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THE LAVAS OF THE MODOC LAVA-BED QUADRANGLE, CALIFORNIA

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ABSTRACT

The Modoc Lava-Bed quadrangle includes an area in which is seen the transition from the Cascade Mountain province to the Great Basin plateau province, with mountains of volcanic accumulation (dissected and undissected) characteristic of the former, and fault-block mountains and high plateaus, typical of the latter.

The oldest volcanic rocks, the Cedarville andesite of Miocene age, are a series of pyroclastic formations, with a few interbedded flows, chiefly andesitic. After warping and the development of fault blocks, renewed volcanic activity built several volcanic cones from massive lava flows, chiefly andesitic, called the Massive Lava Group. These eruptions are correlated with the major Cascade activity of Pliocene age.

Lake beds (Lacustrine group) and widespread flows of olivine basalt (Warner basalt) were deposited in the grabens In late Pleistocene time, the lavas of the Platy Andesite Group were erupted from a number of vents located on a fracture zone which encircled the top of one of the Pliocene volcanoes New fault-grabens were formed and further lacustrine deposition took place. In post-Glacial time the Modoc basalts were erupted from a number of parasitic vents on the north and south flanks of the Medicine Lake Highland, the last flow is probably less than 500 years old. During this basaltic activity, several small eruptions of dacite and rhyolite took place on the top of the Medicine Lake Highland; the youngest rhyolite is probably less than 300 years old.

Many of the basalts of the area are abnormally rich in olivine and calcic plagioclase, thus resembling the Porphyritic Central Magma Type of Mull; but they were, in contrast, completely liquid at the time of extrusion.

In attempting to explain the difference in composition between several pairs of associated lavas by fractional crystallization, it was found that the residual liquid after partial crystallization of the less siliceous magma was richer in iron than the more siliceous rock of the pair.

In a partly glassy basalt the pyroxene and iron oxide had not begun to crystallize though over half of the plagioclase had formed crystals. The texture of the basalts suggests that pigeonite is a late-forming mineral in less siliceous basalts which crystallize with ophitic or sub-ophitic texture; and hypersthene and augite are early-forming minerals in more siliceous basalts and andesites which crystallize with intergranular texture.

The abnormally high lime content of the plagioclase phenocrysts of the Lake basalt may be explained with no less difficulty by assuming that the composition

of the liquid surrounding the phenocrysts was changed, than by assuming movement of the crystals from one liquid to another.

Strange globular bodies, found in the vesicular phase of both dacite and rhyolite flows, may represent a liquid fraction, high in volatile constituents, and with the silicate composition approaching Vogt's anchi-eutectic granite, which separated as an immiscible liquid from the dryer lava of the flows.

Contents

Introduction ... 254
Physical Features ... 256
Geology and Petrography ... 257
  General Statement ... 257
  Pre-volcanic Rocks ... 258
  Cedarville Andesite ... 258
  Massive Lava Group ... 259
    Basalt of Bear Mountain ... 260
    Tridymite Dacite of Haight Mountain ... 261
    Andesite of Garner Mountain ... 261
    Basalt near Medicine Lake ... 262
    Rhyolite ... 264
  Lacustrine Beds ... 266
  Warner Basalt ... 266
  Platy Andesite Group ... 269
    Pyroxene Andesite ... 270
    Rhyolite ... 271
    Dacite ... 272
  Modoc Basalt ... 272
  Obsidian Group ... 275
    Dacite ... 276
    Rhyolite ... 278
    Big Glass Mountain Complex ... 280
    Pumice ... 281
Petrology ... 282
  Introduction ... 282
  Basalts ... 282
  Dacite and Rhyolite ... 288

INTRODUCTION

The Modoc Lava-bed quadrangle is located in northern California east of Mount Shasta and north of Lassen Peak (Fig. 1). It has been mapped by the U. S. Geological Survey on a scale of 1/250,000 with a contour interval of 200 feet.

Although several geologists have visited this region, the literature contains very little information about it. J. S. Newberry[1] recorded a few general observations on the eastern part of the

[1] Newberry, J. S., *U. S. Pacific R. R. Expl., 33d Cong. 2d sess., Senate Ex. Doc.* **78,** vol. 13, pt. 6, 1856.

quadrangle. J. S. Diller[2] collected a specimen of obsidian near Medicine Lake which was analysed and described. The area is

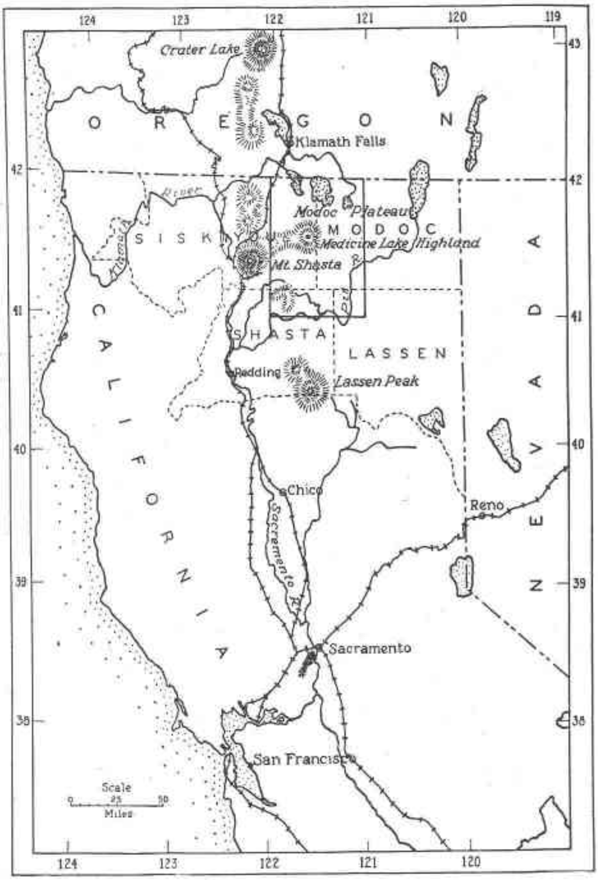

FIG. 1. Map of northern California showing the location of Modoc Lava-bed Quadrangle.

mapped on the geological map of California by J. P. Smith[3] but apparently from vague data. I. C. Russell[4] and G. A. Waring[5] in-

[2] Diller, J. S., *U. S. Geol. Survey Bull.* **148,** p. 228, 1897.

[3] Smith, J. P., *Calif. St. Min. Bur. Bull.* **72,** 1916.

[4] Russell, I. C., *U. S. Geol. Survey Bull.* **199,** 1902. *U. S. Geol. Survey Bull.* **217,** 1903. *U. S. Geol. Survey Bull.* **252,** 1905.

[5] Waring, G. A., *U. S. Geol. Survey, W. S. Paper* **220,** 1908. *U. S. Geol. Survey, W. S. Paper* **231,** 1909.

clude the area in generalized statements about the extent of the plateau basalts of the Pacific northwest. R. J. Russell[6] refers to the Recent lava flows of the Modoc country in his study of the Warner Range of northern California.

A study of the volcanic rocks of this area was sponsored by the Department of Mineralogy and Petrography of Harvard University. Dr. M. A. Peacock and the writer were sent into the field in the summer of 1927. Dr. Peacock's expenses were provided by his Commonwealth Fellowship and those of the writer were paid by Harvard University. During a two month's exploration the party prepared a reconnaissance geologic map using the Modoc Lava-bed quadrangle of the U. S. Geological Survey (scale 1/250,000) as a base and collected a large suite of rock specimens. In the fall of 1928, Dr. E. S. Larsen, Jr., of Harvard University, and the writer had the opportunity to check some of the earlier field observations during a three day trip through the area. The suite of rock specimens was studied by the writer in the Harvard Laboratories during the school years 1927–28 and 1928–29. A report of the study was accepted as a Doctor's dissertation by Harvard University in 1929. A general description of the area by M. A. Peacock was published in The Geographical Review, April 1931. The present report gives the geology and petrology of the lavas.

The writer wishes to express his appreciation to a number of persons for assistance in this work: Professor Charles Palache and Professor E. S. Larsen, Jr., constantly sponsored the entire study; Dr. E. S. Shepherd contributed five chemical analyses of rocks and offered many valuable suggestions; Professor R. A. Daly, Professor Kirk Bryan, Dr. C. S. Ross, and Dr. J. W. Greig were generous with helpful suggestions and criticisms.

PHYSICAL FEATURES

A volcanic highland, called here the "Medicine Lake Highland," is a prominent feature in the approximate center of the Modoc Lava-bed Quadrangle. Its highest point, Mt. Hoffman, is 8,018 feet above sea level. To the west, a series of volcanic peaks links this highland with the base of Mount Shasta. Another group of peaks lies to the southwest, with Grizzly Peak (elevation 6,804 feet)[7] its highest member. At the southern base of Grizzly Peak, the

[6] Russell, R. J., *Univ. of Calif. Publ. in Geol.* **17,** pp. 387–496, 1928.

[7] These elevations from the reconnaissance survey of 1884–5 will probably be changed by the later surveys of the U. S. Forest Service.

Pit River has cut its canyon to an elevation of about 1,500 feet to give the maximum relief in the quadrangle. The physical features of this southwestern quarter of the area are typical of the Cascade Province. All of the peaks, with the exception of the Medicine Lake Highland, have rugged outlines produced by local Pleistocene glaciation and stream erosion. Medicine Lake Highland is a group of volcanic peaks which retain their original constructional slopes. These uneroded cones, however, are a superstructure on a volcanic dome which had been somewhat dissected previous to their eruption. The basalts of the Modoc Lava-beds form the northern and southern slopes of the Highland. In the northern and eastern parts of the quadrangle are a number of isolated peaks or groups of peaks which are dissected fault-blocks. Between them is a vast, undissected plateau ranging in elevation from 4,000 to 5,000 feet underlain by nearly horizontal basalt flows and lacustrine sediments. Here and there the plain is broken by cones of basaltic slag and by fault-scarps of Recent age.[8] The plateau and fault-block area is physiographically like the Great Basin Province.

The study of the geology of the area was facilitated by the consistent relation between geology and topography in the field. The dissected fault-blocks are made up of bedded pyroclastic material with minor amounts of intruded and erupted lava, the Cedarville andesite. The other mountains in the area are made up of lava flows piled up around central vents. The extensive plateau is made up of widespread flows of basalt and a series of lacustrine sediments deposited both above and below the basalt horizon. These basalts have a wide distribution in northern California and Oregon and have been named the Warner basalt.

GEOLOGY AND PETROLOGY

General Statement

Except for a small outcrop of older sandstone that crops out from beneath the volcanic rocks in the valley of Nelson Creek in the southwestern part of the quadrangle, all of the rocks of the area are Tertiary and Quaternary volcanic rocks and associated lacus-

[8] The direction and location of the zones of Recent faults are shown on the reconnaissance geological map in solid lines; the zones of older faults in broken lines. No attempt was made to plot accurately each individual fault.

trine deposits. In Miocene time the earliest eruptions spread lava flows, and pyroclastic material, chiefly of andesitic composition, over a large area, and formed the Cedarville andesite. In the Pliocene renewed eruptions of andesites with some of basalt and rhyolite, from a number of separate vents, yielded the rocks of the massive lava group.

Fault blocks were formed chiefly displacing the Cedarville andesite and in the resulting lowlands in Pliocene or early Pleistocene time lacustrine beds and flows of basalt (Warner basalt) were spread. Beginning in late Pleistocene time and continuing to within a few hundred years of the present time, local eruptions took place from centers in the Medicine Lake Highland. These eruptions are from the earliest to the latest, the platy andesite, the Modoc basalt and cinder cones, and a number of eruptions from several centers of obsidian and pumice (Obsidian Group).

In quaternary time the Medicine Lake Highland was occupied by local glaciers.

Pre-volcanic Rocks

A bed of sandstone crops out beneath the volcanic series in the valley of Nelson Creek about a mile above its junction with the Pit River near the southwestern corner of the quadrangle. The rock is a coarse-grained, feldspathic, micaceous sandstone which shows no bedding and yielded no fossils. It must have been derived from granodiorite bodies exposed in some of the nearby mountains. The formation probably is a terrestrial deposit of early Tertiary age.

No other pre-volcanic rocks are exposed in the quadrangle, but the area is probably underlain by a basement of Jurassic metamorphics, Chico marine sediments, and early Tertiary terrestrial sediments comparable to the series described by Diller from the Pit River valley just south of the area.[9]

Cedarville Andesites

The oldest series of volcanic rocks of the area was recognized in the field by the abundance of pyroclastic material, tilted and warped structure, and the gentle slopes eroded on its non-resistant pyroclastic members. The series shows great range in lithology:

[9] Diller, J. S., *Bull. Geol. Soc. of Am.*, **4**, pp. 205–224, 1893. *U. S. Geol. Survey Geol. Atlas, Folio*, **15**, 1895.

RECONNAISSANCE GEOLOGICAL MAP
OF THE
MODOC LAVA-BED QUADRANGLE
CALIFORNIA

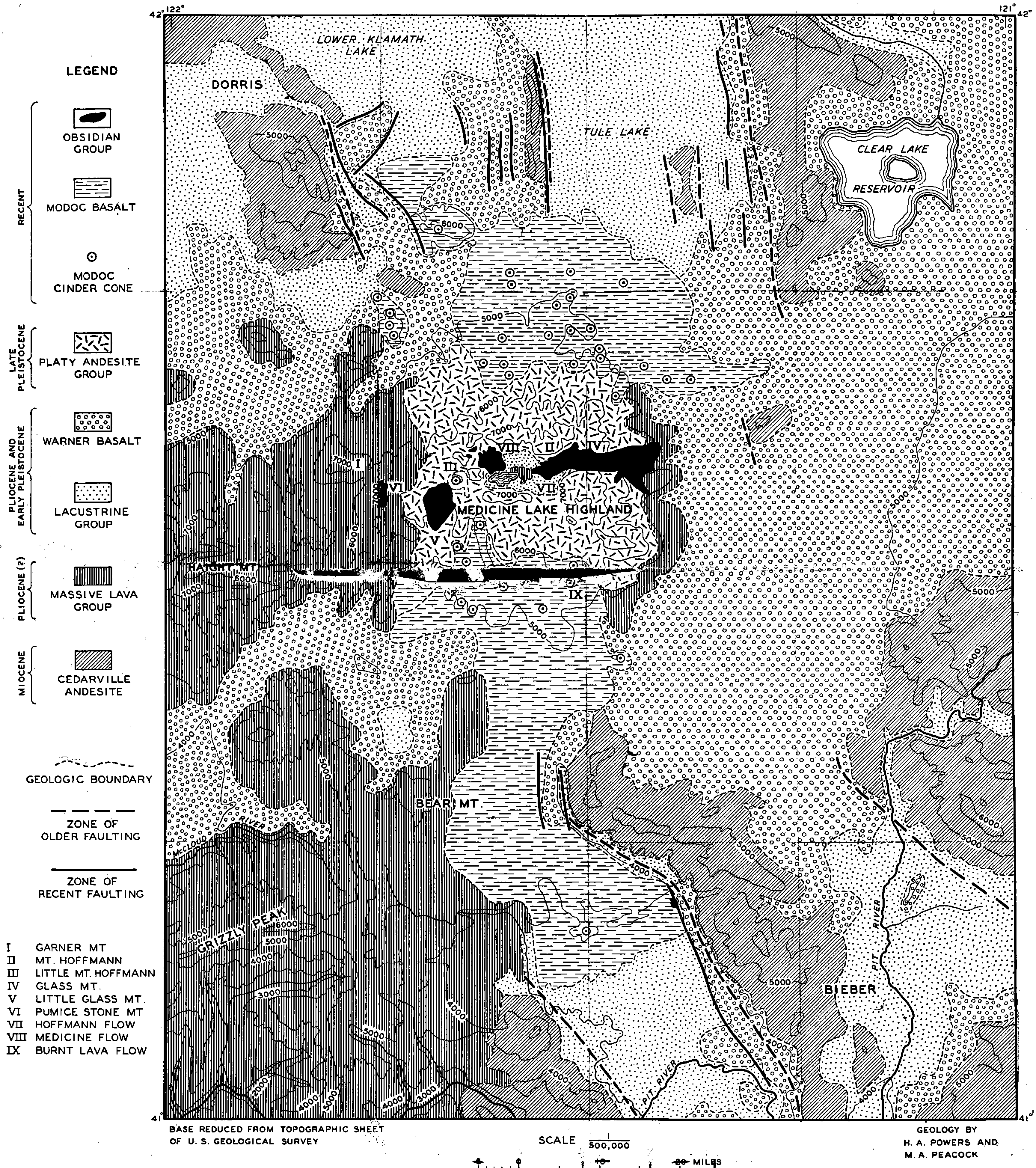

PLATE I. Geological reconnaissance map of Modoc Lava-Bed Quadrangle. Base map is U. S. Geol. Survey Modoc Lava-Bed Quadrangle. Geology by H. A. Powers and M. A. Peacock.

basaltic flows, intrusives, and pyroclastics; andesitic flows and pyroclastics; and rhyolitic intrusives and pyroclastics. It may be correlated with the Cedarville Andesites of Miocene age in the Warner Mountains.[10] Whether it represents both the Upper and Lower Cedarville or only one of them is not known. The flows and intrusives of basalt form cap rocks or resistant ledges and thus appear more abundant than they actually are. The basalt is typically dark gray to black and has a fine-grained, compact texture. Most of the specimens collected have the ophitic or intersertal texture common to the typical plateau basalt.[11] They are notable for the presence of chlorophaeite which is not found in the younger basalts of the area. A specimen of the basalt chosen for analysis—Table I, column 19141—contains pyroxene, olivine and labradorite in ophitic texture and a trace of chlorophaeite. A few of the basalts show an intergranular texture in which the pyroxene occurs in subhedral grains interstitial to the plagioclase tablets.

Andesitic members are most abundant in the series, and of these the pyroclastic rocks predominate. The lava specimens collected are all pyroxene andesites with both hypersthene and augite as phenocrysts. Fragments of hornblende andesite are found in detrital material.

Rhyolites are represented chiefly by beds of pumice-tuff. Fragments of pumice three to four inches in diameter are included in a matrix of smaller fragments of the same material. One dike of compact, reddish felsite was found which shows a brecciated border zone cemented by colorless to white opal. Local rumors of gold-bearing quartz veins may have originated in the discovery of some similar opalized dike.

Massive Lava Group

Following the Cedarville Andesite a group of massive basalts, andesites, and rhyolites were extruded from several vents. These rocks are readily distinguished by certain field characteristics. Their original flow surfaces have been removed by severe erosion. In the higher mountain peaks, the rock is exposed in rugged crags and barren rock-slopes. The flows are thick and massive with no

[10] Russell, R. J., Basin Range Structure and Stratigraphy of the Warner Range, Northeastern California: *Univ. of Calif. Publ. in Geol.*, **17**, pp. 402–416, 1928.

[11] Washington, H. S., Deccan traps and other plateau basalts: *Bull. Geol. Soc. of Am.*, **33**, pp. 765–804, 1922.

platy or columnar jointing. On the lower slopes, most of the lava is covered by residual and washed soil and the few outcrops are small and uninstructive. Pyroclastic members were not seen. The name Massive Lava Group is proposed for them from their massive character.

The exact geologic age of these lavas can not be determined. Severe glaciation of their outcrops shows that they are older than the Pleistocene. On the other hand, they do not seem to have been warped and faulted by the movements which modified the members of the Cedarville andesite. This would place them chronologically above the Miocene tuffs and below the glaciated surface. Probably their eruption was coincident with the major Pliocene activity which was widespread throughout the Cascade region.

The group is made up of several lithological types which occur in different parts of the area as follows:

Basalt of Bear Mountain, an even-grained olivine basalt.

Tridymite dacite of Haight Mountain, a hornblende-bearing hypersthene-tridymite dacite.

Andesite of Garnet Mountain, a hypersthene-augite andesite.

Basalt near Medicine Lake, a porphyritic olivine basalt.

Rhyolite.

Basalt of Bear Mountain. The olivine basalt of the Bear Mountain area is buried almost completely beneath a red, residual soil which supports a heavy growth of pine timber. The few outcrops consist of small exposures of massive rock which weathers into huge rounded bowlders. Neither good columnar jointing nor marked flow-structure is apparent. The relation of the Bear Mountain rock to the lavas of the Grizzly Peak highlands is obscured in the soil-covered slopes of the McCloud and Bear Creek valleys. The contact of the basalt with the older Fort Mountain horst of Cedarville andesite also is located in a soil-covered lowland with no physiographic feature nor outcrop to indicate the relation of the two formations. On the northern and eastern sides, the basalt of Bear Mountain is covered by the Warner basalt. The two rocks are lithologically similar, but the basalts of the plateau show columnar jointing, vesicular surface phases, and a poor soil cover.

In hand-specimen, the Bear Mountain basalt is a light gray, loose-textured, uniform-grained rock, in which clear, yellow olivine grains are conspicuous in the network of colorless plagioclase crystals. In thin section, the type specimen is holocrystalline and contains about 60 per cent of plagioclase, 20 per cent of augite, 17 per cent of olivine, and 3 per cent of opaque ore. In texture and composition of minerals, the rock is similar to the Warner basalt.

An analysis of this rock is given in Table I, column 19071. It is almost a counterpart of the analyses of the basalts from the Cedarville andesite and the Warner basalt.

Tridymite Dacite of Haight Mountain. The only specimen of hornblende-bearing lava from the Massive Lava Group was collected from Haight Mountain. This peak is one of the highest in the area, and has been eroded most severely. It was dissected on the northeast side by a small alpine glacier and subsequently modified by normal stream erosion.

The rock is a light-colored porphyry in which dark-green prisms of hornblende and a few transparent plagioclase phenocrysts are conspicuous against a light, aphanitic ground mass. The hornblende phenocrysts make up four or five per cent of the rock. The phenocrysts are well-developed prismatic crystals of common hornblende, pleochroic in shades of green. Every individual is characterized by a thin reaction rim consisting mainly of magnetite dust and a small number of minute grains of monoclinic pyroxene. This reaction rim around intratelluric hornblende crystals is a common phenomenon in eruptive rocks. In many cases, as in the rock being described, the amount of reaction has been so slight that the form of the original crystal has not been destroyed. It is probably true that hornblende forms only if pressure on the system is sufficient to keep a considerable quantity of water in solution in the magma. If this amount of water is not held in solution, the hornblende becomes unstable and reacts with the magma. It is suggested that the common narrow reaction rim on intratelluric hornblende crystals is developed during the interval between the sudden loss of pressure in a magma system incident to the first breaking through to the surface and the final consolidation of the magma after its eruption as surface flows.

In addition to the hornblende, a few slightly-zoned, twinned, euhedral crystals of labradorite are present as phenocrysts. The ground mass is an intergranular growth of plagioclase tablets and hypersthene prisms with interstitial tridymite. The tridymite makes up about 20 per cent of the rock.

Andesite of Garner Mountain. The group of mountains west of the Medicine Lake Highland, of which Garner Mountain is the outstanding peak, was not studied in detail, but specimens taken from a number of scattered outcrops all proved to be closely related varieties of pyroxene andesite. Along the base of the steeper slopes, this andesite is covered by the later Plateau basalts. The contact of the Garner Mountain Andesite and the rock of Haight Mountain is located in the valleys of Antelope and Trout creeks and is obscured by a soil mantle.

In hand-specimen the rock is a dark-colored, fine-grained porphyry in which the glassy plagioclase phenocrysts are the only easily determined component. In thin-section the plagioclase phenocrysts make up about 30 per cent of the type specimen. They are notably twinned, show a number of recurrent zones, often include blebs of groundmass material, and have not been resorbed to any great extent. They range from one to five millimeters in the greatest dimension. The prismatic pyroxene phenocrysts, usually less than two millimeters long, make up about two per cent of the rock. About a third of these are augite and two thirds, hypersthene. The groundmass is an intersertal assemblage of small tablets of plagioclase (about 50 per cent), elongated prisms of hypersthene (about 15 per cent), irregular grains of opaque ore, and interstitial brown glass (about 30 per cent).

A chemical analysis of this rock is given in Table I, column 19145. The feldspar content is somewhat higher than that of the average Cascade andesite with similar silica percentage.

Basalt near Medicine Lake. The type locality for the "Lake" basalt is the eastern floor of the Medicine Lake basin where it crops out in low, glaciated mounds which protrude through a mantle of pumice and lake gravel covering the basin floor. The rock is also exposed in ledges which form the steep eastern shore of the lake. These outcrops consist of massive blocks of lava which apparently have been disarranged by ice-movement and give no clue as to the attitude of the lava flow.

This type area of the Lake basalt is completely surrounded by cinder cones and flows of younger platy andesite which form the rim of the lake basin and most of the upper slopes of the Medicine Lake Highland. On the northern and eastern slopes of the Highland, between the lower edges of the platy andesite flows and the younger basalts of the plateau, the Lake basalt is exposed in a number of scattered outcrops, of which some are small islands completely surrounded by the Warner basalt. The evidence is clear that both the Warner basalt and the platy andesite were poured out on a surface which had been eroded in the Lake basalt.

From this distribution of outcrops and relation of formations, it is concluded that the early eruptions of Lake basalt piled up a broad volcanic dome. On top of this partly eroded dome, the superstructure of platy andesite cones was built, and the base of the resulting highland was buried beneath the flood of basalt which formed the plateau.

In hand-specimen, the type Lake basalt is a porphyry in which tabular crystals of glassy plagioclase, making up from 20 to 30 per cent of the bulk, stand out as phenocrysts in a loose-textured, light gray groundmass. Some of the plagioclase individuals are as much as 10 millimeters in length. A few scattered crystals of clear, yellow olivine are also visible as phenocrysts and form one per cent of the rock.

In thin-section, the plagioclase phenocrysts show a large central part (about eight-tenths of the volume of the average crystal) which has a uniform composition of ab15-an85. This slightly zoned core is surrounded by a narrow band of material which shows two significant zones (see Plate IIa). From the sharp break at the edge of the core, the anorthite content (indicated by extinction angle) decreases uniformly for a short distance. Then there is a distinct break in the gradation caused by a slight but abrupt drop in anorthite content. From this break, the plagioclase again gradually becomes poorer in anorthite to the outer edge of the phenocryst. The width of this zoned band seems to be about constant, regardless of the size of the central core. A few crystals which do not show the zoned border have irregular surfaces due to resorbtion. Most of them are so poorly twinned that it is impossible to compare accurately their composition with that of the crystals which do not show resorbtion. The last addition to the phenocrysts has about the same composition as the small plagioclase crystals in the groundmass, which are calcic andesine. The phenocrysts include an occasional grain of opaque ore, and some of them include small blebs of micro-aphanitic material which probably represents small amounts of magma trapped during the growth of the phenocrysts. These blebs are usually oriented along some crystallographic direction. A few long prisms of apatite are scattered through the plagioclase with no regard for crystallographic orientation. This lack of control suggests that the apatite formed after the crystallization of the plagioclase host.

The olivine phenocrysts are well-formed crystals about one millimeter in diameter which show no evidence of resorbtion but there is a suggestion of slight zoning on the edges of some of the crystals.

The optical constants give a composition of fay 23-for77 for the olivine.

The holocrystalline groundmass is an intergranular arrangement of tabular plagioclase, granular olivine, and prismatic pyroxene crystals, with about six per cent of opaque ore disseminated through the mass. The plagioclase crystals are slightly zoned, showing a constant decrease in anorthite from the center outward. Albitic twinning is prevalent, and extinction angles on the twins indicate an average composition of about an45. The olivine in the ground mass, about four per cent of the rock, occurs in small equant grains occupying spaces in the mesh of tabular plagioclase. Its composition is fay33-for67, 10 per cent more fayalite than is contained in the phenocrysts. The pyroxene makes up about 12 per cent of the rock, and is interstitial to the feldspar in grains so small that accurate determination of optical constants is impossible.

Two chemical analyses of the type specimen are given in Table I, columns 19144. The two chips which were analysed contained slightly different amounts of the plagioclase phenocrysts. Thus the two chemical analyses differ by amounts appropriate to this difference in mineralogical composition. The rock is extremely rich in the anorthite molecule, much of which, of course, is present in the plagioclase phenocrysts.

Rhyolite. Two rhyolitic flows were found in the Medicine Lake Highland which belong to the Massive Lava Group. One of them crops out in two small areas on the Davis Road about nine miles south of Pumice Stone Mountain, and the other is crossed by the road to Klamath Falls about 10 miles north of Medicine Lake. The northern flow was poured out on a slope which was comparable to the present northern slope of the Highland. The distribution of outcrops of the southern flow indicates that it also probably consolidated on a surface which sloped away from the present center of the Highland. The attitude of these two flows adds more evidence for the existence of a dome of Medicine Lake basalt as the foundation of the Medicine Lake Highland.

The rock forming the southern flow is an homogeneous black obsidian, occasionally banded with very fine layers of a lighter colored glass, and contains a few small, globular spherulites. The glass contains a few scattered acicular crystallites of feldspar, too small for determination, and a number of minute, lens-shaped bubble-holes. The feldspar crystallites and the bubble-holes are oriented

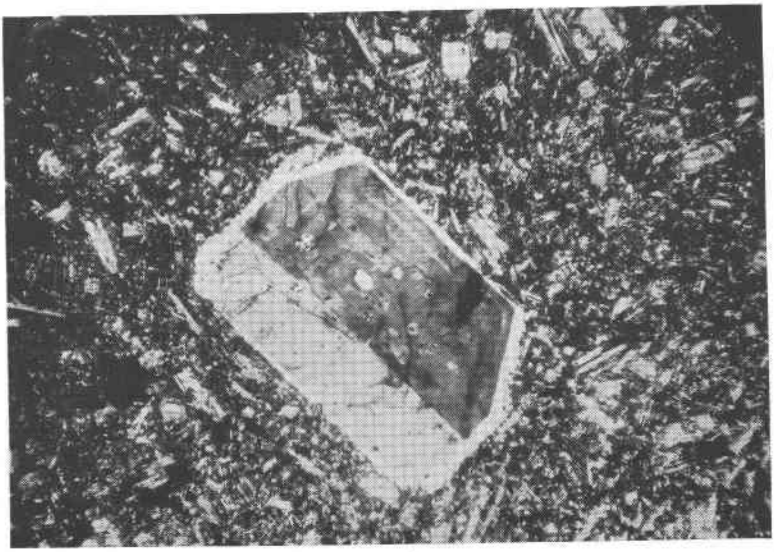

PLATE IIa. Photomicrograph, (x115) with crossed nicols, of a plagioclase phenocryst in the basalt of the Massive Lava Group near Medicine Lake, showing the large core of slightly zoned, calcic feldspar, and the narrow shell of highly zoned, more sodic feldspar.

PLATE IIb. Section in a platy andesite flow northwest of Medicine Lake showing the slightly glaciated surface, the vesicular upper phase about eight feet thick, and the inner platy phase of the flow. This exposure is a small Recent fault-scarp.

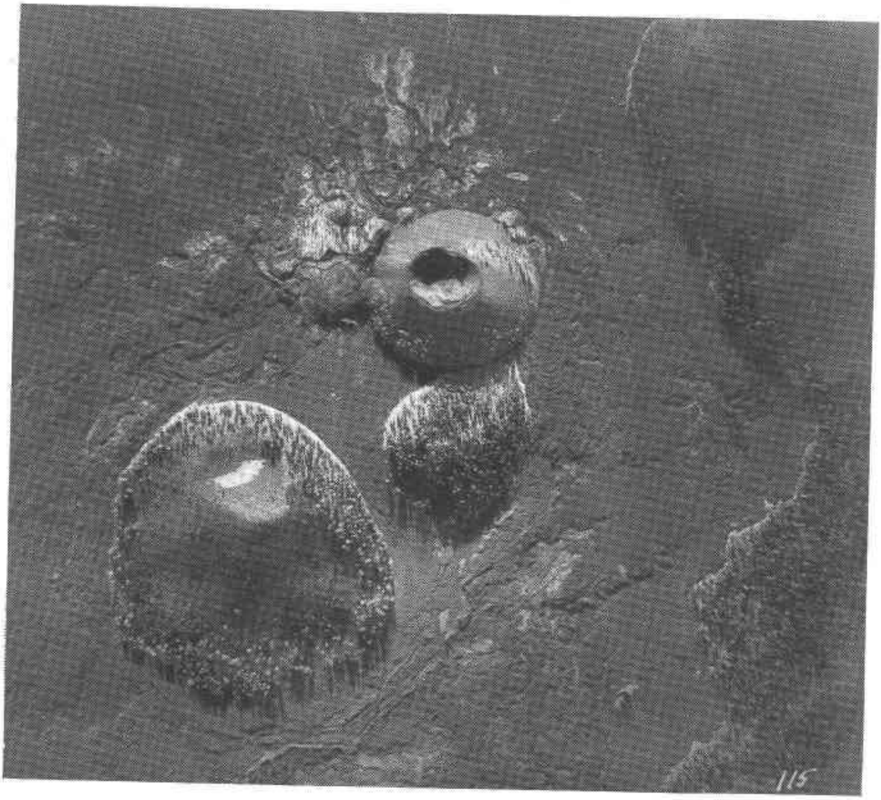

PLATE III. Aerial view of the recent cinder cone and the basaltic lava of Burnt Lava Flow southeast of Medicine Lake. The crater in the cone is about 80 feet deep. The lava has spread out in a comparatively smooth sheet surrounding the two older cinder cones. Photo, Brubaker Aerial Surveys, Portland, Oregon.

parallel to flow-bands which are made up of streaks of crystallites and an occasional crystal of oligoclase about .01 millimeter in length. The smaller crystallites form lines which bend around the few larger crystals. The flow-bands themselves are contorted. The growth of the crystallites must have taken place during the last stages of movement in the flow when viscosity was high enough to permit the preservation of the folded and contorted structures. The localization of a large part of the crystallization to these fine streaks was probably influenced by a local concentration of mineralizers. The index of refraction of the glass for sodium light is $1.4905 \pm .0005$ and its specific gravity is $2.36 \pm .01$. The chemical composition of the type specimen is given in Table I, column 19007.

The northern flow is composed of two textural varieties, a homogeneous glass and a finely-banded crystalline lithoidite. The glass forms the bottom of the flow and is several feet in thickness, though the upper and lower contacts of the glass were not visible. It is a stony-looking obsidian, with typical conchoidal fracture but a decidedly dull luster. Thin edges are semi-translucent and show a deep brown color. The rock is perfectly homogeneous and shows neither flow-structure nor spherulites. Microscopically it consists of a felt-like network of crystallites embedded in pure glass. A little opaque dust, probably magnetite, and an occasional minute prism of some indeterminable pyroxene are disseminated through the glass. The crystallites make up about 30 per cent of the rock, and interfere with an accurate determination of the refractive index. It was determined in white light to be $1.498 \pm .001$ and the specific gravity is $2.44 \pm .01$. The chemical composition is given in Table I, column 19044.

The crystalline facies is composed of thin bands of reddish, porous material alternating with dense, dark gray layers which have a glassy appearance. In thin-sections, the dense layers are composed of a felted mass of minute feldspar laths, including a few specks of hematite and a light green mineral probably a pyroxene. There is no glass visible. The porous layers are bounded by a narrow zone characterized by a concentration of hematite. They consist of slightly coarser crystals of feldspar and patches of tridymite, dusted with hematite specks. These layers probably represent small areas rich in volatile constituents which were drawn out into bands by movement of the flow. The presence of the volatiles favored the development of tridymite and of the larger feldspar crystals. The texture, while appearing typically rhyolitic in hand-specimen, is seen to be truly trachytic with a complete absence of spherulitic or poikilitic intergrowths of feldspar and silica. A glimpse at the norm of this rock shows the presence of only 25 per cent of normative quartz which is to be expected in a rock with the trachytic texture, since it has been shown that siliceous lavas containing less than 26 per cent of normative quartz are characterized by trachytic texture.[12]

Lacustrine Beds

After extensive block faulting of the Cedarville andesite, a great thickness of lake beds and basalts were deposited in the fault-graben depressions and built up widespread plateaus above which the upper parts of the upthrown blocks rose. The first sediments were deposited in large shallow lakes. They were covered by widespread flows of basalt. Recurrence of faulting[13] then formed a number of small grabens in the basalt surface in which lake beds were formed by deposition which has continued to the present.

The Lacustrine beds are made up chiefly of silt, ash, and diatomaceous earth but include some minor deposits of fluviatile origin. The beds range in thickness from less than an inch to several feet. The sandy or ashy layers are more thinly bedded, while the diatomaceous members often consist of several feet of massive, structureless earth. No attempt was made to study the stratigraphy of the series.

Warner Basalt

Nearly half of the surface of the quadrangle is underlain by these basalts. They may be traced eastward into the Alturas Quadrangle where Russell, calling them the Warner basalt, has described them as the most widespread unit in the area.[14] To the north, much of the surface rock of the Oregon plateau east of the Cascade Range can be correlated with some assurance with the Warner basalt. The writer has travelled over the formation as far north as Bend, Oregon, and the rock is very constant in composition, form of occur-

[12] Powers, H. A., The relation of chemical composition to texture of ground mass in siliceous lavas: *Jour. Geol.*, **37**, pp. 268–71, 1929.

[13] Two periods of faulting have been described also from the area just north of this quadrangle by Johnson and Gilbert:

Johnson, D. W., Block faulting on the Klamath Lake Region; *Jour. Geol.*, **26,** pp. 229–236, 1918.

Gilbert, G. K., Studies in Basin Range Structure; *U. S. Geol. Survey. Prof. Paper* **153,** 1928.

[14] Russell, R. J. *Loc. cit.*, p. 416.

rence, and geological relations. As shown by Russell[15], these are the basalts which have been correlated erroneously by Waring and J. P. Smith with the Miocene basalts of the Columbia River section.

In the Warner Mountain area, Russell found conformity between the Cedarville Series and the Warner basalt, and his greatest period of faulting is later than the Warner basalt.[16] In the Modoc area, however, a major period of faulting followed the eruption of the Cedarville andesite and some erosion occurred before the pouring out of the Warner basalts. This lack of coincidence over a distance as small as 60 miles is in accord with the conception that the Great Basin faulting has reached its maximum development in different areas at different times.

The Warner Basalt is made up of a number of thin flows of basalt with great areal extent. In a fault-scarp west of Tule Lake a vertical section of 130 feet exposes 12 separate flows but does not show the bottom of the formation. The top and bottom flows are each at least 50 feet in thickness, two others are less than two feet thick and the other eight flows are from three to four feet thick. In a number of places where the total thickness of the series is exposed it is less than 50 feet. The formation probably averages a little over 100 feet in thickness.

The flows are almost universally vesicular at top and bottom, the upper vesicles being nearly spherical while the lower ones are usually pipe-like with the length of the pipe making a slight angle from the vertical in the direction of the flow-movement. Most of the flows show well-developed columnar jointing in which a five- or six-inch cross-section is most common. The flows have a pahoehoe type of surface which has been altered slightly by erosion.

The Warner basalt is a light gray, equi-granular loose textural rock with many honey-yellow olivine crystals and irregular grains of a greenish pyroxene disseminated through a feldspar matrix. The rock is remarkably constant in its composition and appearance over the whole area. Some 75 specimens were studied in thin-section and the texture and relative abundance of the various constituents is practically identical in all of them. The type specimen is coarse-grained for a basalt, the constituents having an average diameter of about one millimeter. The plagioclase is in slightly-zoned tablets. Monoclinic pyroxene fills the interstices between the other grains

[15] *ibid.*, p. 417.
[16] Russell, R. J., *Loc. cit.*, p. 422.

and often includes several crystals of plagioclase and olivine poikilitically. It has a purple-brown color in thin-section but is non-pleochroic. It has the following optical properties: $\alpha=1.693$; $\beta=1.701$; $\gamma=1.722$ (all $\pm.003$) $2V=53°$. Using Winchell's diagrams these data indicate a pyroxene with about the following composition: Diopside 40, hedenbergite 45, clinoenstatite 15. About two per cent of opaque ore, probably magnetite, occurs in the pyroxene or along the boundaries between pyroxene and the other constituents. Rare specimens contain a few phenocrysts of calcic plagioclase which show much included groundmass material and no resorbtion nor recurrent zoning, so they probably were formed entirely in place in the flow. The chemical analysis is given in Table I, column 19123.

In the following table the composition of the plagioclase and olivine was determined from optical data, and the approximate composition of the pyroxene was computed from the rock analysis by subtracting the known amounts of plagioclase and olivine. The small amount of normative nephelite does not exist in the rock.

Norm		Mode		Composition Minerals	
Or	0.0				
ab	17.8	plag.	60	ab 33—an 67	
an	40.0				
ne	0.8			$FeSiO_3$	41
di	15.1	px.	15	$MgSiO_3$	17
ol	24.0			$CaSiO_3$	42
il	1.7				
ap	0.3	ol	23	fay 18—for 82	
		opaque	2		

The composition of the olivine and the pyroxene shows that the iron silicate molecule has been concentrated in the late-formed pyroxene. This concentration of iron in the residual liquid during the crystallization of basaltic magma has been discussed recently by Fenner,[17] and the enrichment of late-formed pyroxene in clinoenstatite or clinohypersthene has been emphasized by Barth.[18]

[17] Fenner, C. N. *Am. Jour. Sci.*, (5) **18,** 1929, pp. 225–53. Fenner, C. N. *Min. Mag.*, **22,** pp. 539–560, 1931.

[18] Barth, T. F. W., *Am. Min.*, **16,** pp. 195–208, 1931.

Platy Andesite Group

A group of lava flows with some cinder cones, made up predominately of pyroxene andesite characterized by a well developed platy jointing, and containing two small flows of rhyolite and a minor intrusive of dacite makes up most of the Medicine Lake Highland. The name platy andesite group is proposed for this group. The flows issued from a number of vents grouped around the top of the older volcano. Three recognizable vents are found in the ridge north of Medicine Lake, and four partly destroyed craters exist in the south ridge. The other peaks are more or less isolated cones. The structure of the cones and ridges is partly revealed by slight faulting on their slopes. Within the cones are small lava flows which dip in all directions away from each center of eruption, and the more extensive flows spread out radially from each vent.

These vents were grouped in such a manner on top of the old dome that the overlapping of the bases of the cones completely enclosed a large basin which is now partly occupied by Medicine Lake. On the topographic map, the lake basin with its encircling rim of ridges and cones suggests a partly dissected crater or caldera. The field evidence cited above reveals the error in this impression. However, the crude circular grouping of the platy andesite vents suggests fracturing around the circumference of the old crater, with subsequent minor eruptions along this circle of weakness. The area within this circular fault-zone may have subsided somewhat below its original position, with a tendency toward the formation of a caldera, but it could not have settled far because the old lava forms much of the floor of the lake basin upon which a number of the platy andesite flows were extruded. This subsidence, if any, played no great part in the formation of the present caldera-like topography which is due entirely to the arrangement of the centers of platy andesite eruption.

The original symmetrical shape of the cinder cones has been only slightly altered by erosion. One of the craters in the north ridge has been sufficiently well preserved to contain a small crater lake. The surface exposures of the flows themselves all show striations and ice polish but, in most cases, little more than a glassy surface slag has been removed. In one locality a small cirque has been cut in a flow at an elevation of about 6,600 feet, and several small cliffs have been formed by the plucking action of ice. On the whole, the flows have been modified by much less severe glacial erosion than that which has carved out the rugged surfaces of the Massive Lava volcanoes at similar elevations.

In the chronological column, the Platy Andesite Group is located above the Massive Lava Group and below the Modoc Basalt Group. These relations are clearly established by field evidence. However, no locality was seen which showed the relation between the platy andesite and known Warner basalts. A few contacts of the two formations are shown on the map, but they were either obscured by soil or were located from a distance by topographic extrapolation. The available evidence indicates a Pleistocene age for the Platy andesite group.

Pyroxene Andesite. The most abundant rock of the Platy Andesite Group is the fine-grained pyroxene andesite which occurs in pyroclastic cones and widespread flows. Consolidation of the lava has yielded structures which are peculiar to the flows of this formation. The surface usually shows remnants of a black, highly vesicular, hypo-crystalline phase of unknown original thickness. By a decrease in size and number of vesicles, and an increase in crystallinity, this phase grades into a slightly vesicular, micro-crystalline, dark gray rock which shows no megascopic flow-structure. These two intergrading phases make up a surface layer, often as much as 20 feet thick, which is sharply separated from the main body of the flow. The inner part of each flow crystallized as a light gray, almost lavender, rock, with a very pronounced platy jointing parallel to the average flow-surface (see Plate IIb). The rock breaks along these joint-planes into flat slabs which average about an inch in thickness. In place, the rock has much the appearance of a bedded sediment. In hand-specimen, it is a fine-grained, feldspathic rock which rarely shows a few small phenocrysts of glassy plagioclase.

Microscopically the rock is composed of 65 to 70 per cent of minute tabular crystals (about .2 mm. long) of medium oligoclase arranged in definite trachytic texture and 10 to 15 per cent of minute prismatic crystals of pyroxene desseminated through the spaces between the plagioclase individuals. Most of the pyroxene is monocoinic, probably augite, but some appears to be hypersthene. A small amount of indeterminable crystalline material, probably excess silica and potash feldspar, fills the remaining spaces. In some specimens, especially from flow-surface phases, the interstitial material is glass. Small amounts of opaque oxide are dusted through the slides. One or two of the rocks show a few small grains of olivine, and many of the rocks have an occasional phenocryst of medium andesine or hypersthene. In general, however, the different flows are remarkably uniform in composition and texture.

Cones of red cinders and slag have been built up over the vents. These vesicular phases show essentially the same mineral constituents and texture which characterize the flow-rock. The red color is caused by a cloud of minute flakes of hematite scattered through the rock. In slags which show flow-structure, the hematite is somewhat concentrated in irregular streaks which emphasize the flow-lines. The individual scales of hematite occur indiscriminately in feldspar pyroxene, or interstitial material, often crossing grain-boundaries, and show no individual orientation with the direction of flow-banding. It would seem, therefore, that they had been formed after crystallization and movement in the lava had ceased. Their origin may be due either to oxidation and concentration of the iron contained in the rock along planes accessible to invading oxidizing agents; to concentration of iron-bearing volatiles in the shear-planes of the rock during crystallization as discussed by Fuller;[19] or even to an introduction of iron in an oxidizing medium from some source outside of the rock itself during the last fuming stage of the eruption. Textural evidence fits equally any one of these three possible modes of origin.

Two specimens from one of the flows were analysed, No. 19063, the platy phase and No. 19064 the vesicular surface phase. The two are practically identical, and are high in soda, iron oxides, and phosphorus relative to Lassen andesites with comparable silica content.

Rhyolite. There are two rhyolite flows; one on the inner slope of the west rim of Medicine Lake basin and the other partly surrounding the base of Mount Hoffmann. Both flows are almost completely buried beneath a cover of residual soil and late pumice drift. A small cirque is found in the flow on the inner side of the west rim of the basin, but even here the walls have broken down and exposures are poor. The readiness with which the rock breaks down may be attributed to the fact that the glass of both flows has been shattered by perlitic fracturing.

The material collected from both flows is of one type. In thin-section, the rock contains about 10 per cent of phenocrysts in a

[19] Fuller, R. E., The mode of origin of the color of certain varicolored obsidians: *Jour. of Geol.*, **35**, p. 572. 1927.

glassy matrix. Most of the phenocrysts are zoned plagioclase crystals with a composition about sodic andesine. Some of them show evidence of resorbtion during a late stage in their development, though the last zone on all of them apparently was in equilibrium with the groundmass. A few crystals of angite and about two per cent hypersthene prisms are the remaining intratelluric minerals. The glass of the groundmass contains perhaps 20 per cent of minute plagioclase crystallites which are too small for accurate determination. The index of refraction of the glass is $1.493 \pm .0005$ for sodium light. No chemical analysis was made of this rock, but the index of the glass indicates a rhyolitic composition with about 72 per cent of silica. The perlitic cracks in the rock are all bounded by a narrow zone of indeterminable holocrystalline material in which are scattered a few flakes of hematite. This devitrification and formation of hematite were probably caused by moving solutions during the final stages of consolidation of the flows.

Dacite. The rock exposed at the top of Mount Hoffmann is a holocrystalline, light colored porphyry which probably was intruded in a cinder cone. Many small cavities in the rock are lined with botryoidal crystobalite. The thin section shows about 10 per cent of small, zoned plagioclase crystals (composition about medium andesine) and a few prisms of augite and hypersthene as phenocrysts in a holocrystalline groundmass. This is made up of a mat of minute tabular feldspar crystals and elongated hypersthene prisms contained in a matrix of indeterminable material which is dusted with small grains of opaque iron oxide. The interstitial material probably is a mixture of silica and alkali feldspar, so that mineral composition is that of a dacite or quartz latite.

Modoc Basalt

A group of Recent basalt eruptions began after the glaciation and continued to the present time. The youngest of these is certainly not over 500 years old. (See plates III and IVa.)

Very little chemical or mechanical decomposition has modified the surface of the flows. The meager amount of soil covering has been supplied by wind transportation of material from later pumice eruptions and from the exposed lake beds in the plateau. On the most recent of the flows, Burnt Lava Flow, only a few scattered pockets of pumice are found and most of the surface is unaltered lava. In the region just south and west of Tule Lake those basalts lie in the graben's which were formed by the late faulting of the Warner basalt.

The name Modoc basalt is proposed for this group of flows. Most of the flows and cinder cones of the Modoc Basalt are found in two areas: one, the Modoc Lava beds on the northeast slope of the Medicine Lake Highland; the other, on the southern slope of the Highland. A few flows are scattered along the eastern and western flanks of the Highland, and a few eruptions took place at the top of the Highland in the vicinity of Medicine Lake. Little Mount Hoffmann is a Modoc basalt cone containing small, irregular intrusives, and several other small cinder cones were built on the platy andesite surface due north of Little Mount Hoffmann.

The eruption of the Modoc basalts was characterized by the formation of a great number of cinder cones. However, some flows issued from small fissure vents on the flanks of the Lake basalt. These sources are often marked by open throats which extend into the country rock at various angles. The road along the northern edge of Burnt Lava Flow passes almost over the mouth of one of the throats from which that flow was extruded.

The rock of most of the Modoc flows is dark gray, usually aphanitic, variably vesicular, and rarely visibly porphyritic. Locally, in surface slags and in the cinder cones, the iron of the rock has been oxidized, giving a brick-red color to the specimens. Thin-sections show that the red rocks have been impregnated with minute plates of hematite. The dissemination of the hematite, regardless of mineral-boundaries in the rock, and the field distribution of the oxidized material shows that the oxidation is of deuteric rather than atmospheric origin. Column 19086, Table I, gives the analysis of an oxidized cinder from a cone just west of Medicine Lake on the top of the Highland. Most of the iron is in the ferric state. The ratio of soda to potash is higher than in the other analysed Modoc basalts (see columns 19142, 19116, and 19143) and the total amount of phosphorus is higher. The vent from which this rock was erupted pierces an unknown thickness of the platy andesite, whereas the other analysed flows were not in contact with it so far as known from the field occurrence. The ratio of soda to potash and the total phosphorus is high in the platy andesite, so it may be that some assimilation of the platy andesite will account for these same characteristics in this particular flow of Modoc basalt.

The principal mineral constituents of the basalts are plagioclase, pyroxene, olivine, glass, and iron oxides. Plagioclase makes up from 45 to 55 per cent of the rocks in which its amount can be measured by the Rosiwal method, and varies in composition from medium labradorite to calcic andesine. Olivine ranges from zero to 20 per cent, and the pyroxene and glass vary antipathetically, either or both making up from 40 to 50 per cent of the rock. Most of the specimens show from 5 to 10 per cent of micro-phenocrysts (one millimeter) of labradorite and an occasional euhedral olivine crystal. The feldspar phenocrysts are slightly zoned and twinned, but do not show resorbtion or recurrent zoning. They often have included blebs of groundmass or small olivine crystals.

The texture of the rock differs considerably within definable limits. The most crystalline rocks range from ophitic types with late interstitial pyroxene to intergranular types with pryoxene prisms and plagioclase tablets of contemporaneous development. The least crystalline limit of texture is an intersertal arrangement of euhedral tablets of plagioclase, equant grains of olivine, and a mesostasis of brown glass dusted with iron oxide crystals. These partly glassy rocks may be an arrested stage of the development of either an ophitic or an intergranular holocrystalline type. Between the ophitic texture and the most glassy texture with no pyroxene are types which range from near-ophitic specimens with pyroxene in fibrous aggregates extinguishing in large units to near-glassy specimens in which the glass is replaced by a cryptocrystalline aggregate. In these the minute fibrous crystals are indeterminable but can be seen to be crystallographically parallel by their extinction positions.

The chemical composition of one of the holocrystalline ophitic rocks is given in Table I, column 19142. This rock shows 64 per cent of normative plagioclase, whereas a Rosiwal measurement shows only 45 per cent of plagioclase in the mode. The feldspar is too small for accurate determination, but its composition is about a sodic labradorite. The composition from the norm is a calcic labradorite, so without doubt some of the normative anorthite actually belongs in the pyroxene. This would reduce the per cent of normative plagioclase. Further, in a fine-grained rock, the Rosiwal determination invariably gives too high a percentage of the high index and opaque constituents. It is likely, therefore, that the rock actually contains about 55 per cent of plagioclase and 35 per cent of pyroxene.

One of the partly glassy rocks has the chemical composition given in Table I, column 19116. The norm shows too much plagioclase as in the other rock, though this glassy rock is slightly more siliceous and probably contains a little more feldspar than does the first one. The mode of the glassy rock shows 41 per cent of plagioclase, 44 per cent of glass (including the opaque ore) and 15 per cent of olivine. For the reason mentioned above, the amount of plagioclase probably should be higher at the expense of the glass. The norm of the rock shows only two per cent of olivine, while the mode shows nearly 15 per cent. If crystallization had continued slowly to completion, much of this early olivine would have been resorbed and would have reappeared as pyroxene, using silica which is included in the glass of the rock. Further, it is obvious that the 40 per cent of residual liquid, represented by the glass, is very much enriched in the iron metasilicate molecule and is relatively very low in feldspar, since the early olivine is rich in the forsterite molecule and since nearly three-fourths of the total feldspar of the rock has precipitated out of the liquid.

The intergranular texture is found in rocks which are so fine-grained that the mineral assemblage can not be studied in detail. Specimens from Burnt Lava Flow are good examples of this type. In thin-section, a few microphenocrysts of labradorite and olivine are disseminated through the intergranular groundmass of tabular plagioclase and grains of pyroxene. Both hypersthene and augite appear to be present but the grains are too small for accurate determination. An analysis, Table I, column 19143, shows that the composition of this type is intermediate between an ophitic basalt and a pyroxene andesite. The rock has quartz in the norm so the modal olivine can not be in equilibrium with the groundmass.

Obsidian Group

Six different eruptions of lava and three separate pumice outbursts have occurred in Recent time within or near the circle of platy andesite vents on the top of the Medicine Lake Highland. Two extrusions of lava belong to an early episode, and the rest of the activity belongs to one grand display which took place so recently that it has a place in the legends of the Modoc Indians.[20] Since most of the rocks of this group are obsidians the name obsidian group will be applied to it.

[20] According to "Lava Jack" Stambaugh of Malin, Oregon, who has spent much of his life with the Modoc Indians.

"Medicine Flow" and "Hoffmann Flow," composed of dacitic lava, were erupted during the early activity. Both flows support a sparse growth of pines, though no soil has formed in place on their surfaces. Their age might be guessed as 800 or 1,000 years, with Hoffmann Flow slightly the older of the two.

Big Glass Mountain, Little Glass Mountain, and two small flows about a mile and a half northwest of Medicine Lake were formed during the later episode. Pumice cones were formed at vents which are closely associated with each of these centers of extrusion. Little Glass Mountain and the two small flows northwest of the lake are made up of rhyolitic obsidian. Big Glass Mountain is made up of lava varying in composition from rhyolite to dacite, with rhyolite in greatest abundance. All of these eruptions have occurred certainly within the last 500 years.

Dacite. Medicine Flow was extruded upon the comparatively level floor of the large lake basin between the north shore of Medicine Lake and the northern rim of platy andesite cones. The lava covers about one square mile and has a thickness of about 100 feet on the margins and 250 feet near the center. The thickest part of the flow probably marks the location of the vent from which the lava was extruded.

Hoffmann Flow occupies the floor of the northeast pass in the basin rim between Mount Hoffmann and Red Shale Butte. It has been partly buried by the later flows from Big Glass Mountain, so that the true size of the flow is unknown. The exposed area is a trifle less than that of Medicine Flow. The thickness at the western edge is about 75 feet, and the top of the flow rises slightly toward the east. The exact position of the vent is unknown, but apparently it lies to the east under the flows from Big Glass Mountain, and probably it coincides with the vent from which these later lavas were extruded.

The pine growth on Hoffmann Flow is rather more dense than that on Medicine Flow. With this exception, the two flows are identical in appearance. The flow fronts originally must have been nearly continuous walls of solid lava, varying from 50 to 100 feet high, standing with a slope considerably greater than that of the talus which has accumulated since movement ceased in the flows (see Plate IVb). The existing slope of the talus is even greater than the angle of repose for the heterogeneously-sized component blocks. Considered as a whole, the tops of the flows are compara-

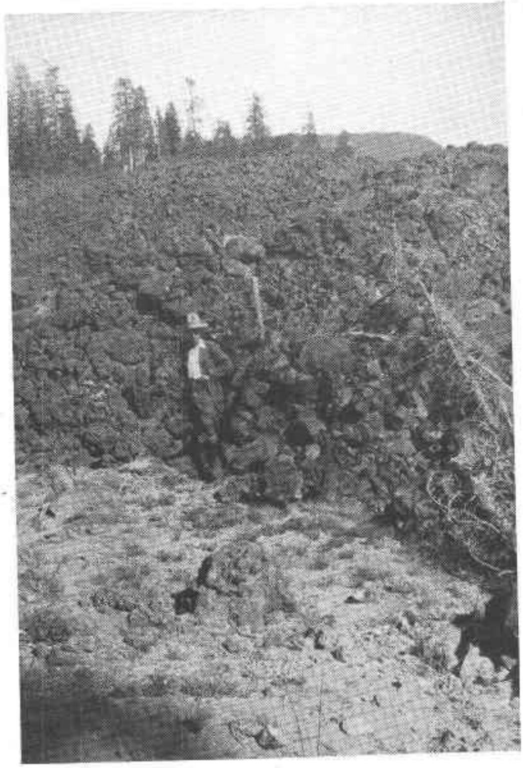

PLATE IVa. Edge of Burnt Lava Flow showing the blocky, irregular detail of the surface as contrasted to its general smooth appearance in the aerial photo.

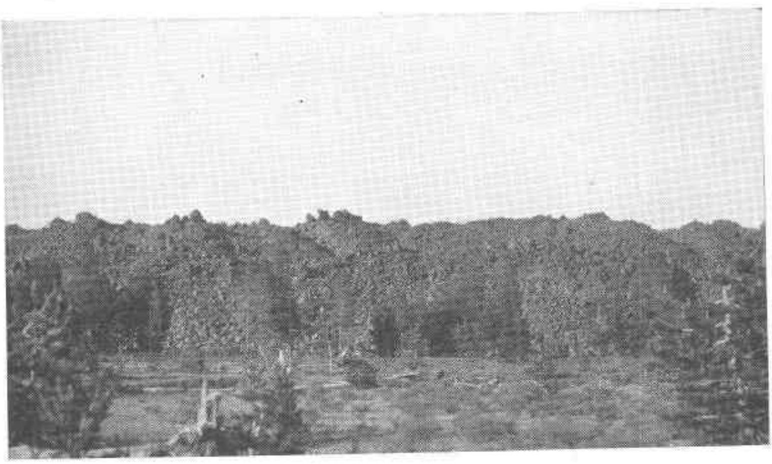

PLATE IVb. Margin of Medicine Flow, the dacite flow north of Medicine Lake. The flow front is about 150 feet high. Photo, M. A. Peacock.

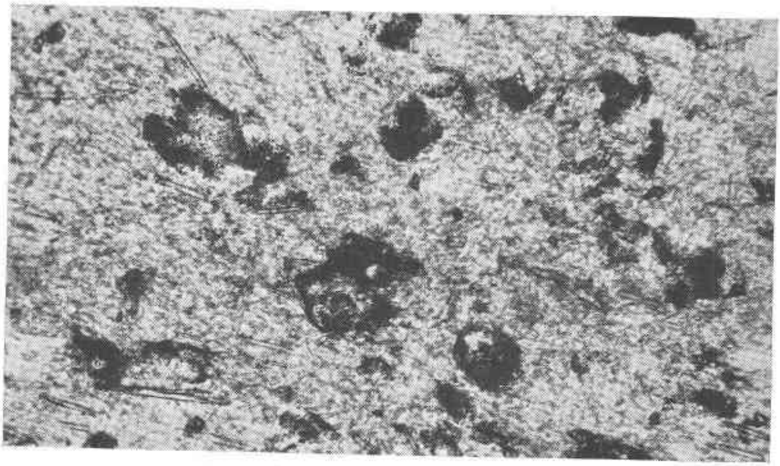

PLATE Va. Photomicrograph, (x115) with plane polarized light, of the dacite of Medicine Flow. The main groundmass contains many tabular plagioclase crystals, but the small globules are composed of finer crystals with none of the plagioclase tablets.

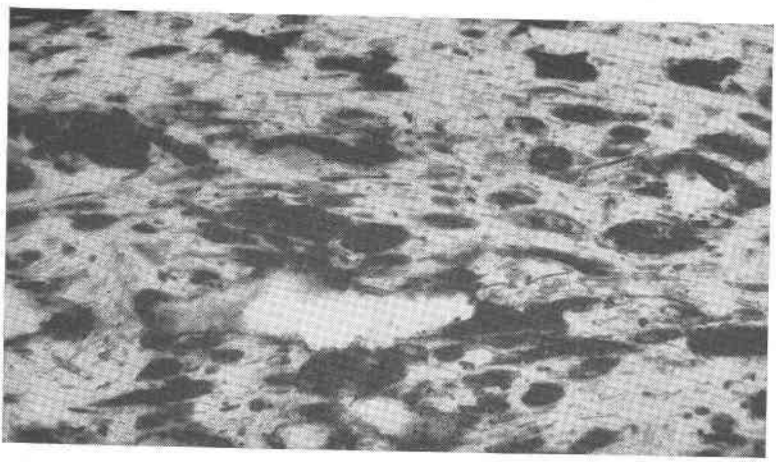

PLATE Vb. Photomicrograph, (x115) with plane polarized light, of the glassy rhyolite of the surface phase of Little Glass Mountain flow. The glass of the ground mass carries scattered plagioclase tablets. The globules, drawn out and contorted by the flow movement, are holocrystalline and contain none of the tablets.

tively flat, rising with a very low gradient toward the centers of extrusion. Hoffmann Flow rises about 200 feet in three miles, a gradient of about one and a half per cent, and Medicine Flow has a slightly greater average slope. In detail, however, the surfaces are extremely rugged with a relief of as much as 50 feet. There has been no formation of residual soil on the tops of the flows, but depressions in the surface have been partly filled by drifted pumice from later eruptions. In these pumice-filled pockets and in fractures in the lava, the scrubby pines and some minor vegetation have gained a foothold. Most of the surface, however, is barren, unaltered lava.

Both flows are composed of a dense, dull lustered rock in which a few small plagioclase phenocrysts are visible in an aphanitic groundmass. Some of the surface lava shows textural variations ranging from coarse scoria to finely vesicular pumice, but the relative amount of the vesicular phase is small.

The typical dense variety contains from 7 to 10 per cent of phenocrysts in a microcrystalline groundmass. Most of the phenocrysts are zoned crystals of andesine with an average composition of An40. The individuals are bounded by well-developed crystal-faces, have an average length of about one millimeter, and are twinned after the albite, Carlsbad and pericline laws. The other phenocrysts are well-formed prisms of pyroxene, mostly hypersthene containing iron and magnesia in the molecular ratio of $FeSiO_3:MgSiO_3::25:75$, but a few are monoclinic with the optical constants of common augite. A fraction of a per cent of iron ore is disseminated through the rock, occurring both as rod-shaped grains and octahedral or globular masses. The groundmass is made up of about 50 per cent of minute tablets of twinned plagioclase in more or less trachytic arrangement, with indeterminable crypto-crystalline material filling the interstices.

The petrography of the vesicular types differs in one respect, aside from the vesicularity, from that of the dense phase. Through the groundmass of the vesicular rocks are scattered numerous minute areas (as much as 10 per cent in some specimens) which are slightly darker in color than the bulk of the groundmass, and which are free from the feldspar microlites which characterize the rest of the rock (see Plate Va). These patches are somewhat irregular in shape but in general are equant and nearly circular, with well-defined boundaries against the groundmass. The material of the globules is perceptibly crystalline, but individual crystals can not be distinguished. They do not show the radiating-fibrous structure typical of small spherulites. The history of crystallization of these globules undoubtedly has been different from that of the bulk of the groundmass which is characterized by feldspar tablets, though no entirely satisfactory explanatory theory has yet presented itself.

Chemical analyses were made of a specimen of the dense, common phase, and two specimens of the vesicular types which contain the strange globules; Table I, columns 19000, 19018, and 19018a respectively. There is very little difference between the three analyses. One vesicular rock contains more ferric oxide than do the other two, and both vesicular rocks are slightly richer in the alkali feldspars than the dense phase. The increase in alkali feldspar may be due to the presence of the globules. All three are similar to the dacites of Lassen Peak. The Lassen dacites, however, all contain biotite, while no traces of biotite have been found in the Medicine Lake rocks.

Rhyolite. Little Glass Mountain is typical of the rhyolitic lava eruptions of Recent age. The flows cover an eliptical area about three miles long and two miles wide on the outer slope of the southwest rim of the Medicine Lake basin. The highest point of the pile is near the northwest edge of the area covered by the lava, probably over the vent from which the flows were extruded. The total thickness of the lava pile at this point must be between 800 and 1,000 feet. On the margins, the flows are from 100 to 150 feet in thickness. The flow fronts are similar in appearance to those of Medicine and Hoffmann Flows. The flow surface rises from the margins toward the center by a series of alternating steep and gradual elevations giving a terraced effect in profile. In detail, the character of the surface of each terrace is somewhat comparable with that of the dacite flows, though a great deal more pumiceous slag is found on the surface of the rhyolite.

The flows are made up of a great many textural varieties of a porphyritic obsidian. Most of the surface rock is an exceedingly porous, glass sponge. The porespaces are much larger than those of a typical pumice, but the ratio of porespace to glass is sufficient to allow the rock to float on water. Another extreme textural phase is a glassy scoria with cavities as large as a man's fist which are usually partly lined with thin scales and rosettes of microcrystalline rhyolite. All gradations in vesicularity between dense obsidian and these two extreme phases may be found interbanded with each other in rather well-defined layers. The bands, varying from a few inches to tens of feet in thickness, are, in some cases, highly contorted and, in all cases, show some evidence of flow movement after the banding had been produced. Where the flow fronts have been somewhat broken down the dense obsidian is the dominant type, and it is quite probable that a crystalline phase exists at greater depth in the flows.

The rock is a glass with a few crystals of plagioclase and hypersthene as phenocrysts, identical with those which are found in the earlier dacite. The number of phenocrysts varies in different specimens but some are present in every textural phase of the rock, and no concentration by settling in the flow can be detected. The groundmass is rhyolitic glass carrying 10 or 15 per cent of plagioclase crystallites which are usually oriented with their long axes in the planes of flowage. A specimen of the dense obsidian, No. 19033a, analysed by E. S. Shepherd, has the composition of a rhyolite with 73.3 per cent of SiO_2. The index of refraction of the glass for sodium light is $1.491 \pm .0005$, and its specific gravity is $2.39 \pm .01$.

In the vesicular phases, increasing in number with the increase in vesicularity, are found elongated areas of apparently holocrystalline material so finely crystalline that the individuals are not determinable (see Plate Vb.) The texture and crystallinity of these areas is the same as that of the similar areas found in the vesicular dacite. The boundary is sharp between these blebs and the glass of the groundmass. The shape of cross-sections of these bodies varies from nearly circular to extremely thin and contorted lens-shapes. In all cases, the shape appears to be dependent on the flow structure of the rock. The general form and relation to flow lines suggests that these crystalline bodies represent globules of material, isolated from the bulk of the lava, which have been drawn out and contorted by the movements of the flow prior to complete consolidation. An occasional lens may be traced through a narrow thread of crystalline material into an open vesicle which has a thin cryptocrystalline lining. Apparently the origin of the elongated crystalline lenses, of the vesicles, and of the crystalline vesicle-lining has some common control. A number of samples of the vesicular glass, containing as much as 20 per cent of the crystalline blebs, were analysed by E. S. Shepherd and were found to have a remarkably uniform composition which is identical with that of the dense obsidian.

The index of refraction of the glass from the specimens containing the crystalline bodies is the same to the third decimal place as that of the dense obsidian. The two glasses, therefore, must have the same chemical composition and, further, the crystalline blebs must have a similar composition since their presence or absence does not change the bulk composition of the rock.

Big Glass Mountain Complex. Big Glass Mountain, whose flows cover an area of about nine square miles, is the largest accumulation of Recent siliceous lava in the region. The high point of the mountain has an elevation of 7850 feet, and the probable elevation of the pre-flow surface beneath the peak is 7050 feet, giving a possible thickness of 800 feet at the center of the pile. The vent, marked by this peak, was located on the eastern rim of the Medicine Lake basin, so that the lava flowed both down the inner slope toward the basin floor and down the outer slope of the Medicine Lake Highland. The most extensive flows reached a distance of about five miles from the vent, covering the outer slope down to an elevation of about 5,000 feet,

The slopes of the mountain are formed by a series of terraces or steps, of which there are three on the western side and seven on the long eastern side. Each of these terraces seems to be formed by an individual gush or wave of lava which has solidified with a precipitous wave-front from 100 to 200 feet high. (See Plate VI.) The three top waves are fairly symmetrical about the center of eruption, so that the top of the mountain resembles a pile of three discs, progressively smaller in area, one on top of the other.

The lavas of the Big Glass Mountain flows range in composition from rhyolite to dacite. The southeastern tongue which extends the farthest from the vent is similar in structure and appearance to the dacitic Hoffmann Flow, except for its lack of vegetation. The greater part of the rock is a holocrystalline dacite porphyry which is similar in texture and mineral composition to the earlier dacite of both Hoffmann and Medicine Flow. Its chemical composition, given in Table I, column 19106, is practically identical with that of the Medicine Flow rock. In one respect the late dacite flow differs radically from the older two dacite bodies. A large streak of

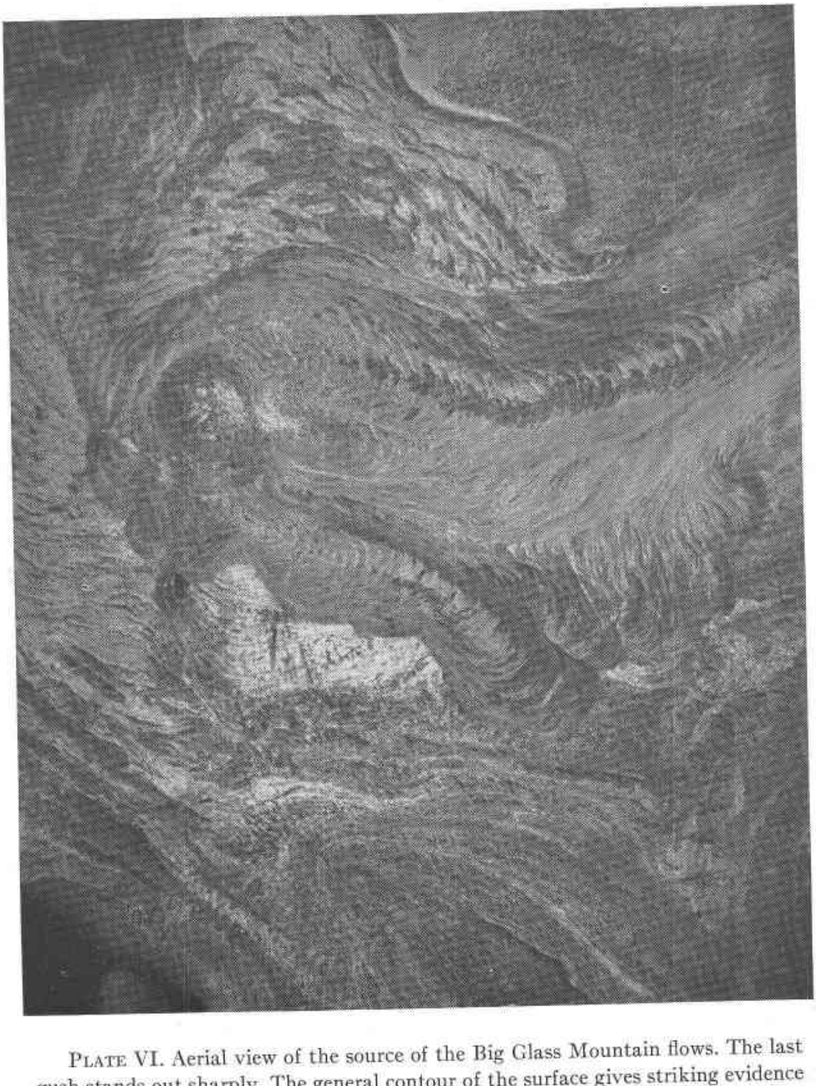

PLATE VI. Aerial view of the source of the Big Glass Mountain flows. The last gush stands out sharply. The general contour of the surface gives striking evidence of the extreme viscosity of the flow. The contrasting color of different surface wrinkles is due to different vesicularity of the surface froth. The different flow fronts are from 100 to 200 feet high. Photo, Brubaker Aerial Surveys, Portland, Oregon.

glassy obsidian, about 30 feet wide and 100 feet long, is exposed in the surface of the dacite flow. Field relations force the conclusion that it was an integral part of the dacite flow, but there is no sign of gradation between the two rock bodies. The obsidian is strikingly different from the dacite, being a nonporphyritic glass with only a small percentage of feldspar microlites. Herdsman and Shepherd analysed the rock with the results which are given in Table I, columns 19103. The differences between the two analyses are probably no greater than those resulting from slightly different analytical technique. The rock is a rhyolite similar to that of Little Glass Mountain. The index of refraction of the glass is 1.4930 $\pm .0005$ and its specific gravity is $2.38 \pm .01$.

The next higher terrace of the eastern slope appeared from a distance to be a flow of rhyolitic obsidian and slag overlying the dacite flow.

The fourth terrace from the top is made up of a complex of interbanded obsidian and vesicular slag. The rock has a dull luster and shows a larger number of feldspar microlites than the obsidian from the lens in the dacite. The index of refraction is $1.497 \pm .001$ and the specific gravity is $2.45 \pm .01$. A chemical analysis by Shepherd (Table I, column 19103c) shows that the rock has a composition between the rhyolite and the dacite. Across the top of this terrace is a lens of glassy obsidian about 50 ft. wide and several hundred feet long. The rock is similar to the other rhyolitic obsidians in appearance and index of refraction and undoubtedly has the same composition. To all appearances it was an integral part of the flow with the intermediate composition.

The third terrace from the top, overlying the lava just described, is a flow of rhyolitic glass and froth interbanded on a gigantic scale. Some of the vesicular streaks are 50 feet in width. The dense obsidian has the composition given in Table I, column 19103b. Its index for sodium light is $1.4915 \pm .0005$ and its specific gravity is $2.39 \pm .01$. The rock has no phenocrysts and only a few feldspar microlites. A specimen of the associated pumiceous rock was found by Shepherd to have almost exactly the same composition.

Pumice. Outbursts of pumice preceded the eruption of the Recent rhyolitic lava. The most violent of these eruptions occurred just west of the Little Glass Mountain vent. A large cone was built at this point, Pumice Stone Mountain, which has an elevation of 7,300 feet, about 800 feet above the prepumice surface. Just south of the big cone is a smaller one which is perfectly preserved. The throat of this cone is lined with red pumice whose color is due to disseminated scales of hematite, formed by the action of the gases escaping from the vent.

Two small pumice vents were opened in the locality northwest of Medicine Lake. They both have blown open older basaltic cinder cones, so the piles surrounding the vents are mixtures of basaltic cinders and rhyolitic pumic.

Several small cones are found at the northern edge of Big Glass Mountain. The existing cones are so close to the edge of the lava that it may well be presumed that part of the pumice record has been obliterated by the lava flows.

An analysis of the rhyolitic pumice from Pumice Stone Mountain is given in column 19041, Table I. The rock has typical pumice texture and is composed of glass with a few phenocrysts of plagioclase and hypersthene. A bit of glass from a streak in a bread-crust bomb has an index of refraction of $1.4915 \pm .0005$.

PETROLOGY

Introduction

The lavas of the Modoc Lava-bed Quadrangle range in composition from olivine-rich basalts to rhyolites. Their field affinity with the main Cascade volcanoes in northern California indicates that they belong in the Cascade volcanic series. The mineralogy and chemistry of the Modoc rocks conclusively relates them to the Cascade lavas. This series of Cascade rocks, typified by the lavas from Lassen Peak, has been discussed by Bowen as a normal subalkaline series derived by fractional crystallization in the hornblendic line of descent from primary basaltic magma. Bowen's line of attack has been employed in this study of the petrology of the Modoc lavas. In the detailed consideration of the relations of the different lavas, a number of points were encountered which are at variance with Bowen's thesis. These observations are summarized in the following pages, but no attempt is made to fit them into existing petrologic theory.

Basalts

Lavas of basaltic composition were erupted during every period of volcanic activity in the Modoc area, and have a greater areal distribution than any other type. However, they show only slight variation in their chemical composition. The average of six analyses of these basalts is comparable to the composition of the average Mull basalt of the Porphyritic Central Type[21] and differs notably in alumina and iron oxide from the average of 63 plateau basalts described by Washington.[22]

Bowen gives convincing evidence that the anorthite-rich rocks of the Mull Porphyritic Central Type have been derived by the concentration of early-formed crystals.[23] Accepting Bowen's conclusion, the composition of the basalts of the Modoc and their intimate field association with andesitic volcanoes indicate that they have been derived by the concentration of calcic plagioclase and magnesian olivine during the differentiation of the andesitic magma. The Modoc rocks differ from the Mull porphyries in that they contain no relic phenocrysts of plagioclase.

	Plateau basalts	Basalts from Modoc	Mull Porphyritic Central Type
SiO_2	49.5	49.4	50.0
Al_2O_3	13.6	18.3	18.0
Iron oxide	13.0	8.7	9.0
MgO	6.3	8.2	5.0
CaO	9.3	10.4	10.0
Na_2O	2.7	2.7	2.5
K_2O	0.9	0.5	0.4
TiO_2	2.3	0.9	1.3

Of the analysed Modoc specimens, the basalts which show the greatest chemical similarity are three which were erupted from different centers in three different periods of volcanism: No. 19141 from the Cedarville andesite; No. 19071 from the Massive Lava Group; and No. 19123 from the Warner Basalt. These rocks contain 62 per cent of calcic labradorite (an 68), 23 per cent of forsterite-rich olivine, 12 to 15 per cent of pyroxene, and a small amount of magnetite. K_2O is less than 0.3 per cent in all of them. They seem to represent an extreme concentration of anorthite and forsterite, yet they carry no relic phenocrysts.

Two analysed specimens (Nos. 19142 and 19143) from the Modoc Basalt show a greater chemical variation. The less siliceous one (and the older in the chronological column) contains 65 per cent of medium labradorite (an 58 norm minerals), 10 per cent of

[21] Thomas, H. H., and Bailey, E. B. Tertiary and post-Tertiary Geology of Mull, p. 22, 1924.

[22] Washington, H. S., Deccan traps and certain other plateau basalts; *Bull. Geol. Soc. of Am.*, **33,** p. 797, 1922.

[23] Bowen, N. L., The Evolution of Igneous Rocks, Princeton, Chap. 9, 1929.

olivine, and has 0.5 per cent of K_2O. The more siliceous one (and younger) contains 65 per cent of calcic andesine (an 47), 5 per cent of norm quartz, and has 1.6 per cent of K_2O. The change from olivine to quartz in the norm, and the increase of the alkali feldspars at the expense of anorthite are the most striking differences between the two. The geologic relations of the basalts of this group indicate that all of them were erupted from the same general center and presumably are differentiates from the same local magma. The pair of analyses then should be excellent material for a quantitative study of differentiation. A simple calculation shows the difference between the two analyses in term of norm minerals. To produce the more siliceous rock, 55 per cent of plagioclase (an 60) and 25 per cent of olivine containing about 50 per cent by weight of fayalite must be subtracted from the less siliceous one. Theoretically, the first 55 per cent of plagioclase crystals from a melt of the composition of the less siliceous rock would have, if reaction kept pace with crystallization a composition of ab 38–an 62. This is almost exactly the composition computed for the plagioclase representing the difference between the two rocks. The computed olivine is richer in fayalite than is the melt from which it must precipitate, whereas the actual crystals which would form would contain only about 20 per cent of fayalite. Removal of the early natural olivine would leave a residual liquid containing a greater amount of iron silicate than is contained in the rock which we wish to produce.[24] There is no natural phenocryst-forming mineral in which the concentration of iron with respect to magnesia is so great that its removal instead of olivine would give the desired Fe/Mg ratio in the melt. A possible combination might be the removal of the necessary amount of magnesia-rich olivine by fractional crystallization, and the removal of the excess iron and silica from the residual liquid by other means. It is not reasonable to assume removal of quartz phenocrysts from basaltic magma. Nor is it likely, judging from the textural evidence offered by basaltic rocks, that magnetite forms early as phenocrysts in any appreciable quantity. There is considerable evidence according to Fenner and Zies that magnetite is carried in notable quantities by volatiles.

[24] The concentration of iron in the residual liquid during crystallization of basaltic magma is one of the strong objections advanced by Fenner against the thesis that fractional crystallization is the only important factor in the differentiation of magmas.

Surely there would be a very marked concentration of volatiles in the residual liquid in the case being considered where 80 per cent of the original magma must be crystallized before the residual liquid reaches the desired composition. If the excess iron and silica be disposed of by removal with escaping volatiles, a residual liquid with the composition of the siliceous basalt may be derived from the less siliceous rock.

The holocrystalline basalts of the area may be separated into two groups on the basis of texture: the one, ophitic group, in which the pyroxene and plagioclase have the poikilitic relation known as ophitic and sub-ophitic texture; the other the intergranular group, in which pyroxene and plagioclase each occur in hypidiomorphic crystals which bear an intergranular relation to each other. The dividing line between the two groups is very sharp though, of course, those rocks which are partly glassy can not always be assigned with assurance to one or the other group. Neither augite nor hypersthene is present as phenocrysts in either type of basalt.

The writer has never seen the description of an ophitic basalt which contains pyroxene phenocrysts, whereas their occurrence in many intergranular basalts and low-silica andesites is commonly known. Further, as Washington mentioned[25] but did not stress, the composition of phenocrysts pyroxene is entirely different from that of the pyroxene of an ophitic basalt.[26] The relative molecular proportions of CaO, MgO, FeO, and Fe_2O_3 in the average analysis of eight augite phenocrysts[27] and three ophitic pyroxenes[28] is given for comparison. The ratio of iron to magnesia, low in the phenocrysts and high in the ophitic pyroxene, points to an early crystallization of the former and a late crystallization of the later.

	CaO	MgO	FeO	Fe_2O_3
Phenocryst pyroxene	47.0	43.0	8.0	2.0
Ophitic pyroxene	34.0	38.0	27.-	0.5

Thus it would appear that the ophitic texture represents a set of conditions under which pyroxene can not crystallize as pheno-

[25] Washington, H. S., *loc. cit.*, p. 798.

[26] Since the preparation of this manuscript, Barth has studied the difference in composition between phenocryst and groundmass pyroxene and showed that they probably represent a continuous reaction series between wo, en, and hy. Barth, Tom Crystallization of pyroxenes from basalts; *Am. Min.*, **16**, pp. 195–208, 1931.

[27] Augites from Haleakala, Vesuvius, Etna, Kilimanjaro, Alban Hills, Stromboli, and Nishigatake analysed by Washington and others.

[28] Pyroxenes from the Goose Creek diabase and Whin sill and related dikes.

crysts, and the intergranular texture, a set of different conditions under which pyroxene is able to crystallize as one of the early minerals and form phenocrysts.

Many of the basalts show variable amounts of glass which always contains most of the iron oxide in dendritic crystals. In some rocks with a large amount of glass no crystalline pyroxene is present. One such rock was analysed, No. 19116, and a comparison of the norm, mode, and calculated norm of the glass gives an insight into the progress of crystallization in that lava.

Norm				Mode		Norm of glass
or	4.4					6.
ab	28.3	spar	63.9	labradorite	41	25.
an	31.2					22.
wo	5.5					13.
en	11.1	px	28.6	glass	44	6.
hy	12.0			(with iron oxide)		8.
ol	2.2			olivine	15	—
qu						11.
mt	2.1					5.
il	2.4					

The Lake basalt contains 73 per cent of feldspar which has a composition (from the norm) of or 5–ab 35–an 60.[29] In a feldspar melt of this composition, less than five per cent can exist as crystals with a composition ab 15–an 85. In the rock, the unzoned cores of the phenocrysts have this composition but make up about eight-tenths of the bulk of the phenocrysts or about 33 per cent of the total feldspar. It is obvious that these phenocrysts could not have formed in equilibrium with a melt of the composition of the rock. The nature of several definite stages in the development of the phenocrysts is clearly indicated by a study of the textural relations and composition of the rock constituents. However, the nature of the processes which brought about these stages is a matter of speculation.

The slightly zoned cores of the plagioclase phenocrysts which make up eight-tenths of their volume or twenty-four per cent of the rock indicate that equilibrium was maintained between melt and phenocrysts during most of the time involved in their growth. At the end of this time the phenocrysts had a composition of An 85 and a melt in equilibrium with such a plagioclase would contain

[29] These calculations were made on the material analysed by Herdsman which contained 30 per cent of phenocrysts.

plagioclase with An 60. The zoned margin of the phenocrysts shows that the next step was a period of crystallization under conditions which did not permit equilibrium and with a rapid change in environment. Further, the zoned margin is divided into two stages, the later of which coincides with the crystallization of the groundmass after extrusion. The groundmass contains plagioclase with only 45 parts of anorthite. Therefore, during the short time represented by the inner band of zoning, the environment of the phenocrysts was changed from a melt containing plagioclase An 60 to one with plagioclase An 45.

There are two general ways in which this could be accomplished: either by transferring the phenocrysts from one liquid to another or by changing the composition of the liquid without moving or altering the phenocrysts. Transferring the phenocrysts would involve either floating or sinking the early crystals into another part of the magma. Changing the liquid could be done either by mixing with another magma of appropriate composition, by concentrating a liquid fraction of appropriate composition which was immiscible in the parent magma, or by selective transfer of certain elements from one part of the magma to another.

There are two important objections to the processes involving gravitative movement of phenocrysts. First, in any given case, the question of whether or not the crystals will float, sink, or remain suspended is a matter of conjecture. It certainly does not depend entirely on the relative specific gravity of the crystals to the liquid rock as we can estimate them in the laboratory. Factors such as viscosity and rigidity of the liquid under small forces must be equally important, and can not be estimated quantitatively. Second, the maintenance of appropriate temperature relations between different zones of magma in a system which would produce such a rock as the Lake basalt is almost too complicated in its adjustment to be reasonable.

Mixing of two magmas with different compositions seems possible. Evidence from the rock requires only that the mixing must have been perfect, as there are no streaks or bodies of variable composition.

The two other possible methods involve a change of composition of the liquid by differential movement of constituents, either by liquid immiscibility or by transfer with volatiles. Fenner[30] and

[30] Fenner, C. N., The Katmai magmatic province; *Jour. Geol.*, **34**, pp. 673–772, 1926.

Bowen[31] have recently discussed the role of volatile constituents in magmas, but still the knowledge concerning their amount and behavior in a magma is far from complete. The question of limited miscibility in dry silicate melts has been settled conclusively in laboratory experiments.[32] However, limited miscibility in systems involving water and other volatile constituents has not been disproved, and until such proof is forthcoming, one may be justified in considering limited miscibility as a possible phenomenon.

Dacite and Rhyolite

The location of the Recent flows of dacitic and rhyolitic lava on the top of the Medicine Lake Highland indicates that they represent small bodies of magma developed within the Highland volcanic focus.

The two dacite flows, Medicine Flow and Hoffmann Flow, are next younger in age than the platy andesite flows from the same focus. The difference in composition between the Medicine Flow dacite and the platy andesite may be represented by 35 per cent of plagioclase An 25, 4 per cent of augite, 5 per cent of magnetite, $1\frac{1}{2}$ per cent of ilmenite, and $1\frac{1}{2}$ per cent of quartz (all norm minerals). This general assemblage of minerals is not greatly different from those which one would expect to find as early phenocrysts is the platy andesite magma, except that the plagioclase has an impossible composition. The calculated phenocrysts have the same composition as the total plagioclase of the magma. The natural early crystals would be decidedly more calcic than the magma, so this fact alone rules out the possibility of expressing the difference between the two rocks solely in terms of early phenocrysts. The composition of one or both magmas has been influenced by some factor other than the removal of early phenocrysts.

The chemical composition of all the rhyolite which is present as pure glass is remarkably constant. Four analyses of obsidians from both Big and Little Glass Mountains are almost identical. They also are quite similar to the older obsidian of the Massive Lava Group. If these compositions be expressed in terms of normative quartz and feldspar, their mutual resemblance becomes even more striking, and their approach to the composition of Vogt's graphic granite anchi-eutectic is most impressive.

[31] Bowen, N. L., The Evolution of Igneous Rocks, Chap. 14, **1928.**

[32] Greig, J. W., Immiscibility in silicate melts; *Am. Jour. Sci.*, **13,** pp. 1–44, 133–154, 1927.

Bowen, N. L. The Evolution of Igneous Rocks, Chap. 2, **1928.**

Anchi-eutectic	qu:or:plag::26:29:45	or:plag::40:60
Obsid. Massive Lava Gr.	qu:or:plag::32:28:40	or:plag::41:59
Obsid. Little Glass	qu:or:plag::31:27:42	or:plag::39:61
Obsid. Big Glass	qu:or:plag::30:27:43	or:plag::38:62
Obsid. Big Glass	qu:or:plag::30:28:42	or:plag::40:60
Obsid. Big Glass	qu:or:plag::31:28:41	or:plag::41:59

The difference betwen the dacite and the typical rhyolite may be calculated in terms of norm minerals. It amounts to 27 per cent of plagioclase (An 52), 8 per cent of hypersthene ($FeSiO_3$ 51 $MgSiO_3$ 49). The computed plagioclase has a composition which agrees with that of the first 27 per cent of crystals which would form from the dacite magma, but the computed hypersthene is much richer in iron than the natural hypersthene which exists in the dacite as phenocrysts. Here, as in the case of the Modoc basalts, excess iron would have to be removed from the residual liquid to give the composition of the rhyolite.

The two older dacitic flows are made up of uniform dacite throughout. Likewise, Little Glass Mountain and two small flows consist of rhyolitic glass and pumice of remarkably uniform composition. However, Big Glass Mountain ranges in composition from the type dacite to the type rhyolite. It presents a problem in differentiation which was not solved satisfactorily in the course of this work. However, the texture of both the dacite and rhyolite shows phenomena which may have a decided significance in an interpretation of their differentiation.

The vesiculated rhyolite from all of the glassy flows contains minute globular or lenticular bodies of cryptocrystalline material which have sharp boundaries against the glass of the groundmass. Deformation of these bodies was caused by the flow-movement of the rock so they must have existed before movement ceased. They are often linked with open vesicles lined with a thin shell of cryptocrystalline material which formed due to volatiles within the vesicles. The material in the globular bodies must have the same composition (at least with regard to the major constituents) as the typical rhyolite, as a specimen which contains over twenty per cent of the globules had a chemical composition identical with another in which no trace of the globular material could be found.

The surface specimens from the dacite flows show similar small bodies. There they are more minutely crystalline than the groundmass and stand out because of their finer texture and the absence in them of the plagioclase tablets of the main groundmass. Three samples from a dacite flow were analysed: the type dacite, No.

19099; an unoxidized vesicular phase, No. 19018; and a vesicular phase showing deutric oxidation of iron No. 19018a. Both vesicular specimens showed the small globular bodies, and all three showed the same percentage of phenocrysts as determined by the Rosiwal method. Ferric iron is high in the specimen which showed the oxidation. Otherwise the three analyses differ only slightly. The two surface phases, however, show a similar departure from the dense phase, namely a slight increase in potash feldspar and free silica. This difference conceivably may be caused by the presence of the small globular bodies which probably have a composition similar to those in the rhyolite.

The exact nature of the origin of these globular bodies is not obvious. That they are of primary origin seems clearly indicated by their textural relations. The fact that they occur only in vesiculated surface rock, and are often connected with open visicles seem to relate them to the presence of volatile constituents. For want of a better explanation, it is suggested here that these bodies represent a liquid fraction, rich in volatiles and with a silicate composition similar to that of Vogt's graphic-granite anchieutectic, which separated from the relatively dry magma due to limited miscibility.[33] If this be true, it is possible that the small bodies of rhyolite were formed by the separation of this material from larger bodies of dacite within the volcanic focus.

TABLE 1

	19141 Gonyer	19123 Herdsman	19071 Gonyer	19142 Gonyer	19116 Herdsman
SiO_2	46.00	47.10	47.26	48.98	51.46
Al_2O_3	18.24	18.52	18.56	18.92	17.69
TiO_2	0.74	0.90	0.88	1.16	1.25
Fe_2O_3	2.00	tr	1.42	2.22	1.37
FeO	7.43	7.91	7.96	7.12	9.05
MnO	0.12	tr	0.08	0.09	0.18
MgO	10.04	10.89	9.62	7.42	5.13
CaO	11.56	11.98	11.54	10.04	8.92
Na_2O	2.34	2.33	2.24	3.04	3.37
K_2O	0.22	tr	0.20	0.44	0.77
H_2O+	1.51	0.10	0.30	0.34	0.44
H_2O-	0.18	0.18	0.06	0.05	0.30
P_2O_5	0.04	0.09	0.08	0.14	0.14
	100.42	100.00	100.20	99.96	100.07

[33] Such an immiscible fraction is considered possible by Arrhenius and Evans. Arrhenius, S., Worlds in the Making, Harper, p. 20, **1908.** Evans, J. W., *Quart. Jour. Geol. Soc.*, **81,** pt. 2, p. 341, 1925. Evans, J. W., *Faraday Soc.*, Symposium on Physical Chem. etc. p. 465, **1924.** Evans, J. W., *Cong. Geol. Internat.* (*Canada*), p. 248, **1913.**

TABLE I (*Continued*)

qu	—	—	—	—	—
or	1.1	—	1.1	2.2	4.5
ab	17.3	17.8	18.7	25.2	28.3
an	38.6	40.0	41.7	37.0	31.2
ne	1.1	0.8	—	—	—
di	15.2	15.1	12.0	9.7	10.2
hy	—	—	3.3	10.0	18.4
ol	20.6	23.9	19.6	9.6	2.2
mt	3.0	—	2.1	3.3	2.1
il	1.4	1.7	1.6	2.3	2.4
ap	0.2	0.3	0.3	0.4	0.4
wo[1]	7.9	7.8	6.1	5.0	5.5
en	5.1	4.9	6.1	10.2	11.1
hy	2.2	2.4	3.0	4.5	12.0

	19144 Gonyer	19144 Herdsman	19086 Gonyer	19143 Gonyer	19145 Gonyer
SiO_2	49.66	49.80	54.56	55.46	57.22
Al_2O_3	19.79	21.81	17.52	17.70	19.16
TiO_2	1.12	1.04	1.28	0.68	0.92
Fe_2O_3	4.80	1.64	8.70	1.58	2.21
FeO	5.40	6.43	0.32	5.12	4.55
MnO	0.06	tr	0.04	0.08	0.12
MgO	4.16	4.40	4.34	5.86	3.32
CaO	10.90	10.82	8.14	8.12	6.12
Na_2O	3.37	3.04	3.94	3.00	4.28
K_2O	0.72	0.60	0.90	1.58	1.64
H_2O+	0.18	0.10	0.10	0.50	0.81
H_2O-	—	0.10	0.05	0.01	0.05
P_2O_5	.17	0.10	0.22	none	0.11
	100.33	99.88	100.11	99.69	100.51
qu	—	—	7.0	4.8	6.4
or	3.9	3.3	5.6	9.4	9.4
ab	28.8	25.7	33.5	25.2	36.2
an	36.7	44.2	27.2	30.3	28.4
di	13.4	7.0	6.9	8.1	0.9
hy	7.3	10.6	7.6	17.8	13.0
ol	0.6	4.1	—	—	—
mt	7.0	2.3	hm 8.6	2.3	3.3
il	2.1	2.0	0.6	1.4	1.7
ap	0.3	0.3	0.3	—	0.3
			tn 2.4		
wo	7.0	3.6	3.7	4.2	0.5
en	9.8	8.0	10.8	14.7	8.1
hy	4.0	6.0	—	7.0	5.3

[1] Proposed Change in Calculation of Norms of Rocks, T. F. W. Barth, *Min. und Pet. Mit.*, **42,** 1931, pp. 1–7.

TABLE I (*Continued*)

	19063 Gonyer	19064 Gonyer	19106 Herdsman	19099 Herdsman	19018 Gonyer
SiO_2	59.98	59.98	67.20	67.70	68.12
Al_2O_3	16.71	17.28	16.22	16.32	15.73
TiO_2	1.30	1.20	0.30	0.30	0.42
Fe_2O_3	2.52	2.56	0.34	0.27	0.32
FeO	5.04	4.88	3.03	3.20	2.74
MnO	0.11	0.15	tr	tr	0.03
MgO	2.22	2.10	1.32	1.25	1.24
CaO	4.84	4.72	3.43	3.35	3.30
Na_2O	5.12	4.92	4.02	3.89	3.56
K_2O	1.63	1.68	3.36	3.22	3.78
H_2O+	0.19	0.21	0.32	0.22	0.31
H_2O-	nd	nd	0.12	0.05	nd
P_2O_5	0.43	0.44	0.06	0.06	0.12
S	nd	nd	0.20	0.20	nd
	100.09	100.12	99.92	100.03	99.67
qu	9.9	10.7	19.7	21.8	22.4
or	9.6	9.9	20.0	18.9	22.2
ab	43.1	41.5	34.1	33.0	29.9
an	17.9	20.1	16.1	15.9	15.6
C	—	—	—	0.6	0.1
di	2.8	0.4	—	—	—
hy	9.3	10.1	8.1	8.1	8.0
mt	3.7	3.7	0.5	0.5	0.5
il	0.9	0.9	0.6	0.6	0.8
ap	1.0	1.0	0.3	0.3	0.3
wo	1.4	0.2	0.0	0.0	0.0
en	5.6	5.3	3.3	3.1	3.1
hy	5.1	4.9	4.8	5.0	4.9

	19018a Shepherd	19041 Herdsman	19044 Herdsman	19103c Shepherd	19103b Shepherd
SiO_2	68.44	71.30	71.50	72.64	73.34
Al_2O_3	15.44	13.76	14.66	14.07	13.35
TiO_2	0.49	0.20	0.22	0.36	0.30
Fe_2O_3	1.17	0.47	0.33	0.77	0.58
FeO	2.08	2.02	2.28	1.45	1.27
MnO	0.04	tr	tr	0.02	0.02
MgO	1.46	0.42	0.44	0.49	0.37
CaO	3.47	1.66	1.50	1.60	1.41
Na_2O	3.72	3.85	4.53	4.25	4.13
K_2O	3.32	3.88	4.07	4.08	4.45
H_2O+	0.31	1.95	0.20	0.11	0.33
H_2O-	0.08	0.35	tr	nd	0.03
P_2O_5	0.21	0.03	none	0.11	0.18
Cl	0.03	nd	nd	nd	0.08
S	0.03	0.21	0.21	nd	0.10
BaO	0.06				
	100.35	100.10	99.94	99.95	99.94

TABLE 1 (*Continued*)

qu	24.5	28.8	24.0	27.8	28.9
or	19.5	22.8	24.5	24.5	26.7
ab	31.4	32.5	38.2	35.6	34.6
an	15.6	8.0	7.2	7.2	4.5
C	—	0.2	—	—	—
di	0.9	—	—	—	1.4
hy	5.1	3.9	4.7	2.7	1.5
mt	1.9	0.7	0.7	1.2	0.9
il	0.9	0.5	0.5	0.8	0.6
ap	0.3	0.1	—	0.3	0.3
wo	0.5	0.0	0.0	0.0	0.7
en	3.5	1.0	1.1	1.2	0.9
hy	2.0	2.9	3.6	1.5	1.3

	19103 Herdsman	19103 Shepherd	19033a Shepherd	19007 Herdsman
SiO_2	72.75	73.59	73.59	74.10
Al_2O_3	14.34	13.78	14.03	13.33
TiO_2	0.20	0.27	0.31	0.20
Fe_2O_3	tr	0.60	0.42	tr
FeO	2.10	1.30	1.43	1.68
MnO	tr	0.02	0.02	tr
MgO	0.43	0.33	0.36	0.38
CaO	1.34	1.39	1.38	1.45
Na_2O	3.73	4.19	4.04	3.86
K_2O	4.27	4.32	4.34	4.50
H_2O+	0.30	0.14	0.12	0.29
H_2O-	0.22	nd	0.06	0.05
P_2O_5	nil	0.12	0.09	nil
Cl	nd	nd	0.03	nd
S	0.22	nd	0.02	0.22
	99.90	100.05	100.24	100.06
qu	29.4	28.8	29.7	30.0
or	25.6	25.6	25.6	26.7
ab	32.0	35.6	34.1	32.5
an	6.4	6.1	6.1	5.6
C	1.0	0.2	0.4	—
di	—	—	—	1.4
hy	4.3	2.1	2.5	2.8
mt	0.2	0.9	0.7	0.2
il	0.5	0.6	0.6	0.5
ap	—	0.3	0.3	—
wo	0.0	0.0	0.0	0.7
en	1.0	0.8	0.9	0.9
hy	3.3	1.3	1.6	2.6

19141	Basalt, ophitic. Cedarville andesite, Stone Coal Valley near Pit River bridge. ″III, 5, 4, 5.
19123	Basalt, ophitic. Warner Group, Laird's Ranch. ″III, 5, 4, 5.
19071	Basalt, ophitic. Massive Lava Group, Bear Mountain. (II)III, 5, 4, 5.
19142	Basalt, ophitic. Modoc Basalt, near Burnt Lava Flow. II(III), 5, 4, ″5.
19144	Basalt, porphyritic. Massive Lava Group, near Medicine Lake. Gonyer analysis, II, 5, ″4, (4)5. Herdsman analysis, II, 5, 4, (4)5.
19116	Basalt, intersertal. Modoc Basalt Group, near Sharp Mountain. II(III), 5, (3)4, (4)5.
19086	Basalt, intergranular. Modoc Basalt Group, cinder cone northwest of Medicine Lake. II, (4)5, 3″, 4(5).
19143	Basalt, intergranular. Modoc Basalt Group, Burnt Lava Flow. II, ″5, (2)3, 4.
19145	Andesite, porphyritic. Massive Lava Group, Garner Mountain. II, ″5, 3, 4.
19063	Andesite, trachytic. Platy Andesite Group, south of Medicine Lake, platy phase. II, 4(5), (2)3, 4″.
19064	Andesite, trachytic. Surface phase of 19063. ″II, 4(5), ″3, 4″.
19106	Dacite, porphyritic. Obsidian Group, Big Glass Mountain. I(II), 4, 2(3), (3)4.
19099	Dacite, porphyritic. Obsidian Group, Medicine Flow. I(II), 4, 2(3), (3)4.
19018	Dacite, porphyritic. Obsidian Group, surface phase of Medicine Flow. I(II), 4, (2)3, 3″.
19018a	Dacite, porphyritic. Obsidian Group, oxidized surface phase of Medicine Flow. I″, 4, 2(3), (3)4.
19041	Pumice, rhyolitic. Obsidian Group, Pumice Stone Mountain. I, 4, 2, 3(4).
19044	Obsidian, trachytic. Massive Lava Group, north slope Medicine Lake Highland. I, 4, ″2, 3(4).
19103c	Obsidian, rhyolitic. Obsidian Group, Big Glass Mountain. I, 4, 2, 3(4).
19103b	Obsidian, rhyolitic. Obsidian Group, Big Glass Mountain. I, 4, 1(2), 3″.
19103	Obsidian, rhyolitic. Obsidian Group, Big Glass Mountain, Herdsman analysis, I, 4, ″2, 3″. Shepherd analysis, I, 4, ″2, 3(4).
19033a	Obsidian, rhyolitic. Obsidian Group, Little Glass Mountain. I, 4, ″2, 3″.
19007	Obsidian, rhyolitic. Massive Lava Group, south slope Medicine Lake Highland. I, ″4, (1)2, 3.