UNITED STATES DEPARTMENT OF THE INTERIOR

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STRATIGRAPHY AND MAJOR ELEMENT GEOCHEMISTRY OF THE LASSEN VOLCANIC CENTER, CALIFORNIA

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This report is preliminary and has not been reviewed for conformity with U. S. Geological survey editorial standards and stratigraphic nomenclature.

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ABSTRACT

Detailed geologic mapping of 200 km^2 in and near Lassen Volcanic National Park, California and reconnaissance of the surrounding area, combined with reinterpretation of data in the literature, allow definition of the Lassen Volcanic Center and provide the stratigraphic framework necessary for interpretation of major-element chemical data.

The Lassen Volcanic Center developed in three stages. Stages I and II produced Brokeoff Volcano, an andesitic composite cone that erupted mafic andesite to dacite 0.6 to 0.35 my ago. Volcanism then shifted in character and locale. Domes and flows of dacite and rhyodacite, and flows of hybrid andesite were erupted on the northern flank of Brokeoff Volcano during the period from 0.25 my ago to the present; these rocks comprise Stage III of the Lassen Volcanic Center.

Rocks of the Lassen Volcanic Center are typical of subduction-related calc-alkaline volcanic rocks emplaced on a continental margin overlying sialic crust. Porphyritic andesite and dacite with high Al_2O_3, low TiO_2, medium K_2O, and FeO/MgO 1.5-2.0 are the most abundant rock types. Early mafic andesite and late rhyodacite and hybrid andesite are subordinate in abundance. The Lassen Volcanic Center is surrounded by basaltic volcanoes. Two types of basaltic magmas are recognized: low-K, high-alumina olivine tholeiite, and calc-alkaline basalt and andesite.

Major-element chemical trends of rock sequences indicate a mafic to silicic evolution for magmas of the Lassen Volcanic Center, probably owing to crystal fractionation of calc-alkaline basalt. The Brokeoff Volcano developed by crystal fractionation involving olivine, augite, plagioclase, and magnetite and later hypersthene. Continued fractionation at higher crustal levels included hornblende and biotite, and produced the silicic rocks. Hybrid andesites were formed by mixing of silicic magma and calc-alkaline basalt.

INTRODUCTION

Scope

The goals of this study were to identify rocks associated with the Lassen Volcanic Center, to map their extent, and to establish a volcanic stratigraphy, thereby providing a framework for the interpretation of geochemical data. Whereas the volcanic stratigraphy and major-element chemical characteristics can be used to constrain petrologic hypotheses, modern petrologic modeling requires additional data and is beyond the scope of this report. For example, the lack of major-element analyses of phenocrysts precludes a rigorous approach to the calculation of fractionation trends. Work to obtain trace-element data, phenocryst compositions and abundances, and volume estimates of units is in progress. Petrologic modeling of the Lassen Volcanic Center will be attempted at such time as it is warranted. Petrologic interpretations included in this report are based on the limited data available at the time of its writing and should be considered as preliminary.

Previous Work

Early geologic investigations in the Lassen area recognized its affinities with the Cascade Range, the ruined Brokeoff Volcano, and the youthfulness of the silicic domes around Lassen Peak (Whitney, 1865; Diller, 1886, 1895). A discussion of this earlier work is contained in Williams' (1932) Geology of Lassen Volcanic National Park. Williams produced the first large scale (1:50,000) geologic map of the area, and his volcanic stratigraphy provides the basis for all subsequent work.

A Masters thesis by Wilson (1961) contains reconnaissance geologic mapping at 1:62,500 of a substantial area to the west and south of Williams' map. Wilson recognized and interpreted the volcanic history of Maidu Volcanic Center. Macdonald (1966) summarized southern Cascade geology and published geologic maps covering four 15-minute quadrangles, including the northern third of Lassen Volcanic National Park (LVNP) (Macdonald, 1963, 1964, 1965; Macdonald and Lydon, 1972). The Westwood Sheet of the State of California Geologic Map summarizes geologic mapping up to Macdonald's work (Lydon and others, 1960). Lydon (1968) mapped and interpreted volcanic rocks of the Mt. Yana center, preserved on Butt Mountain. P. A. Bowen (written communication, 1983) remapped the southwest corner of LVNP and obtained significant chemical data on rocks of the Lassen area. The U.S. Geological Survey has been conducting geologic mapping in LVNP since 1975 (Muffler and others, 1982a) with the goal of producing a geologic framework for geothermal studies and volcanic hazard assessment. Harwood and others (1981) and Helley and others (1981) produced detailed geologic maps of the areas between the Sacramento Valley and western boundary of the Lassen Peak quadrangle (121°45').

Major-element analyses have been performed on 250 rock samples from LVNP and vicinity (Williams, 1932; Macdonald, 1983; Smith and Carmichael, 1968; Gedeon, 1970; Fountain, 1975; P. A. Bowen, written communication, 1983; Clynne, unpublished; Muffler, unpublished). These data have been compiled and evaluated. Despite the abundance of data, a modern petrologic synthesis of the Lassen area has not been published.

G. B. Dalrymple (written communication, 1982) has provided K-Ar ages for 15 rock samples, mostly from Brokeoff Volcano, and a few other radiometric ages are available (Wilson, 1961; Gilbert, 1969; Crandell and others, 1974; Helley and others, 1981). Glacial stratigraphy and chronology provide some additional age control (Crandell, 1972; Kane, 1975, 1982).

Although geologic studies are numerous, detailed geologic mapping, geochronology, and chemical data of the quality necessary for detailed interpretation of the volcanic history and a modern petrologic synthesis of the Lassen magmatic system are not available. The subsequent sections are based on the literature and unpublished U.S. Geological Survey data and summarize knowledge to the time of this writing.

Definitions

Most classifications of igneous rocks rely on modal mineralogic data or a combination of mineralogic and chemical data. However, accurate modal data for volcanic rocks are difficult to obtain; therefore, classification based on chemical criteria is preferable. The abundance of major-element chemical data for rocks of the Lassen Volcanic Center facilitates the use of a chemical classification. The classification used in this study is a modification of the total alkalies versus silica classification used by Cox and others (1979). Because the rocks of the Lassen Volcanic Center are all subalkaline, the names are based solely on silica content (recalculated to 100 wt.%, anhydrous). Rocks with less than 52 wt.% SiO_2 are basalts, rocks with 52-57 wt.% SiO_2 are mafic andesites, rocks with 57-63 wt.% SiO_2 are andesites, rocks with 63-68 wt.% SiO_2 are dacites, rocks with 68-72 wt.% SiO_2 are rhyodacites, and rocks with greater than 72 wt.% SiO_2 are rhyolites. The rock names are modified by applying mafic phenocryst names in order of increasing mode. Thus "augite-hypersthene andesite" denotes a rock with 57-63 wt.% SiO_2, containing more phenocrysts of hypersthene than augite. When a group of analyses of a single rock unit straddles a rock name boundary, the average or mode of the group is used.

The term Lassen Volcanic Center refers to volcanic vents in the vicinity of Lassen Volcanic National Park, California that produced rocks in three major stages. Stages I and II cover the growth of an andesitic composite cone, Brokeoff Volcano, during the period from 600,000 to 350,000 years ago. Stage III covers intermediate to silicic rocks erupted as domes, flows, and pyroclastics during the period 350,000 years ago to the present.

Surrounding the Lassen Volcanic Center are shield volcanoes and lava flows of mafic composition, many of which were erupted contemporaneously with development of the Lassen Volcanic Center. The mafic rocks can be divided into two groups; the first with tholeiitic affinities and called low-K, high-alumina olivine tholeiite (HAOT), and the second with calc-alkaline affinities and called Lassen calc-alkaline basalt and andesite (LCBA).

Regional Geology - Pre-Late Pliocene

The Western Cordillera of North America have been the site of episodic magmatic activity throughout the Mesozoic and Cenozoic Eras caused by subduction of the Farallon Plate beneath the North American Plate. Magmatism in the Cascade arc is typical of that generated by consumption of an oceanic plate with the volcanic activity located on an overlying continental margin. The Cascade arc has a complex Cenozoic history. Poorly preserved pulses of magmatic activity occurred in Eocene (Armstrong, 1978) and Oligocene to Early Miocene time (McBirney, 1978). Neogene volcanism is better understood; pulses of activity occured in the Middle Miocene (Columbian Episode, 16-14 m.y.), late Miocene (Andean Episode, 11-8 m.y.), Pliocene (Fijian Episode 6-3 m.y.) and Quaternary (Cascadian Episode 2-0 m.y.) (Kennett and others, 1977).

The Lassen area is part of the Cascade Range geologic province, a linear belt of Tertiary and Quaternary volcanic rocks extending from northern California to British Columbia (fig. 1), capped by the

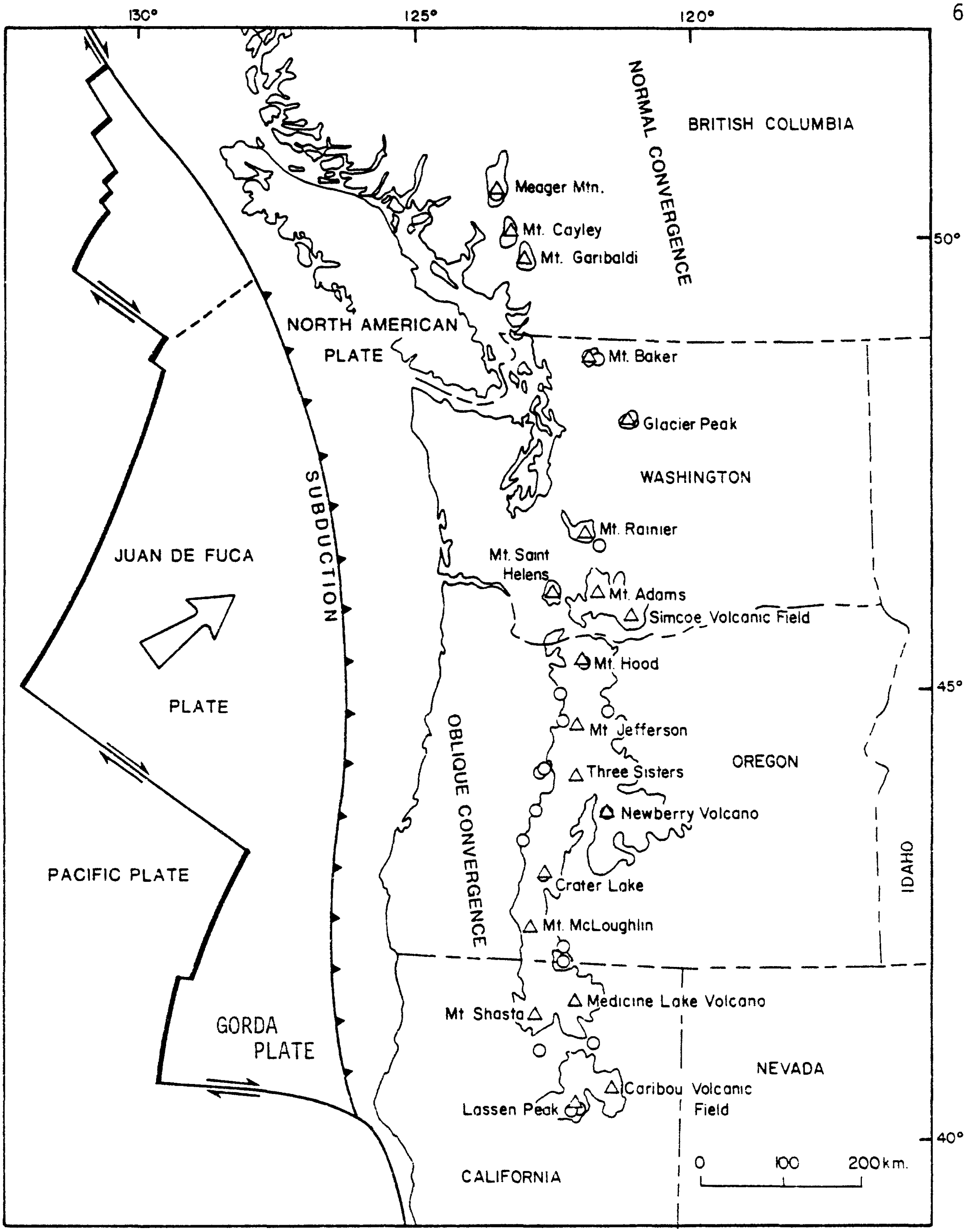

Figure 1 Location and tectonic setting of the Lassen Volcanic Center. Arrow indicates the direction of plate covergence and the solid line delineates Quaternary volcanic rocks.

familiar modern cones (e.g., Mt. Shasta, Mt. St. Helens, and Mt. Rainier). The southernmost Cascade Range, south of Mt. Shasta, is bordered by the Sierra Nevada on the south, the Modoc Plateau on the east, the Klamath Mountains on the west, and the Great Valley on the west and southwest.

The southernmost Cascade Range forms a broad ridge of late Pliocene and Quaternary volcanic rocks dominated by pyroxene andesite flows and pyroclastic rocks with subordinate basaltic and silicic rocks. These rocks are the products of several large composite cones and numerous smaller shield volcanoes and lava cones in various stages of preservation. The southernmost Cascade Range occupies a broad depression between the Sierra Nevada and the Klamath Mountains called the "Lassen Strait" by Diller (1886).

Rocks within LVNP and vicinity are entirely late Pliocene and Quaternary volcanic rocks (Williams, 1932; Macdonald, 1966). The nearest outcrops of non-volcanic rocks are those of the Sierra Nevada granitic and metamorphic complex 20 km southeast near Lake Almanor. A few small outliers of the Sierra Nevada complex occur in deep canyon bottoms 15-20 km south of Mineral, and outliers of Klamath Terrane occur 35 km northwest of Manzanita Lake.

Unconformably overlying the granitic and metamorphic basement outliers are Late Cretaceous marine sandstone, shale, and conglomerate of the Chico Formation, deposited in the "Lassen Strait" (Taft and others, 1940). The Chico Formation has been correlated with similar rocks around Mt. Shasta and near the California-Oregon border (Popenoe and others, 1960), providing the basis for the "Lassen Strait" Cretaceous seaway. Inclusions within the lavas and pyroclastic rocks are either altered volcanics or vein quartz of hydrothermal or metamorphic origin. The Walker "O" No. 1 well near Terminal Geyser in southwestern LVNP, was drilled from a surface elevation of 1,775 m, and penetrated 1,215 m of altered volcanics before bottoming at 550 m above sea level (Clynne and others, 1982). Williams (1932) suggested that Chico Formation rocks underlie LVNP at an elevation of approximately 1,200 m; however, they were not encountered in the Walker "O" No. 1 well. Nevertheless, it is likely that marine sedimentary rocks of the Chico Formation underlie the Lassen region.

The Montgomery Creek Formation of Eocene age unconformably overlies the Chico Formation at some localities. The Montgomery Creek Formation is composed of nonmarine sandstone and conglomerate probably derived from erosion of the Sierra Nevada-Klamath basement complex (Helley and others, 1981).

Eocene to Pliocene rocks of the western Cascades volcanic belt, so abundant in the main Cascade Range, are sparse in the southernmost Cascades (Macdonald, 1966). In the Lassen area, late Pliocene to Quaternary volcanic rocks of the High Cascades Volcanic Series directly overlie either the Mesozoic basement complex or late Cretaceous or Eocene sedimentary rocks.

Hietanen (1981) correlates Sierra Nevada structures west of the Melones Fault zone with Klamath structures west of the Trinity thrust fault. An eastward projection of Klamath rocks south of Mt. Shasta nearly isolates the southernmost Cascades from the main

Cascade Range. Within the southernmost Cascades the variety of volcanic rock types is greater and the proportion of silicic rocks larger than in the main Cascade Range, suggesting a contribution from or differentiation control by thick sialic crust. Macdonald (1966) suggested that the southernmost Cascades trend is controlled by underlying Sierra Nevada-Klamath structures. Eaton (1966), from seismic profiling, interpreted the crust in the Lassen area to be 35 km thick.

The presence of sialic crust under the southernmost Cascades is not yet substantiated. Hamilton (1978) suggested that the "Lassen Strait" originated by offset of the Sierra Nevada and Klamath Terranes produced by a combination of rifting, rotation, and strike-slip faulting during the interval from late Cretaceous to mid-Tertiary. His suggestion is supported by paleomagnetic data indicating that the Klamath Mountains and adjoining Cascades have been rotated westward relative to the Sierra Nevada (Craig and others, 1981). Griscom (1980), from magnetic and gravity data, suggested the presence of a major northeast-southwest-trending fault concealed beneath volcanic cover. Interpretation of gravity anomalies by Pakiser (1964) and LaFehr (1965) suggested that the southernmost Cascades consist of a 6- to 10-km thick pile of volcanic, intrusive, and sedimentary rocks resting on a basaltic crust.

In summary, although granitic basement thinned by rifting may be present beneath graben-filling basalt extruded during rifting, this remains to be proven unambiguously. However, marine and nonmarine sedimentary deposits are likely to underlie the Lassen area at some depth, perhaps beneath 6-10 km of volcanic cover.

Volcanic rocks older than Pliocene are sparse in the southernmost Cascade Range (south of Mt. Shasta). Miocene activity included mafic shield volcanoes as well as intermediate and silicic rocks that occur as erosional remnants on uplifted blocks of Sierra Nevadan basement and in a north-south trending belt lying to the east of Susanville (Grose and McKee, 1982). Pliocene volcanic rocks, mostly basalt to mafic andesite shield volcanoes and valley-filling lava flows, occur as a northwest-southeast trending belt of centers lying between Susanville and the Sacramento Valley that are progressively younger to the west (Grose and McKee, 1982). The present axis of the southernmost Cascade Range is marked by a belt of Quaternary centers from the LVNP area to Mt. Shasta.

Tectonic Setting

The late Cenozoic plate tectonic setting of the Cascade Range is shown in figure 1. Orogenic volcanism in the southern Cascades is the result of the interaction of the Gorda and North America plates. Relative convergence between the Gorda and North America plates is about 5 cm/yr (Minster and Jordan, 1978). Estimates of the subduction rate of the Gorda Plate are in the range from 2 to 4 cm/yr (Acharya, 1981; Riddehough, 1978; Nishimura and others, 1981; Silver, 1971), and are compatible with the relative convergence rate but are very slow compared to other subducting plates.

Calc-alkaline volcanism remains the clearest evidence for plate convergence. Seismic profiling indicates that an oceanic trench is present but has been filled by glacially-derived terrigenous sediments during low sea level stands in the Pleistocene (Silver, 1971). The lack of unambiguous Benioff-zone seismicity may be attributed to the proximity of the Gorda Ridge to the subduction zone and to the youth (5 m.y.) and high temperature (200°C) of the subducting slab (Silver, 1969; Blackwell, 1982). Independent evidence bearing on the depth of the inclined slab beneath the Cascades is lacking, but seismic data compiled by Smith and Knapp (1980) suggest a shallowly dipping seismic zone below the Coast Ranges in northern California. Riddehough (1979) has studied the gravity profile of the southern Washington continental margin and proposed that the slab dips at a low angle until it is east of the Coast Range where its dip increases so that it reaches a depth of 100-120 km beneath the Cascade axis.

Regional Geology-Late Pliocene to Recent

The volcanic history of the Lassen area is complex, and although the generalized history is known, the details are only partially understood. Workers have concentrated on the younger western portion of LVNP and vicinity, and, therefore, it is better understood than the older eastern portion.

Late Pliocene to Holocene volcanic rocks of the Lassen area were assigned to the High Cascade Volcanic Series by Macdonald (1966).

They were extruded primarily from long-lived volcanic centers including andesitic composite volcanoes and flanking silicic domes and flows. Three centers have been recognized:

- Lassen Volcanic Center, centered in the southwestern corner of LVNP and including Brokeoff Volcano and flanking domes (Williams, 1932)
- Maidu Volcanic Center (termed Maidu Volcano by Wilson, 1961) centered in the area of Battle Creek Meadows near Mineral
- Dittmar Volcanic Center (Clynne and others, 1982) centered near Warner Valley in the southeastern corner of LVNP; Saddle and Kelly Mountains are the largest remnants.

Additional composite cones have been recognized north of LVNP (Macdonald; 1966; Till and others, in press) and west of Lake Almanor (Lydon, 1968b).

Each volcanic center has produced eruption products spanning a wide range of composition from mafic andesite to rhyodacite or rhyolite. Each has had a similar history, consisting of three stages: (1) an initial cone-building period of mafic andesite and andesite lava flows and pyroclastics; (2) a later cone-building period characterized by thick andesite and silicic andesite lava flows, and (3) silicic volcanism flanking the main cone. The silicic magma chamber of Stage (3) provides a heat source for development of a hydrothermal system within the core of the main cone. Alteration of permeable rocks of the cone facilitates increased erosion in the central area of the volcano. The result is preservation of a resistant rim of the thick later cone-building lava flows and flanking silicic rocks surrounding the altered and eroded core of the composite cone.

Dittmar and Maidu Volcanic Centers have reached this stage, and their hydrothermal systems are extinct. Lassen Volcanic Center, however, hosts active silicic volcanism and a well developed hydrothermal system, including all the thermal features in LVNP and Mill Canyon (Muffler and others, 1982b).

Late Pliocene to Holocene volcanism in the Lassen area began with deposition of the Tuscan Formation, now exposed as a broad sheet on the eastern side of the Sacramento Valley. The Tuscan Formation consists of up to 500 m of mafic andesitic and andesitic material emplaced as volcanic mud flows and debris flows with minor interbedded mafic lava flows, dacitic ash-flow tuffs and alluvial deposits. The Tuscan Formation was deposited unconformably on Sierra Nevada basement complex or on late Cretaceous and early Tertiary sedimentary rocks (Anderson, 1933; Lydon, 1968a; Helley and others, 1981).

At least four centers of eruption of Tuscan Formation rocks are indicated; Mt. Yana, Maidu Volcanic Center, and two more in the Burney area north of LVNP (Lydon, 1961). Dittmar Volcano is another possible source. The apparent thickness of the Tuscan Formation underlying the Lassen area is less than 150 m (Lydon, 1968a). The age of the Tuscan Formation spans the range $\sim$ 3.5 m.y. to $\sim$ 2 m.y., controlled by K-Ar dates on samples from the top and bottom of the formation (Lydon, 1961; Gilbert, 1969).

Regional Structural Geology

The dominant structural element in the Lassen area is a large number of north- to northwest-trending normal faults, many with well preserved scarps (Macdonald, 1966). North of LVNP, these have a north-south orientation, whereas south of LVNP the dominant direction is north-northwest. Offsets range from insignificant to 300 m or more (Macdonald, 1983). Pliocene(?) rocks show the largest offsets, and progressively younger rocks show decreasing offsets, suggesting that faulting began contemporaneously with late Pliocene(?) volcanism (Macdonald, 1983). Latest Pleistocene rocks in many areas are unfaulted, indicating that the magnitude of faulting has decreased, although frequent small earthquakes in the Hat Creek Valley and Lake Almanor Depression indicate that faulting is still active (Robinson and Byerly, 1948; Klein, 1979; D. A. Stauber, oral communication).

The larger faults show a complex system of en echelon offsets creating steplike scarps (Hat and Butte Creek Rims, for example). Two major fault systems are arranged such that a block of rock 6-12 km across is downthrown between them, creating a graben. North of LVNP, this graben is expressed as the Hat Creek Valley; south of LVNP, as the Lake Almanor Depression. Along strike of these two valleys lies the Central Plateau of LVNP, a complex of young volcanic rocks filling the graben (Heiken and Eichelberger, 1980).

UNIT DESCRIPTIONS

Pre-Maidu Volcanic Center

Tertiary Andesite (Ta)

The lowest stratigraphic unit in the map area is designated Tertiary Andesite. Patches of andesite outcropping beneath the Rockland Tephra in the Canyon Creek area and beneath the Basalt of Camp Forward in the North Fork of Digger Creek represent an eroded terrane upon which the younger rocks were deposited (see Sheets 1 and 2 for location of geologic and geographic features described in text). The Tertiary Andesite consists of several similar rock types that can be collectively described as porphyritic (20-40% phenocrysts) hypersthene-augite andesites. Zoned and sieved as well as clear plagioclase phenocrysts up to 5 mm in size dominate the phenocryst assemblage. Augite is more abundant than hypersthene, and corroded olivine is a common accessory. The groundmass is medium to dark gray and hyalopilitic with plagioclase, pyroxene and magnetite microlites in glass charged with magnetite dust. Outcrops are deeply weathered with visibly altered groundmass material and with mafics and plagioclase partially altered to clays. Flow directions are ambiguous, although flows in the Canyon Creek area appear to have come from the east. Sparse outcrops prevent a thickness estimate for the Tertiary Andesite.

Lydon (1968a) describes sparse olivine basalt and pyroxene andesite flows interbedded with the abundant tuff breccias of the Tuscan Formation. The Tertiary Andesite could represent an eroded surface of the Tuscan Formation, but several lines of evidence suggest that it is younger. Tertiary Andesite is 200-250 m higher in elevation than the nearest rocks of the Tuscan Formation. Helley and others (1981) make no mention of flow rocks in the Tuscan Formation in the immediately adjacent Manton Quadrangle. Tertiary Andesite lacks tuff breccia, which makes up the bulk of the Tuscan Formation.

In summary, Tertiary Andesite consists of rock types similar to those found in composite volcanoes and is younger than the Tuscan Formation yet older than the Brokeoff Volcano. Possibly it represents distal lava flows of the Maidu Volcanic Center or of an unrecognized composite volcano.

Basalt of Camp Forward (Tbcf)

In the area north and east of Camp Forward are the eroded remnants of a basaltic shield volcano. The volcano is constructed of flows 5-10 m thick that dip gently away from a vent in the vicinity of Hill 4110. Interbedded pyroclastics are lacking, and the lavas are deeply weathered. A thick cover of bright red soil makes outcrops sparse. The age of the Basalt of Camp Forward is unknown; however, its deeply weathered and eroded state suggests that it is Tertiary. The Basalt of Camp Forward overlies Tertiary Andesite in the North Fork of Digger Creek and was already eroded when partially covered by the Rhyolite of Blue Ridge.

Two similar varieties of basalt are found in the Basalt of Camp Forward. Stratigraphically lower flows are medium- to dark-gray olivine basalt with 10% phenocrysts of 1 mm euhedral olivine, and sparse small plagioclase and augite phenocrysts. Stratigraphically higher flows are more porphyritic olivine-augite basalt. They contain 5% phenocrysts of olivine with iddingsite alteration, nearly 10% of 2 mm augite phenocrysts, and 2% of 1 mm euhedral, oscillatorilly-zoned plagioclase. The groundmass of both types contains plagioclase, pyroxene and magnetite microlites with interstitial cryptocrystalline material in pilotaxitic arrangement. Glomeroporphyritic clots of augite + plagioclase + olivine are abundant in the augite-rich flows. Xenoliths of milky vein quartz with light-green rims of fine-grained clinopyroxene are common in all flows.

Maidu Volcanic Center

Andesites of Maidu Volcanic Center (Qamv)

Rocks of this unit crop out in three areas along the southern border of the study area; a small patch of altered olivine-pyroxene andesite, pyroxene-andesite, and pyroclastic breccias in the bottom of Nanny Creek, and two larger areas of olivine-pyroxene andesite and pyroxene andesite lavas with sparse pyroclastic breccias on the west side of Martin Creek and on Hampton Butte. The latter two outcrop areas continue beyond the map area, through the vicinity of Black Oak Campground.

Andesites of Maidu Volcanic Center are predominantly thin olivine andesite and olivine-pyroxene andesite with subordinate pyroxene andesite lava flows and include lenses and layers of pyroclastic breccia of similar lithologies. These flows are less porphyritic (generally less than 20% phenocrysts) and contain less plagioclase and hypersthene and more olivine and glass than overlying units. Dips of lavas and breccias are shallow and northerly. The rocks are weakly to strongly altered and moderately weathered.

Andesites of Maidu Volcanic Center include Wilson's "Mineral Andesite", "Round Valley Tuff Breccia", and "Hampton Andesite" (fig 2). Because the lithologies and attitudes of Wilson's units are similar, and because they occur only at the edge of my study area, I have treated these units as Andesites of Maidu Volcanic Center. It is likely that Wilson's three units represent lateral facies variations of similar eruptive episodes. However, they are a heterogenous group of rocks; i.e. individual flows are of small volume and restricted lateral extent.

Emplacement of material erupted from Maidu Volcanic Center as lahars contributed to the Tuscan Formation (Lydon, 1968a). Lahars of the Tuscan Formation can be seen interbedded with Andesites of Maidu Volcanic Center in Battle Creek Canyon northeast of Cold Creek Butte. K-Ar dates of the uppermost Tuscan Formation near Bluff Springs (sec. 1, T29N, R1E) of 1.95 $\pm$ 0.25 m.y. (Gilbert, 1969) and of Quaternary Andesites of Maidu Volcanic Center (sec. 23, T29N, R3E) of 1.88 $\pm$ 0.06 m.y. (G. B. Dalrymple, written communication, 1982) suggest that the two units are contemporaneous.

CORRELATION OF UNITS OF THE MAIDU VOLCANIC CENTER

	Northern Flank of Maidu Volcano Units of Wilson (1961)		Units of this Report
	Maidu Domes	Qdmv	Dacites of Maidu Volcanic Center
Silicic	-- -- --	Qamr	Andesite of Martin Creek
	Rockland Pumice Tuff Breccia		-- -- --
	Blue Ridge Rhyolite	Qrbr	Rhyolite of Blue Ridge
Maidu Volcano	Turner Mountain Andesite	Qatm	Andesite of Turner Mountain
Upper Series			
	Hampton Andesite		
		Qamv	Andesites of Maidu Volcanic Center
Maidu Volcano	Round Valley Tuff Breccia		
Lower Series	Mineral Andesite		

Figure 2. Correlation of units of the Maidu Volcanic Center.

Andesite of Turner Mountian (Qatm)

Conformably overlying the Andesites of Maidu Volcanic Center are lavas of a distinctive lithology, named Andesite of Turner Mountain by Wilson (1961), after a type locality on the southern flank of Maidu Volcano. I have not visited Turner Mountain; however, Wilson's description is compatible with the rocks as described here.

Lavas of this unit form the crest of the ridge culminating at 6927 feet above Black Oak Campground and are exposed as a dipslope northwest to Hazen Flat, indicating that they came from a vent to the south. Sparse interflow breccias (Wilson, 1961) and thick individual flows indicate these to be flank flows. Lack of interflow breccias, sparse platy and thick massive jointing, and a more coarsely crystalline groundmass support the interpretation that the unnamed hill between Dry Lake and Cowslip Campgrounds is a thickly ponded flow. However, that the hill is an intrusive plug cannot be precluded.

The Andesite of Turner Mountain is porphyritic, containing phenocrysts of clinopyroxene, orthopyroxene and plagioclase; xenocrystic olivine is present in most samples. The light-gray groundmass has an intergranular texture composed of plagioclase microlites, pyroxene and magnetite grains and interstitial cryptofelsite. Inclusions of milky vein quartz from 1-3 cm across are common in some flows, as are altered fragments of volcanic or sedimentary rocks.

The Andesite of Turner Mountain contains abundant crystal clots of an unusual nature. These are not the typical hypidiomophic granular, multimineralic aggregates common in andesites and called glomerporphyritic clots by many workers (e.g. Garcia and Jacobsen, 1979). Rather, they are large mono- and bi-mineralic clusters of intergrown pyroxene crystals. Two types occur. The more common type consists of aggregates of clinopyroxene up to 1 cm in diameter. A colorless, euhedral core crystal with small inclusions of olivine and plagioclase is surrounded by light-green, oscillatorilly zoned crystals. These nucleated on the surface of the core crystal and grew until they interfered. Some crystals maintain optical continuity with the core crystal. The aggregates, as a whole, have euhedral outlines. Vague to distinct exsolution lamallae are common.

The other type of pyroxene aggregate consists of a xenocrystic core crystal of corroded olivine (Fo_{70-80}) surrounded by numerous, small, mutually interfering orthopyroxene crystals. These aggregates are up to 1 cm in diameter and are in various stages of development from thin orthopyroxene rims on olivine to clusters of orthopyroxene alone, interpreted to have completely replaced the olivine xenocryst.

The Andesite of Turner Mountain also contains abundant clusters of plagioclase phenocrysts. Their size and abundance varies between flows; generally they are 1-3 mm in diameter. The larger clusters have an unzoned, anhedral calcic core surrounded by intergrown, strongly oscillatorilly zoned plagioclase crystals. Smaller clusters lack the calcic core. All crystals are unusual in that they lack regular twinning.

The rock contains about 15-20% pyroxene phenocrysts and an equal amount of plagioclase. Small individual orthopyroxene crystals occur but are subordinate in amount to the clusters. Individual clinopyroxene phenocrysts are absent.

The lack of multimineralic clusters argues against synneusis as the mechanism of cluster formation. Most, if not all, the orthopyroxene clusters were formed by breakdown of olivine, a process that has been previously documented (Cox and others, 1979). The presence of several different monomineralic clusters in the same rock, the scarcity of individual crystals, and the growth pattern of crystals suggest the origin of cluster formation to be a nucleation phenomenon.

Rhyolite of Blue Ridge (Qrbr)

The Rhyolite of Blue Ridge was named and described in detail by Wilson (1961); a brief summary is given here.

Two extensive plateaus of silicic rocks occur on opposite flanks of Maidu Volcanic Center; Blue Ridge on the northwest and Mill Creek on the south and southeast. The plateaus are of subequal size, covering an outcrop area of 170 km^2 at an average thickness of 150 m. The minimum volume of silicic rock is thus 25 km^3. In addition Wilson found three other smaller silicic units in high stratigraphic position on Maidu Volcano; the Dacite of Stover Mountain, the Rhyolite of Lost Creek Plateau, and the Rockland Tephra.

The summit and central areas of Maidu Volcanic Center are now occupied by an oval-shaped depression approximately 8 by 5 km in diameter. Despite abundant hydrothermal alteration and a lack of boundary faults, Wilson attributed the depression to caldera collapse caused by extrusion of the voluminous Rockland Tephra. The Rockland Tephra however, is not related to the Maidu Volcanic Center but to the Lassen Volcanic Center. Futhermore, although caldera collapse may follow extrusion of voluminous lava flows, this is not typically the case (Williams and McBirney, 1979).

Wilson reports a K-Ar age of 1.52 m.y. (no uncertainty given) for glass from the Rhyolite of Blue Ridge. Subsequent K-Ar ages reported by Gilbert (1969) of 1.15 $\pm$ 0.07 m.y. (whole rock) and 1.24 $\pm$ 0.11 m.y. (plagioclase) may be more accurate.

When fresh, the Rhyolite of Blue Ridge is a light-gray to black, sparsely porphyritic, flow-banded perlite; however, the rock is typically devitrified, white to tan in color, and the mafic minerals are oxidized and weathered. The rock contains 5-10% phenocrysts dominated by oscillatorilly and reversely zoned andesine. Oxyhornblende (1-2%) and traces of hypersthene and biotite are the mafic minerals. The remainder of the rock is colorless perlitic glass, which is partially to wholly devitrified.

The Rhyolite of Blue Ridge is the most silicic and differentiated rock from the Lassen region yet analyzed, as it contains 75% SiO_2 and has a D.I. of 90.5. Chemical analyses of the "Rhyolite of Lost Creek" and the "Rhyolite of Mill Creek Plateau" are significantly less silicic; actually the rocks are dacite and rhyodacite respectively.

Dacites of Maidu Volcanic Center (Qdmv)

Williams (1932) reported the existence of the dacite domes of Christie Hill and Morgan Mountain, described them as hornblende-biotite dacites, and tentatively attributed them to Brokeoff Volcano. Wilson (1961) recognized three additional domes (Plantation Dome, Doe Mountain, and Radio Relay Hill) described them as hornblende-biotite dacites and pyroxene dacites, and correlated them with Maidu Volcanic Center. Six more dacite bodies are here correlated with the Maidu Volcanic Center. Dacite of Canyon Creek and a small unnamed body are exposed in Mill Canyon below Brokeoff Volcano (Muffler and others, 1982b). The Dacite of Rocky Peak (a dome and thick lava flow) and the Dacite of Growler Spring (a thick lava flow) were mapped separately and will be described in subsequent sections. A small body of altered dacite crops out near McGowen Lake, and a larger dome crops out in the South Fork of Bailey Creek Canyon.

Christie Hill is composed of a porphyritic medium-gray hornblende dacite with 25% phenocrysts. Plagioclase phenocrysts comprise 20% of the rock and are weakly oscillatorilly zoned crystals of calcic andesine 1-3 mm long. Oxyhornblende phenocrysts, 2-3 mm long with thin magnetite rims, comprise 4% of the rock. Hypersthene crystals 1 mm in size comprise 1% of the rock. Small augite crystals 0.25-0.5 mm long and biotite flakes are sparse components. The groundmass consists of plagioclase, pyroxene and magnetite microlites set in colorless glass. Pyroxene-bearing mafic inclusions are common. The rock is typically oxidized to shades of red.

Plantation Dome refers to the dacite body comprising the twin-peaked ridge east of Plantation Gulch. The light-gray but often oxidized porphyritic dacite is similar to that of Christie Hill. Phenocrysts make 20% of the rock. Plagioclase crystals up to 5 mm in length of sodic andesine with reversely zoned rims compose 15% of the rock. Oxyhornblende crystals up to 5 mm long and partially to completely replaced by granular magnetite and acicular hypersthene comprise 5% of the rock. Rounded and embayed pinkish quartz, biotite partially replaced by hypersthene and magnetite, and small hypersthene phenocrysts are present in small amounts. The groundmass consists of an irregular felsic intergrowth of quartz, plagioclase, hypersthene and magnetite. Mafic inclusions are common.

Morgan Mountain is a heterogeneous body of porphyritic hornblende-pyroxene dacite. Plagioclase phenocrysts up to 5 mm in size but mostly about 2 mm comprise 15-20% of the rock. The most common type is sodic labradorite with oscillatory zoning however, strongly sieved crystals and crystals with calcic cores are common. Hornblende pseudomorphed by magnetite is typically the most abundant mafic mineral, comprising up to 5% of the rock; however, some samples lack hornblende completely. In these samples variable amounts of pyroxenes occur, augite dominanting over hypersthene. Rounded and embayed quartz crystals are always present, occasionally in amounts up to 3%. The groundmass consists of plagioclase, pyroxene and magnetite microlites set in colorless glass. Mafic inclusions, both the pyroxene-plagioclase and hornblende-plagioclase varieties, are abundant.

A small body of dacite ($\sim 0.1\ km^2$) with a domical outcrop pattern underlies lavas of Brokeoff Volcano in the canyon of the South Fork at Bailey Creek. This dacite is tentatively correlated with the Dacites of Maidu Volcanic Center based on its stratigraphic position. The rock is a porphyritic biotite-hornblende dacite with about 15% phenocrysts. Plagioclase phenocrysts up to 5 mm in size comprise about 10% of the rock. Most are clear and show strong oscillatory zoning in the andesine composition range; many have more calcic cores. Crystals with sieved zones occur sparsely. Rounded phenocrysts of quartz about 1 mm in size make up 1% of the rock. Hornblende and biotite are strongly corroded and partially converted to magnetite. Mafic minerals also include sparse euhedral augite and hypersthene and corroded olivine. The groundmass is pilotaxitic with plagioclase, pyroxene and magnetite microlites and interstitial cryptofelsite.

A small body of strongly flow banded and deeply weathered dacite crops out 0.4 km northeast of McGowen Lake. The dacite is almost completely buried by lavas of Brokeoff Volcano, Andesite of Huckleberry Lake, and till. The rock is a hornblende dacite with about 10% small plagioclase phenocrysts. Little can be said about this dacite; however, in view of its similarity and proximity to other Dacites of Maidu Volcanic Center, it is probably related to them.

Evidence concerning the age of the Dacites of Maidu Volcanic Center is scarce however, some age constraints may be placed on the rocks. The domes were intruded through the older Andesites of Maidu

Volcanic Center as can be seen in the Nanny Creek area. Wilson (1961) interpreted the Andesite of Martin Creek lavas overlying the southern and eastern end of Plantation Dome to have been uplifted by emplacement of the dome. The position of these lavas, while not requiring uplift, nevertheless indicates that they predate Plantation Dome. Lavas of the Andesite of Martin Creek flowed south toward Maidu Volcanic Center and must have been erupted long enough after the collapse of Maidu Volcanic Center so that drainage to the south was established. A preliminary K-Ar age data on Plantation Dome indicates an age of 1.0-1.1 m.y. (G. B. Dalrymple, written communication, 1982).

The Dacites of Maidu Volcanic Center and the associated units, Dacite of Rocky Peak and Dacite of Growler Spring, form a mineralogically and chemically heterogeneous group of rocks emplaced on the northern flank of a composite volcano significantly after cone formation. They occupy a similar stratigraphic and petrologic position (relative to Maidu Volcano) as the Lassen dacite domefield bears to Brokeoff Volcano.

Dacite of Growler Spring (Qdgs)

In Mill Canyon, overlying the dacite dome of Morgan Mountain and underlying the Andesites of Mill Canyon, is a body of mafic dacite here called Dacite of Growler Spring. The body probably is the truncated margin of a lava dome as it has a minimum thickness of 150 m and flow structures are absent. Jointing is predominantly massive, although poorly developed platy jointing is seen locally.

Sparse altered olivine crystals weathered to orange clay, large strongly sieved plagioclase with a chalky appearance, and resorbed oxyhornblende give the rock a distinctive field appearance.

Dacite of Growler Spring is a porphyritic pyroxene-hornblende dacite with about 30% phenocrysts of plagioclase, hornblende, augite, olivine, hypersthene and quartz. Evidence of disequilibrium is abundant. Plagioclase phenocrysts occur in two populations of subequal abundance. Crystals 1-5 mm in diameter of andesine have strongly sieved cores. Smaller plagioclase phenocrysts are 0.1-1.0 mm in length, and are unsieved labradorite. Completely resorbed hornblende phenocrysts are marked by pseudomorphs of finely-divided magnetite and hypersthene granules. Augite phenocrysts slightly outnumber hypersthene phenocrysts. Both are small being only 0.25-0.5 mm in length. Sparse larger pyroxene crystals are probably derived from disaggregated glomeroporphyritic clots of plagioclase + pyroxene + magnetite, which are common. Olivine occurs as corroded crystals 0.25 to 2 mm long mantled by hypersthene. Quartz phenocrysts with fine-grained rims of augite are rare. The pilotaxitic groundmass is composed of plagioclase, pyroxene and magnetite microlites with interstitial cryptofelsite. Many small mafic xenoliths of plagioclase + pyroxene in various stages of disaggregation are present. Many of the small pyroxene, olivine and plagioclase crystals in the groundmass may be from disaggregated xenoliths.

Andesite of Martin Creek (Qamr)

The Andesite of Martin Creek consists of an eroded volcanic neck and thick lava flows of two-pyroxene andesite. A glaciated, continuous vertical exposure in excess of 50 m on the southeast flank of Hill 6869 consists entirely of massively jointed rock devoid of flow lineation. Hill 6869 represents the highest elevation that Andesite of Martin Creek is found, and although pyroclastic material was not observed, it is likely that the area is the glaciated vent.

Lavas of the unit dip gently to the south indicating that they flowed toward Maidu Volcanic Center, reaching as far as Battle Creek Meadows. The lavas of the Andesite of Martin Creek are distinctive and homogenous in appearance. No interbedded pyroclastic material was observed, and flow contacts are rare. The unit represents the product of a short-lived, small monogenetic cone.

The Andesite of Martin Creek overlies the Andesites of Maidu Volcanic Center in Martin and Nanny Creeks. It is overlain on the northern flank by the Dacite of Rocky Peak, dated at 0.803 ± 0.027 m.y. (G. B. Dalrymple, written communication, 1982). A flow of the Andesite of Martin Creek in the vicinity of Wilson Meadow has been uplifted by the extrusion of Plantation Dome (Wilson, 1961). Hence, the Andesite of Martin Creek was erupted after erosion of Maidu Volcanic Center when drainage toward the central vent had been established but before extrusion of the Dacites of Maidu Volcanic Center and the Dacite of Rocky Peak.

The appearance of the rock in hand-specimen is distinctive and varies little. Dark- and light-green pyroxene phenocrysts 1-3 mm in size are set in a light- to medium-gray holocrystalline groundmass speckled with abundant 0.25-0.50 mm plagioclase phenocrysts. Vague flow lineation is sometimes present, flow tops are moderately vesicular, and milky quartz xenocyrsts surrounded by fine-grained reactions rims of clinopyroxene are common. In thin section the clinopyroxene phenocrysts are mostly monomineralic glomeroporphyritic clots of euhedral augite crystals, although hypersthene is occasionally present. Many crystals, both of augite and hypersthene, are optically zoned and have distinct cores. Total pyroxene is 10%. Plagioclase phenocrysts are abundant (30%) but universally small, 0.25-0.50 mm occasionally reaching 1 mm. The bulk of the crystals are calcic andesine with normally zoned rims; oscillatory zoning is uncommon as are sieved crystals. The groundmass consists of plagioclase, pyroxene and magnetite microlites with sparse interstitial cryptofelsite. Splotches of fine-grained clinopyroxene mark completely reacted quartz xenocrysts. Magnetite pseudomorphs of hornblende occur but are uncommon.

Dacite of Rocky Peak (Qdrp)

Dacite of Rocky Peak consists of a large dome and a thick lava flow that crops out over 8 km^2 southwest of Brokeoff Volcano. Additional Dacite of Rocky Peak is covered by glacial deposits. Wilson (1961) attributed rocks in this area to Brokeoff Volcano;

however, Brokeoff Volcano units (Andesite of Heart Lake and Andesite of Glassburner Meadows) clearly overlie Dacite of Rocky Peak on its northern and eastern sides. A K-Ar date of 0.803 ± 0.027 m.y. (G. B. Dalrymple, written communication, 1982) confirms the field evidence. Dacite of Rocky Peak is correlated with the Maidu Volcanic Center.

Rocky Peak itself is a dome covering the vent area of Dacite of Rocky Peak. The dome has thick, vertical joints spaced 0.5 to 1 m apart and lacks flow structure. The vent fed a 250 m thick flow extending 2-3 km south of Rocky Peak. Glaciation has deeply eroded the area between the dome of Rocky Peak and the thick flow, producing good exposures of the flow interior. The flow is marked by irregular jointing and crystallinity. Rock with glassy groundmass has massive jointing and hackly fracture and weathers to irregularly shaped blocks and chips. More crystalline rock has thick to thin platy jointing and weathers to rectangular blocks or thin plates. The upper part of the flow has a flow lineation marked by alignment of phenocrysts, microvesicularity, brecciation, and zones of devitrification and oxidation. Flow direction was from Rocky Peak to the south and west.

The Dacite of Rocky Peak is a pyroxene-hornblende dacite with a disequilibrium phenocryst assemblage and common mafic xenoliths, similar to other Dacites of Maidu Volcanic Center. Dacite of Rocky Peak contains 20-25% phenocrysts; plagioclase dominates the assemblage. Plagioclase phenocrysts form a heterogeneous population, three-fourths of which are euhedral, 1-4 mm crystals with oscillatory and normal zoning in the andesine composition range. The remainder are anhedral or rounded crystals that show various degrees of sieving. Commonly these are completely sieved and have a thin, clear overgrowth rim. The mafic phenocrysts include magnetite pseudomorphs of hornblende, hypersthene, augite and magnetite. Magnetite pseudomorphs of hornblende are the most abundant mafic mineral in Dacite of Rocky Peak and comprises a few percent of the rock. They range up to 4 mm in length and consist of fine-grained magnetite, often intergrown with pyroxene. Occasionally, oxidized hornblende is preserved in pseudomorph cores. Hornblende is better preserved and more common in the earliest eruptives. Small euhedral crystals of hypersthene up to 0.5 mm in length comprise 1-2% of the rock. Small euhedral crystals of augite up to 0.25 mm in length are sparse except in the dome of Rocky Peak where they are larger and dominate the mafic assemblage. Dacite of Rocky Peak has a light- to medium-gray groundmass composed of plagioclase and magnetite microlites with interstitial cryptofelsite or glass in pilotaxitic or hyalopilotic arrangement. Mafic xenoliths are a ubiquitous feature of the Dacite of Rocky Peak.

Andesite of Cabin Spring (Qacs)

Andesite of Cabin Spring consists of distinctive, porphyritic pyroxene andesite lava flows that crop out west of Red Rock Mountain. These lavas flowed westward from a source obscured by the younger Dacite of Red Rock Mountain and by lavas of Brokeoff Volcano. A preliminary K-Ar date of 0.690 ± 0.034 m.y. (G. B.

Dalrymple, written communication, 1982) confirms the Andesite of Cabin Spring to be older than Brokeoff Volcano.

Andesite of Cabin Spring is a porphyritic hypersthene-augite andesite containing 15% phenocrysts. Plagioclase phenocrysts are small; most are 1 mm or less, clear crystals of sodic labradorite with weak oscillatory zoning. Plagioclase comprises about 5% of the rock. Pyroxene phenocrysts occur in glomeroporphyritic clots up to 5 mm in diameter as well as 1-2 mm sized individuals. Most glomeroporphyritic clots are monomineralic, but a few contain hypersthene and augite. Many augite crystals have optically zoned cores with vague exsolution lamallae and greenish rims. In hand specimen, the light-green cores and dark-green rims give the rock a distinctive appearance. Total pyroxene is about 10% with hypersthene and augite present in subequal amounts. The groundmass is medium gray, microvesicular, and consists of plagioclase, pyroxene and magnetite microlites with light-brown glass in hyalopilitic texture. Irregular bands and zones of devitrification are usually present. Milky vein quartz inclusions up to 1 cm in size with green reaction rims of clinopyroxene can be found at most outcrops.

Dacite of Red Rock Mountain (Qdrr)

The Dacite of Red Rock Mountain is a dome situated on the western flank of Brokeoff Mountain. The unit predates eruptives of Brokeoff Volcano and acted as a barrier to flows of the Andesite of

Canyons, respectively. The lithologies and field relationships are similar in each section. The Dacite of Twin Meadows caps each section.

In the Mill Creek Canyon area, Andesites of Mill Canyon, Andesite of Ski Hill, and Dacite of Twin Meadows form the southern flank of Brokeoff Volcano. Andesite of Ski Hill and Andesites of Mill Canyon are interbedded along their mutual contact which represents a time equivalent, lateral facies change from predominantly cone-building to predcminantly flank activity of Brokeoff Volcano. Andesite of Ski Hill consists of thin, glassy olivine-augite and augite andesite lava flows with interbedded pyroclastic rocks erupted from a central vent. Andesites of Mill Canyon are thicker, more crystalline lava flows of olivine-augite and augite mafic andesite and andesite, probably erupted from a vent on the southern flank of Brokeoff Volcano. The base of Andesite of Ski Hill is not exposed in Mill Canyon. Andesite of Mill Canyon progressively overlaps dacite domes of the Maidu Volcanic Center toward the south.

On the western flank of Brokeoff Volcano, Andesite of Ski Hill forms the base of the Brokeoff section and unconformably overlies older rocks in Bailey Canyon. The Andesites of Mill Canyon are absent, their place being taken by five time, chemically and lithologically equivalent units. The five flow units, Andesite of Onion Creek, Andesite of Rock Spring, Andesite of Bailey Canyon, Andesite of Heart Lake, and Andesite of Blue Lake Canyon, are interbedded with Andesite of Ski Hill and/or overlie pre-Brokeoff

Digger Creek, which surrounded it on three sides. On its western margin, Dacite of Red Rock Mountain overlies Andesite of Cabin Spring. A preliminary K-Ar date of 0.672 ± 0.020 m.y. (G. B. Dalrymple, written communication, 1982) shows Dacite of Red Rock Mountain to be slightly younger than Andesite of Cabin Spring and confirms that it is older than Brokeoff Volcano. Dacite of Red Rock Mountain is tentatively correlated with Maidu Volcanic Center but may be an unrelated eruptive intermediate in age between Maidu Volcanic Center and Lassen Volcanic Center.

Fresh Dacite of Red Rock Mountain is a light-gray porphyritic rock containing 10% phenocrysts. Strongly sieved crystals of plagioclase from 0.5-4 mm in length with clear rims of andesine comprise 6% of the rock. Another 2% of the rock consist of microphenocrysts of clear andesine. Hornblende prisms 1-2 mm in length have rims of magnetite or are completely converted to magnetite pseudomorphs and comprise 2% of the rock. Hypersthene crystals 0.25-0.5 mm in length and rounded quartz phenocrysts rimmed by fine-grained clinopyroxene are minor components. The groundmass consists of plagioclase, pyroxene, and magnetite microlites with clear glass in a hyalopilitic texture. Small mafic xenoliths are common.

Lassen Volcanic Center - Stage I (Early Phase of Brokeoff Volcano)

Stage I of the Lassen Volcanic Center can be divided into two stratigraphic sections exposed in Mill Creek and Bailey Creek

Volcano rocks unconformably. Andesite of Ski Hill is distinguished from the other flow units by its thin, glassy flows with interbedded pyroclastic rocks, whereas the above units lack pyroclastics, are thicker and generally more crystalline. All flow units are olivine-augite or augite mafic andesite or andesite.

Andesite of Ski Hill (Qash)

The Andesite of Ski Hill crops out primarily outside the map area in the Sulphur Works, Diamond Peak and Conard Meadows areas (P. A. Bowen, written communication, 1983). The lavas of the Andesite of Ski Hill occur as thin (typically less than 10 m) glassy, blocky-jointed flows with interbedded pyroclastic debris and are distinguished from Andesites of Mill Canyon primarily by the presence of those features. Lavas of the Andesite of Ski Hill usually have brecciated flow margins and vesicular tops. Toward the core of Brokeoff Volcano the lavas are progressively hydrothermally altered and become barely recognizable in some areas. Incipient alteration is present in some samples from the edges of the map area even though altered rocks were specifically avoided.

In Mill Canyon, the Andesite of Ski Hill occurs below and interbedded with Andesites of Mill Canyon. Away from the center of Brokeoff Volcano, Andesite of Ski Hill grades laterally into Andesites of Mill Canyon as thin flows and pyroclastic rocks pinch out in favor of thicker flows without pyroclastic rocks. In Bailey Canyon, Andesite of Ski Hill occupies a similar relationship with Andesite of Bailey Canyon and Andesite of Heart Lake. The Andesite of Ski Hill also includes small areas of sparsely phyric hypersthene-augite andesite in the bottoms of Bailey Creek and Blue Lake Canyons.

It is likely that Andesite of Ski Hill spans nearly the entire Stage I of Lassen Volcanic Center. K-Ar dates on rocks from the bottom of Bailey Canyon, 0.591 ± 0.13 m.y. and the East Fork of Sulphur Creek, 0.472 ± 0.009 m.y. (G. B. Dalrymple, written communication, 1982) are near the lower and upper contacts of Andesite of Ski Hill.

Chemical data (table 2) indicate that Andesite of Ski Hill is similar to the more silicic samples of Andesites of Mill Canyon. However, in components not concentrated by mafic phenocrysts, for example Na_2O and K_2O, even the mafic Andesites of Mill Canyon are similar to Andesite of Ski Hill, suggesting that the more mafic and crystal-rich Andesites of Mill Canyon may be the result of crystal accumulation in a magma similar to the magma of the Andesite of Ski Hill.

Andesite of Ski Hill is olivine-augite or augite andesite with a phenocryst content ranging from 10-25%. Plagioclase is always the dominant phenocryst. Typically, plagioclase crystals are small, rarely exceeding 2 mm, and zoned in the andesine to labradorite compositional range. Sieved crystals are always present, usually in equal abundance with clear crystals. Augite is the most abundant mafic phenocryst, occurring as euhedral crystals, rarely larger than 1 mm in length. Olivine is usually present as small crystals to 1 mm in length but typically it is embayed or corroded and sometimes partially replaced by serpentine. Small hypersthene phenocrysts, often corroded, are present in small amounts in many samples. Sparse magnetite microphenocrysts are present in about half the samples. Andesite of Ski Hill is characterized by a dark-gray to black hyalopilitic groundmass of plagioclase, pyroxene, and magnetite microlites set in abundant glass charged with magnetite dust. Glomeroporphyritic clots of plagioclase + augite ± hypersthene ± olivine ± magnetite are occasionally present but never abundant.

Andesites of Mill Canyon (Qam)

Deep erosion by Mill Creek has exposed a 300m thick section of lava flows in the canyon walls. Best exposures are found on the east wall where they have been described by Muffler and others (1982a). Although adjacent flows are petrographically distinguishable, the lack of lateral continuity of outcrop and the overall lithologic similarity promoted grouping of the lavas as the Andesites of Mill Canyon.

In the area south of Bluff Falls Campground, Andesites of Mill Canyon progressively overlap dacite flows and domes of Maidu Volcanic Center such that in this area they are the oldest eruptives of Brokeoff Volcano. Northward, the base of Andesites of Mill Canyon is not exposed but probably is not deeply buried. Andesites of Mill Canyon have gentle dips, generally less than 5°. Their flow direction was always within 15° of south. Interbedded pyroclastic material is absent. Rocks lithogically similar to Andesites of Mill

Canyon occur on Mt. Conard where they overlie Andesites of Mill Canyon and are mapped as Andesites of Mt. Conard (Muffler and others, 1982a). Because the Andesites of Mt. Conard occur as thinner flows, have steeper dips, and have interbedded pyroclastics, they are probably closer to their vent and are correlated with Andesite of Ski Hill, the coneward equivalent of Andesites of Mill Canyon. A small outlier near McGowen Lake is an erosional remnant of Andesites of Mill Canyon almost buried by Andesite of Huckleberry Lake.

No thick section of lavas correlatable with Andesites of Mill Canyon occurs on the west flank of Brokeoff Volcano. Five flow units occurring stratigraphically below Dacite of Twin Meadows were mapped. These are the Andesite of Onion Creek, Andesite of Rock Spring, Andesite of Bailey Creek, Andesite of Heart Lake, and Andesite of Blue Lake Canyon. Each is lithologically similar and probably equivalent to the Andesites of Mill Canyon, but contact relations are absent or unexposed. No rocks similar to Andesite of Mill Canyon are found in the northern or eastern flanks of Brokeoff Volcano.

The lack of Andesites of Mill Canyon in the canyon of Bailey Creek despite its similar erosional level suggests that they were erupted primarily from a flank vent on the south side of Brokeoff Volcano.

The Andesites of Mill Canyon are stratigraphically younger than a sample of Andesite of Ski Hill which has a K-Ar age of 0.591 ± 0.013 m.y. (G. B. Dalrymple, written communication, 1982) and stratigraphically older than Andesite of Digger Creek, which has a K-Ar age of 0.388 ± 0.031 m.y. (G. B. Dalrymple, written communication, 1982). A sample from near the top of the Andesite of Ski Hill from the East Fork of Sulphur Creek at Mill Creek Falls, gave a K-Ar age of 0.472 ± 0.009 m.y. (G. B. Dalrymple, written communication, 1982), which approximates the upper age limit of the Andesites of Mill Canyon.

Many individual flows make up the Andesites of Mill Canyon. Each is homogeneous and lithologically distinct, and if the mapping was sufficiently detailed, each could be an individual flow unit. Here they will be described as a generalized unit with the caveat that flows deviating from the general description occur rarely.

The Andesites of Mill Canyon are porphyritic olivine-augite and hypersthene-augite mafic andesites and andesites with plagioclase as the dominant phenocryst mineral. They are distinguished from Stage II lavas (table 1) primarily by their less abundant and smaller phenocrysts, presence of olivine, lower augite/hypersthene ratio, lack of abundant glomeroporphyritic clots, and flow morphology.

Phenocryst content of Andesites of Mill Canyon is variable, generally 20-30%. Plagioclase is always the most abundant phenocryst mineral, typically comprising 75-80% of the phenocrysts. Usually there are two or more populations of plagioclase. Larger phenocrysts (1-2 mm) of labradorite are less common, sometimes have calcic cores, and usually have sieved mantles and thin clear rims. These phenocrysts are normally zoned, but in a blotchy way that suggests smearing of oscillatory zoning by recrystallization. Some large plagioclase crystals are virtually unzoned. Smaller phenocrysts ($\sim$ 0.5 mm) of plagioclase are also labradorite, are more abundant, and are normally zoned over a small range of anorthite content. They lack oscillatory zoning, cores, and sieved zones, but usually have a thin clear rim of groundmass plagioclase composition.

Augite is the dominant mafic phenocryst in the Andesites of Mill Canyon. Typically, euhedral augite crystals are 0.5 to 3 mm in size and make up a few to 10% of the rock. Optical zoning is common, and greenish pleochroism sometimes occurs in augite phenocrysts. Hypersthene is present as small (>1 mm) phenocrysts in many Andesites of Mill Canyon but never in amounts greater than 1-2% of the rock. Sometimes hypersthene is corroded or jacketed by augite.

Olivine occurs as phenocrysts 1-2 mm in size in approximately half the flows of Andesites of Mill Canyon but usually occurs in amounts less than 3% of the rock. It is more common in samples from low stratigraphic position. Olivine is always embayed or corroded and surrounded by fine- to coarse-grained orthopyroxene, indicating a reaction relationship with the liquid.

Magnetite is present in small amounts in all flows of the Andesites of Mill Canyon either as microphenocrysts or groundmass granules. Glomeroporphyritic clots of plagioclase + augite + hypersthene ± olivine ± magnetite are sometimes present but never common. Andesites of Mill Canyon have a medium- to dark-gray pilotaxitic or devitrified hyalopilitic groundmass with plagioclase, pyroxene and magnetite microlites.

Twelve analyses of Andesites of Mill Canyon from the section at Mill Canyon are available. Although the correlation is not perfect and there is some variation of oxide content, the stratigraphically lower flows contain more MgO, FeO and CaO and less SiO_2 and K_2O than flows higher in the section. The chemical trend suggests increased differentiation or removal of mafic phenocrysts. The phenocrysts of Andesites of Mill Canyon display obvious petrographic features of disequilibrium, suggesting that larger phenocrysts have a more complex history than smaller phenocrysts. It is likely that open-system crystal fractionation (O'Hara and Mathews, 1981) and mixing of magmas in the fractionating chamber (Sakuyama, 1981) have been important in the evolution of the Andesites of Mill Canyon.

Andesite of Onion Creek (Qaoc)

The Andesite of Onion Creek consists of a single flow that emerges from beneath Andesite of Digger Creek 0.75 km NW of Rock Spring and continues 4.5 km west as a 30 m cliff that forms the south bank of Onion Creek. Andesite of Onion Creek flowed westward following preexisting drainage, burying a terrane of Tertiary Andesite and Basalt of Camp Forward. Andesite of Onion Creek cannot be correlated unequivocally with Brokeoff Volcano; however, it is young, fresh, and lithologically and chemically similar to lavas of the early phase of Brokeoff Volcano. The flow is unglaciated and little eroded. A blocky vesicular top grades downward into a massively jointed flow core.

The Andesite of Onion Creek is a porphyritic olivine-augite andesite containing 30% phenocrysts. Plagioclase is the dominant phenocryst, comprising 25% of the rock as small 0.5 to 2 mm crystals of labradorite. Two populations of plagioclase crystals are present in subequal amounts. Clear, oscillatory zoned crystals have thin sodic rims. Other crystals contain blebs, stringers and zones of brownish glass indicating considerable internal melting. Augite is the dominant mafic phenocryst, comprising 4% of the rock. It occurs as euhedral and occasionally corroded crystals up to 2 mm in size. Olivine occurs in amounts less than 1% of the rock as small euhedral to embayed or corroded fragments of crystals. Hypersthene and magnetite are minor components, occuring as 0.5 mm or smaller euhedral crystals. The Andesite of Onion Creek has a black glassy groundmass charged with magnetite dust and contains plagioclase, pyroxene, and magnetite microlites.

Andesite of Rock Spring (Qars)

The Andesite of Rock Spring is exposed only over a small area at Rock Spring, its bulk being covered by Andesite of Digger Creek. Only a vesicular flow front 5 to 10 m high is exposed. The phenocryst assemblage, chemistry, freshness, stratigraphic position, and source to the east all suggest Andesite of Rock Spring to be a Stage I lava of Brokeoff Volcano.

The Andesite of Rock Spring is a dark-gray, sparsely porphyritic olivine-augite mafic andesite containing about 10% phenocrysts. Plagioclase crystals, mostly about 1 mm in length, comprise 6% of the rock; they show slight zoning in the labradorite compositional range. Normal and oscillatory zoning are present, and most crystals show evidence of internal melting. Augite and olivine are present in subequal amounts, each comprising about 2% of the rock. Both show slight resorption of the 1-2 mm sized crystals. Magnetite occurs as a very sparse microphenocryst. Glomeroporphyritic clots of augite + plagioclase and olivine + plagioclase are common. The Andesite of Rock Spring has a hyalopilitic groundmass of plagioclase, pyroxene and magnetite microlites with abundant clear glass.

Andesite of Bailey Creek (Qabc)

Andesite of Bailey Creek crops out in the south wall of Bailey Creek Canyon where it unconformably overlies an old dacite dome tentatively correlated with the Maidu Volcanic Center. Andesite of Bailey Creek is interbedded with Andesite of Ski Hill and overlain by Andesite of Heart Lake. Andesite of Bailey Creek is a single 50 m thick flow with massive to blocky jointing.

The Andesite of Bailey Creek is a porphyritic hypersthene-augite andesite containing about 20% phenocrysts. Plagioclase phenocrysts comprise 15% of the rock. They are mostly about 1 mm in length and show normal and oscillatory zoning in the calcic andesine to labradorite composition range. The zoning is more pronounced than in other Stage I andesite plagioclases. The bulk of the phenocrysts are clear; sieved crystals are sparse. Augite comprises 3% of the rock as euhedral crystals up to 4 mm in length, but most are 1 to

2 mm. Hypersthene crystals are less abundant, comprising 1-2% of the rock, are euhedral and mostly 1-2 mm or smaller. Magnetite microphenocrysts are a conspicuous accessory. The groundmass of Andesite of Bailey Creek is medium gray and composed of plagioclase, pyroxene and magnetite microlites and cryptofelsite with a pilotaxitic texture.

Andesite of Heart Lake (Qaht)

The Andesite of Heart Lake crops out as a series of several flows, each 30 m thick, in the Heart Lake area. These lavas flowed westward and partially buried the Dacite of Rocky Peak, a dacite dome of the Maidu Volcanic Center. The Andesite of Heart Lake is overlain on the east by the Dacite of Twin Meadows and on the north by the Andesite of Digger Creek, a Stage II unit of Brokeoff Volcano. A second flow unit is exposed 2.5 km north of Heart Lake in the south wall of Bailey Creek Canyon where it overlies Andesite of Bailey Creek and underlies Dacite of Twin Meadows. The two outcrop areas are very similar appearing and have been correlated on the basis of stratigraphic position and the presence of distinctive serpentinized olivine phenocrysts.

The Andesite of Heart Lake is a porphyritic hypersthene-augite andesite with 20% phenocrysts. Plagioclase phenocrysts comprise 15% of the rock. They are mostly less than 2 mm and have oscillatory and normal zoning in the calcic andesine to labradorite composition range. Crystals with sieving, glass inclusions, sodic rims or calcic cores are present but greatly subordinate. Augite comprises

3-4% of the rock and is the dominant mafic phenocryst. It occurs as both euhedral and embayed crystals up to 2 mm in length. Hypersthene phenocrysts are small, about 1 mm in length, and euhedral. Serpentine pseudomorphs after olivine are a minor but distinctive feature of the Andesite of Heart Lake. Hypersthene coronas around the pseudomorphed olivine indicate a reaction between olivine and magma during crystallization. The Andesite of Heart Lake has a medium-gray pilotaxitic groundmass composed of plagioclase, pyroxene and magnetite microlites with abundant cryptofelsite. A few glomeroporphyritic clots of plagioclase + augite + hypersthene + magnetite are present.

Andesite of Blue Lake Canyon (Qabl)

Andesite of Blue Lake Canyon consists of a small parasitic cone complex in Blue Lake Canyon that overlies Andesite of Ski Hill and is overlain by Andesite of Digger Creek and Andesite of Mt. Diller. The complex was exposed by valley glaciation and consists of remnants of a cinder aggutinate carapace, dikes, and lavas intruded by a small plug. Most of the complex lies buried beneath Stage II lava flows. The dikes are the least porphyritic rock yet found on Brokeoff Volcano, and consist of nearly aphyric olivine andesite. Parts of the plug contain abundant nodules with a two-pyroxene gabbroic mineralogy and hypidiomorphic granular to cumulate textures including rare layering. These nodules can be seen to be disaggregating in the plug to produce rocks with 10-20% xenocryst crystals, a process recently described by Fujimaki (1982). Further study of the nodules is in progress.

The mineralogy, chemistry and stratigraphic position between Andesite of Ski Hill and Stage II lavas tentatively suggest a Stage I affinity for Andesite of Blue Lake Canyon.

The nearly aphyric dike rock of Andesite of Blue Lake Canyon contains a few percent of small olivine and plagioclase phenocrysts. Olivine phenocrysts are 0.25 to 1 mm and slightly to moderately resorbed. Plagioclase phenocrysts are 0.25 mm to 0.5 mm, euhedral, clear crystals of labradorite. Also present are occasional rounded or angular fragments of plagioclase, augite, and hypersthene from disaggregated nodules. The rock has a pilotaxitic groundmass of plagioclase and pyroxene with minor amounts of cryptofelsite. In the plug, the olivine phenocrysts are more completely resorbed and the xenocrystic plagioclase has developed overgrowths on fragmental cores. The groundmass is holocrystalline, coarser than that of the dike and contains a small amount of late-formed hornblende.

Dacite of Twin Meadows (Qdtm)

Stage I of the Lassen Volcanic Center culminated with the eruption of lava flows of Dacite of Twin Meadows on Brokeoff Volcano. The flows are well exposed below the summit of Brokeoff Mountain. Their disposition indicates a vent to the northeast, high on Brokeoff Volcano. Another flow in Blue Lake Canyon may have had the same source. Above Forest Lake, Dacite of Twin Meadows is intruded into Andesite of Ski Hill, Andesites of Mill Canyon, and its own vent breccia, indicating a second vent in this area. The flows of Dacite of Twin Meadows are relatively short (exposed length < 3 km) with thickness increasing away from the source. The flows are 50-100 m thick near their source and 150 to 200 m thick at their distal ends. A flow 250 m thick in Blue Lake Canyon may be ponded. No breccias were found associated with Dacite of Twin Meadows other than the vent breccia near Forest Lake. Jointing of the flows is massive to blocky. All flows are glaciated; hence no pumiceous or vesicular margins are preserved.

The Dacite of Twin Meadows conformably overlies several Stage I units and is unconformably overlain by several Stage II units. The age of Dacite of Twin Meadows is uncertain but constrained by K-Ar dates on the Andesite of Ski Hill of 0.472 ± 0.009 m.y. and on the Andesite of Digger Creek of 0.388 ± 0.031 m.y. (G. B. Dalrymple, written communication, 1982). The unconformable relationship between Dacite of Twin Meadows and Andesite of Digger Creek makes it likely that Dacite of Twin Meadows is aproximately 0.45 m.y. old.

The Dacite of Twin Meadows has some subtle but consistent chemical differences from other dacites of the Lassen Volcanic Center. At equivalent SiO_2, Dacite of Twin Meadows has higher K_2O, FeO, MnO, TiO_2, and FeO/MgO and lower MgO and CaO. These chemical differences suggest a difference in origin and indicate that Dacite of Twin Meadows is more differentiated than other dacites of the Lassen Volcanic Center.

Dacite of Twin Meadows is a sparsely porphyritic, medium- to dark-gray, pyroxene-hornblende dacite. Phenocrysts of plagioclase, hornblende, augite, hypersthene, and magnetite are present in decreasing order of abundance. The total phenocryst content is variable in the range of 8-15%. Plagioclase dominates the phenocryst assemblage. Two populations are present; together they comprise 6-10% of the rock. The more abundant plagioclase phenocrysts are 0.25 to about 2 mm in length, clear, normally and sometimes oscillatorilly zoned in the andesine composition range. Crystals of oscillatorilly zoned and sieved labradorite, many with resorbed calcic cores, make up a small proportion of the plagioclase phenocrysts. They are usually about 2 mm in length and have clear rims of andesine. Hornblende is the most abundant mafic phenocryst, comprising a few percent of the Dacite of Twin Meadows. Hornblende phenocrysts are acicular crystals 0.5 to 1.0 mm, rarely up to 2 mm in length. They are usually yellowish to greenish brown and rimmed by iron oxide. In distal portions of flows, the hornblende is green, and completely lacks oxidation. Closer to the vent the hornblende crystals are less abundant, completely oxidized and pseudomorphed by iron oxide. Augite and hypersthene phenocrysts occur in two populations; augite dominates both populations. The first population consists of small, up to 0.25 mm euhedral crystals. The second population consists of larger, 0.5 to 1 mm, subhedral, occasionally resorbed phenocrysts similar to those in the Stage I andesites. Glomeroporphyritic clots composed of 0.5 to 1 mm crystals of plagioclase, augite, hypersthene, and magnetite are common in the Dacite of Twin Meadows. Aphyric vesicular mafic inclusions composed of felted plagioclase, acicular hornblende and glass are locally abundant.

Hornblende, sodic plagioclase, and mafic xenoliths are most abundant at distal exposures of flows of the Dacite of Twin Meadows. Toward their source, hornblende becomes progressively oxidized in each flow and eventually disappears, suggesting volatile loss or increased temperature. The lower proportion of phenocrysts and the presence of hydrous mafic minerals also support the suggestion that the Dacite of Twin Meadows was erupted from a stratified magma chamber with a cool, volatile-rich top. Petrographic features and relative abundance of the sieved plagioclase and the large augite and hypersthene phenocrysts in the Dacite of Twin Meadows suggest that it is related to the fractionating andesitic magma chamber of Stage I. Whether the Dacite of Twin Meadows originated by stratification of the magma chamber that built the early phase of Brokeoff Volcano or a subsidiary high level chamber cannot be determined. In either case, magma mixing played a role in the origin of the Dacite of Twin Meadows, as shown by the multiple phenocryst populations and mafic xenoliths.

Lassen Volcanic Center - Stage II (Late Phase of Brokeoff Volcano)

Stage II of the Lassen Volcanic Center includes the following map units: Andesite of Bluff Falls, Andesite of Glassburner Meadows, Andesite of Digger Creek, and the Andesite of Mt. Diller. Each is an individual flow unit confined to a specific portion of the southern, western, or northern flank of Brokeoff Volcano. The other Stage II unit, the Andesite of Rice Creek, does not occur in the map area but occupies a similar stratigraphic position on the eastern and southeastern flanks of Brokeoff Volcano where it unconformably overlies Andesites of Mill Canyon (Muffler and others, 1982a).

The Andesite of Bluff Falls overlies the Andesites of Mill Canyon with a slight unconformity as seen in the upper slopes of Mill Canyon. The Andesite of Digger Creek unconformably overlies Dacite of Twin Meadows and Andesite of Heart Lake north of Red Rock Mountain. The Andesite of Digger Creek flowed far enough west to cover unconformably Rhyolite of Blue Ridge and Stage I andesites. In Blue Lake Canyon, the Andesite of Digger Creek is preserved as remnants of a thick valley-filling tongue of lava, subsequently buried by Andesite of Mt. Diller. The small exposures of Andesite of Digger Creek north of Bailey Creek and in the wall of Deep Hole indicate that this flow unit underlies an additional substantial area. The rocks forming the summit area of Brokeoff Mountain are tentatively assigned to the Andesite of Mt. Diller, based on their lithologic similarity and high stratigraphic position.

Stage II lavas are thickest on the western to northwestern flank of Brokeoff Volcano. The ridge of Mt. Diller exposes over 300 m of Andesite of Mt. Diller. On the southern flank of Brokeoff Volcano where Andesite of Glassburner Meadows overlies Andesite of Bluff Falls, total thickness is no more than 200 m. The Andesite of Digger Creek is of similar thickness. The Andesite of Mt. Diller thins toward the east in the area between Pilot Pinnacle and Bumpass Mountain. Mapping by P. A. Bowen (written communication, 1983) suggests that the flow unit thins to about 60 m in the cliffs below Bumpass Mountain.

Preliminary K-Ar ages (G. B. Dalrymple, written communication, 1982) of the Andesite of Digger Creek (0.388 ± 0.031 m.y.) and Andesite of Mt. Diller (0.361 ± 0.027 m.y.) indicate that Stage II was short-lived and imply rapid cone-building during Stage II.

Flow units of Stage II are lithologically similar; they are distinct from other Brokeoff Volcano rock units but are difficult to distinguish from each other. They occur as thick flow units, commonly 50-75 m thick with few internal contacts. Exposed vesicular flow tops are rare, owing to removal by glaciation, except in the area east of Rock Spring where the Andesite of Digger Creek is beyond the extent of glaciation. Platy jointing is characteristic of flow cores. Massive, vaguely columnar jointing is common in the upper and lower parts of flows. Pyroclastic material is sparse; a flow breccia crops out locally below the Andesite of Glassburner Meadows, thin between-flow breccias occur on Mt. Diller, and P. A. Bowen (written communication, 1983) identifies volcanic agglomerates above Sulphur Works that may be related to Stage II andesites. Ash-flow deposits (Qapf) tentatively correlated with Andesite of Mt. Diller are described in a subsequent section.

In general, lavas of Stage II can be described as porphyritic, two-pyroxene, silicic andesites with common glomeroporphyritic clots. They are light gray to black depending on the degree of groundmass crystallinity.

Andesite of Bluff Falls (Qabf)

The Andesite of Bluff Falls contains 30-40% phenocrysts, dominantly plagioclase but including augite, hypersthene, magnetite, and olivine. The plagioclase phenocrysts (20-30% of the rock) are up to 3 mm in size, however, most are 1-2 mm. They occur as two populations. The most common is labradorite displaying oscillatory zoning superimposed on normal zoning with a thin sodic rim similar in composition to the groundmass andesine. The second population displays variable degrees of internal melting (sieving) and thin sodic rims. Subhedral to euhedral augite and hypersthene phenocrysts are present in subequal proportions, each comprising 4-5% of the rock. They are generally less than 1 mm but occasionally as large as 2 mm. Some hypersthene phenocrysts show thin exsolution lamallae, especially in their cores. Magnetite phenocrysts are anhedral to euhedral grains less than 0.5 mm in size and comprise less than 1% of the rock. Olivine phenocrysts are sparse, deeply embayed, anhedral grains that have fine-grained pyroxene reaction rims. Glomeroporphyritic clots up to 1 cm in diameter composed of plagioclase, augite, hypersthene ± magnetite and olivine are common. The light- to medium-gray groundmass consists of plagioclase, pyroxene, and magnetite in either pilotaxitic relationship with abundant interstitial cryptofelsite or hyalopilitic relationship with brownish glass.

Andesite of Glassburner Meadows (Qagm)

The Andesite of Glassburner Meadows is a porphyritic two-pyroxene andesite containing about 35% phenocrysts of plagioclase, augite, hypersthene, and magnetite with occasional resorbed grains of olivine and hornblende. Plagioclase is the dominant phenocryst, comprising 25% of the rock. Crystals are mostly 1 to 3 mm in long dimension but sometimes up to 5 mm. The most common type has oscillatory zoning superimposed on normal zoning, sometimes with an irregular calcic core. Some thin sections have abundant 1/4 to 1/2 mm similarly zoned plagioclase. Completely sieved phenocrysts are uncommon, but many have narrow zones of glass inclusions. All phenocrysts are in the range of calcic andesine to sodic labradorite and have thin sodic rims.

Augite and hypersthene are present in subequal amounts, and comprise 8-10% of the rock. Augite phenocrysts are subhedral to euhedral, mostly less than 1 mm but up to 2 mm, commonly twinned and sometimes optically zoned. Hypersthene phenocrysts are subhedral to euhedral, mostly less than 1 mm but up to 2 mm, and occasionally contain vague exsolution features. Magnetite phenocrysts comprise less than 1% of the rock and are small, 0.1 to 0.5 mm, anhedral to euhedral grains. Anhedral olivine grains are sparse and usually deeply embayed or surrounded by a reaction rim of fine- to coarse-grained pyroxene. Hornblende grains are sparse and partially to completely oxidized to magnetite + pyroxene. Glomeroporphyritic clots of plagioclase, augite, hypersthene ± magnetite and olivine up to 1 cm in diameter are common. The light- to dark-gray groundmass is typically hyalopilitic with plagioclase, pyroxene, and magnetite microlites in abundant clear glass. Some samples have irregular, splotchy devitrified areas.

Andesite of Digger Creek (Qadc)

The Andesite of Digger Creek is the most widespread flow unit of Stage II. It shows a wider range of petrographic and flow features than the other flow units in the group. Vesicular flow tops are common, especially in the area west of Red Rock Mountain, and groundmass textures are variable. Phenocryst mineralogy and modes are similar to the other flow units, but minor differences occur in the percentages of olivine and hornblende. Inclusions are found throughout the unit, the most common being altered volcanic rocks displaying pyroxene hornfels mineralogy and texture. Also common are aggregates of plagioclase, augite, and hypersthene ± magnetite and olivine, sometimes with cumulate or metacumulate textures.

Flows of the Andesite of Digger Creek originated higher on Brokeoff Volcano than Hill 8198 east of Red Rock Mountain. The lava flowed west and Red Rock Mountain acted as a barrier to divert flow north and south. At least one other lava stream is necessary to account for the Andesite of Digger Creek exposed in Blue Lake Canyon and Deep Hole.

The Andesite of Digger Creek is a porphyritic two-pyroxene andesite with about 40% phenocrysts. Plagioclase is most abundant, followed by pyroxene, both augite and hypersthene. Plagioclase phenocrysts comprise about 30% of the rock. They range from very small to about 5 mm; most commonly they are 1-3 mm. They are typically euhedral, although complexly intergrown composite crystals are common. Plagioclase composition ranges from andesine to labradorite with oscillatory zoning superimposed on normal zoning. Sieved phenocrysts with zones of melt inclusions are present but comprise less than 5% of the population. Augite and hypersthene each comprise about 5% of the rock as subhedral to euhedral crystals mostly less than 1 mm but commonly 2 mm or larger. Subhedral to euhedral magnetite 0.1 mm to 0.5 mm in size comprises less than 1% of the rock. Olivine is sparsely present but almost always found, and is usually deeply embayed or surrounded by a fine-grained reaction rim of pyroxene. Hornblende is sparse and is usually found as oxidized relict grains but occasionally as euhedral, magnetite rimmed crystals.

Groundmass textures are generally hyalopilitic with plagioclase, pyroxene, and magnetite microlites, and abundant glass. Samples from flow interiors usually show splotchy devitrification of glass to cryptofelsite.

Andesite of Mt. Diller (Qamd)

The Andesite of Mt. Diller is a porphyritic two-pyroxene andesite containing phenocrysts of plagioclase, augite, hypersthene, magnetite, and olivine amounting to 40% of the rock. Flows of the Andesite of Mt Diller tend to be thinner and have better developed vesicular tops and flow breccias than other Stage II units. A dark-gray to black glassy groundmass and large tabular plagioclase also help to distinguish Andesite of Mt. Diller from the underlying Andesite of Digger Creek.

Subhedral to euhedral, andesine to labradorite plagioclase phenocrysts ranging from 0.25 to 4 mm comprise 30% of the rock. Two populations are present. Phenocrysts displaying oscillatory superimposed on normal zoning are typical, whereas a small proportion of the crystals have weakly to strongly developed zones of internal melting. Each type has a thin sodic rim.

Subhedral to euhedral, greenish augite and brownish hypersthene in subequal amounts comprise 8-10% of the rock. Pyroxene crystals are mostly 1-2 mm in length, but smaller and slightly larger crystals are present. Hypersthene phenocrysts are pleochroic from light-green to pink and occasionally contain vague to distinct exsolution lamallae or blebs. Subhedral to euhedral magnetite phenocrysts range from 0.1 to 0.5 mm and comprise about 1% of the rock. Olivine grains are more abundant than in the other Stage II units yet comprise less than 1% of the rock. They are typically deeply embayed, resorbed, iddingsitized or have fine- to coarse-grained reaction rims of pyroxene. Glomeroporphyritic clots of plagioclase, augite and hypersthene ± magnetite and olivine up to 1 cm in size are abundant.

The groundmass is dark gray to black and is hyalopilitic with plagioclase, pyroxene and magnetite microphenocrysts immersed in glass charged with magnetite dust. Slight hydrothermal alteration of olivine, pyroxene and the groundmass is evident in some samples, especially those collected near the summit of Mt. Diller.

Pyroclastic Flow Deposits (Qapf)

Partially welded pyroclastic flow deposits (designated Qapf) crop out at two localities along the South Fork of Bailey Creek. Both small exposures are in roadcuts in an area covered by thick deposits of glacial till.

The deposits are heterogeneous in terms of lithic clast size, clast distribution, and degree of welding. Clasts range in size from a few millimeters to 20 cm with the coarser clasts concentrated in lenses defining a crude bedding. Breaks in the degree of welding and the clast lenses in the 12-foot high roadcut indicate that several thin ash flows were deposited in rapid succession. The crystal-rich matrix is composed of devitrified ash-sized material that is completely oxidized giving the entire deposit a brick-red color. Close inspection reveals partially collapsed, devitrified pumice lumps that are difficult to distinguish from the matrix. Clasts have the same mineralogy as the matrix. Phenocrysts are dominantly plagioclase but include subequal amounts of augite and hypersthene as well as sparse resorbed olivine; a few glomeroporphyritic clots of the same minerals are present. The lithic clasts have dark, glassy groundmass. The stratigraphic position of the deposits (overlying the Andesite of Digger Creek) and similar phenocryst types and proportions suggest that they are related to the Andesite of Mt. Diller.

Lassen Volcanic Center - Stage III

Subsequent to construction of the late phase of Brokeoff Volcano, volcanism in the Lassen Volcanic Center shifted in locale and character. Rockland Tephra and its associated debris flow erupted from an unlocated vent in the immediate Lassen area, perhaps on Brokeoff Volcano. Andesite of Huckleberry Lake erupted from a parasitic vent on the southern flank of Brokeoff Volcano. Contemporaneous andesitic and silicic volcanism built the dacite domefield and Central Plateau of LVNP, through emplacement of four groups of lavas; Bumpass Sequence, Loomis Sequence, Lassen Sequence, and Twin Lakes Sequence.

The products of Stage III of the Lassen Volcanic Center do not crop out widely in the map area; only the Andesite of Huckleberry Lake and the Rockland Tephra debris flows occur mostly within the map area. However, in order to discuss the geochemistry of the Lassen Volcanic Center, the stratigraphic relationships of the rocks are presented briefly. For the purpose of discussion, Andesite of Viola will be taken as representative of the Twin Lakes Sequence, and the Rhyodacites of Manzanita and Loomis Peaks will be taken as representative of the Loomis Sequence. The Bumpass Sequence and Lassen Sequence are unrepresented in the map area but will be discussed briefly in a subsequent section.

Rockland Tephra (Qrrt)

Wilson (1961) described a "deposit of finely divided acid tuff and pumice blocks" that he designated the Rockland Pumice

Tuff-Breccia and attributed to the Maidu Volcanic Center. Recent work has shown the unit to consist of a total of 30-50 km^3 of initial airfall pumice deposits, subsequent ashflow tuff, and distal ash layers widely distributed in northern and central California (Sarna-Wojcicki and others, in press). Rockland Tephra has been used to collectively designate all phases of the unit and is retained here (Sarna-Wojcicki and others, in press). Helley and others (1981) have mapped the bulk of the Rockland Tephra, directly west of the map area near Manton. Rockland Tephra has a complex depositional history; the description given here applies only to the proximal ashflow deposits found in the map area.

The best exposures of Rockland Tephra are in the area south of Canyon Creek and north of Onion Creek. The deposit is usually nonwelded and friable, although vapor phase crystallization has locally indurated the upper part of the ashflow. Outcrop area of the Rockland Tephra is characterized by intense dissection and white to light-orange soil. The deposit weathers quickly; good outcrops are limited to roadcuts. The Rockland Tephra was deposited on a dissected terrain of Tertiary Andesite, Basalt of Camp Forward and Rhyolite of Blue Ridge. Thickness of the Rockland Tephra is poorly known; nowhere is a complete section exposed. Helley and others (1981) suggest a thickness of at least 60 m near Manton. Incomplete exposures in the Canyon Creek and Onion Creek areas range from 30 to 80 m.

White, loosely-aggregated ash comprises the bulk of the ashflows of the Rockland Tephra. Pumice lapilli and bombs to 20 cm in long dimension and lithic fragments, mostly less than 5 cm each, compose 10-20% of the deposit. The clear glass of the pumice has a characteristic silky texture and contains about 10% phenocrysts. Plagioclase is the most abundant; hornblende, hypersthene and magnetite are sparse. Plagioclase phenocrysts are 1-3 mm, clear, andesine crystals with normal and oscillatory zoning and are often broken. Dark-green to brown hornblende crystals 1-2 mm in length and 0.1 mm hypersthene and magnetite are minor components. Sparse rounded quartz crystals and the broken, corroded sanidine reported by Wilson (1961) may be xenocrystic. Small mafic inclusions of felted plagioclase, hornblende and glass are common, and larger ones, up to 10 cm, occur sparsely. Many types of altered mafic to silicic volcanic rocks occur as lithic fragments. A distinctive quartz-bearing, flow-banded rhyolite is ubiquitous and serves to identify Rockland Tephra. No lithic fragments are recognizable as rocks from Lassen Volcanic Center.

The source of Rockland Tephra is equivocal; Wilson (1961) suggested that it came from Maidu Volcanic Center, and subsequent workers have concurred. Fission-track dating of zircons from Rockland Tephra indicates an age of 350,000 ± 50,000 years for the unit (C. E. Meyer, oral communication, 1982). Rockland Tephra, therefore, is too young to be related to the Maidu Volcanic Center (latest eruptions 700,000-800,000 years ago). Examination of the outcrop pattern of the Rockland Tephra in the Manton (Helley and others, 1981) and Lassen Peak Quadrangles shows a cone shape with the apex pointed toward the Lassen Volcanic Center. The small deposit of Rockland Tephra overlying Andesite of Heart Lake just east of Rocky Peak indicates that the Rockland Tephra is younger than Stage I of the Brokeoff Volcano and adds weight to the suggestion that it came from Lassen Volcanic Center. A comparison by energy dispersive analysis of rhyodacitic Rockland airfall pumice from Manton Quarry and six silicic rocks from the Lassen area (Dacite of Red Rock Mountain, Rhyolite of Blue Ridge, Rhyolite of Mill Creek, two samples of Dacite of Twin Meadows, and Rhyodacite of Kings Creek, a Loomis Sequence unit of the Lassen Volcanic Center) showed the Rockland Tephra to be most like the Rhyodacite of Kings Creek (M. J. Woodward, written communication, 1982). Lassen Volcanic Center is the only young, silicic center south of the Mt. Shasta-Medicine Lake Volcano area. It is, therefore, likely that Rockland Tephra erupted from the Lassen Volcanic Center despite the lack of an obvious vent. Williams (1932) suggested that the Brokeoff Volcano amphitheater is a collapse feature caused by a large pyroclastic eruption. Kane (1975) disputed the idea of collapse, preferring an origin by glacial erosion. While ring fractures related to collapse have not been found and the Brokeoff Volcano amphitheater has obviously been enlarged by glacial erosion, its origin by caldera collapse cannot be ruled out. The major flaw in Williams' idea was the lack of a large volume pyroclastic deposit. The origin of the Brokeoff Volcano amphitheater remains to be proven.

Debris Flows (Qdf)

Qdf is the unit designation given to a previously unrecognized sheet-like fragmental deposit in the west-central part of the map area. The outcrops are confined to elevations below those affected by late Pleistocene glaciation. The deposit overlies Tertiary Andesite, Basalt of Camp Forward, Rhyolite of Blue Ridge, Andesite of Onion Creek, Andesite of Digger Creek and Rockland Tephra, primarily in the drainages of Digger and Rock Creeks. Remnants of eroded Qdf overlie Rhyolite of Blue Ridge northwest of Grays Peak.

Outcrops of Qdf are sparse and good exposures are found only in roadcuts and stream banks. Thickness of Qdf is probably variable; the thickest exposure found was about 8 m in the canyon of the North Fork of Digger Creek. However, the bulk of the deposit in flat areas is probably no more than a few meters thick. Qdf is an enigmatic deposit that can be described as a matrix-supported debris flow. The matrix is light orange in color and weathers to a dark orange. A large component of the matrix is ash, which is mixed with silt and mud. The matrix is compact but unconsolidated and can be dug with a shovel. The deposit was probably emplaced cold. The clasts are centimeter- to meter-sized boulders of a variety of volcanic rocks. Most are Stage II andesite lava fragments resembling Andesite of Digger Creek. Clasts are angular to rounded and have dark-orange-brown weathering rinds up to 3 mm thick, similar to those found on till boulders. The clast content of Qdf is about 20%, but appears higher in many places because the easily eroded matrix leaves a veneer of boulders on the ground surface.

Meter-sized blocks of Andesite of Digger Creek with thin platy jointing probably could not have survived pyroclastic transport. The outcrop pattern of Qdf indicates emplacement by flow from the vicinity of Brokeoff Volcano. A tongue of material flowed down the North Fork of Digger Creek and came to rest on the valley floor below Camp Forward. Remnants of eroded Qdf above Camp Forward and south of the South Fork of Digger Creek suggest that Qdf passed down the drainage as a wave leaving a deposit on the canyon sides and bottom and on the flat terrain above them.

The combination of ashy matrix, abundant Stage II lava fragments, and position of Qdf directly overlying Rockland Tephra suggest that the two have related origins. For example, if Rockland Tephra was deposited at a time when Brokeoff Volcano was covered with snow or ice, debris flows could result when the snow or ice melted. A more definitive statement on the origin of Qdf awaits more detailed lithologic study.

Andesite of Huckleberry Lake (Qahb)

Sometime after cessation of Stage II volcanism, a parasitic vent opened on the southern flank of Brokeoff Volcano. Eruptions built a cinder cone and produced lava flows of Andesite of Huckleberry Lake. The cinder cone has been eroded by glaciation and its position is now marked by a plug of dense rock 2.5 km due north of Huckleberry Lake. The plug was intruded into lava flows interbedded with cinders rafted away from the cinder cone. Dikes of Andesite of Huckleberry Lake that fed the flows are exposed in the cliff just north of the vent.

Lava of the Andesite of Huckleberry Lake produced a thin flow complex covering at least 18 km^2 on the southern flank of Brokeoff Volcano. Lava flowed down the drainages of Nanny and Summit Creeks and probably down Mill Creek. Andesite of Huckleberry Lake covered a previously glaciated surface of Stage II rocks with some relief. Patches of Stage II rocks that were probably buried have been uncovered by subsequent glaciation. The flow complex is thin ($\leq$ 10 m) near its edges and thicker in the center. North of Morgan Mountain, the flows were ponded to a thickness of 100 m. Individual lava flows are thin ($\leq$ 10 m) with massive to blocky jointing. Flow surfaces are blocky with stretched vesicles.

The age of Andesite of Huckleberry Lake is constrained stratigraphically. Andesite of Huckleberry Lake was glaciated by Tahoe and Tioga glacial episodes (Kane, 1975) and is therefore older than 60,000 years. Andesite of Huckleberry Lake overlies pre-Tahoe till on Highway 36 near Mineral Summit (Crandell, 1972) but the age of this till is unknown. If the pre-Tahoe till is Illinoian in age ($\sim$ 130,000 years), then Andesite of Huckleberry Lake is between 130,000 and 60,000 years old. If the pre-Tahoe till is older, then Andesite of Huckleberry Lake could be considerably older. In either case, the cliff just north of the vent of Andesite of Huckleberry Lake was not present at the time that Andesite of Huckleberry Lake erupted, and Mill Creek Canyon was not as deep as it is now.

Andesite of Huckleberry Lake is the most mafic lava found in the Lassen Volcanic Center. Its chemistry is similar to mafic lavas found peripheral to the Lassen Volcanic Center. The parasitic vent occupies a stratigraphic position and is chemically similar to late stage mafic andesites found at Mt. Hood (Wise, 1969; White, 1980) and Mt. Jefferson (Greene, 1968; Williams and McBirney, 1979).

Andesite of Huckleberry Lake was described as a variant of Brokeoff Andesite by Williams (1932); however, he makes no mention of olivine, the most abundant mafic phenocryst. Andesite of Huckleberry Lake is an olivine mafic andesite. Phenocryst content is variable but is usually about 10%. Olivine and plagioclase are present in subequal amounts and augite and hypersthene are common minor components. Olivine phenocrysts range from 0.5 to 2 mm; most are rounded, corroded or embayed. Plagioclase phenocrysts range from 0.5 to 5 mm in length, although most are about 2 mm. Many are fragments of larger broken crystals. A variety of zoning, twinning, and sieving patterns are present, suggesting that most plagioclase crystals are xenocrysts. Most are sodic labradorite and some have reaction rims with the groundmass. A few euhedral unreacted plagioclase crystals may be primary phenocrysts. Augite and hypersthene crystals are present in most samples as minor constituents. They are commonly broken, resorbed, jacketed or reacting with the groundmass and must be considered xenocrysts. Glomeroporphyritic clots of plagioclase + pyroxenes are sometimes found and may be the source of plagioclase and pyroxene xenocrysts. Flow cores of Andesite of Huckleberry Lake are light gray and consist of plagioclase microlites with intersertal granules of augite and magnetite. Flow tops are medium to dark gray with pilotaxitic texture and glass charged with magnetite dust.

Basalt (Qbl)

A small area (∿ 0.25 km^2) of basalt lava mapped by Macdonald (1963) as upper Pleistocene Qbl crops out between the Rhyodacites of Loomis Peak and Manzanita. Qbl is older than either rhyodacite and is almost buried by them. A small, poorly preserved cinder cone marks the vent for the Qbl flows. The cinder cone has been partially overridden and bulldozed by the flow snout of the Rhyodacite of Loomis Peak. The Qbl lava flow is thin (< 10 m) and has a surface grading from aa to block lava.

Qbl is a porphyritic olivine basalt. Phenocrysts of 3 mm plagioclase (5%) and 1-2 mm olivine (5%) are set in a dark-gray, microvesicular, hyalopilitic groundmass of plagioclase, pyroxene and magnetite microlites with abundant dark-brown glass charged with magnetite dust. Some plagioclase phenocrysts have strongly sieved cores and clear overgrowth rims. The remainder are clear and unzoned labradorite. Olivine phenocrysts are euhedral and fresh. A few 1 mm augite phenocrysts are also present.

Qbl is not part of the Lassen Volcanic Center and is one of the most mafic calc-alkaline rocks from the LVNP area yet analyzed. It is a high-alumina basalt with 1.08% K_2O and FeO/MgO = 1.16. Its affinity is with the young basalts and mafic andesites common north and east of LVNP in the Manzanita Lake, Prospect Peak and Harvey Mountain Quadrangles.

Andesite of Red Lake Mountain (Qarl)

The Andesite of Red Lake Mountain is a porphyritic hypersthene-augite mafic andesite containing distinctive xenocrystic clots of olivine crystals and bright-green augite phenocrysts. The unit outcrops over ∿ 15 km^2 southeast of Viola. Andesite of Red Lake Mountain flowed over an eroded surface of Rockland Tephra and spread out as a thin sheet. Upon reaching to within 2 km of the west boundary of the Lassen Peak Quadrangle the lava encountered deep gullies eroded in the Rockland Tephra. Lava streams flowed down the two deepest gullies into the Manton Quadrangle, coalesced along the base of the Battle Creek Fault scarp, and flowed an additional 30 km to the west. Helley and others (1981) map the lava flows as Andesite of Brokeoff. Andesite of Red Lake Mountain has no apparent source within the map area. Its northern contact is with alluvium, and to the east it is covered by till. It can, however, be traced into the Manzanita Lake Quadrangle where Macdonald (1963) mapped it as Andesite of Brokeoff Mountain. However, Andesite of Red Lake Mountain is unlike any Brokeoff Volcano rock yet encountered, and it is younger than Rockland Tephra and hence younger than Brokeoff Volcano. Andesite of Red Lake Mountain is lithologically and chemically similar to lavas from Red Lake Mountain (Macdonald, 1963) and is tentatively correlated with them. Andesite of Red Lake Mountain could have come from Red Lake Mountain only if it predates Andesite of Viola, and hence it must be older than about 100,000 years.

Andesite of Red Lake Mountain is a mafic andesite containing ∿ 55% SiO_2 and 0.9% K_2O with FeO/MgO ∿0.8, similar to many shield volcanoes and lava cones contemporary with and peripheral to Lassen Volcanic Center. Andesite of Red Lake Mountain will be used to illustrate the rock type Lassen Calc-Alkaline Basalt and Andesite in a subsequent section.

Andesite of Red Lake Mountain is a porphyritic hypersthene-augite mafic andesite containing about 40% phenocrysts of plagioclase, augite and hypersthene. Plagioclase phenocrysts range from 0.25 to 2 mm, are slightly zoned in the labradorite compositional range, and comprise 30% of the rock. Euhedral augite phenocrysts comprise 8% of the rock and range from 0.25 to 2 mm in size. Their bright-green color is distinctive in hand specimen. Many contain optically zoned cores. Euhedral hypersthene phenocrysts are a minor component of the rock and range up to 1 mm in size. Xenoliths of 2 mm olivine crystals are common and range from 3 mm to 2 cm in size. The xenoliths have cumulate textures with intercumulus hypersthene and plagioclase. Anhedral olivine grains from disaggregated xenoliths are surrounded by coarse anhedral hypersthene, indicating reaction with the host groundmass. The groundmass is composed of plagioclase, pyroxene and magnetite microlites with variable amounts of glass charged with magnetite dust. Flow tops are marked by large (2-3 cm) oval vesicles and black glassy groundmass, whereas flow cores have small (1-3 mm) vesicles and medium-gray more crystalline groundmass.

Andesite of Viola (Qav)

The Andesite of Viola is a series of lava flows covering 25 km^2 east of Viola. The vent is marked by an eroded cinder cone 2.1 km southeast of Deep Hole (Hill 6924 on the Manzanita Lake 15 minute Quadrangle)(Macdonald, 1963). Andesite of Viola directly overlies Andesite of Digger Creek, which crops out along the southern boundary of Andesite of Viola and in the pit crater, Deep Hole. However, the flows are distinctly less soil covered than Stage II lavas; fields of loose boulders completely lacking soil are common, yet the flows are unglaciated. It is older than the Rhyodacites of Manzanita and Loomis Peak, which are about 0.05 m.y. old. Andesite of Viola is therefore between 0.35 and 0.05 m.y. old. Andesite of Viola has a distinctly disequilibrium phenocryst assemblage indicating it to be perhaps a mixture of low-K high-alumina olivine tholeiite and dacite to rhyodacite of the Lassen Volcanic Center.

Distal portions of flows of Andesite of Viola contain about 5% phenocrysts of plagioclase, olivine and resorbed hornblende. Plagioclase phenocrysts are mostly about 2 mm in diameter, but commonly are up to 5 mm; the strongly sieved crystals are andesine with clear rims of more calcic andesine. Hornblende phenocrysts are completely pseudomorphed by complexly intergrown pyroxene and magnetite. Olivine phenocrysts are small, 0.1 to 0.35 mm in diameter, and are corroded and partially converted to iddingsite. The pilotaxitic groundmass of distal flows of Andesite of Viola is composed of plagioclase, augite, and magnetite microlites with interstitial cryptofelsite. Proximal portions of flows are similar to the above although more porphyritic and contain small (0.25-1 mm) phenocrysts of augite with thin reaction rims and unsieved labradorite plagioclase phenocrysts with calcic andesine rims.

Rhyodacite of Loomis Peak (Qrlo)

Williams (1932) and Macdonald (1963) mapped a rhyodacite flow with a vent under Loomis Peak. Williams (1932) grouped the Loomis Peak flow with similar flows to the east under the name Pre-Lassen Dacite. The Pre-Lassen Dacites are here called Loomis Rhyodacites.

Rhyodacite of Loomis Peak was mapped only along its southern contact with rocks of Brokeoff Volcano, where it overlies Andesite of Mount Diller. Rhyodacite of Loomis Peak is 200-300 m thick where exposed in the north wall of Blue Lake Canyon. The flow has a basal breccia 1 m thick in which rounded clasts of rhyodacite as large as 25 cm are suspended in a glassy, perlitic matrix. The basal breccia grades up into a strongly horizontally flow-banded zone in which reddish pumiceous bands alternate with gray glassy bands. The pumiceous bands locally contain abundant lithophysae and spherulites. The flow interior is, glassier, massively jointed, and only vaguely flow banded.

The Rhyodacite of Loomis Peak is a slightly pumiceous medium-gray glassy porphyritic rhyodacite containing 15% phenocrysts of plagioclase, hornblende and hypersthene with sparse biotite and magnetite in a clear light-brown holohyaline matrix. Plagioclase phenocrysts comprise 12% of the rock, show strong normal and oscillatory zoning in the andesine composition range, are euhedral, and are up to 5 mm in length although most are 2 mm. Many plagioclase phenocrysts are strongly sieved and have clear overgrowth rims. Hornblende phenocrysts are euhedral yellow- to greenish-brown crystals 0.25 to 2 mm in length and comprise 2% of the rock. Small hypersthene crystals up to 0.5 mm in length, euhedral flakes of biotite, and granules of magnetite are minor components of the rock. Mafic xenoliths are abundant, locally reach 1 m in size, and comprise 50% of the rock (Williams, 1932). The mafic xenoliths include a wide variety of textural types.

Rhyodacite of Manzanita (Qrm)

A single, thick flow of rhyodacite southwest of Manzanita lake was mapped and described by Williams (1932) and Macdonald (1963). Their map patterns are correct, and I have little to add to the descriptions. Williams thought the flow to be one of the oldest Pre-Lassen Dacites, whereas Macdonald suggested that it is very young, perhaps even post-glacial. The unit is here called Rhyodacite of Manzanita and is grouped with the Loomis Rhyodacites, which include all of William's Pre-Lassen Dacites. Rhyodacite of Manzanita is younger than Andesite of Viola and probably younger than Rhyodacite of Loomis Peak. It has a weathered, pumiceous carapace, preserved because it is beyond the extent of late Pleistocene glaciation (Crandell, 1972). Soil cover is sparse, and crescentic flow ridges are preserved on the manzanita-covered flow surface.

Rhyodacite of Manzanita contains 15% phenocrysts of plagioclase, hornblende, biotite, hypersthene and magnetite in a holohyaline groundmass. Plagioclase phenocrysts show strong normal and oscillatory zoning in the andesine composition range, are euhedral, and are up to 5 mm in length although most are 2 mm. Sieved crystals were not noted. Plagioclase phenocrysts comprise 12% of the rock. Hornblende phenocrysts are euhedral, yellow- to greenish-brown crystals, 0.25 to 2 mm in length, and comprise 2% of the rock. Biotite phenocrysts are yellow-brown, euhedral flakes 0.25 to 0.5 mm in size and less abundant than hornblende. Small euhedral hypersthene and magnetite phenocrysts to 0.25 mm in size are minor components of the rock. Quartz phenocrysts, described as rare by Williams (1932), were not observed. The Rhyodacite of Manzanita has a groundmass composed of clear brown glass with hairlike microlites of plagioclase and perlitic cracks. Brownish spherulites and vesicular mafic xenoliths of felted plagioclase, acicular hornblende, and glass are common locally.

Basalt of Grays Peak (Qbgp)

Grays Peak is a small tree-covered lava cone approximately 1 km north of Hazen Flat. A lava flow to the southwest, down the course of Panther Creek, suggested to Wilson (1961) that Grays Peak was very young. Another smaller tongue of lava flowed a short distance down an unnamed tributary of the South Fork of Digger Creek. A scoria cone at the summit is poorly preserved; the rock is not exceptionally fresh, and the lava flow has a well developed soil and vegetative cover. The Basalt of Grays Peak may be late Pleistocene as suggested by Wilson (1961), but could easily be 100,000 years old or older.

The Basalt of Grays Peak was mapped and described by Wilson (1961) as a fine-grained olivine basalt containing 6% olivine phenocrysts and some plagioclase. However, in the mapped area, the Basalt of Grays Peak is a light- to medium-gray olivine basalt with 1% olivine phenocrysts up to 1 mm and no porphyritic feldspar. When vesicular, its groundmass is often reddish due to oxidation.

Undivided Glacial Deposits (Qg)

The Lassen area has been the site of repeated Pleistocene glaciation. Terminal and lateral moraine complexes are extensive on the southern and western slopes of Brokeoff Volcano, especially in the valleys of Bailey and Digger Creeks. Ground moraine occurs locally over large areas. Glacial deposits were mapped only where they are sufficiently extensive to obscure bedrock geology.

Crandell (1972) and Kane (1975; 1982) have studied the glacial deposits of the Lassen area. Crandell recognized three ages of till in western LVNP and tentatively correlated them with pre-Tahoe, Tahoe and Tioga glacial advances in the Sierra Nevada. Kane extended Crandell's work to eastern LVNP and Caribou Wilderness. He subdivided Crandell's Tioga deposits into early, middle and late Tioga. Kane assigns pre-Tahoe till to pre-Wisconsin glaciations ($\leq$ 130,000 years B.P.), Tahoe till to the early Wisconsin Stage (45-60,000 years B.P.), and the three Tioga advances to the late

Wisconsin Stage (25-29,000 years B.P., 11-25,000 years B.P. and 9-11,000 years B.P.). Thus, known glacial advances postdate the construction of Brokeoff Volcano, consistent with the lack of evidence for magma-ice interaction.

At their maximum extent, glaciers covered virtually all of LVNP. Tahoe valley glaciers extended to 4500-5000' elevation, Tioga glaciers to 5500'. The deeply eroded state of Brokeoff Volcano is due to ice action. Williams (1932) suggests that at least several hundred feet of bedrock were eroded from the upper slopes of the volcano, and glacial erosion greatly enhanced dissection of the hydrothermally altered core area.

Glacial till was found southwest of Viola for nearly 3 miles beyond the extent shown by Crandell and Kane. This till lacks constructional morphology, is deeply weathered, and is correlated with Crandell's pre-Tahoe till.

Many areas mapped as talus show evidence of protalus movement by ice or snowbanks in post-Tioga time.

Landslides (Qls)

Landslides of hydrothermally altered volcanic rock are common in the core of Brokeoff Volcano. Two occur in the map area. Crandell and Mullineaux (1970) recognized a large landslide in the area around Forest Lake. A red fir log found in a landslide deposit in Mill Creek Canyon nearly 5 km below Forest Lake yielded a radiocarbon age of 3310 ± 55 years (D. A. Trimble, written communication, 1980). At LVNP, Red Fir does not grow at the elevation the sample was found ($\sim$ 1650 m), preferring elevations above 2100 m. A mature Red Fir forest occurs in the area of Forest Lake. On the basis of lithology, P. A. Bowen (written communication, 1983) correlated the Mill Canyon landslide deposits with the Forest Lake landslide. It is likely that the two are the same and that the landslide occurred approximately 3300 years ago.

A second large landslide covers nearly 0.5 km^2 in the area west of Soda Lake. This landslide originated in the hollow on the ridge between Mt. Diller and Pilot Pinnacle, flowed north into Blue Lake Canyon, and turned west, coming to rest 3 km below its origin. The landslide is certainly post-glacial but is covered by mature forest. Comparison of morphologic features with those of the Forest Lake landslide indicates that they are of similar age.

Cognate Inclusions

Mafic Xenoliths

Calc-alkaline volcanic rocks of compositions ranging from andesite to rhyodacite commonly contain fine-grained blobs of material more mafic than the host rock. These mafic xenoliths range from a few mm to 1 m in size, but typically are 10-20 mm in diameter and elliptical to spheroidal in shape with crenulate margins convex toward the host rock. A continuum of textural and mineralogic features can be represented by end-member types based on the presence or absence of phenocrysts and the dominant mafic component.

Heiken and Eichelberger (1980) called the textural end members fine-grained porphyritic and medium-grained nonporphyritic. Porphyritic xenoliths contain combinations of olivine, augite, hypersthene, oxyhornblende, biotite, quartz, calcic and sodic plagioclase. The phenocrysts usually show weak to strong resorption or reaction with the groundmass and, except for small crystals of olivine, augite, and calcic plagioclase, are concentrated near the margin of the xenolith. These phenocrysts are interpreted to have been incorporated into the mafic xenoliths from the host magma. The groundmass of the xenoliths is composed of a felted intergrowth of acicular plagioclase, hornblende or pyroxene, and glass. The groundmass is strongly microvesicular, giving a diktytaxitic appearance. Grain size and elongation typically decrease toward the margins of xenoliths, and a glassy, vesicle-free selvage is often present on xenolith surfaces. On the basis of texture, bulk composition, and phase composition, Eichelberger (1980) and Heiken and Eichelberger (1980) have argued that mafic xenoliths represent mafic magma injected into and chilled within more silicic magma. The injection of hot mafic material may induce convection and stirring within the silicic chamber. Proportions of host versus contaminant will produce rocks of different chemical and macroscopic characteristics. A high mafic to silicic ratio will superheat the silicic host, causing phenocrysts to be resorbed, and will lower viscosity, which favors more thorough mixing. A low mafic to silicic will produce quenched blobs of mafic magma (mafic xenoliths).

Mafic xenoliths are common to abundant in Stage III andesites, dacites and rhyodacites of the Lassen Volcanic Center. Their abundance implies that magma mixing is an important process in the genesis and evolution of silicic rocks of the Lassen Volcanic Center.

Glomeroporphyritic Clots

Glomeroporphyritic clots occur in most Brokeoff Volcano lavas and are conspicuously abundant in Stage II flows. The clots are typically 5 mm-1 cm aggregates of crystals present in the host rock. Plagioclase dominates an assemblage containing augite, hypersthene, magnetite and occasionally olivine. Textures are hypidiomorphic granular to cumulate. Clot crystals are often larger than host-rock phenocrysts. Plagioclase crystals are unzoned or have a mottled zoning suggestive of recrystallization. Adcumulus growth is common, whereas resorbed or sieved zones are absent. Augite crystals are often twinned and contain vague exsolution lamallae. Hypersthene often occurs as anhedral aggregates of small crystals with abundant vermicular magnetite. Where coarse hypersthene is poikilitic, euhedral hypersthene with exsolution lamallae also is found. Anhedral olivine grains occur as inclusions in poikilitic hypersthene. Gabbroic nodules are found in the Andesite of Blue Lake Canyon as glomeroporphyritic clots 5-10 cm in size.

The gabbroic nodules are plagioclase, olivine, augite, hypersthene and magnetite orthocumulates. They represent the cumulus crystals removed from fractionating magma bodies by fractional crystallization at crustal pressures. Subsequent recrystallization in the plutonic environment produced poikilitic orthopyroxene by reaction of intercumulus liquid with olivine (Augustithis, 1979). The crystallization products of intercumulus liquid were fused upon incorporation of the xenoliths into the host magma and quenched upon eruption.

Disruption and disaggregation of nodules is facilitated by partial fusion of intercumulus material and along crystal boundaries. Distribution of crystals in flowing lava can produce porphyritic andesite from aphyric andesite (Fujimaki, 1982). It is suggested that the glomeroporphyritic clots abundant in Stage II andesites originated from disaggregation of gabbroic nodules. In addition, many of the individual phenocrysts may be nodule remnants.

Glomeroporphyritic clots are common in orogenic volcanic rocks, especially andesites (Gill, 1981). Incorporation of glomeroporphyritic clots in magma chambers or erupting lava flows might imitiate open-system crystal fractionation or magma mixing and thus confuse liquid-crystal relationships, liquid lines of descent, and trace-element systematics. Furthermore, the possibility of incomplete degassing of radiogenic argon from plutonic xenoliths (Gillespie, 1982) suggests that whole-rock K-Ar analyses of young andesites with added crystals may indicate ages older than that of solidification. Analysis of plagioclase phenocrysts in a rock with abundant glomeroporphyritic clots from the Dittmar Volcanic Center gave an age of $\sim$ 4.0 m.y., whereas a whole-rock analysis indicated an age of 1.35 m.y. (G. B. Dalrymple, written communication, 1982). Hence, interpretation of petrologic or geochronologic data obtained from rocks with abundant glomeroporphyritic clots must be made with great care.

GEOCHEMISTRY

Introduction

Major-element analyses have been performed on more than 350 rock samples from Lassen Volcanic National Park and vicinity. Williams (1932) summarized the pre-1932 data. Subsequent data sets were taken from Macdonald (1983), Smith and Carmichael (1968), Gedeon (1970), Fountain (1975), Heiken and Eichelberger (1980), P. A. Bowen (written communication, 1983), L. J. P. Muffler (unpublished data), and Clynne (this report). The data sets were edited to include only complete analyses of well located, well characterized, fresh rocks. Iron was recalculated to total FeO, and all analyses were recalculated to 100 percent on an anhydrous basis. The resulting data set of 303 analyses was divided into four subsets:

1. Eruptive products of the Dittmar Volcanic Center, 17 analyses
2. Eruptive products of the Maidu Volcanic Center, 27 analyses
3. Eruptive products of the Lassen Volcanic Center, 208 analyses
4. Eruptive products of peripheral shield volcanoes, cinder cones, and valley-filling lava flows, 51 analyses.

Features of the major element chemistry of subsets 3 and 4 are discussed in subsequent sections. Subsets 1 and 2 are not discussed in this report. Tables containing the entire data set will be published in a forthcoming report.

Lassen Volcanic Center

The 208 rock analyses in subset 3 have been edited by eliminating duplications to 97 analyses representative of Lassen Volcanic Center. For example, the data set of Fountain (1975) contains many analyses of similar rocks; where these could be shown by fieldwork to be of single lithologic units they were averaged. The 97 analyses were placed into eleven groups, here called sequences, representing the distinctive rock types in the three stages of the evolution of Lassen Volcanic Center. Stages I and II represent the growth of Brokeoff Volcano, and Stage III the development of the Lassen Domefield and associated eruptives. The process of grouping is a product of my understanding of the Lassen Volcanic Center based on geologic mapping and interpretation of previous work. The sequences are presented in stratigraphic order; i.e., oldest to youngest. Note that the word "sequence" refers to chemical grouping only. The intention is to separate the sequence names used here from the unit names on the geologic map as there may or may not be a direct correlation. The sequences are first briefly described (table 1), and then the chemical data are presented.

Lassen Volcanic Center - Stage I (Early Phase of Brokeoff Volcano)

Stage I of the Lassen Volcanic Center is represented by three sequences of lavas: the Mill Canyon Sequence, the Ski Hill-Conard Sequence, and the Twin Meadows Sequence. During Stage I, the evolution of the Lassen Volcanic Center progressed irregularly.

TABLE 1. GENERALIZED PETROGRAPHIC AND PETROLOGIC CHARACTERISTICS OF THE LASSEN VOLCANIC CENTER

	Brokeoff Volcano								
	Stage I		Stage II	Stage III					
UNIT	Ski Hill-Conard, Mill Cyn. Sequences	Twin Meadows Sequence	Digger-Diller, Rice Cr. Sequence	Rockland Tephra	Andesite of Huckleberry Lk.	Bumpass Dacites	Loomis Rhyodacites	Lassen Rhyodacites	Twin Lakes Andesites
ROCK TYPE	ol-augite and augite andesites	px-hornblende dacite	augite-hyp andesite	hornblende rhyolite	olivine andesite	px-hornblende dacite	hb-biotite rhyodacite	hb-biotite rhyodacite	augite andesite
MINERALOGY phenocrysts	10-30%, 2mm	8-15%, 2mm	30-40%, 2mm	10%, 2mm	10%, 2mm	10%, 1-5mm	15-20%, 2mm	30%, 2mm	5-10%, 1-5mm
	plag aug ol hy	plag hb px	plag hy aug	plag hb hy	ol=plag	plag hb px	pl bio hb px qz	pl bio hb px qz	pl hb aug,ol, qz; strong
	disequilibrium	disequilibrium	disequilibrium	equilibrium	equilibrium	disequilibrium	disequilibrium	disequilibrium	disequilibrium
groundmass	hyalopilitic, pilotaxitic	hyalopilitic	hyalopilitic	holohyaline	intersertal	hyalopilitic	holohyaline	holohyaline, hyalopilitic	hyalopilitic
glomero-porphyritic clots	sparse	sparse	abundant	absent	sparse	sparse	absent	absent	absent
mafic xenoliths	absent	abundant	sparse	common	absent	sparse to abundant	sparse to abundant	abundant	sparse
CHEMISTRY SiO_2	56-61%	66-68%	60-63%	70%	54%	64-68%	69-71%	68-70%	56-60%
K_2O	1.0-2.0%	3.0%	1.6-2.3%	2.7%	0.9-1.1%	1.9-2.3%	2.7-3.2%	2.5-2.8%	1.1-2.0%
FeO/MgO	1.3-1.7	2.4-2.7	1.3-1.7	2.9	0.9-1.0	1.5-2.0	2.1-2.4	1.7-2.0	1.2-1.4
MORPHOLOGY	thin flows abundant inter-bedded pyroclastics	thick flows	thick flows	ashflow tuff	thin flows	domes, thick flows	thick flows	domes, pyroclastic flows	thick flow complexes, shield volcanoes
APPROXIMATE AGE (Ka yrs)	600-450	450	450-360	350	130-60	250-200	50	50-0	50-0

Eruptions of mafic andesite to silicic andesite lavas and pyroclastic materials built the large composite cone, Brokeoff Volcano. Stage I culminated in the eruption of differentiated dacite lava flows (Twin Meadows Sequence).

Coverage and representativity of the analyzed samples is fair for the Mill Canyon Sequence, poor for the Ski Hill-Conard Sequence Group, and good for the Twin Meadows Sequence.

Mill Canyon Sequence The Mill Canyon Sequence represents most of Stage I of the Lassen Volcanic Center and includes lavas exposed on the western and southern flanks of Brokeoff Volcano. The analyses are all of olivine and (or) pyroxene mafic andesites and andesites erupted as flank lavas that are the pyroclast-free lateral equivalent of the Ski Hill-Conard Sequence. Analyses of the following lithologic units are included: Andesites of Mill Canyon, Andesite of Rock Spring, Andesite of Onion Creek, Andesite of Heart Lake, Andesite of Bailey Canyon (this report), and Andesite of Hanna Falls (Muffler and others, 1982). Outcrops of these units are limited to Mill Creek Canyon and the South Fork of Bailey Creek Canyon, the Heart Lake area, along Onion Creek, and at McGowen Lake.

Ski Hill-Conard Sequence The Ski Hill-Conard Sequence is the coneward lateral equivalent of the Mill Canyon Sequence and represents lavas from the core area of Brokeoff Volcano. Like the Mill Canyon Sequence, these lavas span the full range of preserved Stage I rocks of the Lassen Volcanic Center, except for the Dacite of Twin Meadows. Outcrops of unaltered rock in the hydrothermally altered core of Brokeoff Volcano are sparse, and lateral continuity of flows is poor; hence, stratigraphic relationships between samples are often ambiguous. Large amounts of the core area have been removed by erosion. The Andesites of Ski Hill and Andesite of Mt. Conard (Muffler and others, 1982a; P. A. Bowen, written communication, 1983) comprise the bulk of the analyses in this group. Pyroclastic debris comprises a large portion of the rocks in these units; however, analyses of pyroclastic material are nonexistent. The analyzed rocks are mostly from the Mt. Conard area. The above factors may combine to make the analyses of Ski Hill-Conard Sequence poorly representative of the rocks actually present. The Ski Hill-Conard Sequence occurs only along the margins of my map area. Nevertheless, a few generalizations can be made. The lavas are generally dark, glassy, porphyritic hypersthene-augite andesites and olivine-augite andesites that occur in thin (∿3-8 m) flows. Pyroclastic material is abundant and mudflow material occasionally present.

I have no reason to dispute the suggestion of Williams (1932) that the vent for Stage I rocks was in the vicinity of Sulphur works. Age data on the Ski Hill-Conard Sequence and laterally equivalent Mill Canyon Sequence are limited to two K-Ar dates (G. B. Dalrymple, written communication, 1982), suggesting that these rocks accumulated during the interval between approximately 600,000 and 450,000 years ago.

Twin Meadows Sequence The Twin Meadows Sequence represents the culmination of Stage I of the Lassen Volcanic Center. This sequence includes the pyroxene-hornblende dacites of the Dacite of Twin Meadows that are exposed near the summit of Brokeoff Mountain and in Blue Lake Canyon. The Twin Meadows Sequence represents a short-lived volcanic episode that occurred about 450,000 years ago.

Lassen Volcanic Center - Stage II (Late Phase of Brokeoff Volcano)

Stage II of Lassen Volcanic Center is characterized by emplacement of thick silicic andesite lava flows on the flanks of Brokeoff Volcano. Stage II units are separated from Stage I units in some areas by an unconformity. Because Stage I rocks are widely exposed and readily accessible, they have been widely sampled and analyzed. Their homogeneous mineralogy and chemistry have promoted the petrogenetic interpretation that Brokeoff Volcano is a composite volcano with little diversity (Williams, 1932; McBirney, 1968; Fountain, 1975). Stage II rocks, however, are only a veneer, obscuring underlying Stage I rocks. I have divided Stage II units into two groups: the older Rice Creek Sequence and the younger Digger-Diller Sequence, respectively on the east and west flanks of Brokeoff Volcano. Coverage and representativity of the analyzed rocks is fair for the Rice Creek Sequence and good for the Digger-Diller Sequence.

Rice Creek Sequence The Rice Creek Sequence consists of a single flow unit named Andesite of Rice Creek that covers at least

42 km^2 and probably more than 50 km^2 on the east flank of Brokeoff Volcano. A broad plateau in the Rice Creek area forms the bulk of the unit. Outcrops at Kings Creek Falls and in the upper Hot Springs Creek drainage indicate that additional Andesite of Rice Creek underlies younger dacite flows in these areas (P. A. Bowen, written communication, 1983).

The Andesite of Rice Creek is a porphyritic augite-hypersthene silicic andesite characterized by abundant glomeroporphyritic clots of plagiocase + clinopyroxene + orthopyroxene ± olivine ± magnetite. The Andesite of Rice Creek probably originated from a vent on the northeastern flank of Brokeoff Volcano and flowed east and south.

Wider variability of chemistry and phenocryst content than in the lithologically similar Digger-Diller Sequence suggest that the Andesite of Rice Creek could be further divided with additional systematic fieldwork.

Digger-Diller Sequence The Digger-Diller Sequence includes the mapped units: Andesite of Bluff Falls and Andesite of Glassburner Meadows in the Brokeoff Mountain area, Andesite of Digger Creek in the Red Rock Mountain area, and Andesite of Mt. Diller in the Mt. Diller area. Cumulatively, these units cover at least 52 km^2. The Digger-Diller Sequence is at least 350 m thick in the vicinity of Mt. Diller, thinning considerably to the southwest and east. No vent areas are preserved; however, distribution of the flows supports William's (1932) speculation that they erupted from a vent or vents in the vicinity of Sulphur Works.

The Digger-Diller Sequence rocks are porphyritic, augite-hypersthene silicic andesites characterized by abundant glomeroporphyritic clots of plagioclase + clinopyroxene + orthopyroxene ± olivine ± magnetite. The units are difficult to distinguish from each other in the field, petrographically or chemically.

K-Ar dates indicate Stage II to be of relatively short duration; emplacement of Stage II rocks occurred in the interval between about 450,000 and 360,000 years ago.

Lassen Volcanic Center - Stage III

Stage III of the evolution of Lassen Volcanic Center is characterized by silicic volcanism. Eruption of the Rockland Tephra took place from a vent that has not yet been located at about 350,000 years ago. Eruption of dacite and rhyodacite domes and flows and hybrid andesite flows from at least 20 vents took place in a broad zone on the northern and northeastern flanks of Brokeoff Volcano. These are subdivided into four sequences: Bumpass Sequence, Loomis Sequence, Lassen Sequence and Twin Lakes Sequence. An additional sequence, the Huckleberry Lake Sequence, represents a single flow unit of mafic andesite on the southern flank of Brokeoff Volcano.

Except for the Huckleberry Lake Sequence, Stage III rocks are not well represented in the map area. The discussion presents my interpretation of the work of Williams (1932), Macdonald (1983), Fountain (1975), and P. A. Bowen (written communication, 1983). I have examined and collected samples from most of the volcanic features discussed.

Bumpass Sequence The Bumpass Sequence includes a group of hornblende and pyroxene dacite domes and thick flows erupted from vents on the southern and eastern side of the Lassen dacite domefield. The major features included in this group are the Bumpass Mountain dome and flow (P. A. Bowen, written communication, 1983), the Reading Peak domes, the Flatiron Ridge flow, the Ski Heil Peak dome, and the unamed dome immediately east of Lake Helen. Lavas of the Bumpass Sequence are less porphyritic than the Stage III rhyodacites and are hornblende-pyroxene dacites. Preliminary K-Ar dates on Reading Peak and Bumpass Mountain suggest that they erupted in the period 250-200,000 years ago (G. B. Dalrymple, written communication, 1982).

Loomis Sequence The Loomis Sequence represents a group of thick, glassy, sometimes pumiceous, rhyodacite lava flows designated Pre-Lassen Dacite by Williams (1932). These erupted principally from a vent now covered by Lassen Peak, except for an additional vent near Hill 7263 (Rhyodacite of Manzanita). The source of additional Pre-Lassen Dacite flow remnants on Mt. Conard is uncertain, but they probably erupted from the vent covered by Lassen Peak.

Lavas of the Loomis Sequence are glassy hornblende-biotite rhyodacites generally less porphyritic and showing less phenocryst disequilibrium features and carrying fewer mafic inclusions than rocks of the Lassen Sequence. The age of the flows is poorly known. Williams (1932) thought they were all erupted in a single episode before the eruption of any of the Lassen Domes. Macdonald (1983) agrees with Williams except for indicating that the Manzanita Flow represents a second, younger eruptive episode. However, the Loomis Sequence lavas postdate the Bumpass Sequence but predate the Lassen Sequence. I suggest that most, if not all, the Loomis Sequence represents a single episode of volcanism that occurred late in the history of Stage III, perhaps about 50,000 years ago (U-Th data of D. A. Trimble, personal communication, 1983).

Lassen Sequence The Lassen Sequence represent at least 10 rhyodacite domes and associated pyroclastic flows, the most prominent of which are Lassen Peak, Crescent Crater and Chaos Crags. The detailed age relationships are uncertain, but the domes probably range in age from about 50,000 years to 1,050 years (^{14}C data of S. W. Robinson, written communication, 1983; U-Th data of D. A. Trimble, personal communication, 1983).

The lithologies of the domes are heterogeneous. Phenocryst content and character vary within and between domes. However, in general the rocks are porphyritic hornblende or hornblende-biotite rhyodacites. Disequilibrium features in the phenocrysts are common, and all domes contain variable proportions of mafic inclusions.

Twin Lakes Sequence The Twin Lakes Sequence is an unusual group of lava flows, called quartz andesites by previous workers, that are spatially and temporally associated with the silicic rocks of the Lassen Volcanic Center silicic rocks. The Twin Lakes Andesites (Williams, 1932) that form the Central Plateau of Lassen Volcanic National Park erupted from three centers, marked by the cinder and lava cones of Hat Mountain, Fairfield Peak, and Crater Butte. Two lithologically similar flows have been added to Williams' Twin Lakes Andesites; Qay of Macdonald (1963), here renamed Andesite of Viola, and the young flow erupted from the cinder cone between West Prospect and Prospect Peaks, hereafter called Prospects Flow. I have also assigned the 1915 lava flow from Lassen Peak and the lavas of Cinder Cone to the Twin Lakes Sequence because of their obviously hybrid origin (Finch and Anderson, 1930; Macdonald and Katsura, 1965).

Lavas of the Twin Lakes Sequence are characterized by a black, glassy groundmass, large phenocrysts of strongly resorbed sodic plagioclase, and quartz xenocrysts with augite reaction rims. Olivine, augite, calcic plagioclase, and magnetite pseudomorphs of hydrous mafic minerals, each in various degrees of disequilibrium, are present in most flows. Mafic inclusions are sparsely present. In total, the mineralogical variety and disequilibrium of the Twin Lakes Sequence indicate them to be hybrid lavas.

The eruptive history of the Twin Lakes Sequence parallels that of Stage III of Lassen Volcanic Center. Williams (1932) thought the Twin Lakes Andesites to be older than Brokeoff Volcano; however, the

Andesite of Viola directly overlies Stage II andesites and is younger than Rhyodacite of Loomis Peak. Macdonald (1964) indicates the Hat Mountain flows to be younger than Loomis Sequence flows at Dersch Meadows; my reconnaissance mapping has confirmed this interpretation. The age of the Fairfield Peak and Crater Butte flows remains ambiguous and can only be assumed to be similar to Hat Mountain. Each is glaciated but retains a well defined cone. The Prospects Flow is undoubtedly Holocene (Williams, 1932; Macdonald, 1964), and Cinder Cone has a short history culminating in 1851 (Finch and Anderson, 1930; James, 1966). The Twin Lakes Sequence thus represents a time span beginning perhaps 100,000 years ago and continuing to the present.

Major-Element Chemistry

The major-element chemical analyses and normative mineralogy of rocks from the Lassen Volcanic Center are given in table 2. AFM and oxide component diagrams are given in figures 4-14. Figure 3 is the key to the symbols used for the rock sequences in figures 4-14.

Rocks of the Lassen Volcanic Center contain 53 to 71 wt % SiO_2. For purposes of discussion, all rocks in the Mill Canyon, Ski Hill-Conard, Rice Creek, Digger-Diller, Twin Lakes and Huckleberry Sequences will be called andesites, all rocks in the Twin Meadows and Bumpass Sequences will be called dacites, and all rocks in the Loomis and Lassen Sequences will be called rhyodacites.

Table 2. Chemical Analyses of Lassen Volcanic Center Rocks

[Oxides adjusted to sum to 100% without water. CIPW normative minerals are reported in weight % and were calculated using the exact formulae of Washington (1917). D. I. = Thornton and Tuttle's differentiation index. Sources of data: M numbers, L. J. P. Muffler (unpublished data); B numbers, P. A. Bowen (written communication, 1983); C numbers, Clynne (this report); F numbers, Fountain (1975), numbers proceeded by an A are averaged values; D numbers, MacDonald (1983); SC numbers, Smith and Carmichael (1968). Unit symbols not given in text: Qamc, Andesite of Mt. Conard (Muffler and others, 1982a); Qarc, Andesite of Rice Creek (Muffler and others, 1982a); Qdb, Bumpass Dacites; Qrl, Loomis Rhyodacites; Qrla, Lassen Rhyodacites; Qatl, Twin Lakes Andesites]

Analysis number Sample number Unit	1 B366 Qamc	2 B9042 Qamc	3 B336 Qash	4 B265 Qash	5 C0439 Qash	6 C0495 Qash	7 C1797 Qash	8 B266 Qash	9 B337 Qash	10 B338 Qash	11 B8012 Qash
SiO_2	60.16	58.71	60.62	59.82	60.25	59.90	58.26	60.86	59.80	60.38	60.38
Al_2O_3	17.05	17.86	17.59	17.10	17.98	17.23	18.10	18.04	17.37	17.96	17.81
FeO	5.70	5.90	5.06	5.69	4.82	5.52	5.91	4.79	5.69	4.95	5.09
MgO	3.48	3.60	3.83	3.58	4.04	4.19	3.89	3.44	4.04	3.60	3.80
CaO	6.79	6.90	7.09	7.04	7.27	6.50	7.28	6.87	6.80	7.23	7.02
Na_2O	3.80	3.98	3.62	3.75	3.58	3.75	3.65	3.79	3.59	3.81	3.74
K_2O	1.93	1.72	1.31	1.92	1.21	1.78	1.75	1.31	1.65	1.20	1.25
TiO_2	0.75	0.93	0.62	0.73	0.62	0.81	0.82	0.63	0.72	0.62	0.66
P_2O_5	0.25	0.30	0.17	0.27	0.15	0.23	0.23	0.20	0.25	0.17	0.16
MnO	0.10	0.09	0.08	0.10	0.07	0.08	0.10	0.08	0.10	0.08	0.08
FeO/MgO	1.64	1.64	1.32	1.59	1.19	1.32	1.52	1.39	1.41	1.38	1.34
Q	9.09	6.64	11.46	8.58	11.23	8.90	6.64	11.78	9.50	10.80	10.78
C											
Or	11.29	10.00	7.66	11.26	7.15	10.55	10.33	7.65	9.59	7.03	7.32
Ab	31.91	33.03	30.27	31.56	30.26	31.77	30.89	31.76	29.85	31.90	31.26
An	23.58	25.30	27.50	24.00	29.45	24.90	27.83	28.10	25.98	28.10	27.70
Di	6.80	5.26	5.06	7.42	4.64	4.85	5.59	3.59	4.61	5.20	4.65
DiWo	3.42	2.65	2.56	3.74	2.36	2.46	2.82	1.82	2.33	2.63	2.36
DiEn	1.62	1.27	1.33	1.79	1.27	1.29	1.39	0.92	1.18	1.34	1.22
DiFs	1.76	1.34	1.17	1.89	1.01	1.10	1.38	0.85	1.10	1.23	1.08
Hy	14.55	15.47	15.23	14.56	15.75	16.98	16.61	14.57	16.90	14.46	15.35
HyEn	6.97	7.53	8.09	7.08	8.80	9.14	8.31	7.58	8.71	7.55	8.13
HyFs	7.58	7.94	7.14	7.49	6.95	7.84	8.30	6.99	8.19	6.91	7.22
Ol											
OlFo											
OlFa											
Il	1.41	1.74	1.16	1.37	1.18	1.54	1.56	1.18	1.34	1.16	1.23
Ap	0.60	0.71	0.41	0.64	0.36	0.54	0.55	0.48	0.57	0.40	0.37
Salic	75.86	74.98	76.88	75.40	78.09	76.11	75.70	79.29	74.92	77.83	77.05
Femic	23.36	23.18	21.85	23.99	21.92	23.90	24.31	19.81	23.43	21.22	21.60
D. I.	52.28	49.68	49.39	51.40	48.64	51.21	47.87	51.19	48.93	49.73	49.36

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	12 B35A Qash	13 B35B Qash	14 B157 Qash	15 M0884 Qam	16 B166B Qam	17 C0436 Qam	18 M0873 Qam	19 C0436B Qam	20 F58 Qam	21 M0876 Qam	22 M0875 Qam
SiO_2	60.23	60.36	59.92	56.84	60.31	57.50	55.35	55.45	63.75	57.27	60.06
Al_2O_3	17.05	17.09	17.58	17.20	17.00	17.20	15.94	15.87	15.39	17.20	16.95
FeO	5.67	5.58	5.79	6.79	5.65	6.63	6.79	6.78	5.01	6.60	5.70
MgO	4.34	3.90	3.31	4.36	3.77	4.21	7.97	8.02	3.28	5.20	4.19
CaO	6.49	6.69	6.57	7.89	6.41	7.59	9.27	9.26	5.33	7.27	6.38
Na_2O	3.53	3.73	3.91	3.81	3.80	3.76	2.92	2.83	3.93	3.60	3.67
K_2O	1.70	1.67	1.87	1.56	2.00	1.61	0.82	0.84	2.26	1.59	1.93
TiO_2	0.69	0.66	0.75	1.08	0.74	1.05	0.66	0.66	0.79	0.88	0.79
P_2O_5	0.22	0.22	0.20	0.37	0.23	0.34	0.16	0.16	0.18	0.28	0.24
MnO	0.08	0.10	0.10	0.11	0.10	0.11	0.12	0.12	0.08	0.11	0.10
FeO/MgO	1.31	1.43	1.75	1.56	1.50	1.57	0.85	0.85	1.53	1.27	1.36
Q	10.05	9.88	8.55	3.87	9.09	5.23	2.33	2.76	14.42	4.52	9.16
C											
Or	9.85	9.74	10.95	9.21	11.77	9.51	4.86	4.99	13.38	9.39	11.38
Ab	29.32	31.22	32.79	32.26	32.09	31.82	24.69	23.97	33.23	30.48	31.05
An	25.17	24.74	24.73	25.22	23.40	25.30	27.98	28.10	17.67	26.07	24.08
Di	4.13	5.53	5.21	9.50	5.65	8.39	13.78	13.66	6.28	6.68	4.94
DiWo	2.10	2.79	2.62	4.79	2.85	4.23	7.07	7.01	3.17	3.39	2.50
DiEn	1.09	1.39	1.20	2.35	1.40	2.06	4.23	4.21	1.57	1.79	1.29
DiFs	0.95	1.34	1.40	2.36	1.40	2.10	2.47	2.44	1.54	1.50	1.15
Hy	17.84	16.12	15.09	17.04	15.91	16.97	24.75	24.90	13.09	20.53	17.34
HyEn	9.53	8.22	6.98	8.50	7.97	8.42	15.62	15.76	6.59	11.17	9.15
HyFs	8.31	7.90	8.12	8.54	7.94	8.55	9.13	9.14	6.50	9.37	8.19
Ol											
OlFo											
OlFa											
Il	1.29	1.24	1.42	2.04	1.40	1.99	1.26	1.26	1.50	1.67	1.50
Ap	0.50	0.52	0.48	0.88	0.55	0.81	0.38	0.38	0.43	0.67	0.57
Salic	74.40	75.58	77.03	70.56	76.34	71.86	59.85	59.81	78.71	70.46	75.66
Femic	23.76	23.41	22.19	29.46	23.50	28.16	40.16	40.20	21.30	29.55	24.35
D. I.	49.22	50.85	52.29	45.34	52.95	46.56	31.87	31.71	61.04	44.39	51.59

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	23 M0830 Qam	24 F57 Qam	25 F59 Qam	26 F56 Qam	27 F55 Qam	28 B172 Qam	29 F60 Qam	31 C0372 Qaoc	31 C1775 Qars	32 C0409 Qabc	33 C0178 Qaht
SiO_2	59.82	60.15	61.48	60.91	64.34	55.92	55.93	58.52	55.94	59.45	60.54
Al_2O_3	17.31	16.46	15.85	16.38	15.85	17.04	16.64	18.22	18.07	18.03	16.66
FeO	5.75	5.86	5.52	5.86	4.62	7.05	7.46	6.14	6.82	6.10	5.89
MgO	4.00	4.19	4.14	3.91	3.05	5.65	5.81	3.89	4.70	3.05	3.59
CaO	6.47	6.35	6.00	6.11	4.89	7.62	7.68	6.79	7.74	6.41	6.04
Na_2O	3.67	3.96	3.86	3.57	3.92	3.87	3.42	3.72	3.48	4.08	3.88
K_2O	1.87	1.83	2.00	2.01	2.35	1.52	1.55	1.53	1.70	1.67	2.03
TiO_2	0.78	0.89	0.85	0.93	0.70	0.94	1.15	0.84	1.06	0.83	0.97
P_2O_5	0.24	0.21	0.20	0.24	0.20	0.26	0.23	0.24	0.37	0.28	0.29
MnO	0.09	0.09	0.09	0.09	0.08	0.12	0.12	0.11	0.12	0.10	0.10
FeO/MgO	1.44	1.40	1.33	1.50	1.51	1.25	1.28	1.58	1.45	2.00	1.64
Q	8.99	8.34	10.67	11.25	15.59	0.77	2.57	7.57	3.22	8.14	9.75
C											
Or	11.07	10.84	11.84	11.85	13.92	9.00	9.14	9.03	10.02	9.88	12.01
Ab	31.09	33.50	32.65	30.21	33.16	32.72	28.97	31.44	29.48	34.54	32.84
An	25.20	21.72	20.02	22.74	18.71	24.64	25.48	28.53	28.67	25.93	22.04
Di	4.37	6.95	6.96	4.95	3.50	9.43	9.13	2.97	6.04	3.36	4.99
DiWo	2.21	3.52	3.53	2.50	1.77	4.79	4.64	1.50	3.05	1.68	2.51
DiEn	1.11	1.80	1.84	1.25	0.87	2.54	2.46	0.72	1.54	0.72	1.21
DiFs	1.05	1.63	1.59	1.20	0.86	2.10	2.04	0.75	1.45	0.95	1.27
Hy	17.23	16.46	15.78	16.67	13.33	21.04	21.99	18.30	19.70	15.93	15.87
HyEn	8.85	8.63	8.47	8.49	6.71	11.53	12.02	8.96	10.16	6.87	7.73
HyFs	8.39	7.83	7.31	8.18	6.61	9.52	9.98	9.34	9.54	9.06	8.14
Ol											
OlFo											
OlFa											
Il	1.48	1.69	1.62	1.77	1.33	1.79	2.19	1.60	2.01	1.58	1.83
Ap	0.58	0.50	0.48	0.57	0.48	0.62	0.55	0.58	0.89	0.67	0.70
Salic	76.35	74.40	75.18	76.05	81.37	67.12	66.15	76.58	71.39	78.48	76.63
Femic	23.66	25.61	24.83	23.97	18.64	32.88	33.87	23.44	28.63	21.53	23.39
D. I.	51.15	52.68	55.16	53.31	62.67	42.49	40.67	48.05	42.72	52.55	54.59

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	34 C0410 Qaht	35 C0451A Qabl	36 B210 Qarc	37 B138B Qarc	38 B316 Qarc	39 B354 Qarc	40 B138A Qarc	41 B8042 Qarc	42 B142 Qarc	43 B239B Qarc	44 F2A Qdtm
SiO_2	58.85	58.03	60.19	63.01	62.85	62.89	63.72	62.75	59.39	62.14	67.63
Al_2O_3	17.52	17.66	17.58	17.32	17.18	16.78	17.07	16.69	17.63	17.21	15.65
FeO	6.04	5.64	5.78	4.40	4.69	4.86	4.27	4.77	6.07	4.68	3.48
MgO	3.89	5.19	3.33	2.86	2.73	2.83	2.79	2.85	3.53	3.18	1.44
CaO	7.17	7.86	6.20	5.78	5.39	5.41	5.52	5.34	6.53	6.37	3.41
Na_2O	3.71	3.54	3.86	3.97	3.96	4.00	3.97	4.35	3.88	3.51	4.44
K_2O	1.66	1.04	2.05	1.91	2.25	2.25	1.90	2.25	1.86	2.21	2.95
TiO_2	0.80	0.74	0.74	0.53	0.66	0.66	0.53	0.72	0.79	0.49	0.76
P_2O_5	0.25	0.21	0.21	0.14	0.21	0.21	0.15	0.20	0.21	0.13	0.17
MnO	0.10	0.09	0.10	0.08	0.09	0.09	0.08	0.09	0.10	0.08	0.07
FeO/MgO	1.55	1.09	1.74	1.54	1.72	1.72	1.53	1.67	1.72	1.47	2.42
Q	7.60	7.04	8.87	13.72	13.19	12.98	15.13	11.40	7.69	12.89	19.53
C											
Or	9.82	6.14	12.03	11.17	13.20	13.26	11.13	13.21	10.95	12.98	17.41
Ab	31.37	29.97	32.48	33.28	33.21	33.73	33.31	36.66	32.63	29.50	37.57
An	26.27	29.22	24.26	23.55	22.26	21.06	22.96	19.30	25.07	24.57	14.08
Di	6.34	6.87	4.07	3.24	2.40	3.57	2.69	4.79	4.78	4.97	1.43
DiWo	3.20	3.51	2.04	1.64	1.21	1.79	1.35	2.41	2.40	2.51	0.71
DiEn	1.55	1.96	0.94	0.79	0.56	0.83	0.66	1.14	1.11	1.23	0.29
DiFs	1.59	1.41	1.09	0.82	0.64	0.94	0.67	1.24	1.27	1.23	0.43
Hy	16.50	18.86	15.72	12.74	13.16	13.19	12.62	12.40	16.36	13.31	8.14
HyEn	8.14	10.96	7.29	6.27	6.17	6.18	6.23	5.93	7.64	6.65	3.30
HyFs	8.36	7.90	8.43	6.47	6.99	7.02	6.40	6.47	8.72	6.67	4.83
Ol											
OlFo											
OlFa											
Il	1.52	1.40	1.40	0.99	1.24	1.26	0.99	1.35	1.48	0.92	1.45
Ap	0.60	0.50	0.50	0.33	0.50	0.50	0.36	0.47	0.50	0.31	0.40
Salic	75.06	72.37	77.65	81.72	81.86	81.03	82.53	80.57	76.35	79.94	88.59
Femic	24.96	27.64	21.69	17.31	17.30	18.51	16.65	19.01	23.13	19.52	11.42
D. I.	48.79	43.16	53.38	58.17	59.60	59.96	59.57	61.27	51.27	55.37	74.51

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	45 C0485 Qdtm	46 C0498 Qdtm	47 C0446 Qdtm	48 C0123 Qabf	49 F16A Qabf	50 F40A Qagm	51 F3A Qagm	52 F37A Qagm	53 C1835 Qadc	54 C0475 Qadc	55 C0527 Qadc
SiO_2	67.56	66.25	67.66	59.17	60.87	60.67	62.37	62.36	62.03	61.67	61.52
Al_2O_3	16.08	16.16	15.85	17.70	16.44	17.60	16.78	16.61	17.35	17.29	17.58
FeO	3.52	4.00	3.49	5.91	5.79	4.83	4.84	4.82	4.83	4.88	4.86
MgO	1.35	1.49	1.29	3.91	3.74	4.22	3.56	3.62	3.34	3.42	3.44
CaO	3.42	4.00	3.51	7.21	6.95	6.26	5.99	5.99	5.94	6.23	6.41
Na_2O	4.10	4.18	4.17	3.51	3.60	3.78	3.57	3.75	3.81	3.78	3.78
K_2O	3.02	2.84	3.06	1.59	1.58	1.62	1.89	1.86	1.75	1.78	1.53
TiO_2	0.69	0.78	0.70	0.73	0.77	0.78	0.76	0.75	0.68	0.69	0.64
P_2O_5	0.19	0.23	0.21	0.17	0.16	0.15	0.16	0.15	0.19	0.18	0.17
MnO	0.06	0.07	0.05	0.10	0.10	0.08	0.08	0.08	0.08	0.08	0.08
FeO/MgO	2.61	2.68	2.71	1.51	1.55	1.14	1.36	1.33	1.45	1.43	1.41
Q	20.87	18.41	20.51	8.87	11.55	10.49	14.12	13.33	13.09	12.34	12.57
C	0.31										
Or	17.86	16.77	18.08	9.38	9.36	9.60	11.19	11.01	10.31	10.52	9.01
Ab	34.70	35.38	35.29	29.70	30.45	31.97	30.18	31.71	32.26	32.00	31.97
An	15.70	16.94	15.50	27.85	24.03	26.27	24.19	23.01	25.07	24.95	26.50
Di		1.16	0.46	5.63	7.78	3.14	3.70	4.73	2.60	3.93	3.47
DiWo		0.58	0.23	2.84	3.92	1.60	1.87	2.40	1.32	1.99	1.76
DiEn		0.22	0.09	1.39	1.90	0.89	0.97	1.25	0.66	1.00	0.87
DiFs		0.37	0.15	1.40	1.95	0.65	0.85	1.08	0.63	0.94	0.83
Hy	8.81	9.33	8.35	16.79	15.01	16.70	14.81	14.44	14.93	14.55	14.89
HyEn	3.37	3.50	3.13	8.36	7.41	9.62	7.89	7.76	7.66	7.51	7.69
HyFs	5.44	5.83	5.22	8.43	7.60	7.08	6.93	6.68	7.28	7.04	7.19
Ol											
OlFo											
OlFa											
Il	1.31	1.48	1.32	1.38	1.47	1.49	1.45	1.43	1.28	1.31	1.21
Ap	0.46	0.55	0.50	0.41	0.38	0.36	0.38	0.36	0.45	0.43	0.41
Salic	89.43	87.50	89.38	75.80	75.38	78.33	79.67	79.06	80.74	79.79	80.04
Femic	10.57	12.52	10.63	24.21	24.63	21.68	20.34	20.95	19.28	20.22	19.97
D. I.	73.42	70.55	73.88	47.95	51.36	52.06	55.49	56.06	55.67	54.85	53.55

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	56 C1675 Qamd	57 C1678 Qamd	58 B128 Qamd	59 B326 Qamd	60 F7A Qamd	61 F1 Qamd	62 M0855 Qrl	63 M0899 Qrl	64 M0901 Qrl	65 C1694 Qrl	66 C1811 Qrl
SiO_2	62.78	61.74	62.90	60.94	61.92	60.66	69.54	69.61	70.00	69.28	70.46
Al_2O_3	16.78	16.86	16.76	16.78	16.97	16.82	15.91	15.83	15.60	15.81	15.31
FeO	4.88	5.13	4.91	5.55	4.72	5.65	2.63	2.64	2.47	2.68	2.50
MgO	3.31	3.49	2.86	3.73	3.55	3.51	1.22	1.12	1.11	1.45	1.31
CaO	5.33	5.71	5.34	6.10	6.16	6.78	2.89	2.89	2.81	3.36	3.11
Na_2O	3.66	3.88	3.90	3.82	3.86	3.92	4.16	4.26	4.25	4.14	4.12
K_2O	2.34	2.17	2.33	2.05	1.82	1.62	3.06	3.04	3.18	2.74	2.67
TiO_2	0.67	0.72	0.72	0.70	0.76	0.80	0.45	0.46	0.43	0.37	0.36
P_2O_5	0.18	0.22	0.19	0.25	0.16	0.15	0.10	0.10	0.10	0.10	0.11
MnO	0.08	0.08	0.08	0.09	0.08	0.08	0.05	0.05	0.05	0.07	0.05
FeO/MgO	1.47	1.47	1.72	1.49	1.33	1.61	2.16	2.36	2.23	1.85	1.91
Q	13.68	11.25	13.23	9.98	12.30	10.11	24.03	23.69	23.90	23.62	26.15
C							0.75	0.51	0.30	0.16	0.26
Or	13.80	12.84	13.68	11.94	10.78	9.54	18.09	17.99	18.80	16.19	15.76
Ab	30.97	32.82	32.82	31.89	32.64	33.19	35.17	36.06	36.00	35.02	34.83
An	22.47	22.16	21.20	22.34	23.61	23.53	13.67	13.68	13.26	16.03	14.71
Di	2.29	3.87	3.20	4.87	4.87	7.57					
DiWo	1.16	1.96	1.61	2.46	2.47	3.81					
DiEn	0.58	0.98	0.75	1.21	1.29	1.83					
DiFs	0.56	0.94	0.84	1.20	1.11	1.93					
Hy	15.11	15.16	13.43	15.83	13.99	14.18	7.21	6.97	6.71	8.05	7.35
HyEn	7.66	7.72	6.34	7.95	7.54	6.91	3.03	2.78	2.78	3.61	3.26
HyFs	7.46	7.44	7.10	7.88	6.45	7.27	4.18	4.19	3.93	4.43	4.09
Ol											
OlFo											
OlFa											
Il	1.27	1.37	1.35	1.32	1.45	1.52	0.85	0.87	0.81	0.71	0.69
Ap	0.43	0.53	0.45	0.60	0.38	0.36	0.24	0.24	0.24	0.24	0.26
Salic	80.91	79.08	80.94	76.15	79.33	76.37	91.71	91.93	92.25	91.01	91.70
Femic	19.11	20.93	18.44	22.61	20.68	23.63	8.30	8.07	7.75	8.99	8.30
D. I.	58.44	56.92	59.74	53.81	55.72	52.85	77.29	77.74	78.70	74.83	76.73

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	67 DL14 Qrl	68 F101 Qrl	69 DL1 Qrl	70 DB70 Qrlo	71 C0534 Qrm	72 C1629 Qdb	73 C1706 Qdb	74 C1810 Qdb	75 B331 Qdb	76 B9125 Qdb	77 B9072 Qdb
SiO_2	71.22	71.19	69.58	69.60	69.45	66.08	67.50	64.62	64.12	64.79	64.43
Al_2O_3	15.07	14.39	15.55	15.44	16.04	16.34	16.45	16.88	16.99	16.78	16.90
FeO	2.23	2.55	2.64	2.70	2.56	3.76	3.26	3.94	4.09	3.91	4.81
MgO	1.01	1.05	1.25	1.14	1.06	2.23	1.66	2.66	2.69	2.50	2.23
CaO	2.67	3.03	3.11	2.97	2.79	4.51	3.79	5.21	5.39	5.04	4.86
Na_2O	4.39	4.26	4.36	4.35	4.23	4.05	4.18	3.89	4.06	4.15	3.94
K_2O	2.92	2.85	2.88	3.12	3.25	2.28	2.53	2.04	1.94	2.08	2.08
TiO_2	0.34	0.47	0.42	0.48	0.46	0.48	0.44	0.52	0.49	0.52	0.53
P_2O_5	0.09	0.12	0.15	0.12	0.11	0.19	0.12	0.16	0.15	0.15	0.15
MnO	0.06	0.09	0.06	0.07	0.05	0.07	0.06	0.08	0.08	0.08	0.07
FeO/MgO	2.21	2.43	2.12	2.37	2.42	1.69	1.96	1.48	1.52	1.56	2.16
Q	27.48	26.47	25.11	24.74	23.35	18.84	20.80	17.02	15.47	16.18	16.63
C	0.17		0.01		0.76		0.23				
Or	17.10	16.84	16.92	18.35	19.19	13.47	14.97	12.06	11.38	12.21	12.23
Ab	36.34	36.05	36.62	36.36	35.78	34.23	35.35	32.91	34.20	34.90	33.20
An	12.50	11.73	14.33	13.50	13.10	19.70	18.03	22.58	22.27	20.86	22.16
Di		2.12		0.39		1.18		1.81	2.76	2.47	0.74
DiWo		1.05		0.21		0.59		0.91	1.39	1.25	0.37
DiEn		0.42		0.17		0.28		0.45	0.68	0.60	0.15
DiFs		0.65		0.01		0.31		0.44	0.69	0.62	0.22
Hy	3.02	5.62	3.09	2.80	6.69	11.21	9.51	12.26	12.11	11.39	13.22
HyEn	2.49	2.20	3.09	2.66	2.65	5.28	4.15	6.18	5.98	5.59	5.37
HyFs	0.53	3.42		0.14	4.04	5.93	5.36	6.08	6.12	5.80	7.84
Ol											
OlFo											
OlFa											
Il	0.65	0.89	0.80	0.92	0.87	0.92	0.84	0.99	0.93	0.99	0.99
Ap	0.21	0.28	0.36	0.29	0.26	0.45	0.29	0.38	0.36	0.36	0.35
Salic	93.72	91.09	93.02	93.02	92.18	86.25	89.37	84.57	83.31	84.15	84.22
Femic	5.75	8.92	6.85	6.81	7.83	13.76	10.64	15.44	16.15	15.20	15.30
D. I.	80.93	79.36	78.65	79.46	78.32	66.55	71.11	61.99	61.04	63.29	62.06

Table 2. Chemical Analyses--Continued

Analysis number Sample number Unit	78 F90A Qdb	79 C1733 Qrla	80 C1660 Qrla	81 C1736 Qrla	82 C1731 Qrla	83 C1734 Qrla	84 F85 Qrla	85 F84 Qrla	86 C1661 Qrla	87 C0391 Qav	88 C1710 Qatl
SiO_2	67.33	68.46	69.83	69.53	70.42	69.37	70.67	68.03	68.30	59.16	58.15
Al_2O_3	15.21	16.00	15.63	15.79	15.60	15.78	14.40	15.26	15.84	17.70	17.67
FeO	4.00	2.87	2.56	2.53	2.44	2.73	2.78	3.33	3.15	5.83	6.05
MgO	2.12	1.83	1.48	1.48	1.21	1.39	1.48	1.85	1.72	3.01	4.38
CaO	4.44	3.65	3.20	3.30	2.93	3.41	3.32	4.02	3.94	6.75	8.14
Na_2O	3.86	4.05	4.04	4.17	4.13	4.11	3.82	4.11	3.95	4.07	3.41
K_2O	2.28	2.59	2.76	2.69	2.75	2.68	2.89	2.70	2.51	1.97	1.26
TiO_2	0.57	0.39	0.36	0.36	0.36	0.37	0.46	0.49	0.41	1.06	0.70
P_2O_5	0.11	0.11	0.10	0.10	0.11	0.12	0.10	0.10	0.11	0.34	0.14
MnO	0.08	0.05	0.05	0.05	0.05	0.05	0.08	0.11	0.06	0.10	0.11
FeO/MgO	1.89	1.57	1.73	1.71	2.02	1.96	1.88	1.80	1.83	1.94	1.38
Q	21.65	22.60	25.08	24.10	26.32	24.16	26.80	21.07	22.79	7.33	7.50
C		0.17	0.43	0.26	0.79	0.22					
Or	13.47	15.32	16.31	15.91	16.26	15.84	17.07	15.96	14.85	11.65	7.46
Ab	32.66	34.28	34.18	35.28	34.92	34.74	32.31	34.78	33.46	34.40	28.87
An	17.44	17.36	15.20	15.71	13.78	16.11	13.63	15.22	18.05	24.22	29.16
Di	3.22						1.82	3.39	0.66	5.87	8.49
DiWo	1.61						0.91	1.70	0.33	2.94	4.29
DiEn	0.72						0.41	0.77	0.15	1.32	2.17
DiFs	0.89						0.50	0.92	0.18	1.61	2.02
Hy	10.22	9.27	7.90	7.82	7.01	7.94	7.27	8.43	9.15	13.73	16.89
HyEn	4.56	4.57	3.69	3.68	3.02	3.45	3.28	3.84	4.12	6.19	8.74
HyFs	5.66	4.71	4.20	4.14	3.99	4.49	4.00	4.59	5.03	7.54	8.14
Ol											
OlFo											
OlFa											
Il	1.08	0.75	0.68	0.69	0.68	0.71	0.87	0.93	0.79	2.02	1.32
Ap	0.26	0.26	0.24	0.24	0.27	0.29	0.24	0.24	0.26	0.81	0.34
Salic	85.22	89.72	91.20	91.26	92.05	91.07	89.81	87.02	89.14	77.59	72.99
Femic	14.79	10.28	8.81	8.75	7.96	8.94	10.20	12.99	10.86	22.43	27.02
D. I.	67.78	72.20	75.57	75.29	77.49	74.74	76.18	71.81	71.10	53.38	43.83

Table 2. Chemical Analyses--Continued

Analysis number Sample number Map unit	89 F122A Qatl	90 C1753 Qatl	91 DB349 Qatl	92 SC17 Qatl	93 SC15 Qatl	94 C1840 Qatl	95 C0379 Qrrt	96 F19A Qahb	97 F136 Qahb	98 C0451B ---
SiO_2	59.19	60.65	56.71	56.22	55.85	64.83	70.05	54.30	53.06	54.21
Al_2O_3	16.33	16.96	17.23	16.38	16.54	16.81	16.98	16.83	18.42	16.67
FeO	6.10	5.19	6.58	6.44	6.38	3.93	2.99	7.33	6.86	7.22
MgO	4.95	4.01	5.48	7.29	7.28	2.62	1.03	7.72	7.53	7.81
CaO	7.60	6.56	8.38	7.56	8.06	4.92	2.33	8.60	8.38	9.79
Na_2O	3.26	3.69	3.40	3.47	3.43	4.00	3.40	3.06	2.99	2.72
K_2O	1.56	1.83	1.10	1.54	1.37	2.18	2.67	0.91	1.73	0.59
TiO_2	0.76	0.77	0.83	0.80	0.81	0.51	0.40	0.94	0.79	0.70
P_2O_5	0.15	0.24	0.16	0.18	0.16	0.13	0.09	0.17	0.12	0.13
MnO	0.10	0.09	0.12	0.12	0.12	0.07	0.05	0.13	0.12	0.16
FeO/MgO	1.23	1.29	1.20	0.88	0.88	1.50	2.90	0.95	0.91	0.92
Q	8.86	10.44	6.21	1.24	1.03	16.64	31.57	0.63		1.75
C							4.50			
Or	9.22	10.81	6.45	9.10	8.10	12.91	15.77	5.39	10.22	3.48
Ab	27.59	31.20	28.25	29.36	29.02	33.82	28.74	25.87	25.30	22.98
An	25.32	24.34	28.39	24.57	25.69	21.48	10.95	29.50	31.73	31.57
Di	9.38	5.45	9.32	9.57	10.78	1.73		9.81	7.38	13.19
DiWo	4.76	2.77	4.79	4.91	5.53	0.87		5.03	3.78	6.75
DiEn	2.53	1.46	2.87	2.93	3.31	0.43		2.93	2.23	3.93
DiFs	2.08	1.23	1.67	1.73	1.94	0.43		1.85	1.37	2.51
Hy	17.85	15.74	16.84	24.23	23.49	12.16	7.49	26.60	15.34	25.41
HyEn	9.80	8.54	10.67	15.23	14.82	6.09	2.58	16.30	9.51	15.51
HyFs	8.05	7.20	6.18	9.00	8.67	6.07	4.92	10.30	5.84	9.89
Ol									8.25	
OlFo									4.92	
OlFa									3.33	
Il	1.44	1.47	1.56	1.52	1.54	0.98	0.76	1.79	1.50	1.33
Ap	0.36	0.58	0.38	0.43	0.38	0.31	0.23	0.40	0.28	0.31
Salic	70.98	76.78	69.36	64.27	63.83	84.84	91.53	61.41	67.25	59.78
Femic	29.03	23.23	30.00	35.74	36.18	15.17	8.48	38.60	32.75	40.23
D. I.	45.67	52.45	40.91	39.70	38.15	63.36	76.08	31.91	35.52	28.21

+ Huckleberry Lake Sequence

● Twin Lakes Sequence

△ Lassen Sequence

▽ Loomis Sequence

▲ Bumpass Sequence

⊠ Rockland Tephra

□ Rice Creek Sequence

◇ Digger-Diller Sequence

× Twin Meadows Sequence

+ Ski Hill - Conard Sequence

○ Mill Canyon Sequence

Figure 3. Key to symbols on variation diagrams.

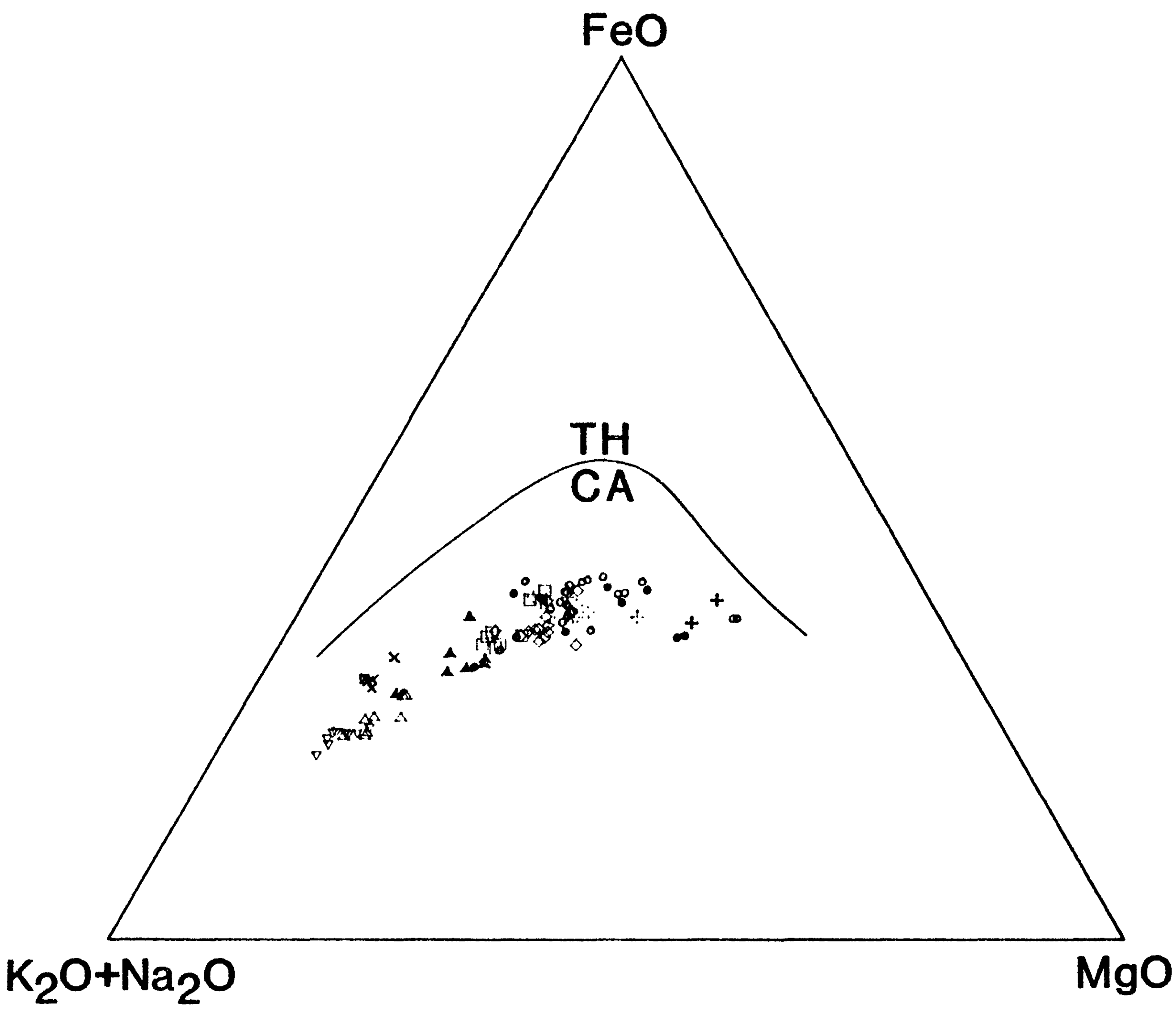

Figure 4. AFM diagram of rocks of the Lassen Volcanic Center. A= total alkalies (K_2O+Na_2O), F= iron as FeO, and M= MgO. The criteria of Irvine and Baragar (1971) were used to delineate the tholeiitc (TH) and calc-alkaline (CA) fields.

Despite the porphyritic nature of most rocks of the Lassen Volcanic Center, the Harker variation diagrams display smooth, regular trends. MgO, FeO, and CaO decrease smoothly and regularly with increasing SiO_2. TiO_2, Al_2O_3, P_2O_5, and MnO decrease somewhat less regularly with increasing SiO_2. K_2O, Na_2O, and FeO/MgO increase with increasing SiO_2. In the following discussions of the variation diagrams, an element from the group, displaying each of the three trends will be emphasized as representative of that trend. The other elements in each group will be mentioned only to present important information or exceptions to the generalized group behavior.

The chemistry of the rocks of the Lassen Volcanic Center is presented in an AFM diagram (fig. 4), in which total alkalies, total iron as FeO, and magnesia are plotted as relative proportions. The analyses plot as a narrow band, suggesting that they are all genetically related. The rocks are strongly calc-alkaline, and plot well below the tholeiitic-calc-alkaline boundary of Irvine and Baragar (1971). The absence of a strong iron-enrichment trend is evident.

MgO, FeO, CaO, and FeO/MgO

The content of the oxide components MgO, FeO, and CaO in rocks of the Lassen Volcanic Center are plotted versus SiO_2 content. Each component behaves similarly and shows a good negative correlation with SiO_2, decreasing by a factor of 3 to 5 over the SiO_2 range from 53-71 wt %. In each case the decrease is regular, with little scatter in the data. The data strongly suggest that the rocks share a commen origin and evolution.

MgO content of Lassen Volcanic Center rocks ranges from ∿1 wt % to ∿8 wt % (fig. 5). MgO correlates negatively with SiO_2, and the trend is continuous and smooth from 1 wt % MgO to 6 wt % MgO. Six rocks have higher MgO content than the trend for their SiO_2 content. These are two andesites of the Mill Canyon Sequence with high modal olivine, probably accumulated, two rocks of the Twin Lakes Sequence from Cinder Cone which are hybrid, and two rocks of the Huckleberry Lake Sequence.

The Mill Canyon and Ski Hill-Conard Sequences have similar average MgO content near 4 wt %. However, the Mill Canyon Sequence shows some variation to both higher and lower values. The higher values tend to be in stratigraphically lower flows containing greater proportions of olivine phenocrysts. The Twin Meadows Sequence is distinct from the other dacites in that it has lower MgO, CaO and higher FeO and FeO/MgO for similar SiO_2.

Stage II andesites have slightly lower MgO, FeO, and CaO than Stage I andesites but similar FeO/MgO ratio at higher SiO_2 content; i.e., FeO/MgO ratio remains constant with increasing SiO_2 in the andesite bulk-composition range. The dacites of the Bumpass Sequence have similar FeO/MgO ratio at even higher SiO_2 content.

Each group of rocks in Stage III shows different behavior. MgO in the Bumpass Sequence, Loomis Sequence, and Lassen Sequence ranges from 3-1 wt.% and shows good correlation with stratigraphic position (i.e., decreasing MgO and increasing SiO_2 with decreasing age).

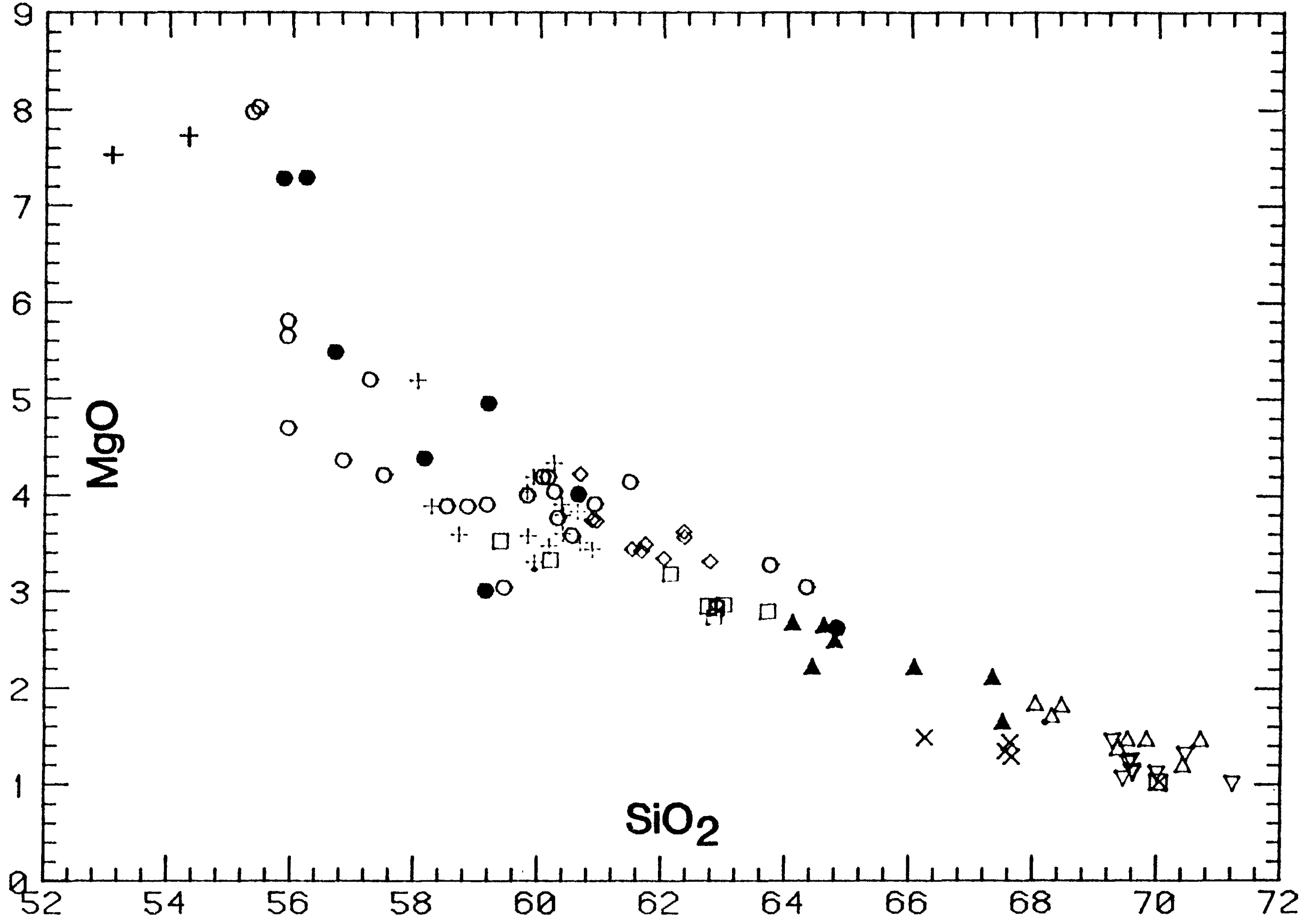

Figure 5. MgO versus SiO_2 of rocks of the Lassen Volcanic Center.

Rocks of the Huckleberry Lake Sequence have the highest MgO content of any Lassen Volcanic Center rock, $\sim$ 8 wt %. Rocks of the the Twin Lakes Sequence show more scatter of MgO, FeO and CaO than any other group, but the scatter is not random. There is an apparent correlation between MgO content and distance from the center of silicic volcanism. Taking Lassen Peak as a reference point, each eruptive center of the Twin Lakes Sequence has progressively higher MgO. There is an additional correlation between age and volume of lava erupted, the older flows having larger volume. Despite the scatter of MgO, FeO, and CaO content, the Twin Lakes Sequence has similar FeO/MgO ratios at all SiO_2 contents, and these ratios are lower at equivalent SiO_2 than FeO/MgO of other rocks of the Lassen Volcanic Center. The chemical characteristics of the rocks of the Twin Lakes Sequence can best be explained by mixing of an increasing proportion of rhyodacite with a decreasing proportion of basalt as the center of the Lassen magmatic system is approached.

Mg numbers of andesites from the Lassen Volcanic Center, defined as the molar ratio $(Mg/Mg+Fe^{+2})100$ calculated when Fe_2O_3 = 0.3, are mostly 55 to 63. The same six rocks mentioned earlier with high MgO have Mg numbers from 69 to 72. Similar explanations apply; two are hybrid and two have accumulated olivine. Rocks of the Huckleberry Lake Sequence are the only rocks with Mg numbers high enough to be in equilibrium with mantle olivine. It is generally accepted that primary mantle magmas must have Mg numbers > 67 (e.g. Gill, 1981).

FeO content of the rocks of the Lassen Volcanic Center ranges from ∿ 7 wt % to ∿ 2 wt % (fig. 6); decreasing linearly with SiO_2 content. There is little scatter in the data. Small gaps in the continuity of the trend probably are an effect of the paucity of analyses of rocks with low SiO_2.

CaO content of rocks from the Lassen Volcanic Center ranges from ∿ 8 wt % to ∿ 3 wt % (fig. 7); decreasing linearly with SiO_2. The data show little scatter; CaO has the best correlation with SiO_2 of any major element. The slight broadening of the trend of the data points at low SiO_2 is probably caused by varying degrees of plagioclase accumulation.

FeO/MgO plotted versus SiO_2 (fig. 8) shows more variability than either FeO or MgO alone, and the behavior of FeO/MgO with increasing SiO_2 is more complex. Disregarding the olivine enriched group, rocks of Stages I and II have constant FeO/MgO with increasing SiO_2, which is generally in the range 1.3 to 1.7. Rocks of the Twin Meadows Sequence are more highly differentiated, and have higher FeO/MgO than even the silicic rocks of Stage III. Rocks of Stage III continue the trend of Stages I and II. The rocks of the Bumpass and Lassen Sequences have FeO/MgO from 1.5 increasing to 2.0 with increasing SiO_2. Samples of the Loomis Sequence have more variable and higher FeO/MgO than the rocks of the Lassen Sequence at equivalent SiO_2.

$FeO/MgO_{57.5}$ for rocks of the Lassen Volcanic Center, 1.4, is somewhat lower than other Cascade volcanic centers (Gill, 1981) but consistent with the thicker crust in northern California (Coulon and

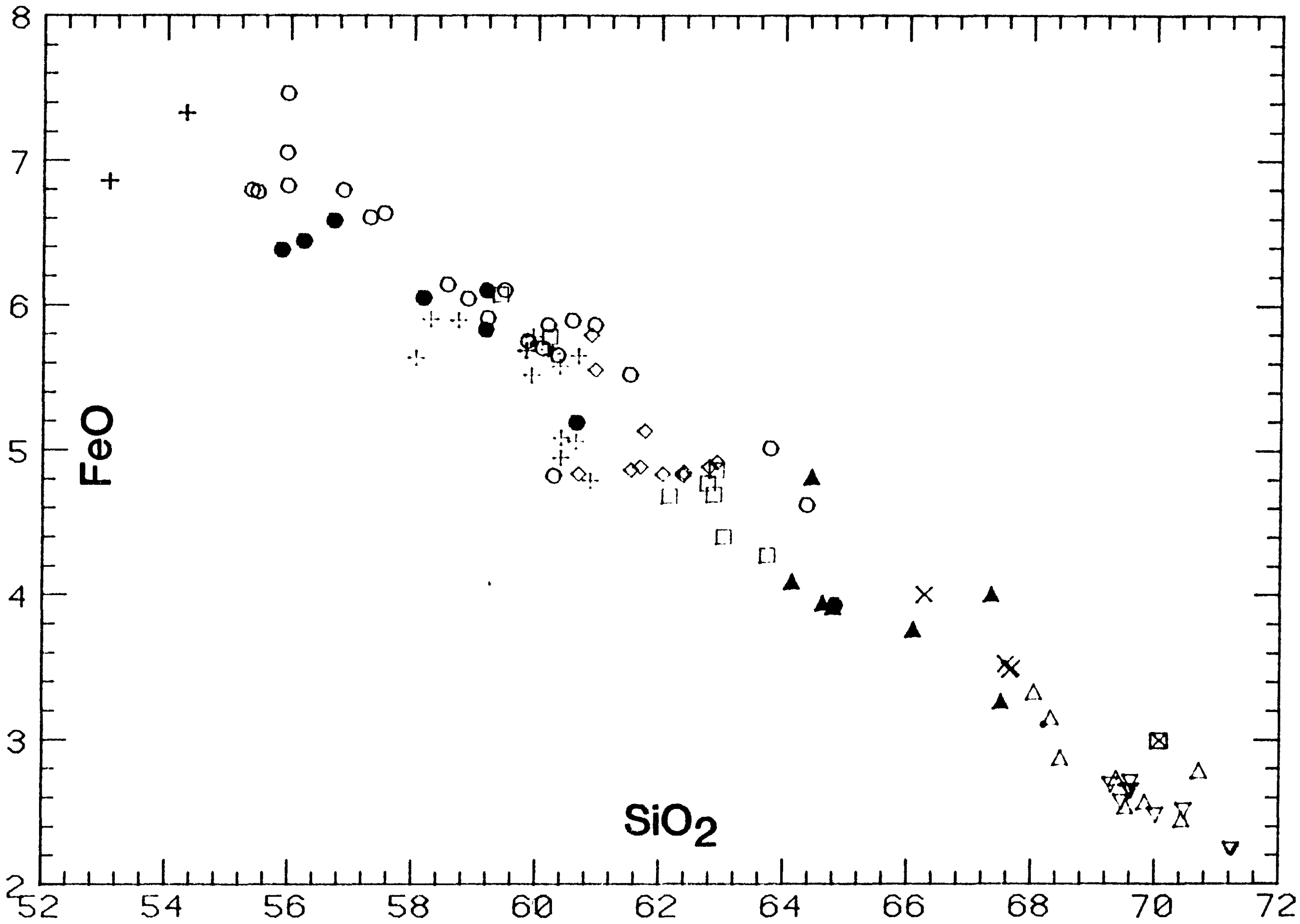

Figure 6. FeO versus SiO_2 of rocks of the Lassen Volcanic Center.

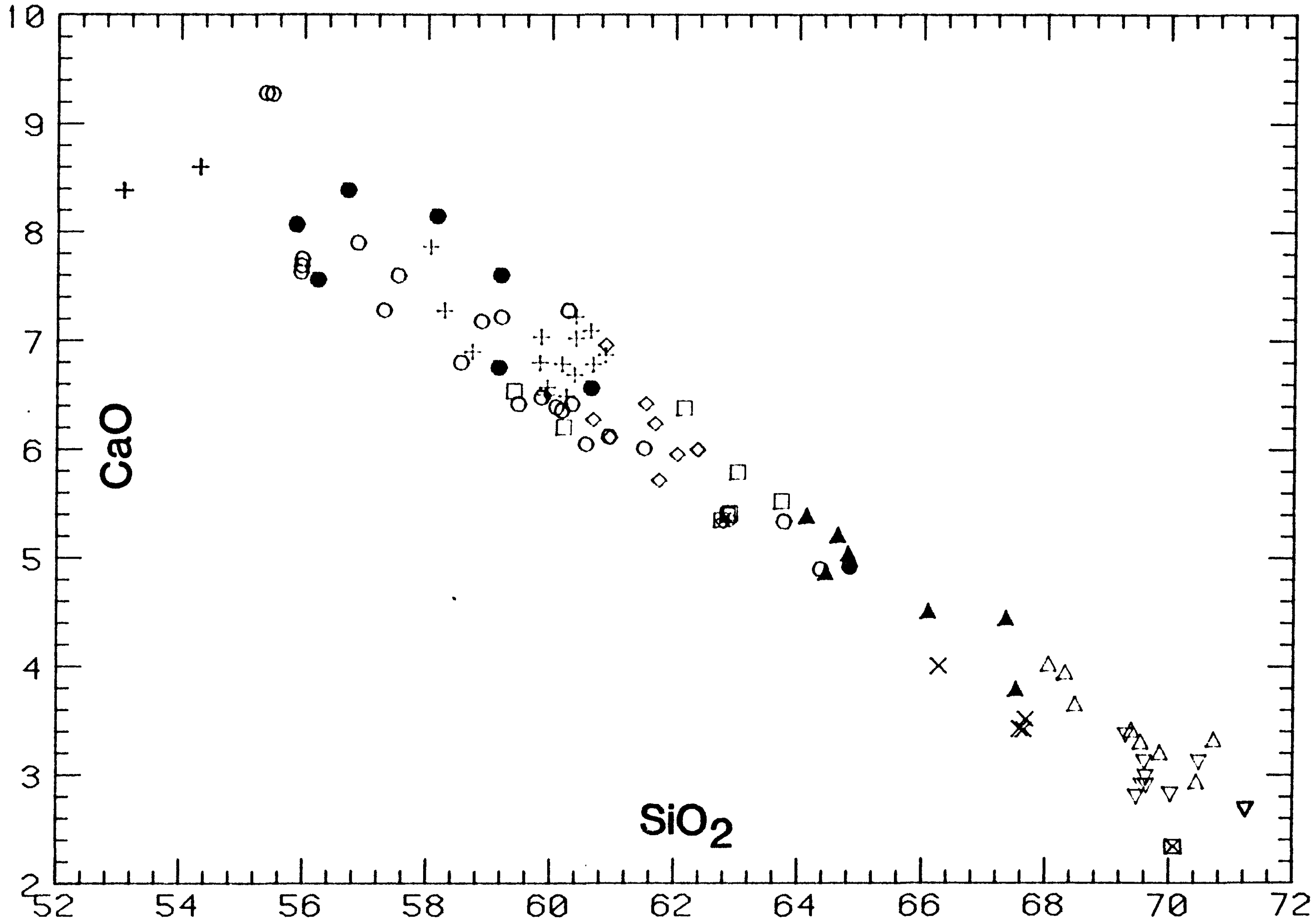

Figure 7. CaO versus SiO_2 of rocks of the Lassen Volcanic Center.

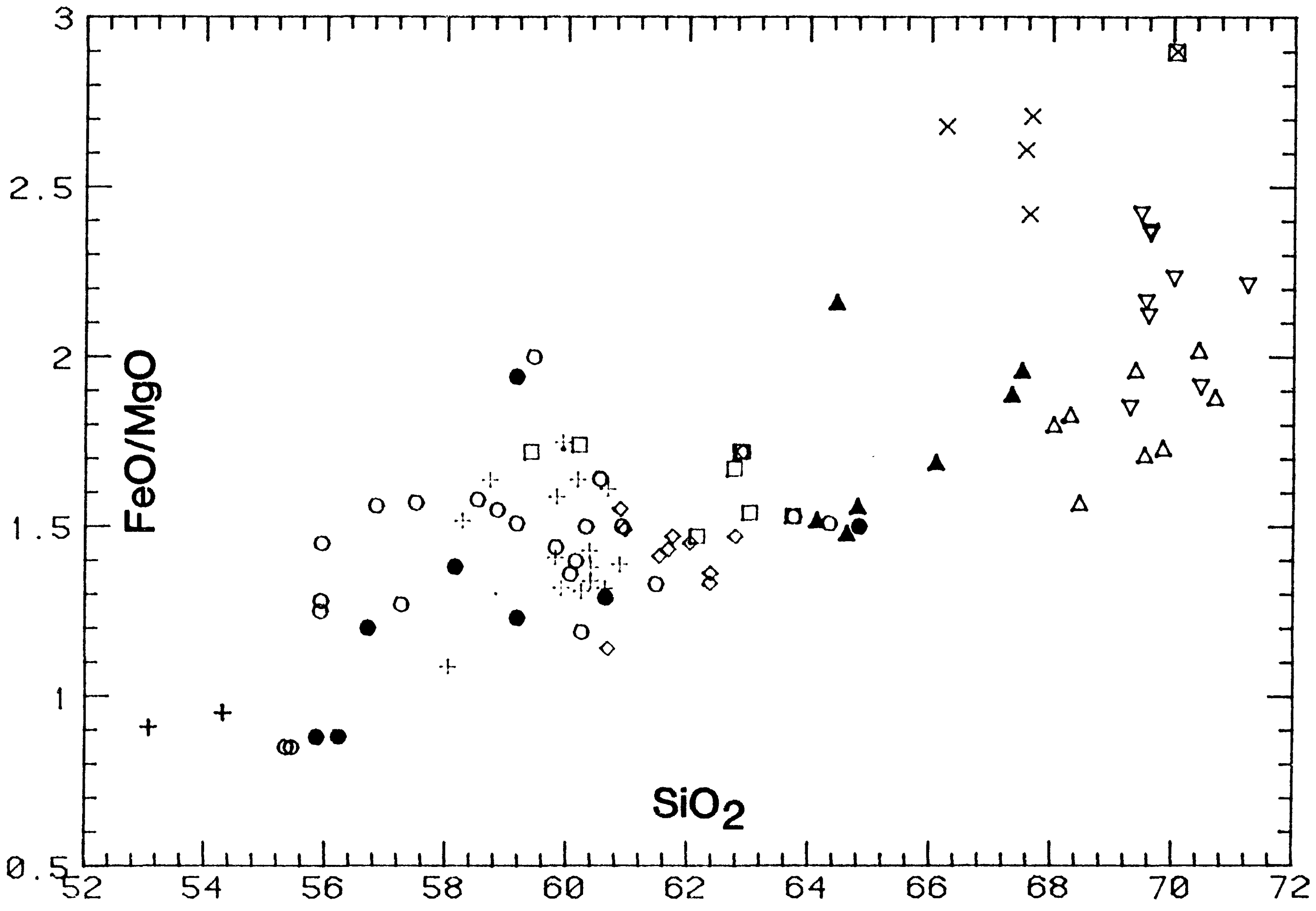

Figure 8. FeO/MgO versus SiO_2 of rocks of the Lassen Volcanic Center.

Thorpe, 1981) All rocks of the Lassen Volcanic Center plot well within the calc-alkaline field on the FeO/MgO versus SiO_2 diagram, drawn according to the criteria of Miyashiro (1974).

TiO_2, Al_2O_3, P_2O_5, and MnO

TiO_2 content (fig. 9) of Lassen Volanic Center andesites decreases with increasing SiO_2, although much scatter is present. Nevertheless, the rock sequences are well distinguished. Average TiO_2 is about 0.75 wt %, illustrating the low TiO_2 content of calc-alkaline andesites. Variation in TiO_2 content in the lower SiO_2 range can be attributed to the initiation of Fe-Ti oxide crystallization and its accumulation in some lavas of Stage I. The Twin Meadows Sequence has higher TiO_2 than the other dacites. An apparent discontinuity occurs between Stage I + II and Stage III rocks at about 0.6 wt % TiO_2.

Al_2O_3 content (fig. 10) of the andesites of the Lassen Volcanic Center are mostly between 16 to 18 wt %, thereby characterizing them as high-alumina (Kuno, 1960). Rocks of the Mill Canyon Sequence show increasing Al_2O_3 with increasing SiO_2 to about 60 wt % SiO_2, then a decline in Al_2O_3. This increase in Al_2O_3 and scatter in the Al_2O_3 versus SiO_2 diagram can be attributed to plagioclase accumulation. Rocks of the Huckleberry Lake Sequence have high Al_2O_3 despite their lack of plagioclase phenocrysts.

P_2O_5 content (fig. 11) of Lassen Volcanic Center rocks decreases with increasing SiO_2. Considerable scatter is apparent,

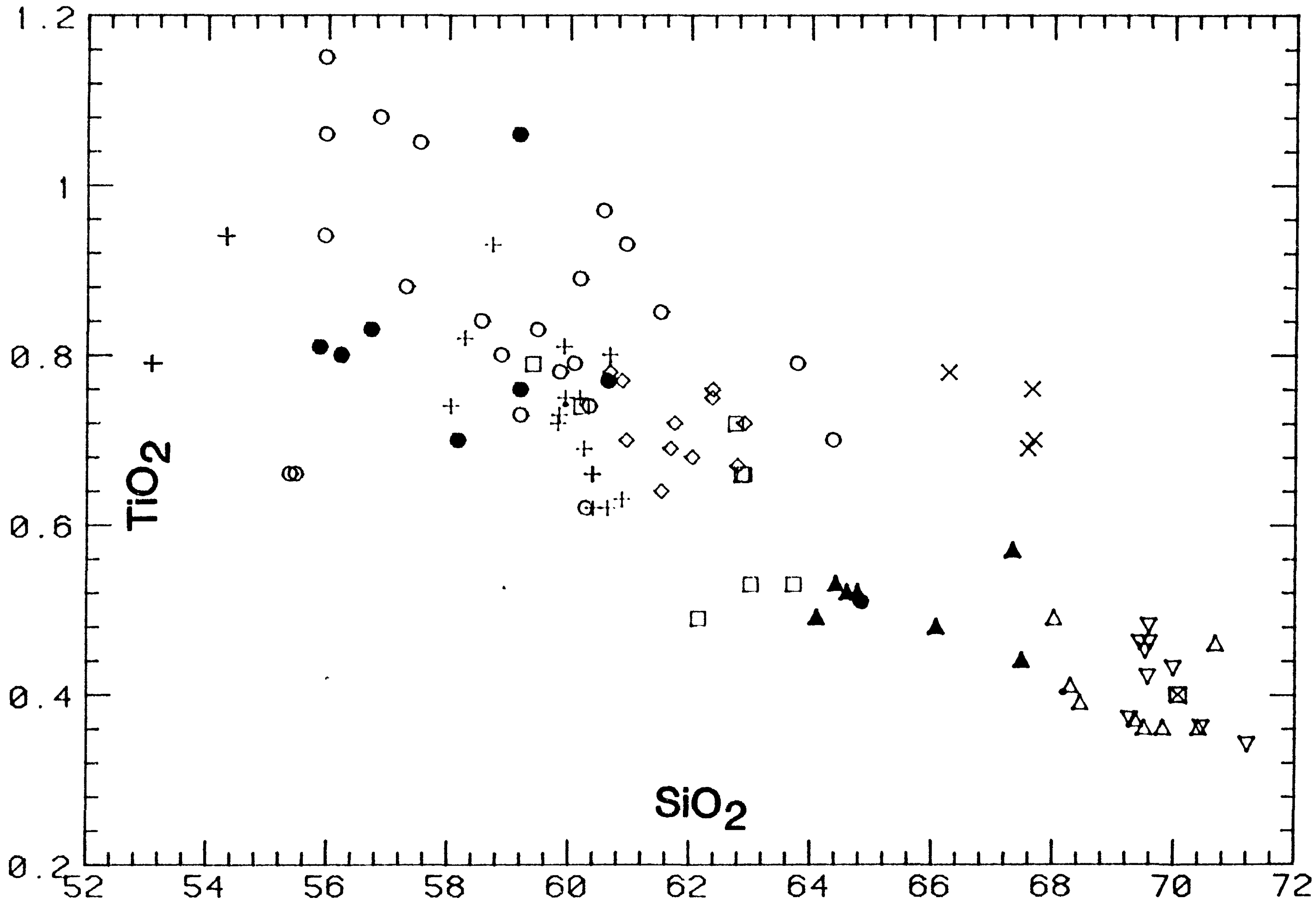

Figure 9. TiO_2 versus SiO_2 of rocks of the Lassen Volcanic Center.

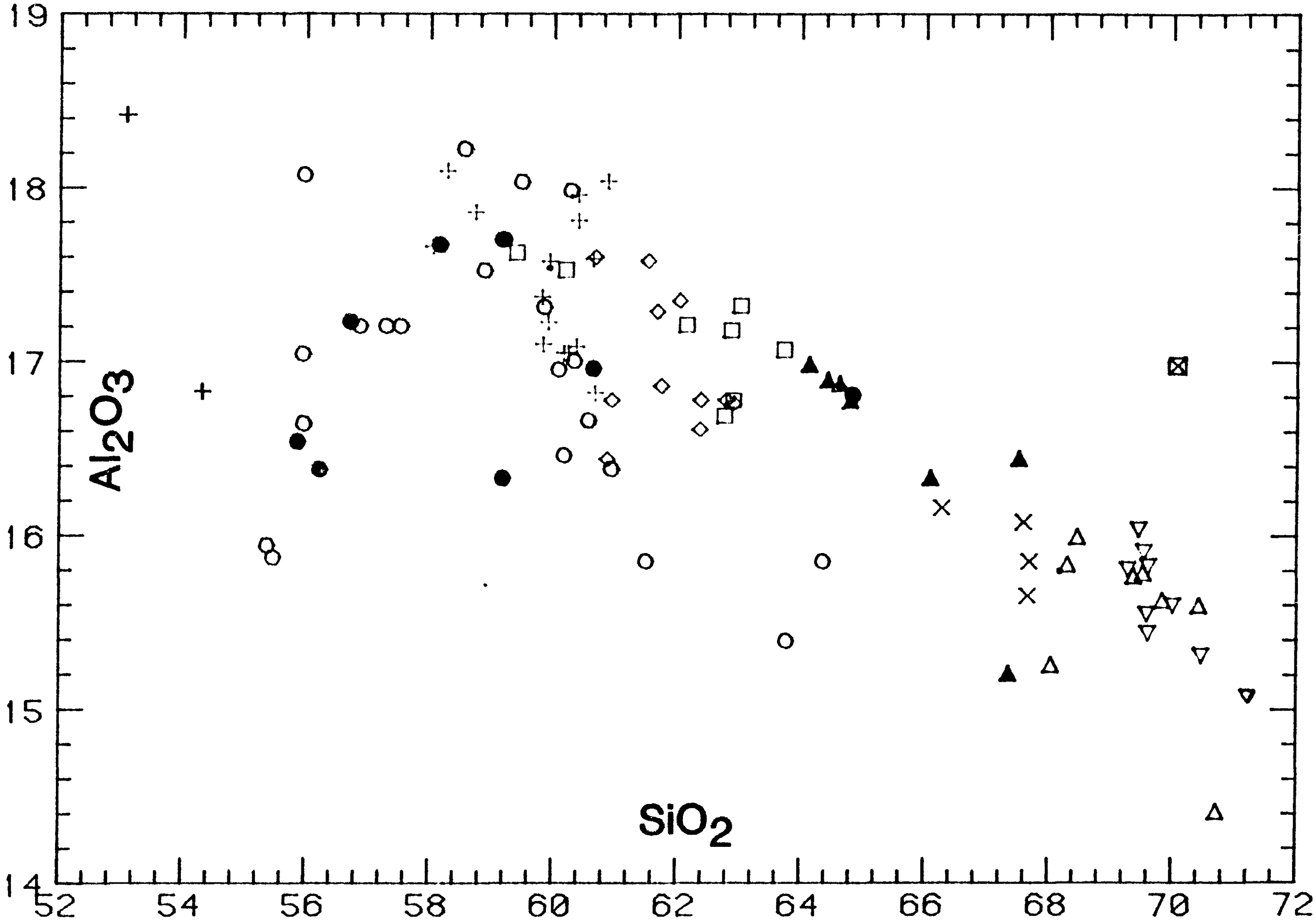

Figure 10. Al_2O_3 versus SiO_2 of rocks of the Lassen Volcanic Center.

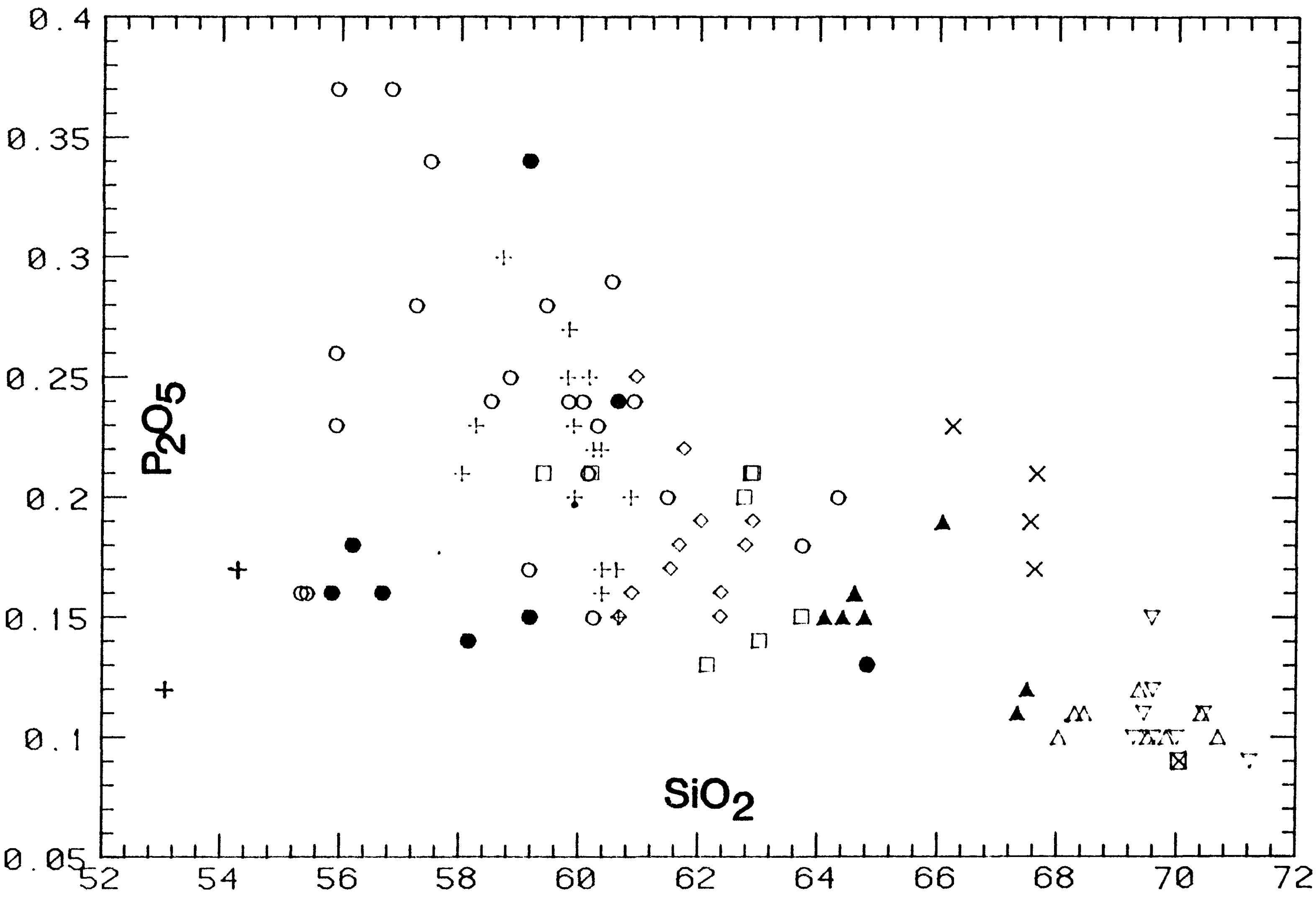

Figure 11. P_2O_5 versus SiO_2 of rocks of the Lassen Volcanic Center.

especially in Stage I rocks, however this is normal for calc-alkaline rocks (Gill, 1981). Huckleberry Lake Sequence rocks are unusually low, and Twin Meadows Sequence rocks high in P_2O_5. Accumulation of accessory apatite in early mafic andesite and andesite magmas may explain the high P_2O_5 in rocks of Stage I.

MnO content (fig. 12) of rocks of the Lassen Volcanic Center ranges from 0.13 to 0.05 wt %, and decreases regularly with increasing SiO_2. Scatter at high SiO_2 content is probably due to small but variable amounts of mafic inclusion material in the groundmass of these rocks.

K_2O and Na_2O

K_2O content (fig. 13) correlates linearly and positively with SiO_2 content in rocks of the Lassen Volcanic Center. Andesites of the Lassen Volcanic Center mostly fall within the upper half of the medium-K silicic andesite field as defined by Gill (1981), however, a few are medium-K mafic andesites. $K_{57.5}$ is $\sim$ 1.6, slightly higher than that reported by Gill (1981) and significantly higher than most other Cascade volcanic centers, perhaps reflecting the thicker crust in northern California.

Two parallel trends can be seen on the K_2O vs. SiO_2 diagram. With increasing SiO_2, Stage I rocks define a trend with similar slope but higher K_2O content than the trend defined by Stage II and III rocks. Similar parallel trends can be seen more clearly on the FeO/MgO ratio vs. SiO_2 diagram.

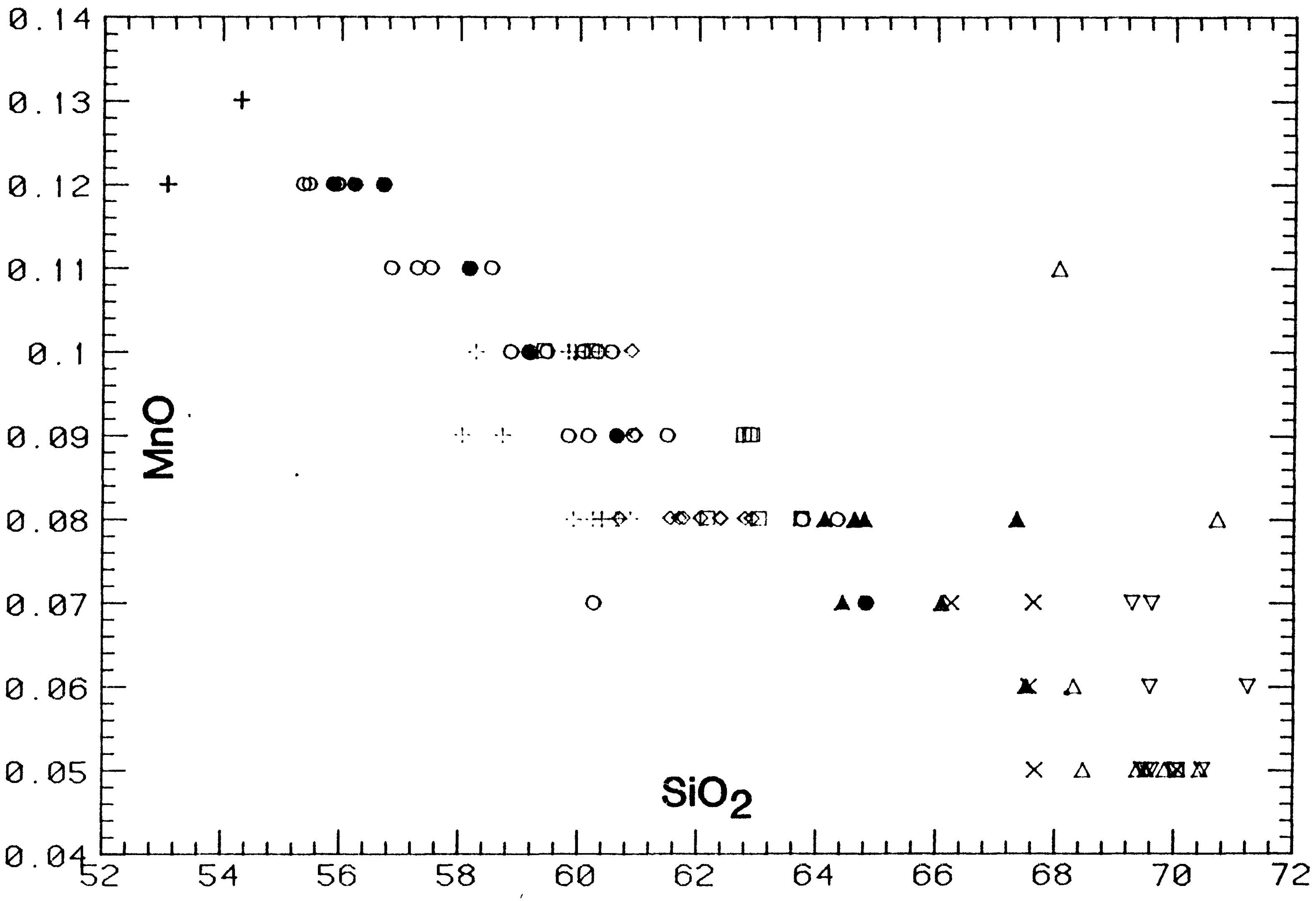

Figure 12. MnO versus SiO_2 of rocks of the Lassen Volcanic Center.

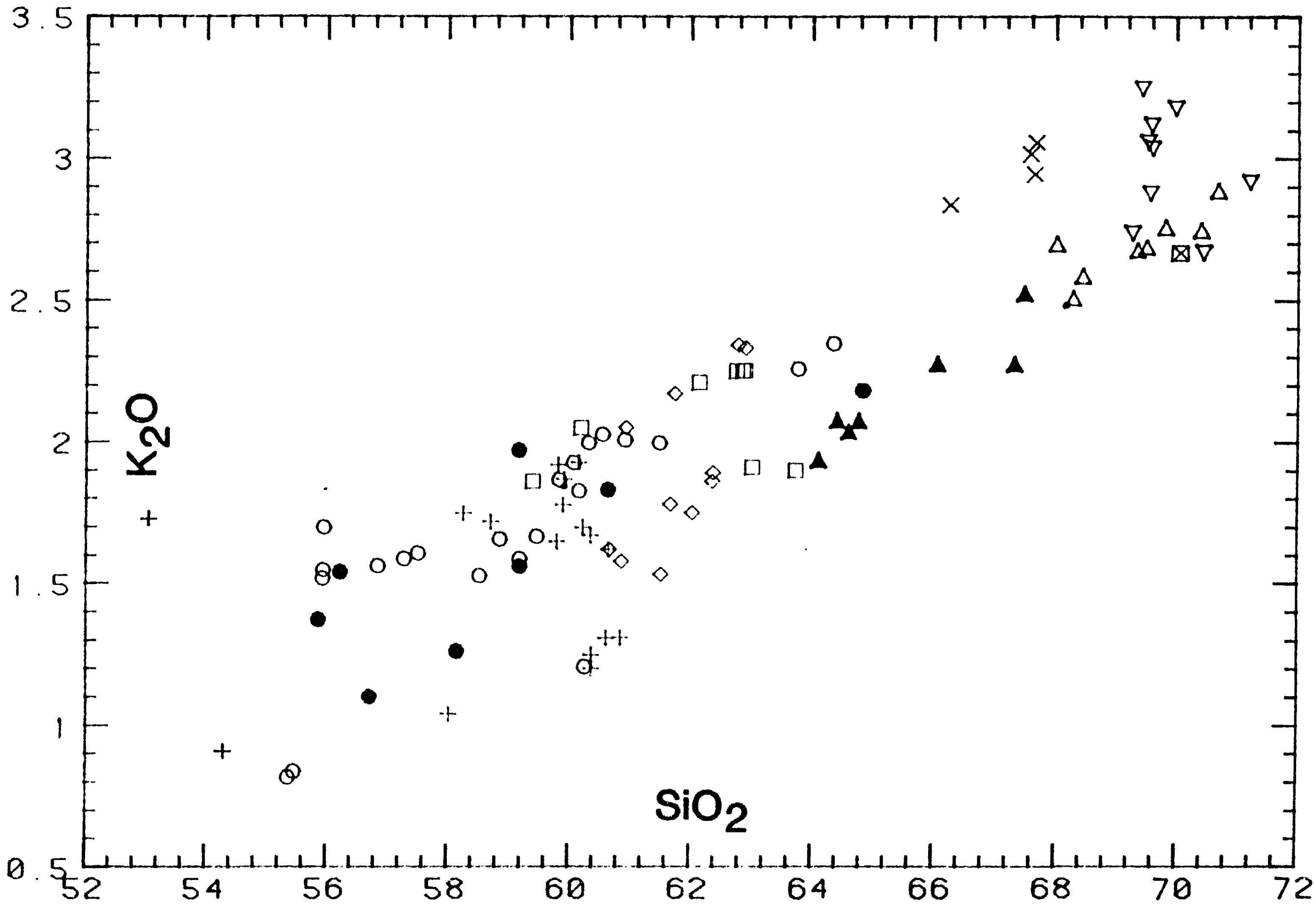

Figure 13. K_2O versus SiO_2 of rocks of the Lassen Volcanic Center.

A good correlation exists between K_2O and SiO_2 content vs. age for the Stage III silicic rocks (i.e., increasing K_2O and SiO_2 with decreasing age). The Loomis Sequence has a wide range of K_2O at constant SiO_2.

Na_2O content (fig. 14) of rocks of the Lassen Volcanic Center ranges from $\sim$ 3.5 wt % to $\sim$ 4.5 wt %, increasing with increasing SiO_2. Some scatter is present, especially in the mafic andesite composition range, and can be attributed to plagioclase accumulation.

Normative Mineralogy

The CIPW norm represents an idealized anhydrous mineralogy into which a magma with given chemistry would crystalize under uniform and slow conditions. Normative mineralogy is reported for rocks of the Lassen Volcanic Center in table 2 and is typical of medium-K, calc-alkaline andesitic suites, (Gill, 1981). Rocks of the Lassen Volcanic Center are quartz and hypersthene normative. The rocks lack normative olivine despite the presence of significant modal olivine in many rocks of Stage I, furthur supporting the interpretation that the olivine is of relict origin. As expected, normative quartz, albite, and orthoclase increase and normative diopside, hypersthene, and anorthite decrease with differentiation. Normative diopside disappears and a small amount of corundum takes its place in many of the the most siliceous rocks of Stage III.

The normative mineralogy corresponds well with the modal mineralogy. The rocks are high in normative feldspar and pyroxene, and these are the phenocysts present in abundance. However, in

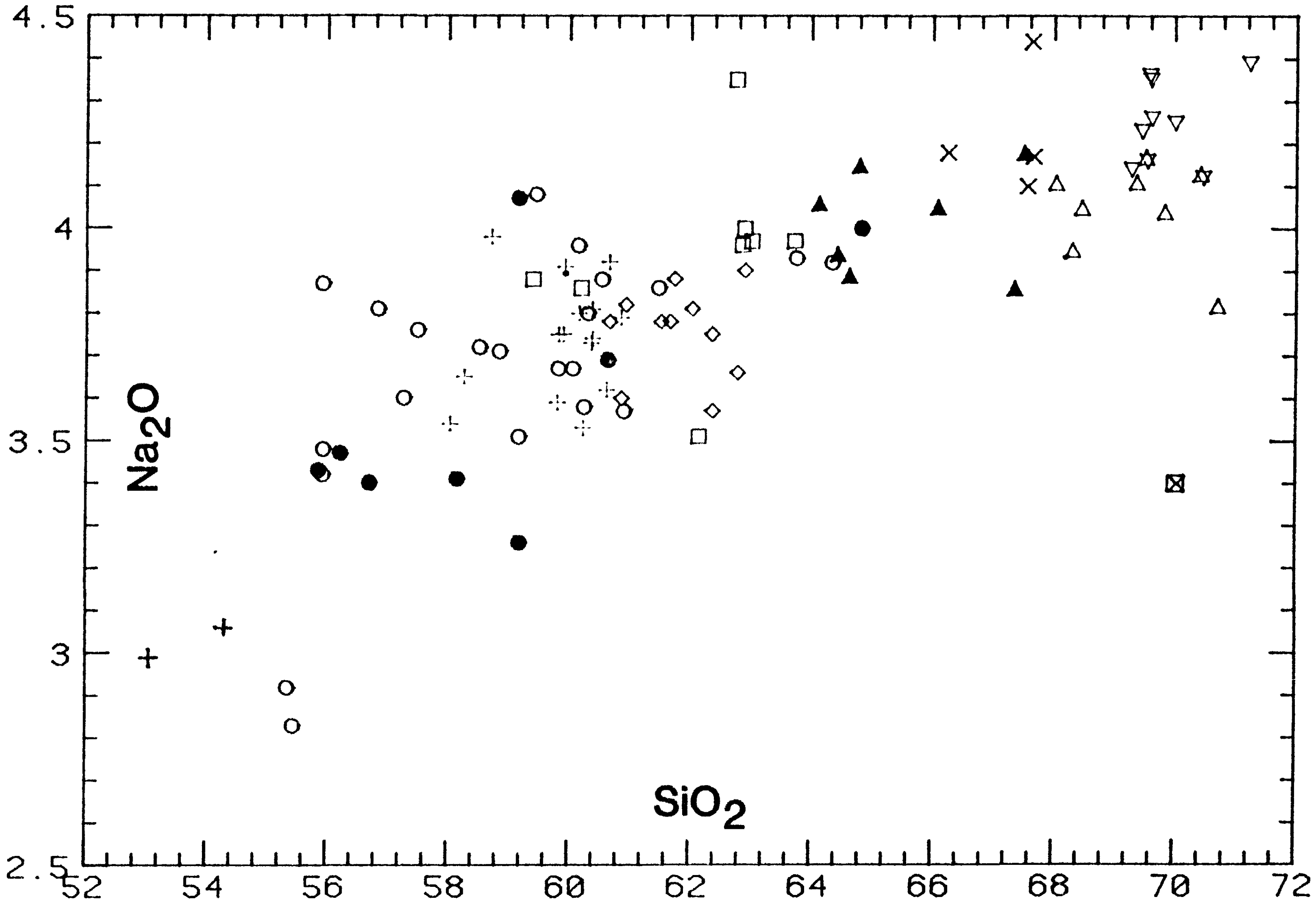

Figure 14. Na_2O versus SiO_2 of rocks of the Lassen Volcanic Center.

rocks of andesitic composition orthoclase and quartz are present as groundmass constituents. The rocks contain about 50% normative plagioclase, which varies regularly with SiO_2 content and corresponds well with plagioclase phenocryst composition. Mafic andesites have normative plagioclase of $\sim An_{50}$ composition, Andesites have normative plagioclase in the range of An_{40-50}, dacites have normative plagioclase in the range of An_{30-40}, and rhyodacites have normative plagioclase in the range of An_{25-30}. The rocks of the Twin Lakes Sequence have variable normative plagioclase in the range of An_{35-50}, even for rocks with similar SiO_2 content, attesting to their mixed origin. The en/fs ratio of hypersthene and augite are more magnesian than that of corresponding whole rock due to the lack of Fe_2O_3 in the chemical analysis and subsequent lack of magnetite in the norm. Similarly, the lack of Fe_2O_3 increases the hy/di ratio in the normative mineralogy.

Isotope Data

Sr and Pb isotopic analyses have been performed on a few rocks from the Lassen Volcanic Center. Although the samples were not collected in a systematic manner, the data place constraints on the origin of magmas of the Lassen Volcanic Center.

Sr isotopic data exist for five samples of the Lassen Volcanic Center: three rocks from Cinder Cone, one sample from the Prospects Flow (Peterman and others, 1970), and a sample whose locality is ambiguous (Church, 1976), but which I believe to be the Andesite of Glassburner Meadows, a Stage II rock. The $^{87}Sr/^{86}Sr$ values of all five samples are identical within analytical uncertainty, ranging from 0.7039 to 0.7041 ± 0.0001, and are similar to those reported for other Cascade volcanoes.

Sr isotope data were reported by Peterman and others (1970) and Church (1976) for three other rocks in the Lassen area: two Lassen Calc-alkaline Basalt and Andesite (Red Lake Mountain [0.7032 ± 0.0001] and West Prospect Peak [0.7030 ± 0.0007], and one of low-K, high-alumina olivine tholeiite, [0.7039 ± 0.0001]). These rock types are described in the petrogenesis section.

Assuming that the limited Sr isotope data are accurate and representative of the rock units analyzed, several suggestions can be made. The Sr-isotope values (all ∿ .7040) are consistant with a mantle origin for magmas of the Lassen Volcanic Center but do not rule out fusion of or contamination by young mafic lower crust. Significant contamination by pre-Mesozoic sialic crust is precluded. Basalts and andesites from the same volcano usually have similar Sr isotope ratios (Gill, 1980). Data on Stage I rocks of the Lassen Volcanic Center are lacking, but if LCBA are similar, then their slightly lower Sr isotope ratios suggest Stage II rocks of Brokeoff Volcano and silicic rocks of Lassen Volcanic Center could be produced by lower crustal interaction with Stage I magmas or prolonged crystal fractionation of Stage I magmas. Hybrid rocks (Twin Lakes Sequence) are produced by mixing of magmas with similar (.7030-.7040) Sr isotope ratios.

Lead isotopic data for four Lassen rocks (two from the Lassen Volcanic Center and two of Lassen Calc-alkaline Basalt and Andesite) were reported by Church (1976). Rocks of the Lassen Volcanic Center are the Andesite of Glassburner Meadows (Stage II, Digger-Diller Sequence) and Rhyodacite of Chaos Crags (Stage III, Lassen Sequence). The others are Andesite of Table Mountain and Andesite of West Prospect Peak (Macdonald, 1983). The Pb isotope values are all essentially identical and fall within the range of mantle values (Gill, 1981), except for $^{207}Pb/^{204}Pb$, which permits involvement of a minor crustal component. Any conclusion drawn from the Pb isotope data must be considered tenative; however, the suggestion is that crustal material is not a significant component in the source of magmas of the Lassen Volcanic Center.

Helium isotopes of gases from the geothermal system at LVNP were measured by Craig and others (1981). $^{3}He/^{4}He$ ratios approximately eight times atmospheric clearly indicate the dominance of mantle helium over crustal helium in the Lassen geothermal system. The heat and helium source of the Lassen geothermal system is the silicic magma chamber underlying the Lassen domefield (Muffler and others, 1982). $^{3}He/^{4}He$ ratios cannot preclude a crustal component as a source of magmas of the Lassen Volcanic Center but do suggest that the primary source for silicic melts of the Lassen Volcanic Center is the mantle.

Minor and Trace-Elements

Some trace-element data are available for many of the analyzed rocks of the Lassen Volcanic Center reported in the literature.

However, the existence of trace-element data was not a criterion for sample inclusion in the major-element data set representative of Lassen Volcanic Center. Therefore, many of the trace-element analyses presented in this section are for samples excluded from the representative data set. All trace-element data reported in the literature are compiled here. Note that data exist primarily for the silica-rich samples of the the Mill Canyon Sequence and are not representative of the sequence as a whole. The Ski Hill-Conard, Rice Creek and Twin Lakes Sequences are under-represented or lack data completely. Therefore the trends noted here must be considered tenative.

Ferromagnesian Trace Elements and Copper

Fountain (1975) analyzed approximately 100 samples for Cr, Ni, Co, V and Cu but reported the data only as plots vs. SiO_2. The symbols used identified sampling groups rather than rock units or individual samples. My reconstruction of the sections sampled by him allows correlation of data points with my rock sequences of the Lassen Volcanic Center at fair reliability for samples of Stages I and II. Silicic rocks of Stage III are less reliably distinguished. Samples of the Huckleberry Lake Sequence are certainly distinguished. Data for the Twin Lakes Sequence are lacking.

The data are presented in summary form in figure 15 as averaged estimates for some sequences. The data are not of sufficient quality to allow detailed analysis; nevertheless, some trends are worth noting.

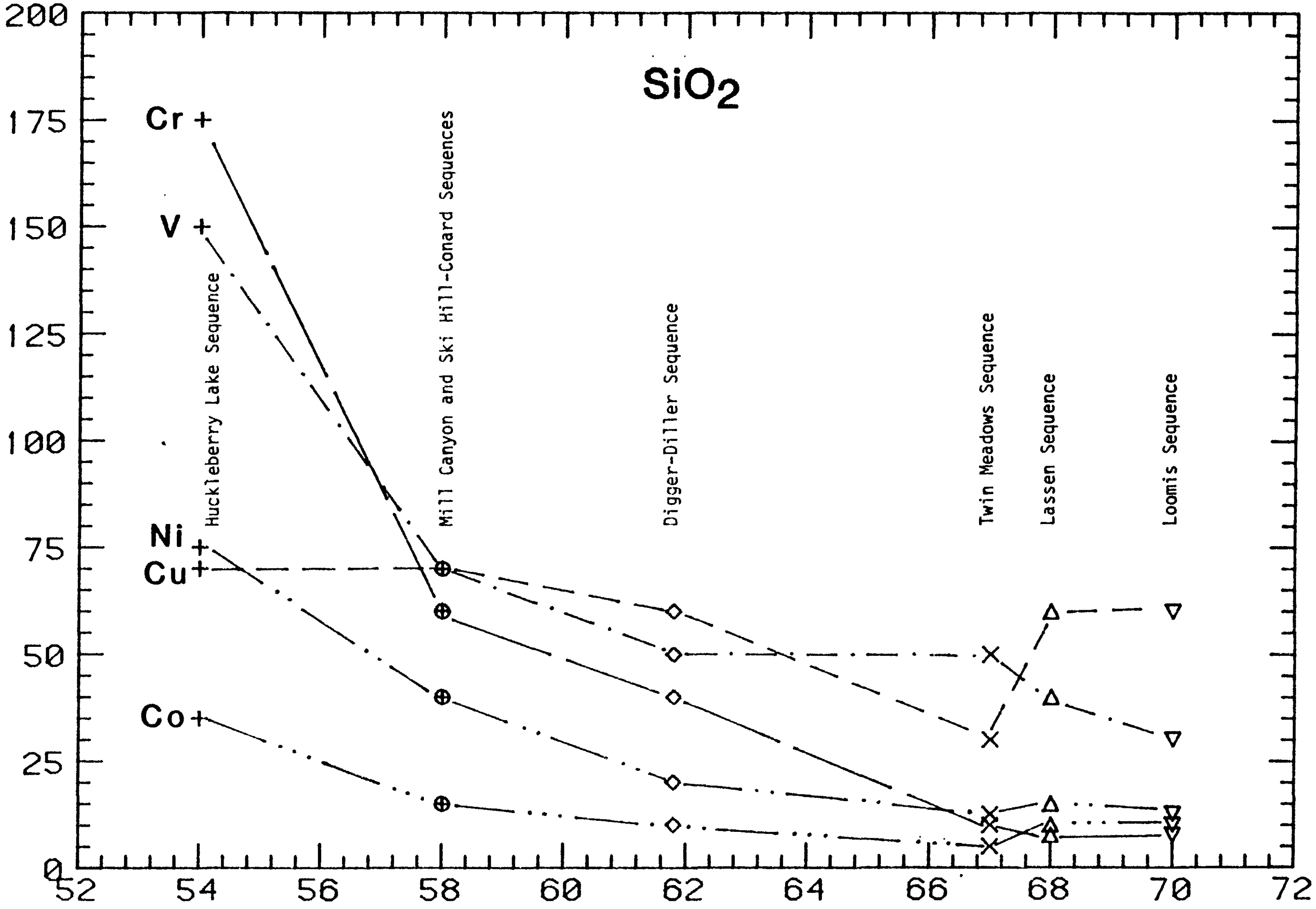

Figure 15. Ferromagnesian trace elements versus SiO_2 of rocks of the Lassen Volcanic Center.

The ferromagnesian trace elements are concentrated in Fe-Mg minerals relative to melt and therefore correlate negatively with SiO_2. Co, Cr, and Cu contents in Lassen Volcanic Center rocks are within the normal ranges for calc-alkaline volcanic rocks (Gill, 1981). Ni contents are slightly higher than normal but within the range of lavas erupted through thick crust. V contents, except for the Huckleberry Lake Sequence, are lower than normal by a factor of two. Ni and Cr contents are much lower than those expected for melts in equilibrium with mantle olivine; even the Huckleberry Sequence has only about half the Ni and Cr necessary for equilibrium with mantle olivine. The Cr and V contents of the Huckleberry Lake Sequence do not plot on reasonable continuations of the trends of the other rocks of the Lassen Volcanic Center.

Rubidium, Strontium, Barium, and Zirconium

Rubidium content of rocks of the Lassen Volcanic Center (fig. 16) is typical of medium-K andesites (Gill, 1981) and correlates positively with K_2O and SiO_2. However K/Rb does not decrease with K_2O and SiO_2 (table 3) as it does in most andesitic suites (Gill, 1981).

Strontium content of rocks of the Lassen Volcanic Center (fig. 17) is typical of medium K andesite suites (Gill, 1981) and is in contrast to the high Sr content reported for other Cascade centers by Church and Tilton (1973). Sr is variable but shows a weak negative correlation with SiO_2 except in the Loomis and Lassen Sequences which are Sr depleted. Rb/Sr does not increase regularly

Table 3 K/Rb and Rb/Sr of Rocks from the Lassen Volcanic Center

Sequence	K/Rb		Rb/Sr	
Mill Canyon	310	(8)	0.12	(6)
Ski Hill-Conard	390	(9)	--	--
Twin Meadows	310	(3)	0.27	(1)
Digger-Diller	350	(12)	0.08	(7)
Rice Creek	315	(7)	--	--
Bumpass	380	(13)	0.10	(7)
Loomis	375	(13)	0.25	(8)
Lassen	375	(12)	0.24	(11)
Twin Lakes	385	(3)	0.08-0.14	(3)
Huckleberry Lake	430	(3)	0.08	(3)

K/Rb rounded to nearest 5

Number in parentheses is the number of samples averaged in each group

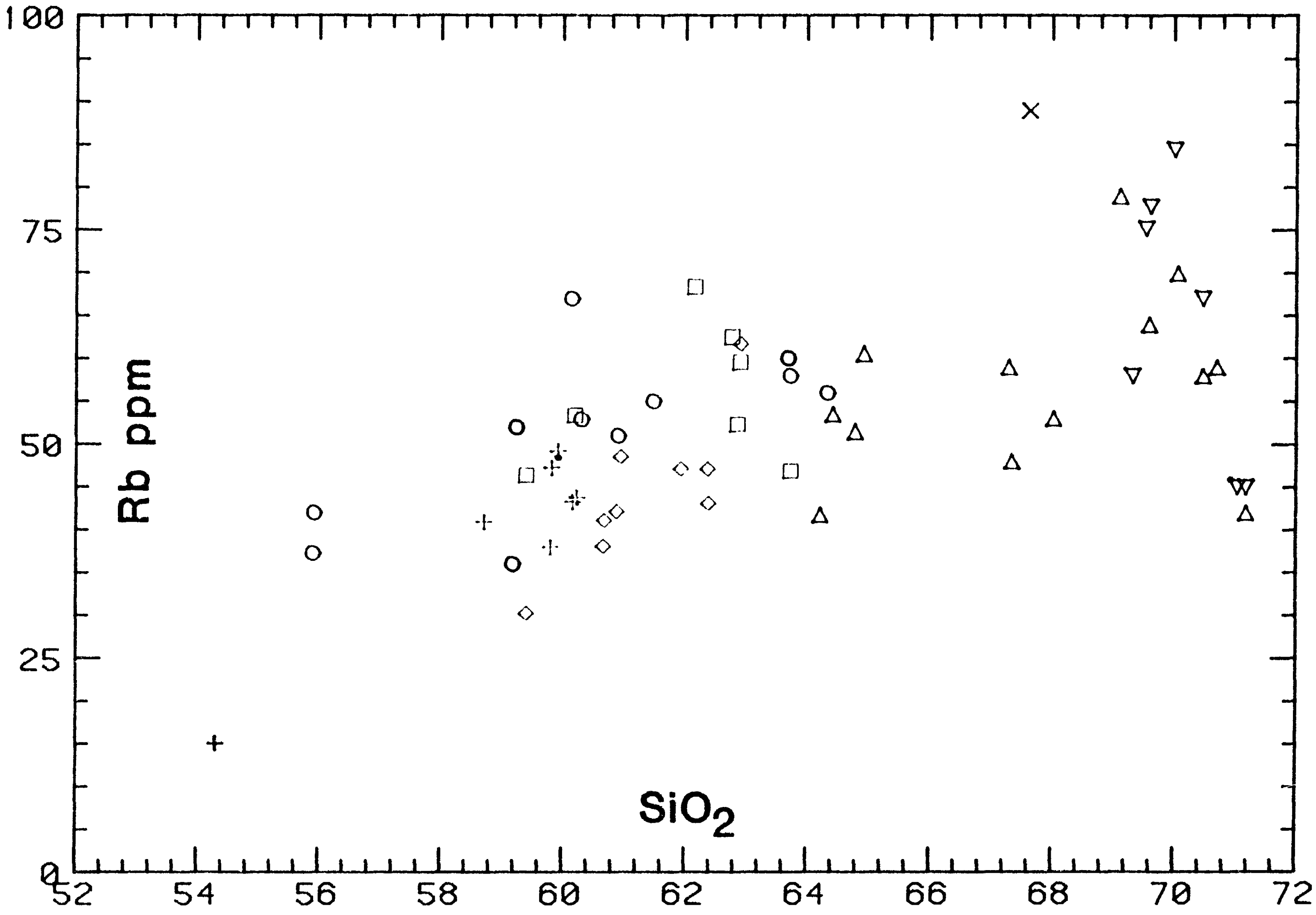

Figure 16. Rubidium versus SiO_2 of rocks of the Lassen Volcanic Center.

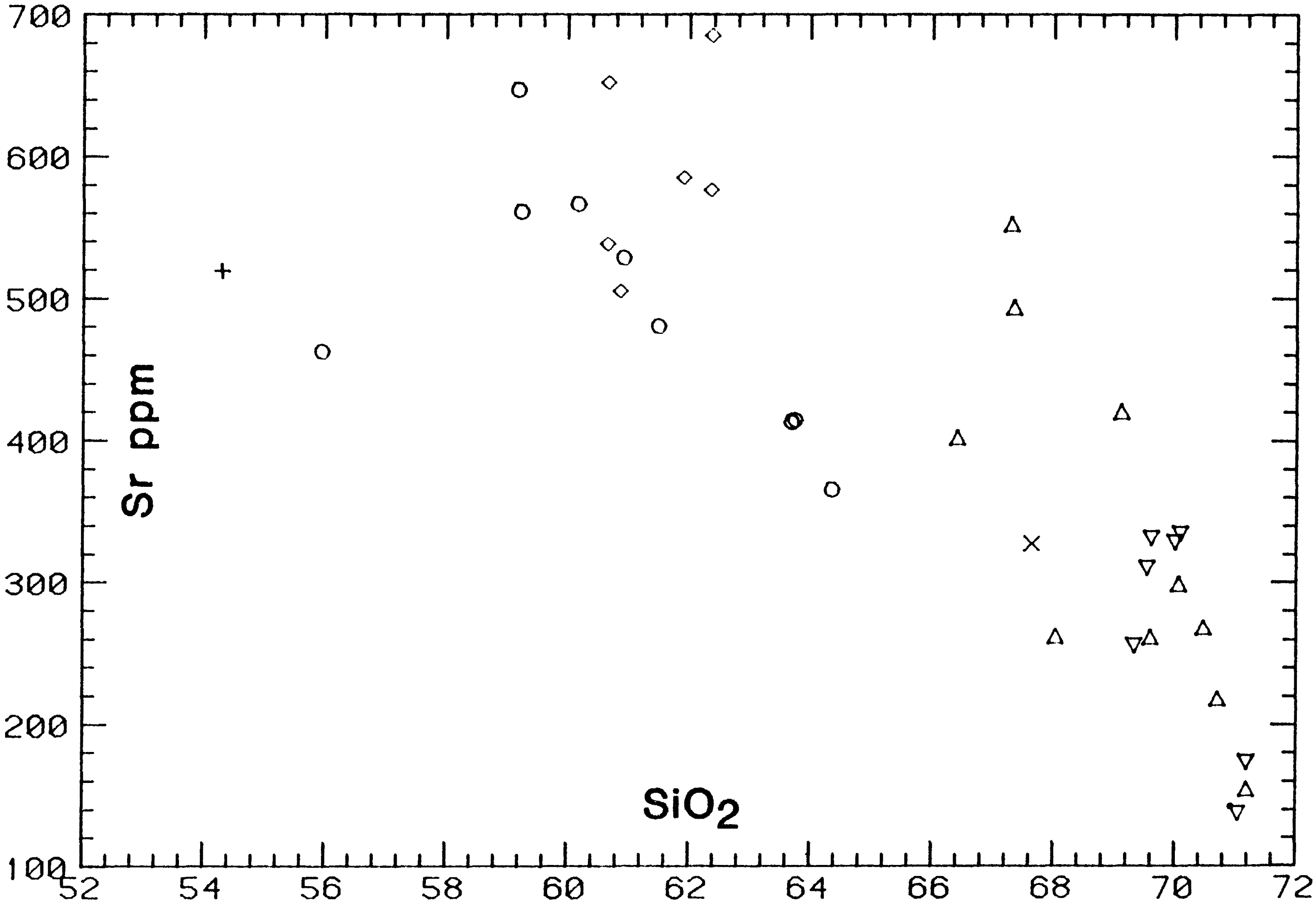

Figure 17. Strontium versus SiO_2 of rocks of the Lassen Volcanic Center.

with increasing SiO_2 as is typical in andesitic suites (Gill, 1981). There are two ranges of Rb/Sr (table 3). The Mill Canyon, Digger-Diller, Twin Lakes, Huckleberry Lake, and the Bumpass Sequences have low Rb/Sr (0.08-0.14), whereas the more differentiated rocks, the Twin Meadows, Loomis, and Lassen Sequences, have higher Rb/Sr (0.24-0.27). No rock of the Lassen Volcanic Center has Rb/Sr approaching 0.50, the value thought to be typical of rocks derived by anatexis of old sialic crust (Hawkesworth and others, 1982). The high Rb/Sr of silicic rocks of the Lassen Volcanic Center is within the range typical of andesitic suite rocks (Gill, 1981)

Barium content of rocks of the Lassen Volcanic Center (fig. 18) varies erratically as is typical of medium-K andesite suites (Gill, 1981), but tends to be higher in the more differentiated rocks.

Zirconium content of rocks of the Lassen Volcanic Center (fig. 19) is equivalent to or slightly higher than those typical of medium-K andesites (Gill, 1981) and shows no correlation with SiO_2. The Loomis Sequence displays a wide range of Zr content.

Scatter in rubidium, strontium, barium, and zirconium content of rocks of the Lassen Volcanic Center may be partially due to comparison of data from different sources. Analyses of silicic rocks from the Lassen Volcanic Center for rubidium, barium, and zirconium (Clynne, unpublished data) by the INAA technique suggest that much of the scatter in the literature data may be due to analytical errors inherent in XRF analyses. Roofward enrichment and subsequent magmatic zonation of incompatible elements by vapor phase

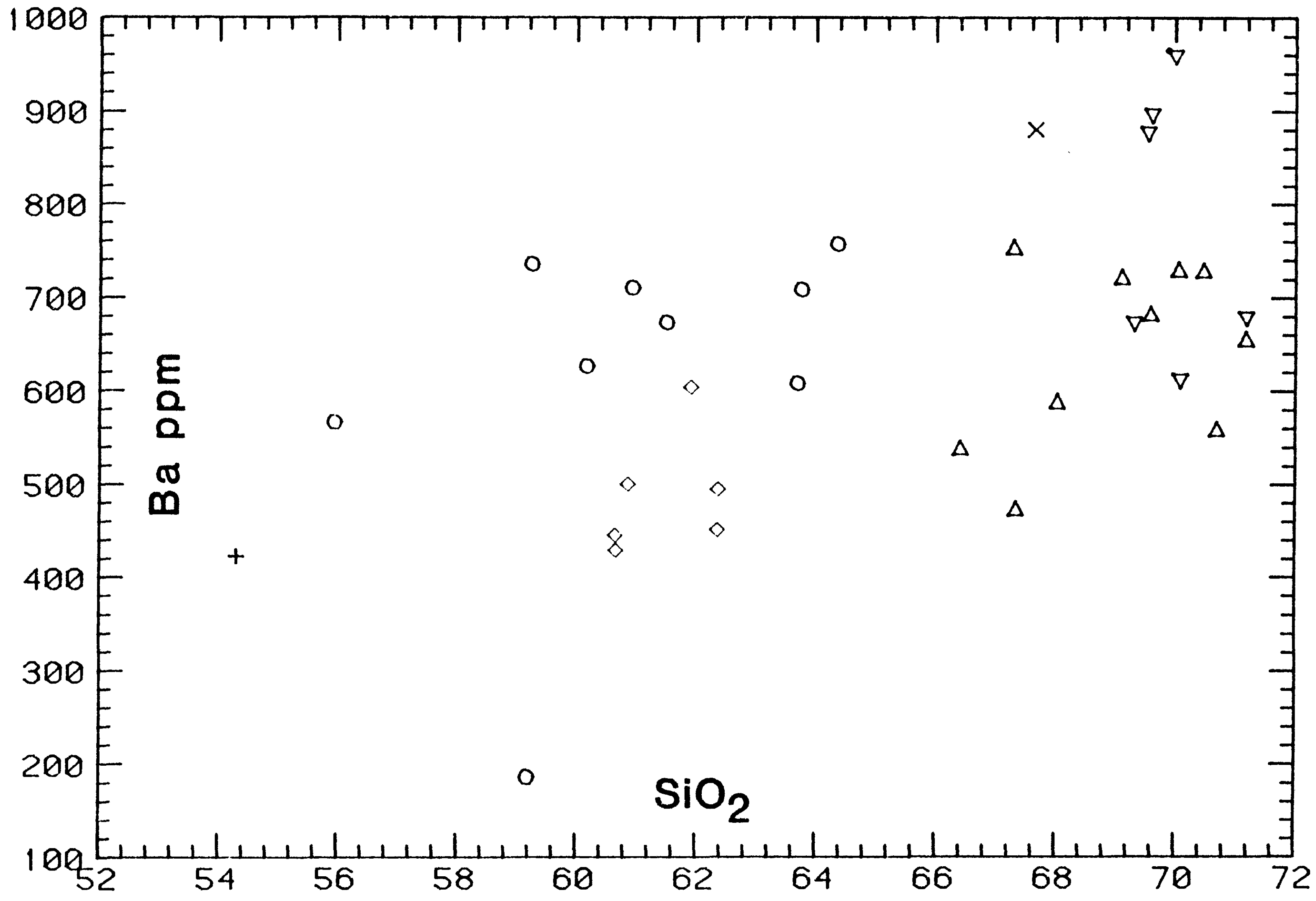

Figure 18. Barium versus SiO_2 of rocks of the Lassen Volcanic Center.

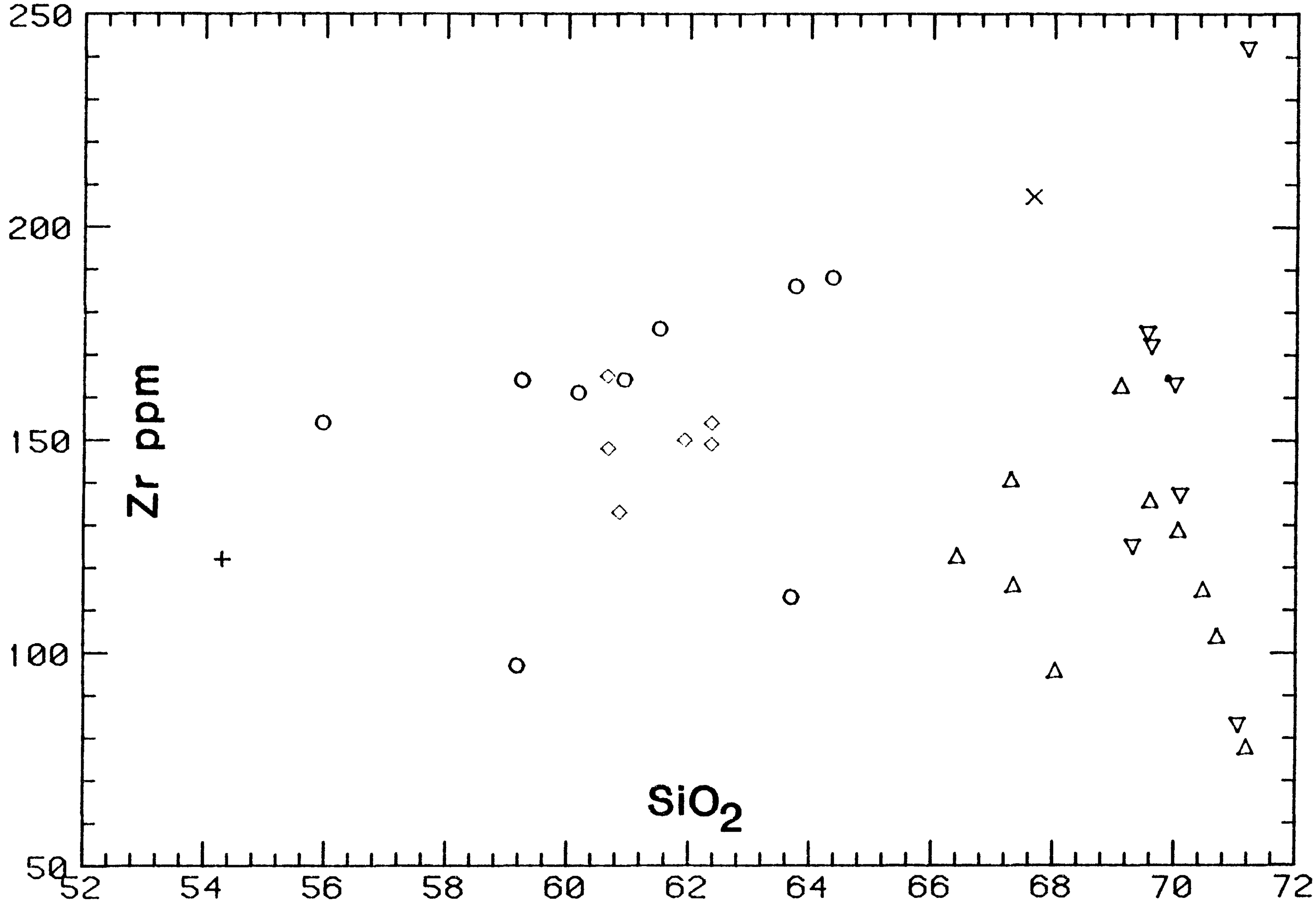

Figure 19. Zirconium versus SiO_2 of rocks of the Lassen Volcanic Center.

transport may also contribute to the variation of rubidium, barium, and zirconium content (Hildreth, 1981).

Rare Earth Elements

Partial rare earth element analyses were reported by Fountain (1975) for six rocks of the Lassen Volcanic Center, and three analyses from the Loomis Sequence from Mt. Conard were made available by L. J. P. Muffler (written communication, 1982). The data are summarized in figure 20. Fountain presented his data graphically normalized to chondrites but did not specify the chondritic abundances used. The three analyses of Muffler are essentially identical; hence an average is shown.

The REE Patterns are typical of medium-K, calc-alkaline andesites. Light REE are enriched, 20-60x chondrites, while heavy REE are 6-9x chondrites. The data suggest slight concentrations of REE with increasing K_2O and SiO_2; however, the data are too limited to be definitive. The large positive Eu anomaly shown by Fountain's Loomis Sequence data is unusual for andesitic suite rocks (Gill, 1981) and is not supported by Muffler's Loomis Sequence data.

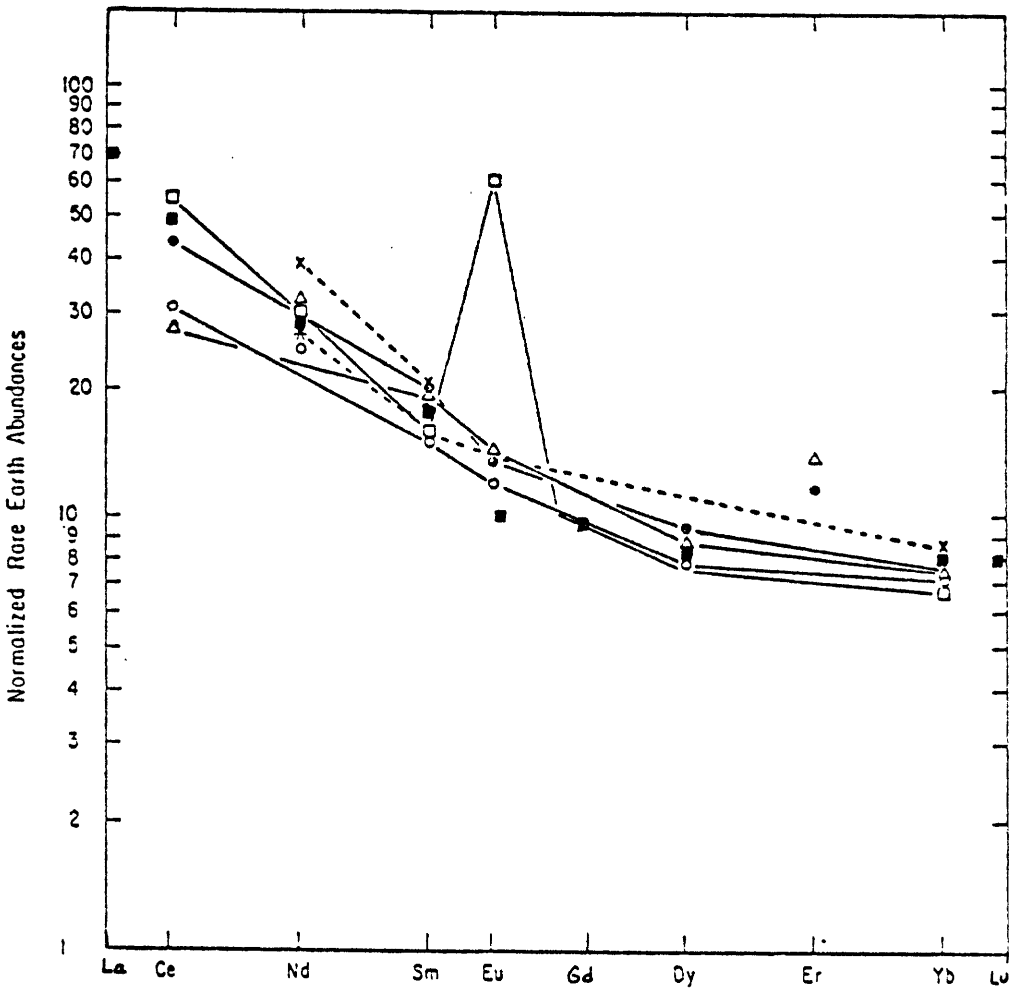

Figure 20. Rare earth elements versus chondrites of rocks of the Lassen Volcanic Center, (modified from Fountain, 1975).

□ Loomis Sequence

■ Loomis Sequence (Muffler, unpublished data)

● Digger-Diller Sequence

△ Digger-Diller Sequence

○ Mafic Inclusion, Loomis Sequence

✕ Lassen Sequence

✱ Huckleberry Lake Sequence

PETROGENESIS

Parent Magma

Crystal fractionation of a calc-alkaline basalt parent magma is the most common mode of genesis for andesite suites (Gill, 1981). The smooth trends on major-element variation diagrams, positive correlation of SiO_2 with time, and high phenocryst content make crystal fractionation an attractive starting point for genetic modeling. However, the chemical characteristics (e.g., Mg number <67, low Cr and Ni content) preclude even the most mafic andesites of Stage I of the Lassen Volcanic Center from being unfractionated partial melts of normal mantle material. Yet, Sr, Pb and He isotope values indicate a mantle origin. The lack of appropriate parent magma in the lavas of Brokeoff Volcano requires seeking evidence of a basaltic parent in the surrounding area.

Two types of mafic lavas occur in the area surrounding the Lassen Volcanic Center. The first is similar to low-K, high-alumina olivine tholeiite (HAOT) from Medicine Lake Highland and found over a broad area of the western United States (Mertzman, 1979). The second is similar to circumpacific calc-alkaline basalt and mafic andesite found worldwide and called high-alumina basalt by many workers (e.g., Kuno, 1960; Waters, 1962; Ewart and LeMaitre, 1980; Walker, 1981; Kay and others, 1982) and here designated Lassen Calc-alkaline Basalt and Andesite (LCBA). Evolved LCBA is very similar to the most mafic lavas of Brokeoff Volcano and is suggested to be their parent.

Low-K, High-alumina Olivine Tholeiite

The low-K, high-alumina olivine tholeiite is a highly fluid magma erupted from fissures and producing valley-filling lava flows. The rock is distinctive, typically aphyric or with sparse olivine or plagioclase phenocrysts in a holocrystalline, often diktytaxitic groundmass composed of plagioclase, augite, olivine, and magnetite. Table 4 compares the range and average major-element composition HAOT of Lassen area with that found at Medicine Lake Highland. The data are displayed as an AFM diagram in figure 21. These olivine normative rocks display a remarkable chemical uniformity. Pertinent characteristics are 49 wt. % SiO_2, >17 wt. % Al_2O_3, low Na_2O, very low K_2O ($\sim$0.25 wt. %), FeO/MgO $\simeq$ 1.0-1.1, and Mg numbers $\geq$ 67. Trace-element data (Macdonald, 1983; Mertzman, 1979) include Cr > 300 ppm, Ni 150-200 ppm, Sr 200-300 ppm, Rb <5 ppm and $^{87}Sr/^{86}Sr$ = 0.7030 ± 0.0003; all suggesting a mantle origin. The chemical uniformity, widespread occurrence and contemporaneous calc-alkaline volcanism led Mertzman (1979) to suggest an asthenospheric source.

Green and others (1967) showed experimentally that fractional crystallization and removal of approximately 15% olivine, 15% clinopyroxene and 15% orthopyroxene from HAOT at 9kb pressure would produce calc-alkaline basalt. However HAOT is unlikely to be the parent magma for Brokeoff Volcano rocks. Its aphyric nature and

Table 4. Comparison of Major Element Chemistry of Low K, High-alumina Olivine Tholeiites from the Lassen Area and Medicine Lake Highland

[All data in weight percent, recalculated anhydrous, Fe as total FeO]

	1	2	3	4
SiO_2	49.07	48.01 - 50.00	48.84	48.25 - 49.93
Al_2O_3	18.10	17.47 - 19.45	17.38	16.90 - 17.97
FeO	9.24	8.54 - 9.86	9.15	8.32 - 10.12
MgO	8.48	7.15 - 9.51	9.10	6.99 - 10.05
CaO	10.81	9.95 - 11.76	10.93	10.34 - 11.69
NaO_2	2.75	2.32 - 3.57	3.15	2.61 - 3.86
K_2O	.25	.16 - .37	.25	.16 - .39
TiO_2	1.00	.76 - 1.20	.94	.59 - 1.41
P_2O_5	.12	.07 - .18	.11	.04 - .17
MnO	.16	.15 - .18	.17	.15 - .18
FeO/MgO	1.09	.98 - 1.30	1.01	.86 - 1.36

Column 1 average of 12 Lassen area low K, high-alumina olivine tholeiites (Macdonald, 1983; Anderson, 1940; Smith and Carmichael, 1969; Fountain, 1975; L. J. P. Muffler, unpublished data, P. A. Bowen, written communication, 1983; Clynne, unpublished data).

Column 2 range of data averaged in column 1.

Column 3 average of seven Medicine Lake Highland low K, high alumina olivine tholeiites (Mertzman, 1979).

Column 4 range of data averaged in column 3.

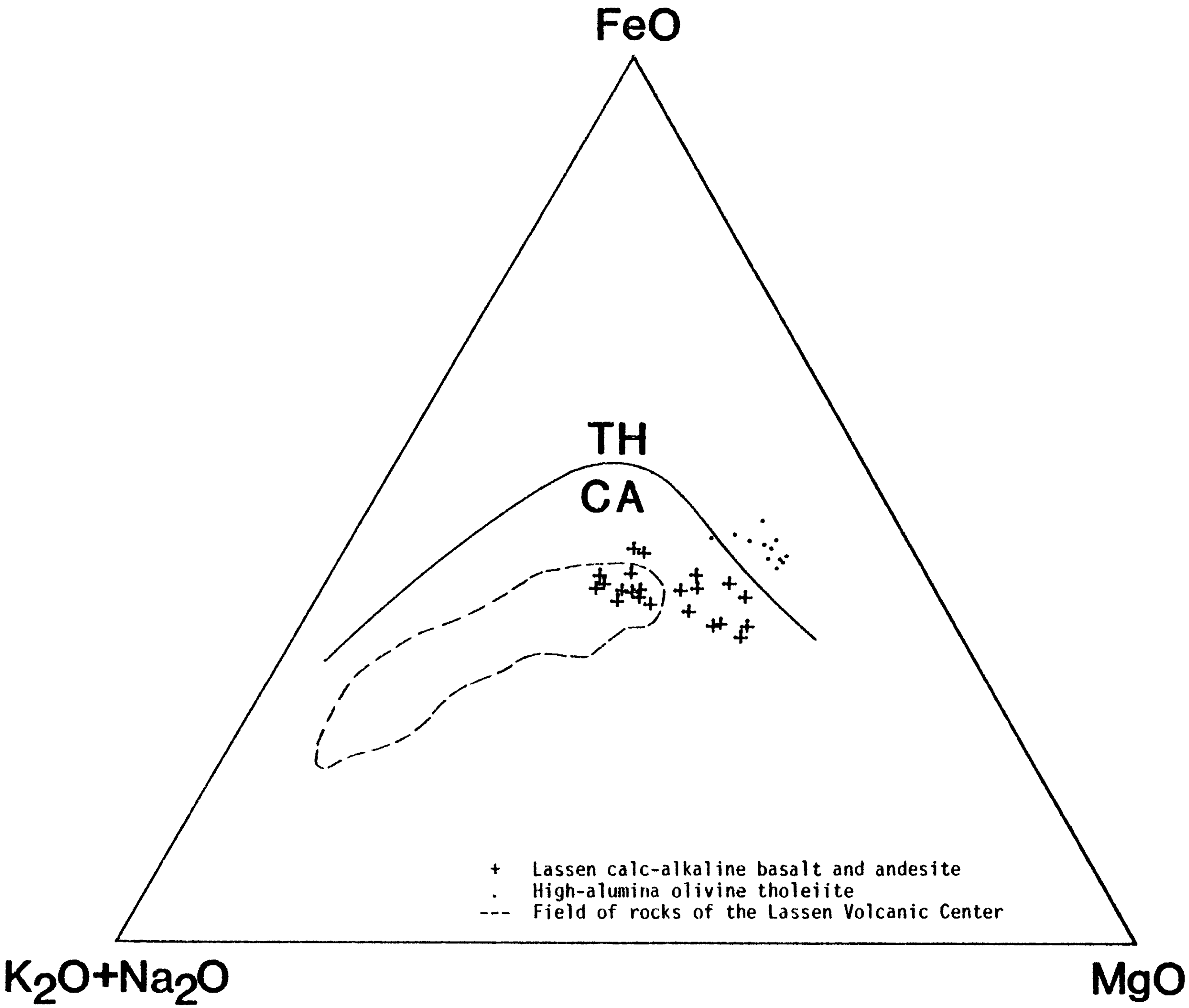

Figure 21. AFM diagram of Lassen calc-alkaline basalt and andesite and high-alumina olivine tholeiite. A= total alkalies (K_2O+Na_2O), F= iron as FeO, and M= MgO. The criteria of Irvine and Baragar (1971) were used to delineate the tholeiitic (TH) and calc-alkaline (CA) fields.

chemical uniformity suggests that it is not significantly affected by crystal fractionation, probably due to rapid ascent. Olivine and plagioclase are the only phenocryst phases found in HAOT. A significant gap appears between the chemical composition of HAOT and LCBA or rocks of Brokeoff Volcano and on an AFM diagram (fig. 21), suggesting that rocks of intermediate composition do not exist or are at least not found at the surface. Crystal fractionation of HAOT is necessary to reduce Cr and Ni and increase K and Si to levels similar to the most mafic andesites of Brokeoff Volcano. Significant fractional crystallization like that proposed by Green and others (1967) would result in iron enrichment (Grove and others, 1982), a feature incompatible with rock compositions of either LCBA or Brokeoff Volcano.

Lassen Calc-alkaline Basalt and Andesite (LCBA)

Shield volcanoes and lava flows with associated cinder cones are common in the area surrounding the Lassen Volcanic Center. Conspicuous, nearby volcanoes include Sifford Mountain, the Prospect Peaks, Red Lake Mountain, Badger Mountain, Table Mountain, Mt. Harkness, and numerous centers that produced the plateau-forming Eastern Basalts of Williams (1932). Chemical and petrographic data on these volcanoes are limited. The samples are mostly from the three centers that are used to illustrate this rock type.

Red Lake Mountain is a late Pleistocene shield volcano that has produced lavas of olivine-augite mafic andesite, described in a previous section. The lavas are porphyritic and show evidence of olivine accumulation. Their chemical homogeneity (four analyses) probably results from sampling a single flow unit.

Sifford Mountain is a late Pleistocene shield volcano probably contemporaneous with Stage III of Lassen Volcanic Center. It has produced a variety of basalt and mafic andesite lavas. Sifford lavas are porphyritic and typically contain 30-40 % phenocrysts. Olivine and augite occur a large (up to 1 cm) zoned crystals but are volumetrically subordinate to small (<1 mm) plagioclase crystals. Groundmass minerals are the same and include magnetite. The seven chemical analyses of Sifford lavas show a continuum from 51 wt % SiO_2 basalt to 58 wt % SiO_2 andesite (table 5). They have high Al_2O_3 and low TiO_2; the most mafic have ∿8 wt % MgO, FeO/MgO ∿1, and ∿1 wt % K_2O. Normative mineralogy shifts from olivine-bearing to quartz-bearing at about 54 wt % SiO_2. Negative MgO, FeO, and CaO and positive K_2O correlations with SiO_2 indicate that Sifford andesites are most likely differentiates of Sifford basalts.

The Eastern Basalts (Williams, 1932) represent a widespread series of lava flows erupted from several centers in eastern LVNP and the adjacent Caribou Wilderness. They are sometimes aphyric, but generally contain minor to moderate amounts of small olivine, plagioclase, and occasional augite and hypersthene phenocrysts (Macdonald, 1964; Till and others, in press). Six analyses of Eastern Basalts show them to be similar to other LCBA lavas. SiO_2 ranges from 52 to 58 wt %, Al_2O_3 is high, TiO_2 low and normative mineralogy shifts from olivine-bearing to quartz-bearing

Table 5. Chemical Analyses of Lassen Area Calc-alkaline Basalts and Andesites

[Oxides adjusted to sum to 100% without water. CIPW normative minerals are reported in weight % and were calculated using the exact formulae of Washington (1917). D. I. = Thornton and Tuttle's differentiation index. Sources of data: M numbers, L. J. P. Muffler (unpublished data); B numbers, P. A. Bowen (written communication, 1983); C numbers, Clynne (this report); F numbers, Fountain (1975), numbers proceeded by an A are averaged values; D numbers, MacDonald (1983); SC numbers, Smith and Carmichael (1968). Unit symbols not given in text: Qbe, Eastern Basalt, (Williams, 1932); Qbs, Basalt and Mafic Andesites of Mt. Sifford, (Muffler and others, 1982a); Qbp, Basalt of Prospect Peak, (Macdonald, 1964); Qbh, Basalt of Mt. Harkness, (Williams, 1932); Qasb, Andesite of Small Butte; Qbcc, Basalt of Cold Creek Butte, (Wilson, 1961)].

Analysis number	1	2	3	4	5	6	7	8	9	10	11
Sample number	C0402	DB492	DB493	B9055	DL6	DL7	C1646	C1649	C1720	M0910	M0913
Unit	Qbe	Qbe	Qbe	Qbe	Qbe	Qbe	Qbs	Qbs	Qbs	Qbs	Qbs
SiO_2	54.87	56.28	56.23	53.80	52.26	58.02	56.63	51.70	53.16	57.62	55.44
Al_2O_3	17.55	18.59	19.66	18.74	17.75	17.40	17.70	16.86	17.12	17.70	17.85
FeO	7.53	6.63	6.02	7.23	7.95	6.36	6.52	8.09	7.80	6.31	7.60
MgO	5.31	4.22	4.05	5.58	7.05	4.88	5.12	8.71	7.17	4.67	5.08
CaO	7.80	8.14	8.31	7.71	8.13	6.79	8.04	9.27	8.65	7.70	8.18
Na_2O	3.72	4.02	3.65	4.19	3.80	3.76	3.49	3.09	3.47	3.61	3.40
K_2O	1.49	1.11	1.11	1.26	1.20	1.48	1.23	0.85	1.06	1.26	1.17
TiO_2	1.14	0.76	0.76	1.02	1.32	0.86	0.85	1.02	1.11	0.77	0.85
P_2O_5	0.45	0.12	0.08	0.33	0.39	0.32	0.30	0.27	0.33	0.24	0.30
MnO	0.14	0.13	0.13	0.13	0.15	0.12	0.12	0.14	0.13	0.12	0.12
FeO/MgO	1.42	1.57	1.49	1.30	1.13	1.30	1.27	0.93	1.09	1.35	1.50
Q	0.54	3.51	5.82			7.61	4.63			6.02	2.98
C											
Or	8.82	6.51	6.56	7.42	7.05	8.69	7.29	5.01	6.25	7.43	6.93
Ab	31.49	33.89	30.73	35.44	31.77	31.52	29.52	26.14	29.39	30.55	28.76
An	26.77	29.31	33.82	28.63	27.77	26.20	28.98	29.64	27.99	28.37	29.97
Di	7.38	8.33	5.44	6.15	7.79	4.33	7.34	11.87	10.43	6.81	7.16
DiWo	3.73	4.23	2.79	3.12	4.05	2.23	3.72	6.08	5.32	3.45	3.61
DiEn	1.89	2.25	1.66	1.64	2.77	1.34	1.96	3.57	2.98	1.76	1.77
DiFs	1.75	1.85	0.99	1.39	1.05	0.76	1.66	2.21	2.13	1.60	1.78
Hy	21.78	15.01	13.40	11.21	13.05	16.89	19.93	12.53	16.51	18.80	21.89
HyEn	11.32	8.23	8.39	6.06	9.40	10.77	10.79	7.74	9.63	9.86	10.89
HyFs	10.46	6.78	5.01	5.15	3.65	6.12	9.14	4.79	6.88	8.94	10.99
Ol				8.44	5.34			12.24	6.56		
OlFo				4.36	3.74			7.28	3.67		
OlFa				4.08	1.60			4.96	2.89		
Il	2.17	1.45	1.44	1.95	2.50	1.63	1.61	1.94	2.10	1.47	1.62
Ap	1.08	0.29	0.19	0.79	0.93	0.76	0.72	0.65	0.79	0.57	0.71
Salic	67.62	73.21	76.93	71.49	66.62	74.05	70.42	60.79	63.63	72.36	68.64
Femic	32.40	26.53	22.81	28.52	33.06	25.71	29.60	39.23	36.39	27.65	31.37

Table 5. Chemical Analyses of Lassen Area Calc-alkaline Basalts and Andesites--Continued

Analysis number Sample number Unit	12 B7171 Qbs	13 B313 Qbs	14 CO374 Qar1	15 C1828 Qar1	16 DB1 Qar1	17 SC14 Qar1	18 F127A Qbp	19 C1741 Qbh	20 MO814 Qasb	21 CO537 Qbcc	22 CO401 Qbl
SiO_2	51.67	57.93	56.04	54.56	54.15	54.69	58.21	52.01	55.73	51.37	51.88
Al_2O_3	16.69	17.82	15.61	16.94	17.06	16.68	17.19	16.49	17.00	17.36	17.33
FeO	7.99	6.23	6.58	6.44	6.36	6.45	6.23	8.84	6.90	8.39	8.23
MgO	7.95	4.18	8.06	7.33	8.08	7.28	5.05	5.61	5.97	8.18	7.11
CaO	8.60	7.58	9.07	9.40	9.16	9.31	7.44	9.07	7.78	9.00	9.04
Na_2O	4.38	3.93	2.81	3.29	3.39	3.45	3.37	3.86	3.61	3.23	3.40
K_2O	1.03	1.24	0.94	0.80	0.59	0.83	1.33	1.55	1.57	0.86	1.08
TiO_2	1.20	0.73	0.64	0.88	0.88	0.91	0.83	1.70	1.01	1.13	1.22
P_2O_5	0.34	0.24	0.14	0.24	0.23	0.29	0.22	0.74	0.31	0.32	0.58
MnO	0.14	0.12	0.12	0.11	0.11	0.12	0.14	0.14	0.12	0.16	0.13
FeO/MgO	1.01	1.49	0.82	0.88	0.79	0.89	1.23	1.58	1.16	1.03	1.16
Q		5.65	3.58	0.62	2.76	0.27	7.61		1.30		
C											
Or	6.10	7.33	5.57	4.71	3.49	4.90	7.86	9.15	9.27	5.07	6.37
Ab	32.20	33.16	23.75	27.82	28.42	29.19	28.51	32.62	30.56	27.33	28.73
An	22.79	27.25	27.20	29.12	29.48	27.57	27.85	23.13	25.55	30.34	28.86
Di	14.34	7.18	13.70	12.95	11.19	13.59	6.27	14.08	9.02	9.98	9.97
DiWo	7.34	3.62	7.04	6.65	5.90	6.98	3.18	7.11	4.59	5.10	5.08
DiEn	4.24	1.78	4.27	3.99	4.52	4.18	1.69	3.52	2.52	2.91	2.79
DiFs	2.77	1.78	2.39	2.31	0.76	2.43	1.39	3.45	1.91	1.98	2.10
Hy		17.26	24.65	22.55	18.09	22.08	19.82	3.26	21.67	11.10	12.17
HyEn		8.61	15.80	14.27	15.48	13.95	10.88	1.65	12.34	6.61	6.94
HyFs		8.65	8.86	8.28	2.61	8.13	8.94	1.61	9.33	4.49	5.23
Ol	18.72							12.83		13.29	10.24
OlFo	10.88							6.16		7.60	5.60
OlFa	7.84							6.67		5.69	4.65
Il	2.28	1.39	1.21	1.67	1.66	1.73	1.58	3.23	1.91	2.15	2.32
Ap	0.80	0.57	0.34	0.57	0.55	0.68	0.52	1.75	0.74	0.77	1.38
Salic	63.69	73.39	60.10	62.27	64.18	61.93	71.83	64.90	66.68	62.74	63.96
Femic	36.14	26.40	39.90	37.75	35.60	38.08	28.18	35.15	33.34	37.28	36.08
D. I.	40.90	46.13	32.91	33.15	34.67	34.36	43.98	41.77	41.14	32.40	35.10

at about 54 wt % SiO_2. The most mafic have ∿7 wt % MgO and ∿1 wt % K_2O with FeO/MgO ∿1.1. Trace-element data are sparse; Cr ranges from 30 to 300 ppm, Ni 30 to 100 ppm, and Sr 500-1,000 ppm with negative Cr and Ni and positive Sr correlations with SiO_2. The chemical continuum and correlations with SiO_2 suggest that the Eastern Basalts are related by crystal fractionation.

The chemical composition of the more silicic (differentiated) LCBA overlaps the chemical composition of the mafic andesites of Brokeoff Volcano (Mill Canyon Sequence). The situation suggests that the two are related and that LCBA volcanic features (e.g., Sifford Mountain) represent young shield volcanoes capable of growing into large composite cones like Brokeoff Volcano, as has been hypothesized for some Central American volcanoes (Carr and Pontier, 1981; Carr and others, 1981; Walker, 1981). Small differences between the characteristics of LCBA and rocks of Brokeoff Volcano may be significant. CaO and Al_2O_3 both show more variation but tend to be slightly lower at equivalent SiO_2 in LCBA, perhaps reflecting plagioclase removal. The small field of overlap between TiO_2 content of LCBA and the mafic andesites of Brokeoff Volcano, and the slight Fe enrichment of LCBA lavas on the AFM diagram (fig. 21) implies that magnetite crystallization and removal has not yet occurred in the bulk of LCBA lavas but has occurred in the Mill Canyon Sequence. Magnetite phenocryst crystallization and removal at Lassen apparently begins at approximately 54 wt % SiO_2.

In summary, the LCBA lavas occur as shield volcanoes and lava cones, pyroclastic material is sparse, and phenocryst abundance variable. The parental magma SiO_2 content may be ∿50 wt %, with 6-8 wt % MgO, FeO/MgO ∿1.1, high Al_2O_3, low TiO_2, and K_2O ∿1.0 wt %. Similar to many California basalts, the Mg number and trace-element content are appropriate for this medium K, calc-alkaline basalt to be a primary partial melt of the mantle. Crystal fractionation of olivine + plagioclase + augite and in later stages hypersthene and magnetite produces rocks with up to 60-62 wt % SiO_2 (e.g., Raker Peak, Sugarloaf, Table Mountain).

The LCBA occur in a position allowing them to be the parent magma for lavas of the Lassen Volcanic Center. Crystal fractionation of LCBA alleviates the problem of lavas of Brokeoff Volcano having chemical characteristics unsuitable for unfractionated partial melts of mantle material.

Fountain (1979) developed a model of the genesis of rocks of the Lassen Volcanic Center. He suggested that 4-5 % partial melting of hydrous garnet peridotite produced an andesitic (58 wt % SiO_2) parent magma. Subsequent crystal fractionation produced what he called the bulk of the Brokeoff Cone (Digger-Diller Sequence) and hornblende dacites (Twin Meadows Sequence). He ruled out production of the flank dacites by crystal fractionation, instead proposing partial melting of hydrous garnet peridotite at greater pressure than above to produce dacitic (64 wt. % SiO_2) magma. Subsequent evolution via hornblende fractionation produced the flank rhyodacites (Loomis and Lassen Sequences). The Bumpass Sequence was produced by mixing of the andesitic and dacitic parents or their differentiation products. Fountain's most important conclusion was that despite smooth major-element variation diagrams, the rocks of Lassen Volcanic Center were not related by a single genetic process.

Fountain's entire model depends upon unrepresentative sampling and is largely based on minimal REE data. It also lacks modal and chemical mineralogic data necessary to evaluate crystal fractionation schemes. Stratigraphic and temporal data presented in this report do not support Fountain's model. Particularly damaging is his failure to recognize Stage I rocks, leading him to propose an andesitic (58% SiO_2) parent for rocks of Brokeoff Volcano. Fountain's work points out the danger inherent in geochemical sampling and modeling without an adequate stratigraphic framework based on field geologic mapping.

The proposal of a detailed genetic model of Lassen Volcanic Center rocks is beyond the scope of this report. Indeed, data elements critical to "state of the art" igneous petrology are lacking; most notably minor- and trace-element analyses, volume calculations, and modal and microprobe analyses of phenocryst mineralogy. Nevertheless, the stratigraphic information in conjunction with the major- and sparse trace-element data presented here can constrain genetic modeling in the sense that plausible models must account for these items.

SUMMARY

Summary of the Lassen Volcanic Center

The three stages of the Lassen Volcanic Center can be summarized as follows:

Stage I - Initial growth of Brokeoff Volcano by eruption of olivine and pyroxene mafic andesite and andesite lava flows and pyroclastics during the period from about 600,000 to 450,000 years ago (Mill Canyon Sequence and Ski Hill-Conard Sequence). Stage I culminated with eruption of differentiated hornblende-pyroxene dacite lavas (Twin Meadows Sequence)

Stage II - Renewed cone growth of Brokeoff Volcano by eruption of homogeneous two-pyroxene silicic andesite lava flows between about 450,000 and 360,000 years ago.

Stage III - Eruption of the Rockland Tephra from an unlocated vent. Eruption on the northern and northeastern flanks of Brokeoff Volcano of dacite and rhyodacite domes, rhyodacite flows, hybrid andesite flows and mafic andesite flows over a period from about 250,000 years ago to the present (Bumpass, Loomis, Lassen, Twin Lakes, and Huckleberry Lake Sequences).

Petrogenesis

The lavas of the Lassen Volcanic Center are related by crystal fractionation of an LCBA parent. The origin of the LCBA parent is obscure. It could be produced directly from the upper mantle (Kuno, 1960; Waters, 1962; Anderson, 1982) or perhaps by crystal fractionation and/or assimilation of crustal material by a mantle-derived magma at or near the base of the crust. Crystal fractionation of LCBA occurs in the crust at a level controlled by its volatile content (Anderson, 1973). Crystallization and removal of olivine + clinopyroxene + plagioclase yields the Mill Canyon and Ski Hill-Conard Sequences from LCBA. Open-system fractionation with periodic mixing of new mafic parent with the fractionating magma is suggested by the irregular chemical variation and petrographic evidence of disequilibrium of Stage I lavas. However, that crystal fractionation is the dominant process is shown by the overall trend to more silicic composition with time.

The Twin Meadows Sequence consists of hybrid lavas with mafic xenoliths that are blobs of quenched mafic magma. Trace-element data suggest that Twin Meadows Sequence lavas represent extreme fractionation of Stage I magmas, perhaps at higher levels in the crust. Some assimilation of crustal material may have accompanied fractionation.

Stage II lavas are a chemically and petrographically homogenous group; no significant variation with time is apparent. Two contrasting origins are suggested. If the Twin Meadows Sequence comes from a separate high-level magma chamber, then Stage II lavas can be easily explained as renewed tapping of the fractionating Stage I magma chamber. An alternative explanation is suggested by the petrography of the glomeroporphyritic clots; disruption and assimilation of mafic cumulate by a Twin Meadows-like magma, could produce Stage II lavas.

Stage III lavas comprising the Bumpass, Loomis, and Lassen Sequences represent continued fractionation of the LCBA parent at higher water pressures, probably at high levels in the crust. Assimilation of crustal material and mixing of magma from deeper levels probably modifies the compositions of these lavas. Rocks of the Twin Meadows Sequence are probably mixtures of mafic parent and fractionated rhyodacite. Andesite of Huckleberry Lake is LCBA that failed to intercept the silicic chamber. The Rockland Tephra appears to be related to the Lassen Volcanic Center, although a likely eruption site cannot be suggested at this time.

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APPENDIX 1. SAMPLE LOCALITIES FOR TABLE 2

Analysis number	Sample number	Latitude North	Longitude West	Unit	Locality Description
1	B366	40°26.35'	121°29.85'	Qash	North of Mt. Conard
2	B9042	40°25.75'	121°30.00'	Qash	Summit of Mt. Conard
3	B336	40°26.05'	121°31.10'	Qash	West side of East Sulphur Creek
4	B265	40°26.58'	121°30.45'	Qash	East Sulphur Creek, North of Conard Meadows
5	C0439	40°24.97'	121°31.12'	Qash	West Side of Mill Canyon
6	C0495	40°27.12'	121°33.93'	Qash	South Fork Bailey Creek
7	C1797	40°26.70'	121°31.08'	Qash	LVNP Road at bend SSE of Diamond Peak
8	B266	40°27.35'	121°33.15'	Qash	Ridge between Brokeoff-Diller
9	B337	40°26.18'	121°31.00'	Qash	West bank East Sulphur Creek
10	B338	40°26.23'	121°30.85'	Qash	East Sulphur Creek
11	B8012	40°26.48'	121°30.70'	Qash	Mill Creek Falls
12	B35A	40°26.75'	121°32.30'	Qash	Ski Hill, above LVNP Chalet
13	B35B	40°26.75'	121°32.30'	Qash	Ski Hill, above LVNP Chalet
14	B157	40°26.95'	121°29.75'	Qash	West of Crumbaugh Lake
15	M884	40°24.76'	121°30.70'	Qam	West side of Mill Creek Canyon lowermost conspicuous cliff
16	B166B	40°24.64'	121°30.50'	Qam	East side of Mill Canyon
17	C0436	40°24.45'	121°30.77'	Qam	West side of Mill Canyon
18	M873	40°24.47'	121°30.45'	Qam	East side of Mill Canyon
19	C0436B	40°24.45'	121°30.80'	Qam	West side of Mill Canyon
20	F58	40°25.10'	121°30.15'	Qam	East side of Mill Canyon

APPENDIX 1. SAMPLE LOCALITIES FOR TABLE 2--Continued

Analysis number	Sample number	Latitude North	Longitude West	Unit	Locality Description
21	M876	40°21.60'	121°30.50'	Qam	East side of Mill Canyon
22	M875	40°24.20'	121°30.30'	Qam	East side of Mill Canyon
23	M830	40°25.10'	121°30.65'	Qam	East side of Mill Canyon
24	F57	40°25.15'	121°30.18'	Qam	East side of Mill Canyon
25	F59	40°24.50'	121°29.50'	Qam	Above Hanna Falls
26	F56	40°25.20'	121°30.20'	Qam	East side of Mill Canyon
27	F55	40°25.25'	121°30.20'	Qam	East side of Mill Canyon
28	B172	40°23.97'	121°29.65'	Qam	Hanna Falls
29	F60	40°24.45'	121°29.60'	Qam	Hanna Falls
30	C0372	40°27.88'	121°41.47'	Qaoc	Onion Creek
31	C1775	40°27.43'	121°40.57'	Qars	At Rock Spring
32	C0409	40°27.75'	121°34.92'	Qabc	South wall Bailey Creek
33	C0178	40°26.00'	121°35.53'	Qaht	South of Heart Lake
34	C0410	40°27.68'	121°34.88'	Qaht	South wall Bailey Creek
35	C0451A	40°28.43'	121°33.57'	Qabl	South wall Blue Lake Canyon
36	B210	40°25.48'	121°28.35'	Qarc	North of Rhodes Meadow
37	B138B	40°27.65'	121°26.80'	Qarc	West of Kings Creek Falls
38	B316	40°25.98'	121°26.95'	Qarc	Panther Crêek
39	B354	40°27.60'	121°26.35'	Qarc	Near Kings Creek Falls
40	B138A	40°27.65'	121°26.80'	Qarc	West of Kings Creek Falls

APPENDIX 1. SAMPLE LOCALITIES FOR TABLE 2--Continued

Analysis number	Sample number	Latitude North	Longitude West	Unit	Locality Description
41	B8042	40°24.25'	121°28.50'	Qarc	NE of Elizabeth Lake
42	B142	40°25.93'	121°27.65'	Qarc	East of Twin Meadows
43	B239B	40°26.85'	121°25.43'	Qarc	NE of Devils Kitchen
44	F2A	Averaged Analysis		Qdtm	Southern flank Brokeoff Mountain
45	C0485	40°25.88'	121°33.53'	Qdtm	Ridge projecting south from summit Brokeoff Mountain
46	C0498	40°26.98'	121°34.48'	Qdtm	West of Brokeoff Mountain, east of Hill 8198
47	C0446	40°28.67'	121°33.18'	Qdtm	NW of Blue Lake
48	C0123	40°24.87'	121°31.92'	Qabf	Bluff Falls Quarry
49	F16A	Averaged Analysis		Qabf	Southern flank Brokeoff Mountain
50	F40A	Averaged Analysis		Qagm	Southern flank Brokeoff Mountain
51	F3A	Averaged Analysis		Qagm	Southern flank Brokeoff Mountain
52	F37A	Averaged Analysis		Qagm	Southern flank Brokeoff Mountain
53	C1835	40°28.65'	121°37.95'	Qadc	USFS road 17 NW of Red Rock Mountain
54	C0475	40°26.73'	121°37.98'	Qadc	USFS road 17 SW of Red Rock Mountain
55	C0527	40°26.98'	121°34.78'	Qadc	Hill 8198 west of Brokeoff Mountain
56	C1675	40°32.02'	121°35.38'	Qamd	West of Manzanita Lake
57	C1678	40°27.90'	121°30.78'	Qamd	LVNP Road near Bumpass Hell trail head
58	B128	40°27.38'	121°29.15'	Qamd	West of Cold Boiling Lake
59	B326	40°28.10'	121°31.90'	Qamd	Summit Pilot Pinnacle
60	F7A	Averaged Analysis		Qamd	Summit and ridge projecting west of Mt. Diller

APPENDIX 1. SAMPLE LOCALITIES FOR TABLE 2--Continued

Analysis number	Sample number	Latitude North	Longitude West	Unit	Locality Description
61	F1	40°26.75'	121°33.50'	Qamd	Summit of Brokeoff Mountain
62	M855	40°25.20'	121°29.75'	Qrl	SE ridge of Mt. Conard
63	M899	40°25.85'	121°30.60'	Qrl	Cliff west side of Mt. Conard
64	M901	40°26.10'	121°30.00'	Qrl	North side of Mt. Conard
65	C1694	40°28.70'	121°28.28'	Qrl	South of Terrace Lake
66	C1811	40°28.23'	121°29.48'	Qrl	LVNP Road west of Reading Peak
67	DL14	40°29.30'	121°31.80'	Qrl	Crescent Cliff
68	F101	40°30.58'	121°27.70'	Qrl	LVNP Road at Badger Flat turnoff
69	DL1	40°30.65'	121°27.70'	Qrl	LVNP Road at west fork of Hat Creek
70	DB70	40°30.30'	121°32.70'	Qrl	Cliff on SE side of Loomis Peak
71	C0534	40°30.58'	121°24.65'	Qrm	NW of summit of Hill 7263'
72	C1629	40°26.18'	121°21.52'	Qrbp	Flatiron Ridge north of Kelly Camp
73	C1706	40°28.70'	121°26.97'	Arbp	Reading Peak east of Cliff Lake
74	C1810	40°27.88'	121°30.28'	Qrbp	Bumpass Mountain LVNP Road at Lake Helen
75	B331	40°27.63'	121°27.60'	Qrbp	LVNP Road just west of Kings Creek Falls Trailhead
76	B9125	40°27.75'	121°30.20'	Qrbp	LVNP Road just south of Lassen Peak Trailhead
77	B9072	40°28.18'	121°31.05'	Qrbp	Ski Hill Peak just north of Emerald Lake
78	F90A	Averaged Analysis		Qrbp	Vulcans Castle
79	C1733	40°30.22'	121°30.02'	Qrla	Unnamed dome NW of Lassen Peak
80	C1660	40°33.40'	121°31.77'	Qrla	Sunflower Flat

APPENDIX 1. SAMPLE LOCALITIES FOR TABLE 2--Continued

Analysis number	Sample number	Latitude North	Longitude West	Unit	Locality Description
81	C1736	40°30.72'	121°29.92'	Qrla	NW side Crescent Crater
82	C1731	40°29.76'	121°28.98'	Qrla	Just east of Devastated Area
83	C1734	40°30.75'	121°30.78'	Qrla	Chaos Crags Dome 1 of Crandell and others (1974)
84	F85	40°31.90'	121°31.85'	Qrla	Chaos Crags Dome 2 of Crandell and others (1974)
85	F84	40°32.10'	121°30.85'	Qrla	Chaos Crags Dome 3 of Crandell and others (1974)
86	C1661	40°32.55'	121°32.32'	Qrla	Chaos Crags Dome 2 of Crandell and others (1974)
87	C0391	40°29.85'	121°36.52'	Qar	North side North Fork Bailey Creek 2.85 km west of Onion Springs
88	C1710	40°28.32'	121°24.35'	Qatl	North of Corral Meadow
89	F122A	Averaged Analysis		Qatl	East of Summit Lake
90	C1753	40°28.65'	121°20.17'	Qatl	Crater Butte, northshore of Horseshoe Lake
91	DB349	Not Reported		Qatl	Lava flow from vent between East & West Prospect Peaks
92	SC17	Not Reported		Qatl	Cinder Cone pre-1851 flow
93	SC15	Not Reported		Qatl	Cinder Cone 1851 flow
94	C1840	40°29.35'	121°30.25'	Qatl	1915 flow, summit of Lassen Peak
95	C0379	40°27.93'	121°41.07'	Qrrt	Onion Creek
96	F19A	Averaged Analysis		Qahb	Southern flank Brokeoff Mountain, north of Huckleberry Lake
97	F136	Not Reported		Qahb	South wall of Cliff above Summit Creek T29N, R4E, Sec 21
98	C0451B	40°28.53'	121°33.63'	None	Gabbroic inclusion from Andesite of Blue Lake Canyon

APPENDIX 2. LOCATION OF SAMPLES IN TABLE 5

Analysis number	Sample number	Latitude North	Longitude West	Unit	Locality Description
1	CO402	40°27.75'	121°13.82'	Qbe	Caribou Wilderness
2	DB492	40°30.6'	121°12.9'	Qbe	Caribou Wilderness
3	DB493	40°30.7'	121°12.3'	Qbe	Caribou Wilderness
4	B9055	40°27.25'	121°17.55'	Qbe	Caribou Wilderness
5	DL6	40°27.2'	121°17.7'	Qbe	Caribou Wilderness
6	DL7	40°25.4'	121°16.5'	Qbe	Caribou Wilderness
7	C1646	40°23.68'	121°23.80'	Qbs	Sifford Mountain
8	C1649	40°21.45'	121°21.42'	Qbs	Sifford Mountain
9	C1720	40°26.20'	121°22.48'	Qbs	Sifford Mountain
10	MO910	40°24.10'	121°23.58'	Qbs	Sifford Mountain
11	MO913	40°23.55'	121°23.80'	Qbs	Sifford Mountain
12	B7171	40°26.30'	121°23.18'	Qbs	Sifford Mountain
13	B313	40°24.85'	121°26.05'	Qbs	Sifford Mountain
14	CO374	40°28.20'	121°41.52'	Qarl	Red Lake Mountain
15	C1828	40°32.45'	121°36.25'	Qarl	Red Lake Mountain
16	DB1	40°30.65'	121°27.7'	Qarl	Red Lake Mountain
17	SC14	not reported		Qarl	Red Lake Mountain
18	F127A	Averaged Analysis		Qbp	Prospect Peak
19	C1741	40°26.18'	121°18.12'	Qbh	Mt. Harkness
20	MO814	40°22.51'	121°26.21'	Qasb	Small Butte
21	CO537	40°21.02'	121°37.67'	Qbcc	Cold Creek Butte
22	CO401	40°30.10'	121°34.13'	Qbl	near Loomis Peak