed for alumina, iron (as ferric oxide), lime, magnesia, titania, manganese, soda, and potash by the same analyst (Table 2).

Results

Petrography of the Lavas

Upon first encounter, Recent lavas of the study area seem all to be uniformly monotonous, black, glassy, vesicular basalt containing scattered phenocrysts of plagioclase and olivine. However, it is possible to recognize six natural types on the basis of the amount, size, and relative abundance of the ubiquitous phenocrysts, as seen under a binocular microscope:

1. Phenocrysts less than 5 per cent, generally smaller than 2 mm, olivine greatly predominant. Representative units are: Little Nash Crater flow, Lava Lake Flow, Fish Lake Flows, Lost Lake Group flows, early Central Group flows, South Group flows, Two Butte flow.
2. Phenocrysts less than 5 per cent, generally smaller than 2 mm, both olivine and plagioclase common. Representative units are: Late Central Group flows, flows from west vent of North Sand Mountain, flows of Inaccessible Alignment, Anderson Creek Flows, Hoodoo Butte, Cinder Pit flow, Twin Craters flows, western extremity of Belknap lava field, Sims flows, Condon Butte.
3. Phenocrysts greater than 5 per cent, generally smaller than 2 mm, plagioclase predominant. Representative units are: Park Creek Flow, flows on west side of Maxwell Butte, Clear Lake Flow,

TABLE 2

CHEMICAL ANALYSES OF LAVAS FROM COLLIER CONE[a]

Constituent Oxide	Sample Numbers[b]										
	255	238	220	227	214	216	217	211	259	208	209
SiO_2[c]	52.40	52.72	54.54	54.78	55.52	56.46	56.73	57.72	58.40	58.60	59.26
Al_2O_3	18.41	18.09	18.93	18.36	19.56	15.48	18.44	18.37	17.46	17.92	16.80
Fe_2O_3	8.73	9.05	9.05	8.87	8.26	12.06	8.58	8.89	9.36	7.62	8.89
CaO	7.60	7.40	7.96	7.90	7.85	7.26	7.30	6.55	6.30	6.72	6.60
MgO	7.73	8.37	4.93	4.99	3.95	3.69	3.71	2.90	3.21	3.41	2.72
TiO_2	Trace	Trace	0.10	0.15	0.15	Trace	0.10	0.15	0.15	0.10	0.20
Mn	0.12	0.15	Trace	Trace	Trace	Trace	0.10	Trace	0.15	Trace	Trace
Na_2O	4.38	3.16	3.62	3.66	3.74	4.16	3.99	4.14	4.12	4.09	4.00
K_2O	0.75	0.72	0.93	0.90	0.81	0.84	1.12	1.09	1.07	1.36	1.36
Sum	100.12	99.66	100.06	99.61	99.84	99.95	100.07	99.82	100.22	99.82	99.83

[a]Analyst: L. L. Hoagland, Oregon State Department of Geology and Mineral Industries, Portland.

[b]Locations of samples given in Appendix B.

[c]All constituents in weight per cent.

flow from south vent of South Sand Mountain, Four-in-One flows.

4. Phenocrysts greater than 5 per cent, generally larger than 2 mm, plagioclase greatly predominant. Representative units are: Blue Lake Crater, Spatter Cone Chain, Yapoah flows, all flows from Collier Cone except those classed below as type 5.
5. Phenocrysts greater than 5 per cent, generally larger than 2 mm, olivine and plagioclase about equally abundant. Single representative is latest Collier flow between Linton Lake and Spring Lake.
6. Phenocrysts greater than 5 per cent, plagioclase and olivine in clusters up to 10 mm in diameter. Representative units are: Scott Mountain Flow, all Belknap flows except westernmost extension near Highway 126.

Samples of the Lava Lake Flow, collected at the junction of Highways 20 and 126 (Figs. 2 and 9), have been selected as petrographic representatives of the first type. One to 2 per cent of the rock is occupied by clear, light yellow olivine phenocrysts containing tiny opaque octahedral grains, presumably a spinel. The olivine grains are generally euhedral, equant, and less than 1 mm in diameter. Plagioclase phenocrysts tend to be intergrown with olivine but are very rare. Under the binocular microscope, wedge-shaped laths of tridymite can be seen encrusting the surfaces of cooling joints and vesicles. The refractive index of this material was determined by immersion methods to be less than 1.480. In thin sections, the groundmass is composed of granules of clinopyroxene set in a matrix of plagioclase microlites (An 68), skeletal magnetite, and light brown glass. Phenocrysts of olivine (Fo 95) are clear and do not display reaction rims, except where they are in contact with tridymite-rich vesicles. Along such contacts a band of close-set magnetite granules occurs within the olivine. No grains of plagioclase greater than 1 mm in length are encountered in these sections, but a few small euhedral crystals of that mineral which show intense normal zoning are invariably present. With respect to this zoning, they are strikingly distinct from the groundmass microlites and are here interpreted as microphenocrysts, that is, an early generation of crystals that failed to attain normal phenocryst proportions before extrusion.

The second petrographic type is represented by samples collected at the westernmost terminus of the Anderson Creek Flow, adjacent to Highway 126 (Figs. 1 and 12). Two to 3 per cent of the rock is occupied by phenocrysts of olivine and plagioclase, and these are generally less than 1 mm in length. Olivine, which is slightly predominant, is unaltered and contains numerous tiny grains of an opaque spinellid. Samples from the interior of the flow are rich in tridymite, but the crustal samples described here contain only traces of that mineral. In thin sections, the groundmass is seen to be a holocrystalline aggregate of plagioclase microlites (An 75) with intergranular clinopyroxene and octahedra of magnetite. Glass seems to be confined to the upper few centimeters of lava crust and to the walls of large vesicles. Most plagioclase phenocrysts contain an intermediate, sodic, corroded zone (An 65), transitional to more calcic core and euhedral rim zones (An 75). Olivine phenocrysts (Fo 85) are generally euhedral but are clear and are not embayed by the groundmass.

In the third petrographic type, 25 to 50 per cent of the rock volume (exclusive of vesicles) is made up of microphenocrysts of plagioclase, olivine, and pyroxene in that order of abundance. Two sets of samples have been selected for detailed description. The first is from the Clear Lake Flow along the east shore of Clear Lake (Figs. 2 and 9). Under a binocular microscope, a third of the rock appears to be occupied by grains of plagioclase and olivine which are less than 0.1 mm in diameter. The remainder is irresolvable, black groundmass and tiny vesicles lined with tridymite. These observations are confirmed by examination of thin sections. Crystals of plagioclase, in spite of their small size, are euhedral and complexly zoned from An 85 in the cores to An 63 along the rims. Olivine and augite tend to be somewhat smaller, but are also euhedral and display thin rim zones. The microphenocrysts are suspended in an intimate mixture of plagioclase microlites (An 63), tiny clinopyroxene granules, magnetite, and dark brown glass.

Another interesting representative of this type was collected at the second vent from the north end of Four-in-One Cone (Figs. 5 and 12). In all samples of Four-in-One lava, phenocrysts of plagioclase and olivine are less than 1 mm in diameter and minute vesicles are unusually abundant, giving rise to a uniformly black, porous, almost frothy rock. In thin sections, the texture is hyalopilitic. Stout, euhedral crystals of plagioclase (An 63), irregular grains of olivine, clinopyroxene, and orthopyroxene, up to 0.1 mm in diameter, and tiny octahedra of magnetite are suspended in a matrix of brown glass. The most striking feature of the groundmass is a dense, felt-like intergrowth of minute prismatic rods of orthopyroxene(?) which pervades the glass. The rods possess parallel extinction but are too small to permit accurate measurement of other optical properties. The rods are also contained within the border zones of the largest mineral grains. If these grains are regarded as microphenocrysts, the emergent lava was about one-half crystallized. Most of the plagioclase phenocrysts are clear and normally zoned from An 80 to An 63, but a few contain an intermediate corroded zone of An 80, surrounding a core of An 55 and rimmed by An 63. Complex zoning is observed in most of the orthopyroxene microphenocrysts. Pyroxene and olivine grains, however, are generally too small for universal stage determinations.

The fourth petrographic type is represented by samples of Yapoah lava collected from a thin, dense flow unit which appears in a cut of Highway 242, just east of the Dee Wright Observatory (Figs. 4 and 11). Phenocrysts of plagioclase, up to 10 mm in length, predominate over smaller phenocrysts of olivine, and together these crystals make up about 10 per cent of the rock. In thin sections, the groundmass is composed of an intersertal mosaic of plagioclase microlites (An 68) and clinopyroxene, enclosing brown glass which is charged with minute opaque granules. Augite occurs up to 0.5 mm in length but is subordinate in size and amount to olivine (Fo 83). Most of the plagioclase phenocrysts are clear and normally zoned from An 80 to An 70, but a few contain intermediate corroded zones of An 88 passing into clear cores of An 60.

The fifth petrographic type is an olivine basalt (Williams, Turner, and Gilbert, 1955, p. 40) and is found along a three-mile segment of the latest Collier lava flow between Linton Lake and Spring Lake (Figs. 5 and 12). Phenocrysts of olivine and plagioclase occupy 20 per cent of the rock and are equally abundant. Under the binocular microscope, some plagioclase phenocrysts display corroded cores, but most are clear. Although olivine phenocrysts are rounded and embayed, they are clear and free of reaction products, even along their rims. Opaque octahedra of unusually large size (0.05 mm) were extracted from the olivine grains, and an X-ray powder pattern was obtained which matched that reported for magnesiochromite (American Society for Testing and Materials, 1962, card 9.353). In thin section, an intergranular texture is revealed in which minute grains of clinopyroxene, magnetite, and thin films of brown glass occur between plagioclase microlites (An 65). Composition of most olivine phenocrysts is Fo 84 but some of the larger crystals are normally zoned to a thin rim of Fo 80. Clear, euhedral phenocrysts of plagioclase are normally zoned from An 83 to An 65. A few plagioclase phenocrysts are reversely zoned from An 46 to An 80 and show strong resorption along the margins of their sodic cores. Euhedral outlines have been restored to the corroded and rounded interiors by accretion of rim zones which pass outward from An 80 to An 63.

The sixth petrographic type is represented by a sample taken from the easternmost tip of the Belknap lava field, adjacent to Highway 242 (Figs. 3 and 10). Under the binocular microscope, clear euhedral crystals of tridymite are seen against a background of black glass and tiny grains of plagioclase. The most striking feature of this lava is the prevalence of a glomeroporphyritic texture in which irregular clusters, up to 10 mm in length, are composed of 1-mm plagioclase and olivine crystals. Within the clusters, plagioclase predominates over olivine and together they make up approximately 10 per cent of the rock. The olivine contains numerous, minute, opaque grains. In thin section, the plagioclase microlites (An 70) appear as unusually well formed, complexly twinned, stout prisms with serrate terminations. The interstices between these prisms are filled with brown devitrified glass and scattered grains of augite and olivine which average 0.1 mm in diameter. Magnetite grains are exceptionally minute, and are confined to the glass. Plagioclase of the clusters occurs both as a criss-cross mosaic of stout prisms (An 70) and as large euhedral phenocrysts (An 80) in subophitic intergrowth with crystals of clear olivine (Fo 82). The phenocrysts of plagioclase are 3 to 5 mm in length and display complex oscillatory zoning. The composition of the zones, however, does not vary more than a few per cent. Some of the large olivine and plagioclase crystals are isolated in the groundmass, but they are indistinguishable from those of the clusters, and, in fact, may have been liberated by disintegration of clusters.

These petrographic data show that the basalt flows, while possessing outward uniformity, belong to distinct types, based upon texture and mineralogy of phenocrysts. In general, four textures are represented: (1) aphyric, or, at best, slightly porphyritic, (2) microporphyritic, in which more than one-half of the rock may be occupied by small but complexly zoned crystals, (3) strongly porphyritic, in which 10 to 20 per cent of the rock is occupied by large phenocrysts, and (4) glomeroporphyritic, in which phenocrysts are grouped in irregular clusters. Three clearly-defined mineralogical associations are represented by the phenocrysts: (1) olivine alone, (2) plagioclase alone, and (3) olivine and plagioclase. Only six of the possible combinations of phenocryst texture and mineralogy have been recognized. The petrographic type to which each of 213 lava samples has been assigned is indicated in Appendix A.

Phenocrysts are generally euhedral and do not show evidence of reaction with their surroundings, except where strongly porphyritic texture prevails. In sections of Yapoah, Four-in-One, and Collier, for example, large phenocrysts of plagioclase commonly contain a sodic core which has been marginally replaced by a calcic rim, similar in composition to surrounding microlites. In the same rocks, some olivine phenocrysts are deeply embayed, suggesting instability between crystal and surrounding liquid.

Silica Content of the Lavas and Ejecta

Results of fused bead analyses of 261 samples of Recent eruptive units from the study area are tabulated in Appendix A. Values of refractive index of the beads and corresponding values of weight per cent silica, interpolated from the graph of Fig. 6, are listed. Silica values obtained through wet chemical analyses are indicated with an asterisk. Sample data appear under the name of the eruptive unit to which they belong. Appendix B contains five index maps (Figs. 10 to 13) on which the locations of samples are plotted. Sample numbers which appear on the maps increase generally from source to terminus within a given unit. The locations of samples which cannot be resolved on the maps are described in Appendix A. Cross-reference is thereby established between the location of any sample and its silica content.

Figure 7 presents a summary of silica variation within and between volcanic units. The maximum and minimum limits of silica content have been extended by one-half per cent, in keeping with the previously stated estimate of analytical accuracy. These data show that Recent basaltic lavas of the study area vary in content of silica from 47 to 59 per cent, and that such terms as olivine basalt, tholeiitic basalt, andesitic basalt, and basaltic andesite (all as defined by Williams, Turner, and Gilbert, 1954), might well be applied to them. Variation in silica content within a few small lava flows is less than 2 per cent, but generally silica varies by at least 3, and in some instances, by as much as 8 per cent. In fact, Harker variation diagrams, similar to those used in characterizing entire volcanic provinces (Williams, 1942, p. 154), can be constructed from chemical analyses of single flows (Fig. 8).

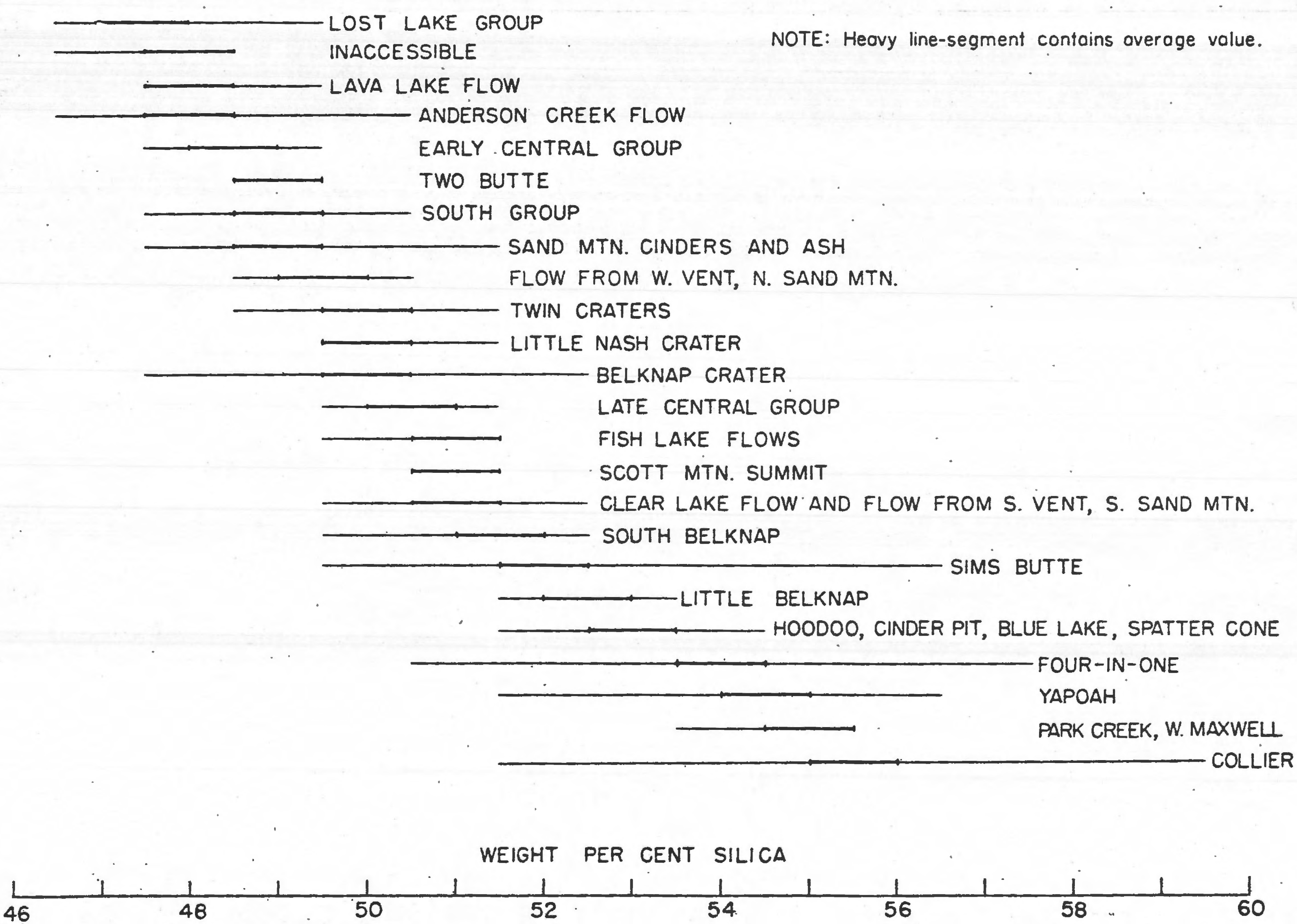

Fig. 7.--Silica Content of Volcanic Units

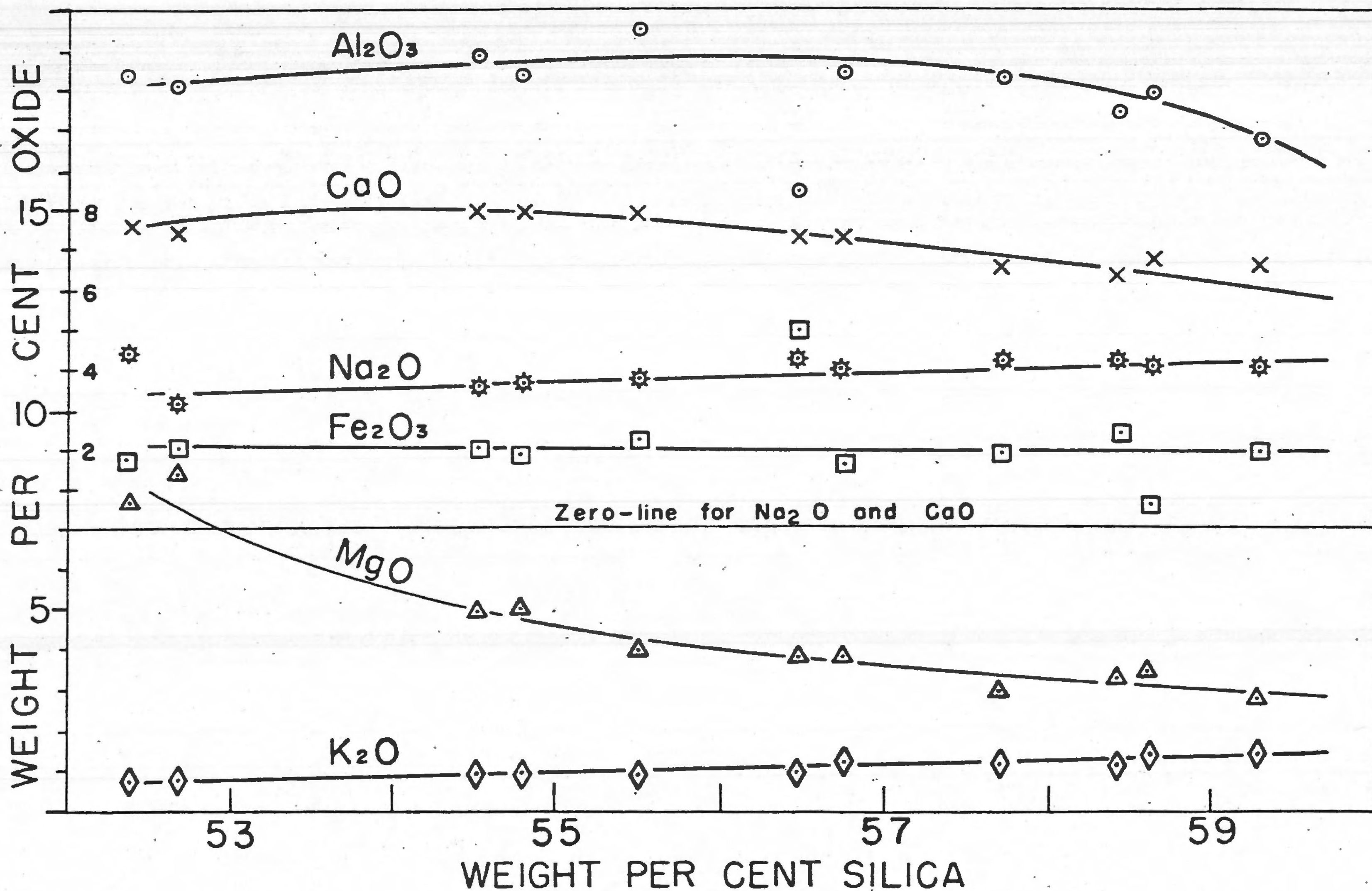

Fig. 8.--Variation Diagram of Lavas from Collier Cone

CONCLUSIONS

Recognition of analytically significant chemical variation between and within lava flows leads naturally to the question: How are such variations related to the mineralogy, volcanic history, and geographic position of those flows?

Chemical and Mineralogical Composition

The mineralogical character and silica content of more than 200 samples have been outlined in previous sections. Increased silica in the lavas is generally attended by a decrease in tridymite, an increase in the amount of glass, and an increase in the proportion of phenocrysts. Plagioclase microlites become more sodic and olivine grains become more obviously rounded and embayed. To each of these generalizations, however, there are many exceptions. Silica can vary between flows by as much as 9 per cent while the appearance of the rock remains outwardly uniform (Anderson Creek and Sims Butte, for example). On the other hand, samples which appear to be very different beneath a binocular microscope or in thin section might contain the same percentage of silica (Clear Lake and South Belknap Flows, for example). It must be concluded that mineralogical composition, especially the porphyritic fraction, is a poor index to chemical composition of the glass-rich basalts included in this study.

Chemical Composition and Eruptive History

If it is assumed that the analytical data represent a sufficiently random and complete sample of each lava unit, average values and ranges of values become significant parameters which can be associated with the units and related to their eruptive history. Average silica values of volcanic units for which this assumption seems reasonable are presented in Fig. 7. Comparison of Fig. 7 with Table 1 reveals no significant correlation between average silica content and age of lava. If more informative but less precise stratigraphic data are included in the comparison, interesting but severely limited correlations emerge. The Lava Lake Flow from Nash Crater and other early flows from the Central Group and North Sand Mountain were succeeded by more silicic lavas from the same vent areas (Fish Lake Flows, late Central Group, and Clear Lake Flow, respectively). Little Nash Crater may be related in the same way to the slightly older Lost Lake Group. A similar, but less pronounced, trend is evident in the lavas of the Belknap shield.

The increase in silica content of lavas within the Central Group was accompanied by a change from petrographic type 1 (phenocrysts of plagioclase lacking) to type 2 (phenocrysts of plagioclase few and small), and within lavas of Sand Mountain, by a change from type 2 to type 3 (phenocrysts of plagioclase small, but abundant). Lavas from Nash Crater, Little Nash Crater, Lost Lake Group and the Belknap vents are of uniform appearance regardless of relative age or silica content.

If attention is focused upon silica variation within flows that were confined to long, relatively narrow channels, it is possible to outline compositional changes which occurred as successive batches of lava emerged from the vents. Reconstructions of this type have been applied to lavas from Collier and Yapoah Cones, with results shown in Fig. 9. It should be emphasized that reconstructed distances from the vent (the abscissa of Fig. 9) are measured along centers of composite lava channels in accordance with interpretations of volcanic history. Such distances are convenient for ordering data and carry only qualitative significance.

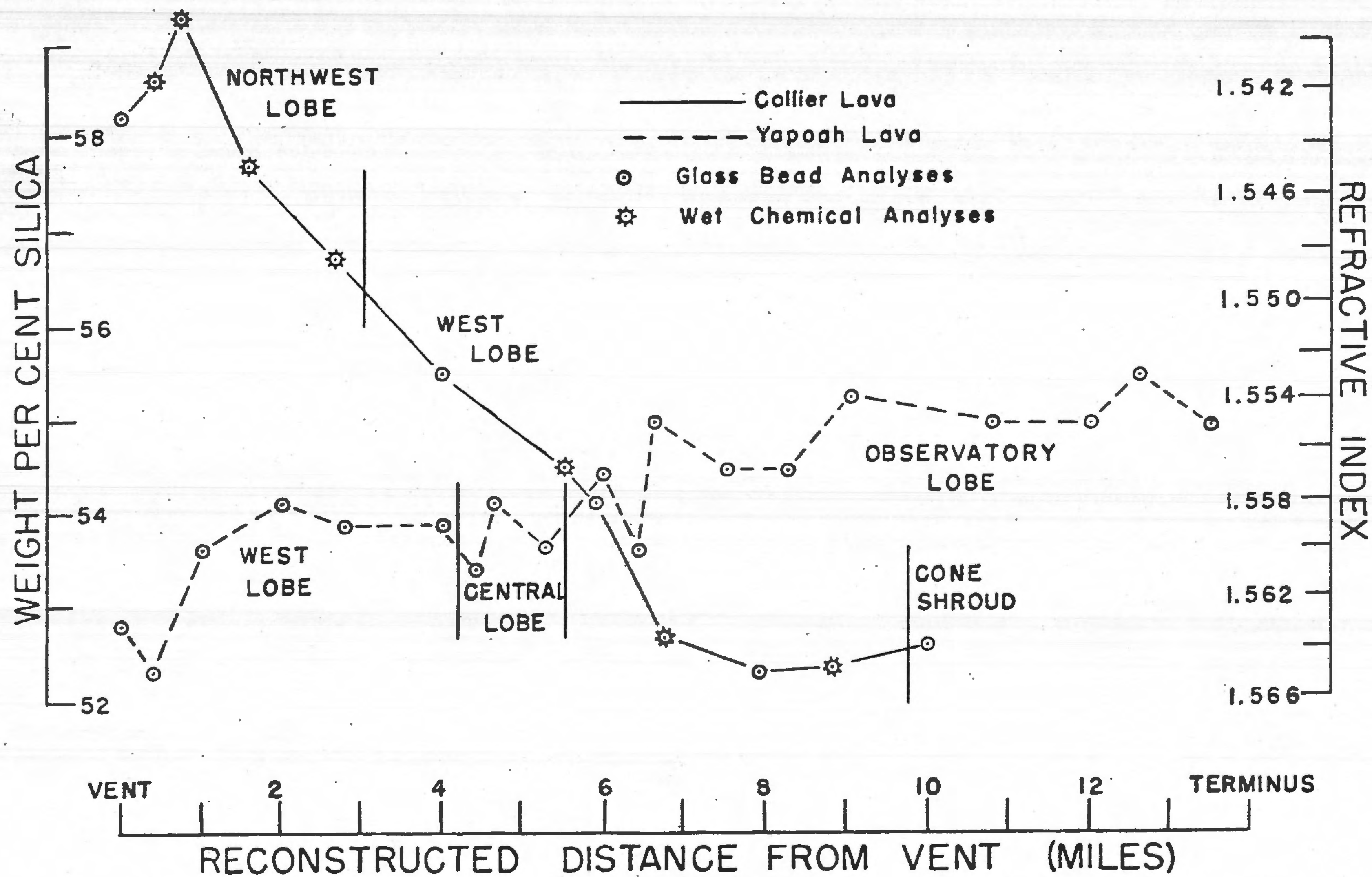

Fig. 9.--Silica Variation in Selected Lava Flows as a Function of Distance from their Vents

Collier and Yapoah lavas are almost indistinguishable except where abundant phenocrysts of olivine appear instead of pyroxene in a low-silica segment of the west Collier lobe. They were erupted from vents which are less than two miles apart. A close genetic relationship is further suggested by the data of Fig. 9, coupled with the fact that Yapoah eruptions preceded those from Collier Cone. The first Yapoah lava contained 55 per cent silica. During succeeding eruptions, silica decreased in a persistent, if irregular, manner until, as the eruptions ceased, values of 52 to 53 per cent were reached. During subsequent eruption of Collier lava, silica continued to decrease, then increased from 52 to 59 per cent as the final Collier lobes were formed.

During the 1959 summit activity at Kilauea Iki, Hawaii, silica content of lavas changed in an irregular fashion (Murata and Richter, 1966), similar in trend and magnitude to that detected in the Yapoah lobes. Changes of this type can be accounted for if it is assumed that the roof of a magma reservoir, from which early formed phenocrysts of olivine and pyroxene have settled, has been pierced by a volcanic conduit. Silicic magma would be withdrawn from the top of the reservoir, followed by less silicic magma, rich in olivine and pyroxene. The resulting lava flow might then become progressively less silicic during eruption.

Paricutin volcano, Mexico, like Collier Cone, erupted lavas which became progressively enriched in silica (Wilcox, 1954). In accounting for this apparent anomaly, Wilcox appealed to a "fortuitous" eruption of magma derived from the side rather than from the top of an horizontally stratified reservoir. The following observations are pertinent to this problem:

1. The Anderson Creek Flow and three separate streams of lava from Four-in-One Cone were not studied as extensively as the Collier lobes but the same compositional trend is associated with

them; it would appear that such trends are not, in reality, unusual, and that fortuitous circumstances are not adequate to account for them.

2. The close correspondence in age, lithology, and geographic position between Yapoah and Collier eruptions, and the sequence of compositional changes which continued without a break from the one to the other, suggest that both were fed from the same source.
3. Wilcox (1954) concluded that settling of early-formed crystals was not an adequate process to account for variations in the lava of Paricutin and that assimilation of sial by basalt magma had played an important role. Quartz-rich xenoliths in various stages of dissolution were found among the ejecta of Paricutin. While insufficient data are at hand to demonstrate the necessity of magmatic assimilation at Collier Cone, variation diagrams of Collier lava (Fig. 8) and Paricutin (Wilcox, 1954, p. 318) are almost identical. Partially melted, frothed xenoliths containing quartz were ejected during the final eruptive phases of both Four-in-One and Collier Cones. Moreover, embayed olivine and corroded sodic feldspar occur together more abundantly in the final Collier lavas than elsewhere.
4. Silica content of Four-in-One lava varies 8 per cent in the same "anomalous" manner as Paricutin lava, but all Four-in-One rocks are devoid of phenocrysts larger than 1 mm and the microphenocrysts seldom exceed 0.1 mm. Advanced crystallization differentiation is therefore unlikely.

The following is offered as an alternate hypothesis: Yapoah and Collier eruptions withdrew successive batches of magma from the roof of the same reservoir. Processes of crystal settling gave rise to a compositional gradient, especially in the upper levels of the magma column. Silica content was about 55 per cent near the roof and decreased to 52 per cent in olivine-rich levels below. At still greater depths, assimilation of sialic material (liquid?) containing sodic plagioclase increased the content of silica to at least 59 per cent. At these levels, olivine was in process of resorption and sodic plagioclase was being replaced by labradorite. The composite magma column was then extruded during Yapoah and Collier eruptions.

Chemical Composition and Geographic Position

If the data of Fig. 7 (silica content of volcanic units) are compared with Fig. 1 (index map), a general correlation between composition and geographic position of Recent lavas is apparent. Average silica content and range of silica variation increases from west and northwest to east and southeast. Two Butte, Park Creek, and West Maxwell rocks do not follow this pattern, but as explained in a previous section, they may antedate the Recent lavas. Minor irregularities in this compositional progression (1 to 2 per cent more silica than would be expected from their geographic position) are introduced by Little Nash Crater, Fish Lake Flows, late Central Group, Clear Lake Flow, and the flow from the south vent of South Sand Mountain. Each one represents a late stage eruption from a vent area which had previously produced less siliceous, less porphyritic, and presumably more primitive lava.

Available evidence suggests, therefore, that silica content of Recent lavas increases from northwest to southeast within the study area, and that minor irregularities in this progression are the result of local crystallization-differentiation. The progression itself is here attributed to the same processes of assimilation which may have been responsible for the silica variations in Four-in-One and Collier lavas. Outcrops of silicic rock of the central Cascade Range are confined to the immediate vicinity of the Three Sisters, adjacent to the southeast corner of the study area (Williams, 1957). Glaciated domes of obsidian and rhyolite occur near Four-in-One and Collier Cones. Recent domes and flows of dacite are abundant on the slopes of Middle and South Sisters. None of these rocks contains quartz phenocrysts (Williams, 1944). Consequently, it is reasonable to suggest that silicic and basaltic magmas may have mixed at depth, ultimately producing hybrid lavas of intermediate compositions, without giving rise to the quartz basalts which are so often associated with this process (Finch and Anderson, 1930; Larsen _et al._, 1938).

If the areal pattern of silica content in Recent basaltic lavas between Three Fingered Jack and North Sister is the result of contamination of basalt magma, and if the source of contamination is a silicic liquid beneath the Three Sisters volcanoes, then confirmation might be achieved through study of Recent basaltic lavas to the east and south of the South Sister. In this area, Recent basaltic lavas are widespread and intimately associated with Recent eruptions of dacite (Williams, 1957).

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APPENDIX A

SILICA CONTENT OF SAMPLES

TABLE 3

SILICA CONTENT OF SAMPLES

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
		Park Creek Flows		
1		3	1.555	55
2		3	1.556	55
		West Maxwell Flows		
3		3	1.556	55
4		3	1.554	55
5		3	1.553	55
6		3	1.555	55
7		3	1.559	54
		Little Nash Crater		
8	Cinders		1.571	51
9	Cone bomb	1	1.576	50
10		1	1.574	50
11		1	1.575	50
12		1	1.575	50
		Lost Lake Group		
13	Cinders		1.590	47
14	Cinders		1.588	48
15	Cinders		1.587	48
16	Cinders		1.583	49
17	Ash from bog		1.585	48
18		1	1.589	48
19		1	1.590	47
20		1	1.589	48
21		1	1.586	48
22		1	1.590	47
		Nash Crater		
23	Cinders		1.570	51
24	Cinders		1.573	50
25	Ash from locality 8		1.568	52
26		1	1.585	48
27		1	1.587	48
28		1	1.583	49
29		1	1.571	51
30		1	1.571	51
31		1	1.571	51
32		1	1.571	51

TABLE 3--Continued

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
33		1	1.573	50
34	Cinders		1.588	48
35	Cinders		1.584	48
	Central Group			
37	Cinders		1.583	49
38	Cinders		1.571	51
39	Cinders		1.577	50
40	Cinders		1.579	49
41	Cinders		1.580	49
42	Cone bomb	1	1.579	49
43	Cinders		1.581	49
44		1	1.583	49
45		1	1.585	48
46		1	1.585	48*
47		1	1.585	48
48		1	1.587	48
49		1	1.585	48
50		1	1.588	48
51		1	1.585	48
52		1	1.583	49
53	Uncertain affinities	1	1.585	48
54		2	1.571	51
55		2	1.572	51
56		2	1.577	50
	Sand Mountain Cones			
57	Cinders		1.576	50
58	Cinders		1.583	49
59	Cinders		1.569	51
60	Cinders		1.570	51
61	Ash		1.585	48
62	Base of Big Lake ash section		1.582	49
63	Ash section		1.582	49
64	Ash section		1.582	49
65	Ash section		1.580	49
66	Ash section		1.578	49
67	Top of Big Lake ash section		1.576	50
68	Ash near Blue Lake Crater		1.584	48
69		2	1.575	50*
70		2	1.582	49
71		2	1.577	50
72		2	1.573	50
73		2	1.578	49
74		3	1.570	51*
75		3	1.569	51

TABLE 3--Continued

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
76		3	1.568	52
77		3	1.569	51
78		3	1.569	51
79		3	1.572	51
80		3	1.573	50
81		3	1.571	51
82		3	1.572	51
83		3	1.572	51
	South Group			
84	Cinders		1.580	49
85	Cinders		1.585	48
86	Cinders		1.578	49
87	Cinders		1.581	49
88		1	1.586	48
89		1	1.585	48
90	Much tridymite	1	1.577	50
91		1	1.588	48
92		1	1.582	49
93		1	1.577	50
94		1	1.580	49*
95		1	1.582	49
96	Head of steptoe in Belknap lava field	1	1.579	49
	Anderson Creek Flows			
97		2	1.577	50
98		2	1.589	48
99		2	1.585	48
100		2	1.586	48
101		2	1.585	48
102		2	1.594	47*
103	Much tridymite	2	1.580	49
104		2	1.594	47
	Inaccessible Alignment			
105	Cinders		1.588	48
106	Cinders		1.589	48
107		2	1.584	48
108		2	1.585	48
109		2	1.584	48
110		2	1.590	47
	Hoodoo Butte			
111	Large bomb	2	1.563	53

TABLE 3--Continued

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
	Cinder Pit			
112	Conduit plug	2	1.563	53
	Blue Lake Crater			
113	S.W. rim bomb	4	1.559	54
114	E. rim bomb	4	1.562	53
115	Base of Suttle Lake cinder section		1.564	53
116	Cinder section		1.564	53
117	Cinder section		1.564	53
118	Cinder section		1.562	53
119	Cinder section		1.564	53
120	Top of Suttle Lake cinder section		1.565	52
	Spatter Cone Chain			
121	N. crater, N. segment	4	1.565	52
122	N. crater, S. segment	4	1.564	53
123	S. crater, S. segment	4	1.563	53
	Belknap Crater			
124	Cinders from locality 127		1.565	52
125	Ash		1.569	51
126		6	1.569	51
127		6	1.565	52
128		6	1.566	52
129		6	1.575	50
130		6	1.583	49
131		6	1.583	49*
132		6	1.572	51*
133		2	1.578	49
134		6	1.587	48*
135		2	1.578	49*
	Little Belknap			
136		6	1.563	53*
137		6	1.565	52
138		6	1.565	52
	South Belknap			
139	Cinders		1.574	50
140		6	1.566	52
141	From locality 140	6	1.567	52*
142		6	1.565	52

TABLE 3--Continued

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
	Twin Craters			
143		2	1.578	49
144		2	1.572	51
	Scott Mountain			
145	Summit flow	6	1.570	51
	Two Butte			
146	Flow, S. base	1	1.583	49
	Sims Butte			
147	Bomb	2	1.569	51
148		2	1.572	51
149		2	1.574	50
150		2	1.563	53
151		2	1.567	52
152		2	1.553	55
153	From locality 152	2	1.550	56
154		2	1.575	50
155		2	1.572	51
156	From locality 155	2	1.573	50
	Condon Butte			
157	Lava on crater rim	2	1.570	51
	Yapoah Crater			
158	Cinders		1.554	55
159	Cinders		1.558	54
160		4	1.563	53
161		4	1.565	52
162		4	1.560	54
163		4	1.558	54
164		4	1.559	54
165		4	1.559	54
166		4	1.561	53
167		4	1.558	54
168		4	1.560	54
169		4	1.557	54
170		4	1.560	54
171		4	1.555	55
172		4	1.557	54
173		4	1.557	54

TABLE 3--Continued

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
174		4	1.554	55
175		4	1.555	55
176		4	1.555	55
177		4	1.553	55
178		4	1.555	55
179		4	1.553	55
180		4	1.554	55
181		4	1.558	54
182		4	1.554	55
183	Base of lava section, locality 182	4	1.552	56
184	Lava section	4	1.552	56
185	Lava section	4	1.554	55
186	Lava section	4	1.553	55
187	Lava section	4	1.554	55
188	Lava section	4	1.551	56
189	Lava section	4	1.553	55
190	Top of lava section, locality 182	4	1.553	55
191	Collapsed tube, roof sample	4	1.551	56
192	Questionable sequence	4	1.556	55
	Four-in-One Alignment			
193	Cinders contaminated with pumice		1.540	59
194	Cinders		1.565	52
195		3	1.550	56
196		3	1.551	56
197		3	1.548	57
198		3	1.553	55
199		3	1.571	51
200		3	1.559	54
201		3	1.556	55
202		3	1.561	53
203		3	1.552	56
204		3	1.565	52
205		3	1.560	54
	Collier Cone			
206	Bomb	4	1.555	52
207		4	1.560	54
208		4	1.540	59*
209		4	1.541	59*
210		4	1.564	53
211		4	1.544	58*
212		4	1.555	55
213	North levee	4	1.554	55
214	Central gutter	4	1.550	56*
215	South levee	4	1.554	55

TABLE 3--Continued

Sample Number	Remarks	Petrographic Type	Refractive Index	Silica (Wt.%)
216		4	1.553	55*
217		4	1.547	57*
218	From locality 217	4	1.554	55
219	From locality 217	4	1.550	56
220	Central gutter	4	1.559	54*
221	From locality 220	4	1.559	54
222	From locality 220	4	1.558	54
223	From locality 220	4	1.554	55
224	From locality 220	4	1.557	54
225	From locality 220	4	1.564	53
226	S. intermediate levee, locality 220	4	1.558	54
227	From locality 226	4	1.556	55*
228	S. marginal levee, locality 220	4	1.556	55
229	From locality 228	4	1.555	55
230	N. intermediate levee, locality 220	4	1.553	55
231	From locality 230	4	1.561	53
232	N. marginal levee, locality 220	4	1.554	55
233	Central gutter	4	1.558	54
234	N. marginal levee, locality 233	4	1.553	55
235	N. intermediate levee, locality 233	4	1.561	53
236	S. intermediate levee, locality 233	4	1.559	54
237	S. marginal levee, locality 233	4	1.554	55
238	Central gutter	5	1.563	53*
239	From locality 238	5	1.556	55
240	N. margin, locality 238	4	1.551	56
241	N. marginal levee, locality 238	4	1.547	57
242	N. intermediate levee, locality 238	4	1.553	55
243	S. intermediate levee, locality 238	4	1.549	56
244	S. marginal levee, locality 238	4	1.551	56
245		4	1.553	55
246	Levee north of locality 247	4	1.553	55
247		4	1.556	55
248	Levee south of locality 247	4	1.551	56
249	Levee north of locality 250	4	1.555	55
250		4	1.550	56
251	Levee north of locality 252	4	1.560	54
252		5	1.565	52
253	Levee south of locality 252	4	1.561	53
254	Levee north of locality 255	5	1.547	57
255		5	1.563	53*
256	Levee south of locality 255	5	1.551	56
257	From locality 256	4	1.551	56
258		4	1.545	57
259		4	1.543	58*
260		4	1.553	55
261		4	1.543	58

APPENDIX B

LOCATION OF ANALYZED SAMPLES

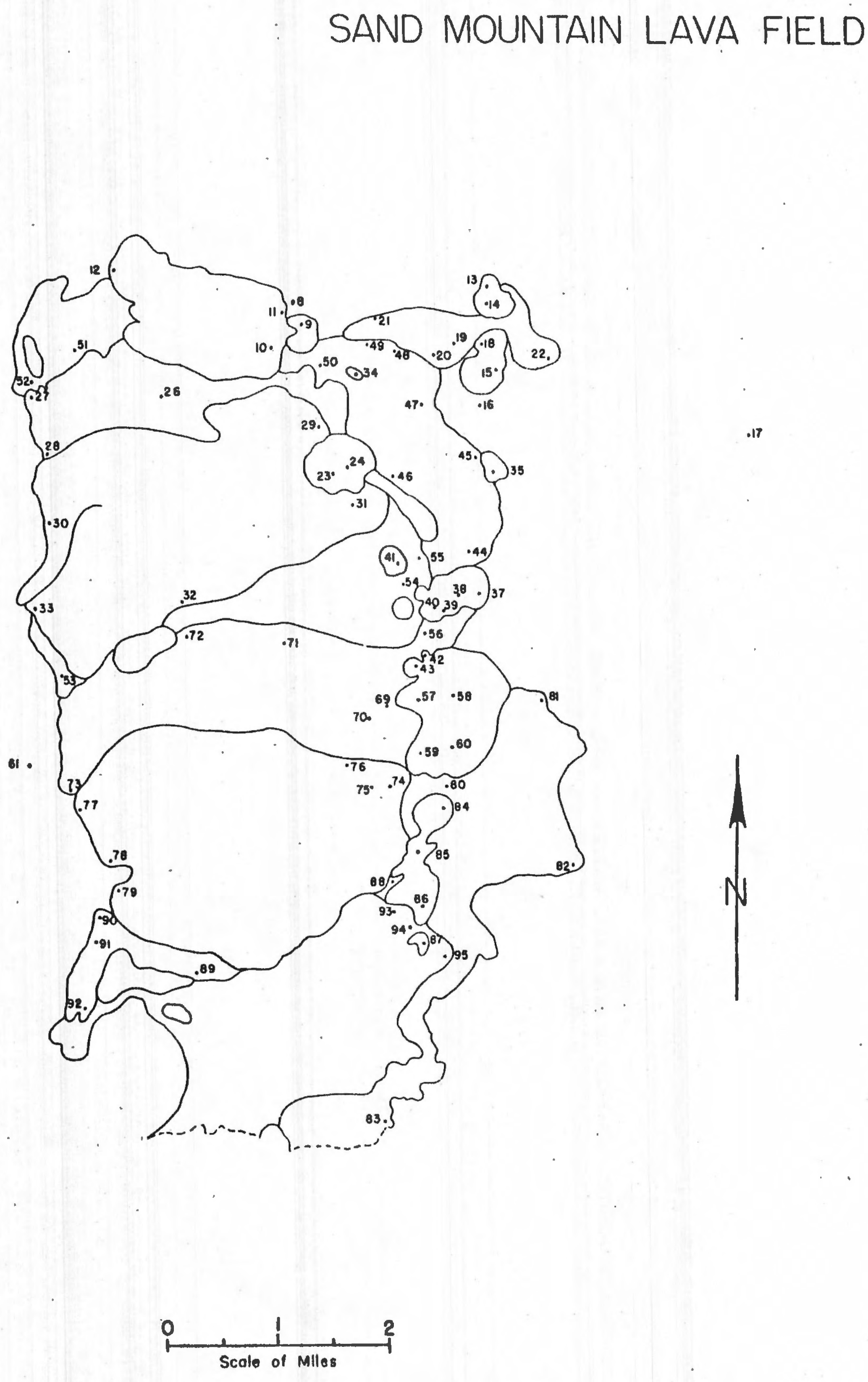

Fig. 10.--Location of Samples Numbered 8 to 95

BELKNAP VOLCANO AND VICINITY

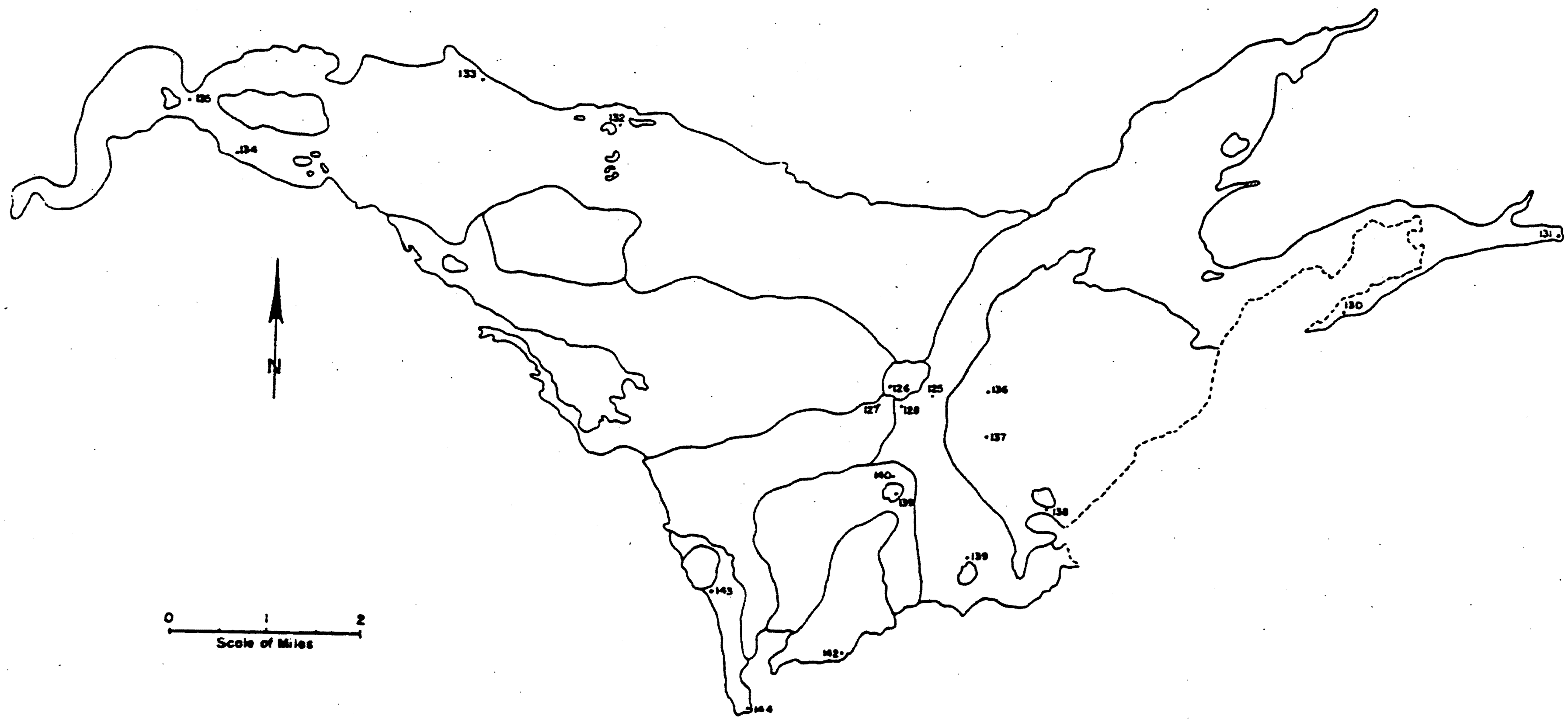

Fig. 11.--Location of Samples Numbered 124 to 144

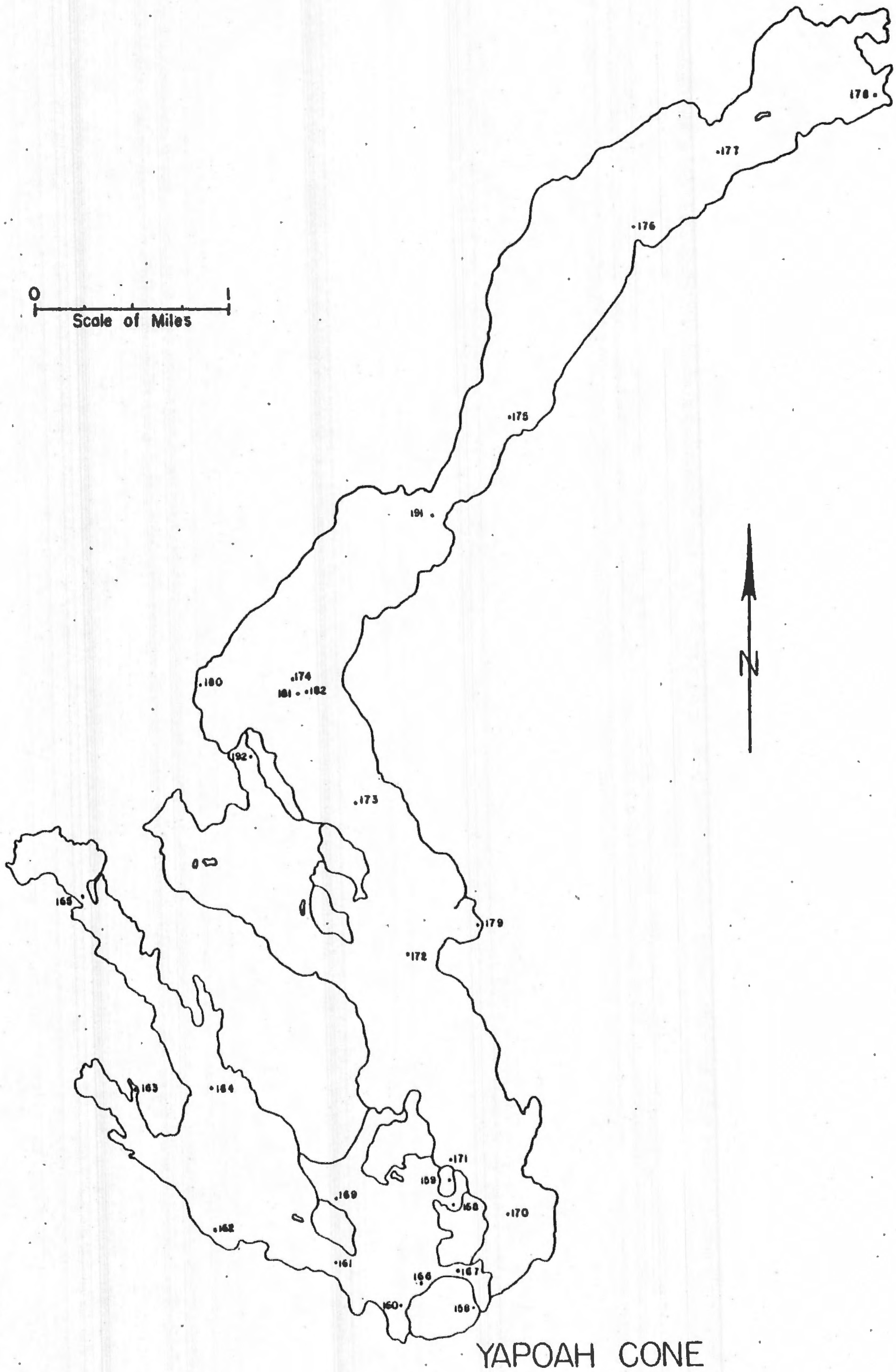

Fig. 12.--Location of Samples Numbered 158 to 192

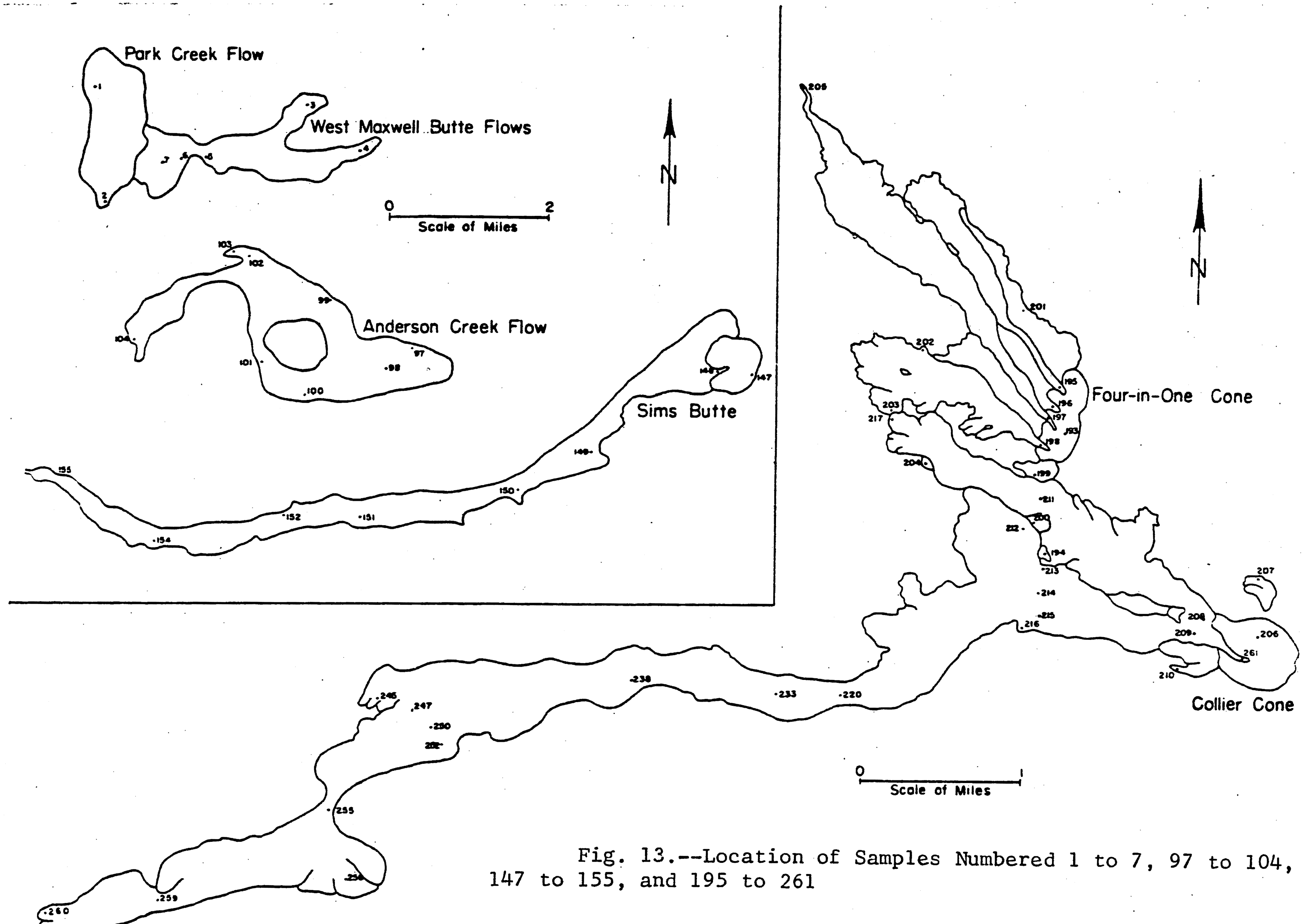

Fig. 13.--Location of Samples Numbered 1 to 7, 97 to 104, 147 to 155, and 195 to 261

RECENT VULCANISM BETWEEN THREE FINGERED JACK

AND NORTH SISTER, OREGON CASCADE RANGE

ABSTRACT

by Edward Morgan Taylor, Ph.D.
Washington State University, 1967

Chairman: C. D. Campbell

Recent basaltic lavas, cinder cones, and ash deposits between Three Fingered Jack and North Sister in the Cascade Range of Oregon are chiefly centered about a large shield volcano called Belknap Crater and along a linear belt of volcanoes referred to as the Sand Mountain Alignment. Several other smaller volcanic craters and lava flows occupy surrounding areas. Nine radiocarbon ages and extensive stratigraphic data reveal a complex volcanic history of at least 2,500 years duration. There is no general correlation or trend between age and geographic position of the volcanoes.

The volcanic materials have been sampled and analyzed in a manner designed to reveal geographic trends in composition variables both within and between eruptive units. Complete chemical analyses were obtained for 12 samples and silica content was measured in 261 samples by a method employing refractive index of the fused rock. The porphyritic fraction of each sample was examined under a binocular microscope and several thin sections from each of six eruptive units were studied. Silica content of the lavas varies from 47 to 59 weight per cent. Within single flows, silica and magnesia may vary as much as 7 and 5.7 per cent, respectively. Most samples are black, glassy basalt containing phenocrysts of plagioclase and olivine. No consistent relation exists between silica content of the rocks and composition, abundance, or

size of phenocrysts.

While no general relationship exists between silica content and age of the lava fields, several flows at the north base of the North Sister display clear compositional trends which are related to their eruptive history. Silica in lavas from Yapoah Cone decreased from 55 to 52 per cent during eruption. This type of change has been observed in the lavas of Hawaii, and is to be expected if settling of early-formed crystals causes a magma column to be enriched in silica above, and impoverished in silica below. Lavas from Collier Cone changed in the opposite sense, from 52 to 59 per cent silica. They contain phenocrysts of corroded sodic feldspar and embayed olivine. Accidental quartz-rich ejecta associated with final eruptions of Collier Cone suggest that assimilation of silicic material in the lower reaches of a magma column contribute to the mixed aspect of phenocrysts and the unusual compositional trend.

The average and the range of silica content of Recent basaltic lavas increases in regular progression through the study area from northwest to southeast, toward the Three Sisters volcanoes. Outcrops of silicic rocks in the Central Cascade Range are restricted to the immediate vicinity of the Middle and South Sisters. These relationships are interpreted as additional evidence that basaltic and silicic material has mixed at depth, giving rise to lavas of intermediate and variable composition.

WSU-363. Marmes Rock-shelter/45-FR-50 — 10,810 ± 275; 8860 B.C.

Shell from Site F-65(5) 8-10A.

WSU-366. Marmes Rock-shelter/45-FR-50 — 10,475 ± 270; 8525 B.C.

Shell from Site F-65(5) 8-10B.

Palouse River series, Washington

Shell and charcoal from Site 45-WT-2, Whitman county, Washington. Samples coll. summer, 1963 by C. R. Nance, unless otherwise stated.

WSU-170. Palouse River — 7300 ± 180; 5350 B.C.

Shell from Pit CL-9 at 94.50 ft below datum, beneath layer of Mazama ash. *Comment*: confirms date of Cascade Point-type Archeological Complex found below volcanic ash.

WSU-171. Palouse River — 150 ± 80; A.D. 1800

Charcoal mixed with corn from Pit CL-13, 1 to 1.1 ft below surface. Coll. 1963 by W. Moore and J. Chatters, WSU Archeol. field crew.

WSU-187. Palouse River — 2740 ± 110; 790 B.C.

Charcoal from Pit CL-5, 95.58 to 94.9′ below datum by fire hearth at Feature 6, (7° 2.5′ S Lat, 15° 1.5′ W Long). *Comment*: should date deposits below slump in this part of site.

Vashon Island series, Washington

Charcoal and shell from Leo Long property at InterQuartermaster Harbor on Vashon Is. Samples coll. 1965 by Dr. R. M. Chatters and subm. by Leo Long.

WSU-348. Vashon Island — 1670 ± 160; A.D. 280

Charcoal from upper midden on Vashon Is.

WSU-349. Vashon Island — 1890 ± 170; A.D. 60

Shell from lower midden on Vashon Is.

WSU-354. Vashon Island — 1740 ± 170; A.D. 210

Shell mixed with finely divided charcoal from lower midden on Vashon Is.

WSU-367. Tucannon River, Washington — 1720 ± 165; A.D. 230

Bone from mouth of Tucannon R., 5 mi S of Starbuck, Columbia county, Washington. Coll. by C. M. Nelson and subm. by Dr. R. D. Daugherty, Anthropol. Dept., Washington State Univ. *Comment*: provides date on lower part of loess.

Wawawai series, Washington

Shell and charcoal from site 3.5 mi down Snake R. from Wawawai, Whitman county, Washington. Coll. 1965 by Richard Sprague, Dept. of Anthropol., Washington State Univ.

WSU-409. Wawawai/45-WT-36-C10 — 7710 ± 150; 5760 B.C.

Shell from Camas Prairie RR cut, near Thorn Thicket Creek; elev. 99.50 to 99.25 ft. *Comment*: indicates relative placement of geological deposits containing sample and its level.

WSU-410. Wawawai/45-WT-36-F4 — 470 ± 610; A.D. 1480

Charcoal mixed with shell from Camas Prairie RR cut; elev. 101.77 ft. *Comment*: indicates relative placement of component assoc. with feature.

WSU-411. Wawawai/45-WT-36-F2 — 834 ± 560; A.D. 1116

Charcoal from Camas Prairie RR cut near Thorn Thicket Creek. Feature 2, elev. 102.50 ft. *Comment*: indicates relative placement of component assoc. with feature.

II. GEOLOGIC SAMPLES

A. Idaho

WSU-283. Troy, Idaho — 3180 ± 210; 1230 B.C.

Charcoal chunks covered by soil from hand-dug soil pit ca. 18 to 24 ft below surface, Site 64-IDA-2923, 5 mi NW of Troy, Latah county, Idaho. Soil enclosing sample is high in volcanic ash. Coll. 1964 by Lowell Garber; subm. by Maynard Fosberg, Dept. of Agricultural Biochem. and Soils, Univ. of Idaho, Moscow, Idaho.

B. Montana

WSU-369. Upper Yellowstone Drainage, Montana — 1230 ± 160; A.D. 720

Charcoal from Site 24, Pa 301, Occupation Level III, ca. 2 mi N of Gardiner, Montana, immediately N of Yellowstone Park (3° 45′ N Lat, 110° 41′ Long). Coll. by G. W. Arthur and subm. 1965 by Montana State Univ., Missoula, Montana.

C. Oregon

Blue Lake Crater series, Oregon

Charcoal from Blue Lake Crater area, Oregon. Samples are from interface cinders from Blue Lake Crater and ash from Sand Mt. volcano. Coll. and subm. by E. M. Taylor, Dept. of Geol., Washington State Univ. (Taylor, 1965).

WSU-291. Blue Lake Crater/T-13-S **3440 ± 250** **1490 B.C.**

Charcoal mixed with ash from road cut exposure at depth 15 ft from surface, from Site R-8-E, #S-16.

WSU-292. Blue Lake Crater/T-14-S **1590 ± 160** **A.D. 360**

Charred tree roots from lava flow at Site R-7-E, #S-28.

WSU-364. McKenzie Pass, Oregon **2883 ± 175** **933 B.C.**

Charcoal mixed with volcanic ash 1 mi W of Dee Wright Observatory, McKenzie Pass, Oregon Cascades, Site TFJ-207. Coll. 1965 by E. M. Taylor.

WSU-365. Three Sisters area, Oregon **2550 ± 165** **600 B.C.**

Charcoal ⅛ mi E of Four-in-One Cinder Cone, Three Sisters area, Oregon Cascades, Site TS-374. Coll. 1965 by E. M. Taylor.

Three-Fingered Jack Quad series, Oregon

Charred wood and root from Three-Fingered Jack Quad area. Coll. and subm. by E. M. Taylor.

WSU-371. Three-Fingered Jack Quad **1950 ± 150** **A.D. 1**

Charred wood near Jack Pine Road, S of Pass Highway. *Comment*: dates 1st eruptions of coarse cinders from Lost Lake Cones, which are among oldest of Sand Mt. volcanic field.

WSU-372. Three-Fingered Jack Quad **3850 ± 215** **1900 B.C.**

Charred root bark mixed with soil and rootlets near Old Santiam Wagon Rd. *Comment*: dates Fish Lake lava flow from Nash Crater, one of youngest flows of Sand Mt. lava fields.

D. Utah

WSU-246. Big Cottonwood Canyon, Utah **5600 ± 170** **3650 B.C.**

Marl from Big Cottonwood Canyon, S of Salt Lake City, Utah. Should date maximum of Lake Bonneville for Pinedale standard. Coll. and subm. by Roald Fryxell, Dept. of Geol., Washington State Univ. and U.S. Geol. Survey. *Comment*: will provide date closely corresponding to age of maximum Lake Bonneville stand during Pinedale time.

E. Washington

WSU-155. Lower Grand Coulee, Washington **12,000 ± 310** **10,050 B.C.**

Shell from Site LGC-2, abandoned quarry in Glacier Peak ash at E wall of Lower Grand Coulee, ca. 8 km N of Soap Lake, Washington. Coll. and subm. by Roald Fryxell.

WSU-231. Round Lake, Washington **10,210 ± 210** **8260 B.C.**

Marl from NW side of Round Lake in Twin Lake area, Washington. Coll. and subm. by Roald Fryxell.

WSU-232. Willow Island, Washington **1440 ± 185** **A.D. 510**

Wood from Willow Is., S of Whiskey Dick at Monolith site. Coll. and subm. by Roald Fryxell.

WSU-243. Moran Prairie, Washington **20,200 ± 550** **18,250 B.C.**

Charcoal of "Miocene" oak from Moran Prairie, S of Spokane, Washington. Log buried by lava flow. Coll. and subm. by Kurt Lunum, Dept. of Forestry, Washington State Univ.

III. OCEANOGRAPHIC SAMPLES

A. Arabia, NE Africa

Red Sea series, between Arabia and NE Africa

Calcareous fragments cementing *Creseis* and planktonic *Foraminifera* from Red Sea from research vessel *Vema*. Coll. 1958 and subm. by Yvonne Herman, Dept. of Geol., Washington State Univ.

WSU-374. Red Sea/V-14-120 **12,625 ± 715** **10,675 B.C.**

Sample at depth 70 cm at (20° 26′ N Lat, 38° 13′ E Long). *Comment*: WSU-374, 375, and 376 give absolute age for onset of unusual conditions which lead to precipitation of submitted "hard crust" in Red Sea. This is 1st instance that cemented calcareous rocks have been cored from ocean bottom. It is expected that precipitation of $CaCO_3$ took place at end of last glacial period as result of temperature increase and temporary separation of basin from Indian Ocean.

WSU-375. Red Sea/V-14-117 **11,950 ± 150** **10,000 B.C.**

Sample at depth 40 cm at (18° 48′ N Lat, 39° 31′ E Long).

WSU-376. Red Sea/V-14-119 **10,825 ± 845** **8875 B.C.**

Sample at depth 55 cm at (20° 50′ N Lat, 38° 17′ E Long).

IV. HYDROLOGIC SAMPLES

Pullman-Moscow Water Dating Project series, Washington-Idaho

Dates reported below resulted from study in which carbon-14 dating techniques were used as inventory technique and as means of contributing to basic knowledge of ground-water accumulation and movement.

In this study of Pullman (Washington) — Moscow (Idaho) groundwater basin of E Washington and W Idaho, data indicate that ground-