GEOLOGY AND PETROLOGY OF THE LAVA MOUNTAINS
SAN BERNARDINO COUNTY, CALIFORNIA

Thesis by

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ABSTRACT

The Lava Mountains are a range of low mountains along the northern edge of the Mojave Desert, California. The pre-Tertiary rocks consist of a few small pendants of metamorphic rocks in Atolia quartz monzonite. Overlying these are small patches of volcanic and sedimentary rocks, probably Tertiary, which project into the later formations. The major sedimentary unit is the middle Pliocene Bedrock Spring formation; it consists chiefly of arkosic sandstone and conglomerate with lesser amounts of siltstone and brecciated volcanic rocks. Overlying this formation are two late Pliocene formations, the Almond Mountain volcanics and Klinker Mountain volcanics in the eastern and western parts of the area, respectively. Small areas of other late Pliocene(?) volcanic rocks are locally present. Overlying these are flows of the Lava Mountains andesite of very late Pliocene age. The Pleistocene(?) Christmas Canyon formation is restricted to the eastern half of the area. A few small dikes of basalt cut this formation. Quaternary gravels, alluvium, and travertine are the youngest deposits.

Within the area, three fault systems converge. The Garlock fault trends N. 75° E. along the north side of the area; it is a left lateral fault. The Blackwater fault trends N. 45° W. in the southeastern part of the region; it has right-lateral and normal displacements. The Brown's Ranch fault zone and its associated faults trend about N. 55° E. in the western part of the area; both left-lateral and dip-slip displacements are found. The Dome Mountain anticline trends parallel to and south of the Garlock fault.

Remnants of late Cenozoic pediments indicate that the drainage at that time was toward the north; later, the eastern part of the region warped, thus blocking the previous drainage direction.

No commercial mines are in the area although extensive prospects are present in the southwestern portion.

All of the volcanic rocks are plagioclase andesite porphyries. Plagioclase (3-23 percent), biotite (0-2 percent), orthopyroxene and clinopyroxene (0-2 percent), quartz (0-3 percent), and opaques (1-11 percent) are found as crystals in a partly-crystalline to glassy groundmass. As the Pliocene volcanic sequence progressed, the lavas became more homogeneous, more effusive, and more frequently erupted. The mineral and chemical compositions did not change systematically. The melt originated by the fusion of quartz monzonite. There is no evidence of fractionation, crystal settling, or continued assimilation during the volcanic sequence.

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Part I: Introduction

The initial purpose of this project, then under the auspices of the U. S. Geological Survey, was to estimate the thickness and extent of Pliocene sediments exposed in the Lava Mountains and to determine the relative position of the vertebrate fossil localities in the stratigraphic section. Toward this end, mapping was done by the author, accompanied by George N. White, in the fall of 1952. As mapping progressed it became evident that much information could also be gathered about the late Cenozoic history of the Garlock and Blackwater faults and their effect on this part of the Mojave Desert. It also became clear that the volcanic rocks of this area were exceptionally well exposed and were relatively unaltered. Furthermore, the entire volcanic sequence was preserved and the activity could be dated accurately as post-middle Pliocene.

This report consists mainly of the results of work by the writer on the problem of the petrology, petrography, and petrogenesis of the volcanic rocks of this area during the period September 1954 to April 1956.

The field work was carried out in two stages: the first extended from September to November 1952. Thirty-four days were spent in the field and about 30 square miles were covered. The second stage included September through December 1954 plus several weekends in 1955. In this stage, 93 more days were spent in the field and the number of square miles mapped was increased to about 125.

The laboratory work, compilation, and writing was done for the most part in Claremont, California, in the office of the U. S. Geological

Survey. The spectrochemical analyses were made by the writer using the facilities of the Division of Geological Sciences at the California Institute of Technology. The chemical analyses were made by analysts of the U. S. Geological Survey in Washington, D. C.

TERMINOLOGY

The sedimentary rock names used throughout this report are in accordance with those suggested by Wentworth (1922). Plutonic rock names follow the recommendations of Travis (1955).

Volcanic sediments and breccias are named in the following manner: "Tuffs" are those rocks that appear to be made up almost entirely of individual mineral and glass fragments. "Tuff breccias" are those made up of angular fragments greater than 2 mm in diameter, usually volcanic, in a matrix of tuff. "Pyroclastic rocks" are those that consist of heterogeneous volcanic material, mostly less than 2 mm in diameter and generally unsorted. "Pyroclastic breccias" are rocks containing larger angular pyroclastic fragments in a pyroclastic matrix. "Flow breccias" consist of angular fragments, greater than 2 mm in diameter, in a lava matrix. "Flow conglomerates" consist of rounded fragments in a lava matrix. "Volcanic breccias" consist of large angular fragments of any of the above rocks in a matrix of volcanic material, usually pyroclastics.

Volcanic rock names are based on the mineral content that can be determined with the unaided eye or hand lens. The primary subdivisions are based on the ratio of potash-feldspars to plagioclase, and on the presence or absence of quartz. The division between basalt and andesite is based on the presence or absence of olivine. For those rocks in which the identification of the visible minerals is doubtful, terms such as dacitic, andesitic, and basaltic are used. This terminology is summarized in table 1.

This technique of naming volcanic rocks conflicts with two commonly used conventions: The first -- identification by means of chemical analyses -- is felt to be unworkable. In the first place, only a small fraction of the rocks of an area can ever be identified if this method is used, and secondly, and more important, the system tends to obscure the difference between rocks that have significant mineral or textural differences. True, volcanic rocks which have a high percentage of glass or submicroscopic material cannot tell the investigator much about their gross composition. It seems, however, that if chemical analyses are made, the information from them should only be added in the form of a modifier to the mineralogical rock name rather than alter the name assigned to it before the analysis was available. A classification system should be independent of the examination method. Only in this way can we avoid the anomaly of many volcanic rocks having two different names -- one before and one after chemical analysis.

The second discarded convention for volcanic nomenclature is the division between andesite and basalt based on the plagioclase composition. This has been found to be unworkable by many petrographers forced to deal with strongly zoned plagioclase. Williams (1942) has stated the hopelessness of this method well. Thayer (1937) found the presence or absence of olivine to be the more workable convention to follow and a modification of his convention is used here.

In the color descriptions of rocks and minerals, the terminology of the Rock Color Chart (Goddard 1948) has been used where possible.

Volcanic rock classification used in this report

Potash feldspar > 2/3 of total feldspar		Potash feldspar 1/3 to 2/3 of total feldspar		Potash feldspar < 2/3 of total feldspar			
				Olivine < 2%		Olivine > 2%	
Quartz > 5%	Quartz < 5%	Quartz > 5%	Quartz < 5%	Quartz > 5%	Quartz < 5%	Quartz > 5%	Quartz < 5%
rhyolite	trachyte	dellenite (quartz latite)	latite	dacite	andesite	quartz basalt	basalt

Light colored fine grained rock: felsite

Dark colored fine grained rock: trap

(Modified after Travis, 1955)

Color names obtained from this chart are always followed by the parenthetical symbol (e.g. 5GY8/2).

In the descriptions of rocks in thin section, the terminology, optical properties, and curves given in Winchell and Winchell (1951) have been used with the following four additions or modifications: 1) The borderline between "hornblende" and "oxyhornblende" has been drawn at $C \wedge Z = 10^{\circ}$. 2) In the description of groundmass compositions, the term "anisotropic 'glass'" has been used. It refers to that portion of the groundmass which shows anisotropic properties -- which are more pronounced in conoscopic light -- but none of the other optical properties necessary to define a "mineral". 3) Opaque materials have been so called without regard to the properties that might distinguish hematite, magnetite, ilmenite, etc. 4) The term "calcic rim" has been used to denote the outermost zone of plagioclase crystals which consists of a more calcic plagioclase than the zone on which it rests.

In describing locations on the geologic map, the following abbreviated system of numbering, modified from the system used by U. S. Geological Survey groundwater geologists, is used: Each of the seven townships and ranges covering the mapped area have been assigned a capital letter as shown on plate 2. The sections within each township have retained the usual numbering system. Each section has, when necessary, been divided into 16 squares and each assigned a small letter, as shown in plate 2. Thus, any 1/16 of a square mile area can be easily referred to as, for example "D23-j". This refers to "NW $\frac{1}{4}$ of SW $\frac{1}{4}$, Sec. 23, T. 29 S., R 41 E".

The terms "Mojave Desert", "Sierra Nevada", and "Basin Ranges" are used to designate the natural provinces as outlined by Jahns (1954, chap. 1, p. 11).

METHODS OF INVESTIGATIONS AND RESULTING ACCURACY

FIELD WORK

The reconnaissance map shown in plate 1 was made by a combination of Jeep-reconnaissance and aerial-photograph interpretation. Mapping progressed at the rate of about 20 square miles per day. No formations were established and only lithologic units have been mapped. The resulting map is, of course, only a first approximation of the distribution of rock types in the area.

The geologic map of the Lava Mountains, plate 2, was made by mapping on aerial photographs at a scale of about 1:20,000. The geology was then transferred to a topographic map at the final scale of 1:24,000.

The geologic map covers parts of three 15-minute topographic quadrangles. The western half is on the Randsburg quadrangle which was made in 1900 by plane table methods, and published at a scale of 1:62,500. The Searles Lake and Cuddeback Lake quadrangles, published in 1948 and 1955, respectively, were made by photogrammetric methods and were published at a scale of 1:62,500. The line along which the Randsburg quadrangle and the Cuddeback Lake quadrangle join has been altered by the writer. The contours of the Randsburg quadrangle have been erased along a zone about 1 inch wide, west of the join line, and the topography has been redrafted so that it more nearly blends with that on the Cuddeback Lake quadrangle. Inasmuch as the newer quadrangles have a contour interval of 40 feet and the older quadrangle has a contour interval of 50 feet, only the even 200-foot contours have been joined across the boundary.

The geology was transferred from air photographs to maps by inspection and by proportional dividers. On the newer maps this presented few problems. On the Randsburg quadrangle, the geology has generally been distorted to "fit" the topography. However, high-angle faults and contacts have been kept nearly straight in order to keep the proportions and the general geometric relations as near reality as possible. As a result of these necessary steps, this portrayal of the geology could be reproduced by another person only with difficulty. On the Searles Lake and Cuddeback Lake quadrangle, however, it is hoped that the geology is as accurate as the topographic maps upon which it is plotted.

MICROSCOPIC STUDY

Mineral Identification and Petrography

The bulk of the microscopic study of the rocks was done on thin sections. Most mineral identifications and all textural studies were made in this way. Some supporting data were obtained by oil immersion methods. It was found that the mineralogy of these rocks was simple if "general" mineral names were used; however, to get data that would allow more specific names (e.g. distinguishing pigeonite from augite) would have taken more time than seemed warranted. The feldspars are especially complex and, although they are the most abundant mineral in the rock, their composition can be stated only in very general terms; the compositional data that are given were obtained by using extinction angles on albite twins with a few supporting determinations with immersion oils.

All thin section studies were done in a predetermined random order. By this method, it was hoped that any "trends" or "formation characteristics" that appeared out of the assembled data could be considered "real" and not simply the result of migrating experimental techniques and personal philosophies.

Modal Analyses

Modal analyses were made on the twenty-four rocks for which chemical and spectrochemical data were available. The modes were obtained by a point-counting technique modified after Chayes (1949). The modifications were outgrowths of discussions with Chayes at the outset of this work and the writer would like to thank him for that help. For each rock, a thin-section cut at an angle that showed no strong linear structures was used. The slides were studied in a pre-determined random order. On each slide between 1,400 and 1,500 points were counted which were laid out to form a grid with cells that measured 0.3 mm in one direction and 1 mm in the other. Cavities in the rock were omitted from the count, but where an identifiable mineral was lost in the thin-section grinding, it was tabulated as if present.

It appeared by inspection that many rocks contained plagioclase crystals which were of two general sizes. This hypothesis was tested on three randomly selected rocks by making measurements of the longer dimension of about two hundred crystals which were selected at random by use of a point-counting stage. The lengths were measured by a micrometer ocular. The results of this study are shown in figure 1. They seem to indicate that two general size classes of plagioclase are present. The smaller class shows the most common length to be about 0.1 mm. The most common length of the larger crystals is not well defined because not enough crystals were measured to get a good statistical sampling. However, there is a distinct minimum on each of the five curves between 0.2 and 0.3 mm. For simplicity, 0.3 mm was selected as the division between "megaphenocrysts" and "microphenocrysts" for the modal analyses and throughout the work.

To determine the reproducibility of point counts for this type of rock and by the method used, two rocks were analyzed three times and one was analyzed twice. For each rock analyzed three times, the first two counts were made within a few days of each other, and the third was made about 10 months later. For the rock which was analyzed twice, the counts were made about 10 months apart. All counts were made with the same microscope and using the same conventions. The results are shown in appendix I. These show that any figure is probably reproducible to within 1.5 percent of the total rock percentage although the percentage error of any value with respect to the average amount of that component present may be much higher. The most extreme examples of variability are in those components present only in small amounts; these, of course, have not been sampled in a statistically satisfactory way.

SPECTROCHEMICAL ANALYSES

Spectrochemical analyses were made on the 24 rocks also analyzed for modal composition and gross chemistry. The facilities at the

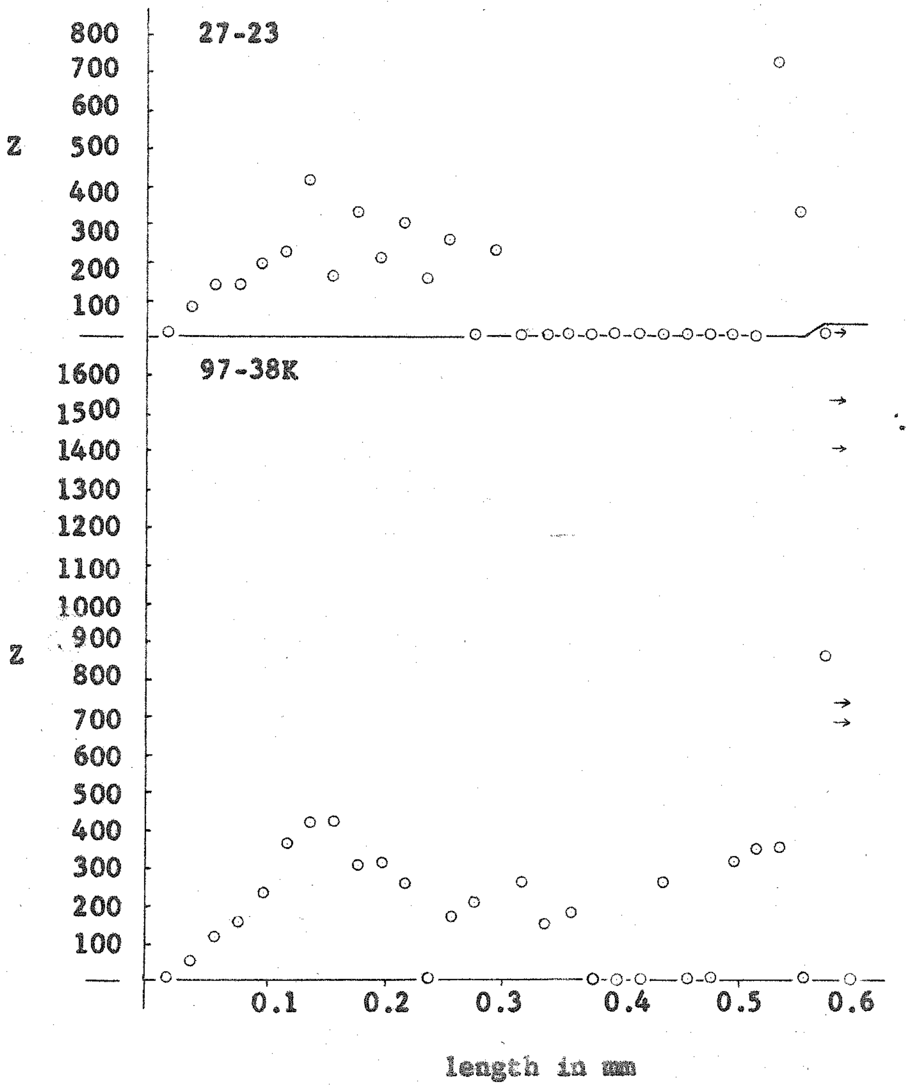


Figure 1a. Graph showing the "natural" division of plagioclase crystals into "megaphenocrysts" and "microphenocrysts". L = maximum length of the crystal; N = the number of crystals of that length; $Z = \frac{1}{2} L^2 N$. "Z" represents the total area, and thus volume, of all plagioclase crystals of any given length. The resulting graph measures, relatively, the volumes of rock accounted for by each size of plagioclase crystals found in that rock. In each thin section, about two hundred crystals were measured which were randomly selected by a point-counting stage; only the crystals that came directly under the cross-hairs were measured. The upper graph is sample 27-23 from the Lava Mountains andesite (Tl); the lower graph is sample 97-38K from the Klinker Mountain volcanics.

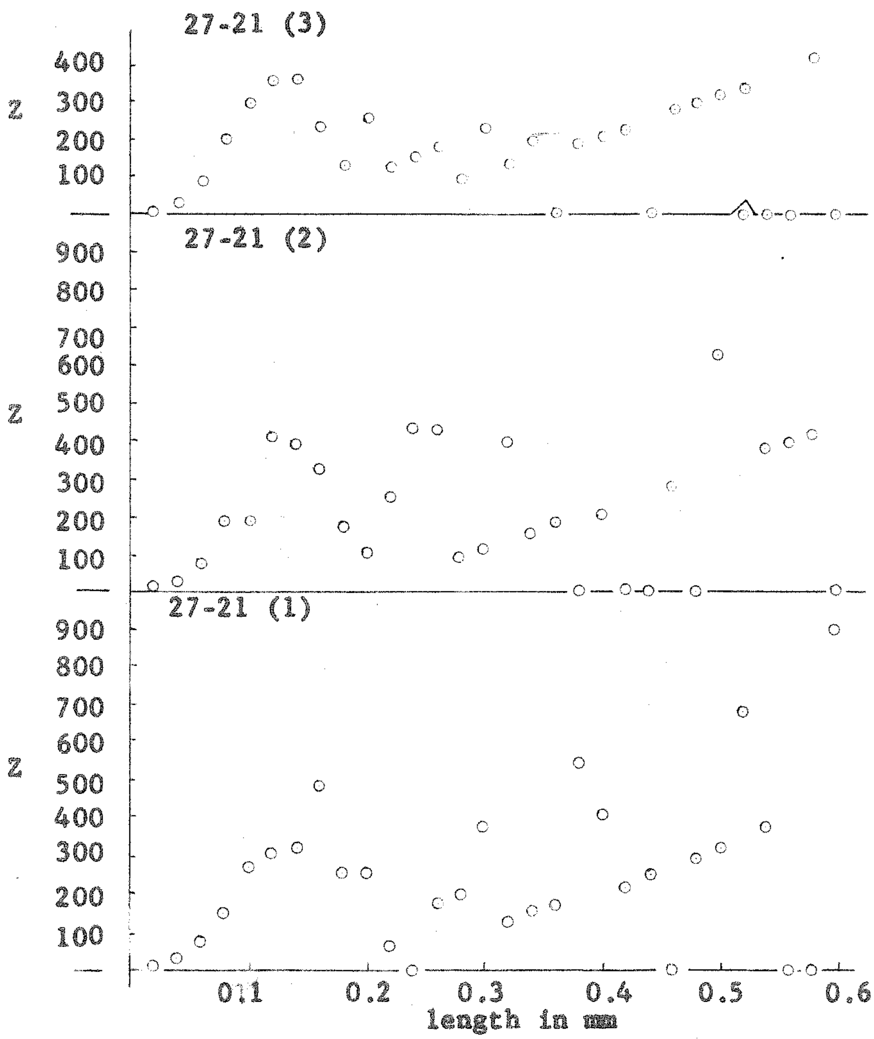


Figure 1b. Graph constructed the same as in 1a. All three are measurements on the same rock. Each graph is made from a thin section cut normal to the other two; this is to test the role of aligned minerals in the results shown in figure 1a. The sample, 27-21, is from the Lava Mountains andesite (Tl).

California Institute of Technology, Division of Geological Sciences, were used, and the analyses were made by the writer under the direction and supervision of Arthur Chodos.

The instruments and procedure used were as follows:

The spectrograph was a Jarrell-Ash 21-foot model with a diffraction grating giving a 5.2 A/mm dispersion in the first order. Each 25-mg sample was held in a graphite anode, shaped in the manner described by Myers (1951); the cathode consisted of 1/8-inch graphite rod pointed in a pencil sharpener. The samples were burned to completion in a 15 ampere D.C. arc. The sample bearing anode was spaced 4 mm from the cathode; the electrode-pair was magnified five times and focused on the 25 micron slit. The laboratory working curves were based on measurements of a standard "pegmatite base", (6 parts quartz, 4 parts microcline, 0.1 part Fe_2O_3) into which known amounts of the element to be measured were added as minerals or oxides. The measured wavelength range was 2300 A to 4800 A. The photographic plates were Eastman Kodak III-O, and they were developed for 4 minutes at 20°C in DK-50 developer.

The densitometry was done on an Applied Research Laboratory Densitometer. All the plate calibrations are based on the known intensities (Dieke & Crosswhite, 1943) of 13 Fe lines in a low-iron pegmatite standard that is used in the laboratory. Eight of these standards were burned for each of the two plates, two at the beginning and end and four in the middle.

Contamination of the sample was negligible for most spectrochemically analyzed elements. Probably some iron and iron-alloy elements were introduced from the hammer used in the initial breaking. Possibly some of the Pb values are high as a result of contamination by chips of paint from the side and handle of the hammer. The "diamond" mortar probably added very little. Some Al was probably added by the sample splitting procedure. During the final grinding, only small amounts of SiO_2 were added. Contamination from the electrodes is limited to V (up to about 40 ppm), B (up to about 5 ppm), and insignificant amounts of Si, Ti, and possibly Fe.

The samples for analyses were collected and prepared in the following manner: At the predetermined portion of the sections or localities to be sampled, two to three pounds of rock, free of weathered surfaces, were collected. These were then reduced to fragments $\frac{1}{2}$ to 1 inch in diameter. The individual fragments were air-jetted to remove the dust and other impurities. Pieces weighing about 150 g were selected and these were then crushed in a "diamond" mortar until the entire sample passed through a 40-mesh cloth screen. The 40-mesh material was then split by means of a pure aluminum Jones-type splitter until one sample of about 10 g was obtained. This was used for the spectrochemical analyses and the balance was retained for chemical analyses. The 10 g sample was then reduced to a flourlike fineness in an agate mortar. The 25 mg samples actually analyzed were grab samples from this final product.

To determine the reproducibility of these spectrochemical analyses, two steps were taken: 1) All samples were analyzed at least in duplicate, four samples were analyzed four times, and one sample was analyzed six times. The results and the mean deviation are shown in appendix I. 2) On each plate, a series of duplicates of "G-1" and "W-1", described and discussed by Fairbairn (1951), were analyzed at the beginning and end of each plate; the values obtained are given in appendix II. The latter step may allow a common basis of comparison for values obtained in this work and values obtained by others who also analyze these standards.

As the result of the differences in the behavior of various elements, and possibly as a result of incomplete mixing for these elements found in high amounts in sparse minerals (e.g. zircon), there is a great range of reproducibility. Consequently, the value used for each element is different. These limits of reproducibility are, of course, much better than those obtained by less ideal conditions involving different operators, different instruments, and different photographic emulsions. Consequently, these limits can only be used as significant for this particular batch of spectrochemical data.

The spectrochemical data have been rounded in two stages: The figures and graphs portray the data rounded to two significant figures. The tables contain the results with all numbers less than 100 rounded to one significant figure. It was found that most of the curves and graphs showed "smoother" statistical-trends if the partially rounded data were used. That the trends are not imaginary can be shown by comparing the curves for Fe, Mn, and Ti as analyzed by both chemical and spectrochemical methods. The tables have used more rounded values to discourage the use of the individual data beyond their reproducibility.

CHEMICAL ANALYSES

The samples for chemical analyses were prepared along with those for spectrochemical analyses. The residue from the sample delegated to spectrochemical analyses was split as many times as necessary to reduce it to about 20 g. That sample, already screened to 40 mesh, was then submitted to the Washington laboratory of the Geological Survey for a "rapid" rock analysis (Shapiro and Brannock, 1956).

Three of the rocks were submitted in duplicate under different sample numbers. The two duplicate samples were "splits" of the same "subsplit" and thus may be considered to be as nearly identical as possible. Duplicates were felt necessary because the accuracy claimed for the analytical method (Shapiro and Brannock, 1956) was probably more conservative than necessary for this type of situation, namely, a group of similar rocks analyzed in the same batch. Inasmuch as all the microscope work indicated that the differences between the rocks would be slight, it was felt that if more analytical precision could be shown for these particular samples, smaller differences between rocks could be considered significant. As shown in appendix I, the reproducibility of most elements was found to be better than that claimed by Shapiro and Brannock. The reproducibility demonstrated here is used throughout this report.

Part II: Geology and volcanic petrology

GEOGRAPHY

The Lava Mountains are in the northwestern part of San Bernardino County, California, 95 miles north of San Bernardino and 85 miles east of Bakersfield (fig. 2). The area mapped is bounded on the north by Spangler valley, an arm of Searles Lake valley, on the west by portions of the Rand Mountains and Summit Diggings, on the south by Red Mountain and Cuddeback Lake valley, and on the east by the alluviated valley containing the U. S. Navy's "Randsburg Wash" firing range.

The climate is warm and arid; annual precipitation averages between 5 and 10 inches (Bailey, 1954), most of which falls in the winter months, sometimes as snow. The flora consists dominantly of "grease-wood" and "sage", and on arkosic and granitic areas Joshua trees are found. Animal life is represented chiefly by rabbits and small rodents, although snakes (including rattlesnakes), coyotes, quail, and groundhogs have been seen. Figure 3 shows the general aspect of the region.

LOCAL HISTORY

Little is recorded about the history of this area except in discussions of the Randsburg Mining District to the west. In that area, gold was first discovered in 1895, tungsten in 1904, and silver in 1919. Each of these discoveries set off a new wave of prospecting in the Lava Mountains and almost every square mile contains claimed areas and evidence of prospector's camps. The well-known

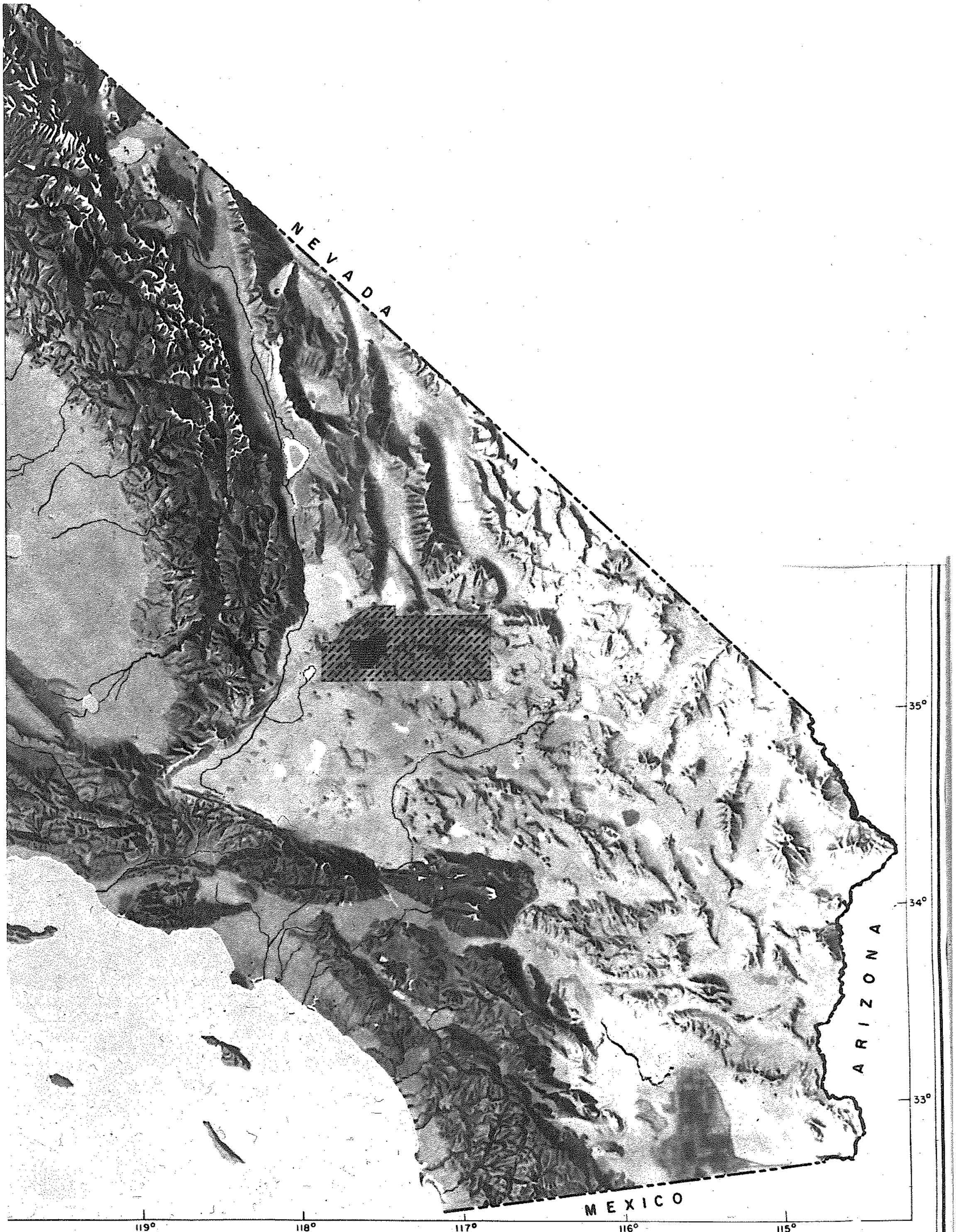


Figure 2. Index map of southern California showing the positions of plate 1 (diagonal dashed area) and plate 2 (heavy horizontal lines) of this report. Scale is about 60 miles per inch.

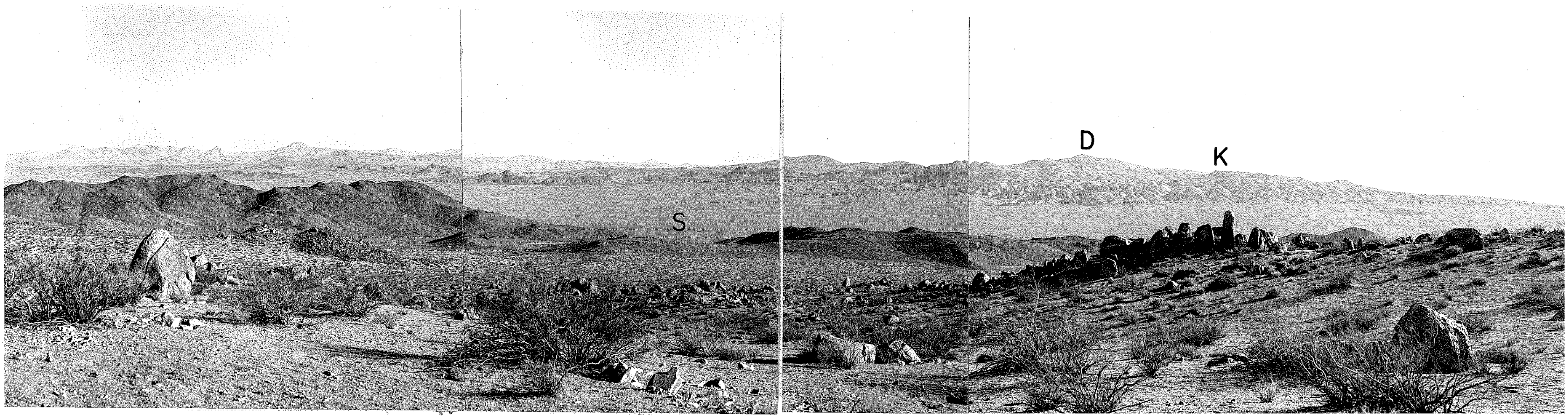


Figure 3a. Panorama view of the Lava Mountains from the north. Spangler Valley (S), Dome Mountain (D), and Klinker Mountain (K) are labeled.

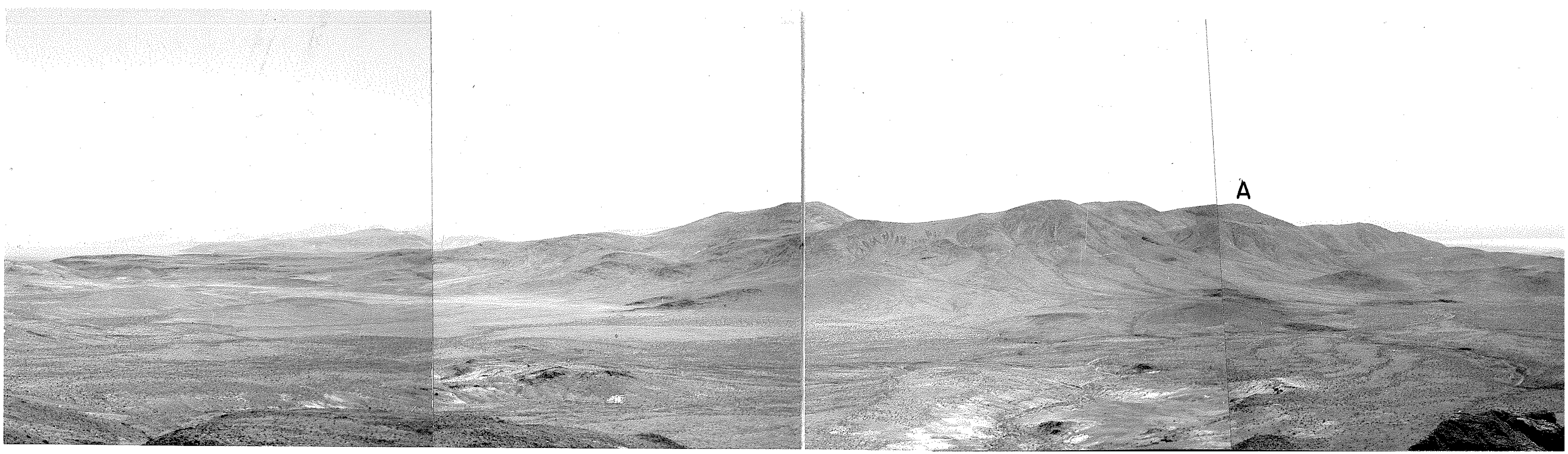


Figure 3b. Panorama view of the eastern Lava Mountains from the west. Almond Mountain (A) and Cuddeback Lake (C) are labeled. The Brown's Ranch fault zone is in the foreground depression.

20-Mule Team Borax trains used to pass a few miles south of this area, across Cuddeback Lake, and the Trona Railway, built in 1914 into Searles Lake valley, is only a few miles north of the region. However, no historical events of note seem to have occurred in, or because of, the Lava Mountains.

PREVIOUS STUDIES

Although the Randsburg Mining District was studied by several geologists soon after its discovery, no geologic map including the Lava Mountains was published until 1925. This was C. D. Hulin's report on the Randsburg quadrangle which, although concerned primarily with the mines and mining district, did summarize the regional geology of the quadrangle including the western portion of the Lava Mountains. A few years later, Hulin made a reconnaissance map of the region now covered by the Cuddeback Lake and Pilot Knob quadrangles and the surrounding areas, and this map was published at a scale of 1:500,000 as part of the geologic map of California (Jenkins, 1938). Since that time no geologic maps of this area have been published.

Below are listed, and annotated, the published works which cover or have bearing on the Lava Mountains area:

Gale, H. S., (1915), Salines in Owens, Searles, and Panamint Basins, southeast California: U. S. Geol. Survey Bull. 580-L, p. 251-323. A description of a chain of lakes formed during the Pleistocene; Searles Lake formed the shorelines on the north side of the Lava Mountains.

Hess, F. L., (1909), Gold mining in the Randsburg quadrangle, California: U. S. Geol. Survey Bull. 430, p. 23-47. A description of the mining that existed at that time with a general description of the regional geology. Describes and names the Garlock fault. No geologic map.

Hulin, C. D., (1925), Geology and ore deposits of the Randsburg quadrangle: Calif. State Div. of Mines Bull. 95. A good general discussion of the quadrangle and mining geology. Includes a geologic map with 10 units; individual descriptions of all the mines in the quadrangle.

Lemmon, D. M., and Dorr, J. V. N., Jr., (1940), Tungsten deposits of the Atolia district, San Bernardino and Kern Counties, Calif.: U. S. Geol. Survey Bull. 922-H. Geology and mine descriptions in the Atolia District.

Thompson, D. G., (1929), The Mohave Desert Region, California; a geographic, geologic, and hydrographic reconnaissance: U. S. Geol. Survey Water Supply Paper 578. A description of the water resources of the Mojave Desert; it includes descriptions of the region surrounding the Lava Mountains.

Walker, G. W., Lovering, T. G., and Stephens, H. G., (1956), Radioactive deposits in California: Calif. State Div. of Mines Spec. Rept. 49. Mine descriptions of radioactive deposits and near-deposits. Mention is made of the "Alpha Beta Gamma Mine" on the north side of the Lava Mountains.

Wynn, M. R., (1949), Desert Bonanza: M. W. Samelson, Publisher, Culver City, Calif. A popular account of the history of the Randsburg Mining district.

SUMMARY OF REGIONAL GEOLOGY

The Lava Mountains lie on the northern edge of the Mojave Desert. The striking differences between the topography to the north and to the south, as shown in figure 2, are a reflection of the fundamental differences in the geology of the two regions. Within the Mojave Desert there are large areas of plutonic rocks which commonly form pediments. Metamorphic rocks are scarce and are generally restricted to small pendants of highly deformed material. All the fossil-bearing Tertiary rocks are middle Miocene or younger, and the fossiliferous mid-Pliocene rocks of the Lava Mountains are among the youngest Tertiary rocks in the Mojave Desert.

North of the Mojave Desert, in the Basin Ranges, the high mountains consist largely of pre-Tertiary plutonic and sedimentary rocks. Thick and highly deformed sections of Tertiary rocks are known within the area but they form a relatively small percentage of the total.

The dividing line between the Mojave Desert and the Basin Ranges is drawn along the Garlock fault -- on both topographic and geologic bases. This fault, which runs along the north edge of this mapped area, trends northeast to east for a distance of more than 100 miles. North of the Garlock fault, the main faults trend north-northwest; south of the Garlock fault, the most prominent fault system trends northwest. To the north, the faults generally form mountain range fronts; to the south, the faults show little effect on topography.

In the accompanying reconnaissance map, plate 1, the general geologic setting of the Lava Mountains is shown. If the Lava Mountains and Red Mountain are considered as a unit, the Tertiary section is seen to be almost surrounded by large areas of plutonic rocks. Exceptions to this are found to the west where the Lava Mountains Tertiary rocks extend beyond the mapped area, and to the east and southeast where late Cenozoic basaltic flows and rhyolitic plugs rest on plutonic rocks.

The Garlock fault, here trending east-northeast, is well defined. The northwest-trending faults are exemplified by the Blackwater fault;

it extends into the Lava Mountains and appears to be truncated by a fault with a trend similar to that of the Garlock.

SUMMARY OF LAVA MOUNTAINS GEOLOGY

STRATIGRAPHY

The oldest rocks found within the area mapped are metamorphic limestones and slates, and phyllites. They occur only in one small area and show extreme deformation and crushing. These rocks are intruded by the Atolia quartz monzonite; the plutonics form large outcrop areas in the northwestern and the southeastern parts of the mapped area.

Overlying these older rocks are local areas of sedimentary and volcanic rocks, presumably Tertiary, which are now found only as small patches projecting through the later formations. The chief sedimentary formation in the mapped area is the Bedrock Spring formation, a new formation, which consists of about 5,000 feet of coarse-grained arkosic sandstones and conglomerates although locally fine-grained sandstones, siltstone, claystone, volcanic breccias, flow breccias, tuffs, and pyroclastics are found. This formation is known to be middle Pliocene in age on the basis of vertebrate fossils.

Overlying the Bedrock Spring formation are three volcanic units: The Almond Mountain volcanics and the contemporary Klinker Mountain volcanics, both new formations, lie with local unconformities on the Bedrock Spring formation in the eastern and western parts of the area, respectively; both volcanic units consist of interbedded tuffs, pyroclastics, volcanic breccias, flow breccias, sandstones, and conglomerates. Overlying these volcanic sections are flows of the Lava

Mountains andesite, a new formation, which is a dark gray andesite. The volcanic rocks of the Bedrock Spring formation, Almond and Klinker Mountain volcanics, and the Lava Mountains andesite are all petrographically similar. Plagioclase, forming 10 to 20 percent of the rock, is almost always present as euhedral megaphenocrysts, and in most rocks as microphenocrysts. Megascopic biotite and oxyhornblende -- or their opaque pseudomorphs -- form 2 to 10 percent of the rocks. Microscopic crystals of orthopyroxene and clinopyroxene usually form less than 2 percent. The groundmass consists of microcrystals, anisotropic "glass" and glass, commonly with a "dust" of fine opaque material.

Along the northeastern edges of the mapped area, fine-grained arkosic sandstones, with minor claystone, siltstone, and conglomerate are exposed in a section about 200 feet thick. This is the Christmas Canyon formation, a new formation, dated tentatively as Pleistocene. The coarser facies of this formation, generally vesicular-andesite boulder conglomerates, are found as residual caps on the higher hills to the south of the finer-grained exposures. A few dikes of basaltic rocks cut the coarser facies of the Christmas Canyon formation. Subsequently, pediment gravels and alluvium were deposited.

STRUCTURE

Faults within the mapped area fall into three general trends: The Garlock fault and associated faults here trend east-northeast in the northern quarter of the map. The Blackwater fault trends northwest and is apparently truncated by a northeast-trending fault. The

Brown's Ranch fault zone trends northeast through the middle of the mapped area; faults of this trend are numerically the most abundant in the Lava Mountains.

Folds are relatively uncommon throughout the region and only the west-southwest plunging Dome Mountain anticline (see fig. 21) is traceable over any great distance. Numerous other minor folds are found but generally they can only be mapped for short distances.

In Pleistocene time the eastern part of the area was warped into a broad east-northeast trending arch and the northwest drainage was deflected. During late Pleistocene time, shorelines were formed by Cuddeback and Searles Lakes, and local patches of travertine were deposited.

DETAILED STRATIGRAPHY

METAMORPHIC ROCKS

The metamorphic rocks within the area are restricted to the northeastern corner of the map. They crop out as low hills projecting slightly above the gravel veneer of this area and as jagged cliffs bordering the shallow canyons.

The major part of the section consists of impure limestones, calcareous sandstones, and siltstones which are brecciated and iron-stained. The breccia fragments are generally medium to very light gray (N5-8), and the matrix grades from rock of similar composition and purity to an iron-stained material which is yellowish-orange (10YR6-7/4-6). From a distance, the unit weathers to shades of yellow and brown (5-10YR4-6/2-6) in the most iron-stained rocks but the average color is nearer medium dark gray (N3-4). The section is estimated to be about 2,000 feet thick although no field measurements were made.

In spite of repeated search, no fossils were found in these rocks. Consequently, their age can only be stated as older than the Atolia quartz monzonite which intrudes them.

In the El Paso Mountains, rocks of Paleozoic age have been described by Hess (1909), Hulin (1925), and Dibblee (1952). Other metamorphic rocks are known to outcrop to the east and southeast of the Lava Mountains as shown on the reconnaissance map (plate 1). A small patch was described by Hulin in the Garlock fault zone near Hardcash Gulch, just west of the mapped area. The Lava Mountains metamorphic rocks may be equivalent to other metamorphic sections in this part of the desert but no attempt has been made to correlate them.

ATOLIA QUARTZ MONZONITE

In the mapped area are two large outcrops of Atolia quartz monzonite, a rock unit first named and described by Hulin (1925). The first is in the northwestern part of the map (plate 2) and the second is in the southeastern part. Small areas are exposed in sections B26, B27, and in the northeastern corner of the map (in C9) where they intrude the metamorphic rocks.

Hulin designated all of the coarse-grained intrusive rocks in the Randsburg quadrangle as Atolia quartz monzinite. He distinguished the following subtypes: One contains orthoclase, plagioclase, and quartz in equal proportions, plus subordinate dark minerals; a second is similar but contains abundant inclusions of foreign rock; a third, darker in color, contains more calcic plagioclase and a higher proportion of mafic minerals than the above types; and a fourth is composed of feldspar and quartz in almost equal proportions and is virtually devoid of dark minerals.

Northwestern Outcrops

The rocks exposed in the northwestern part of the Lava Mountains area largely consist of the fourth type. Generally they outcrop as rolling flat areas or low hills, although along the north and south edges of the outcrop area, the topography is much more rugged as a result of late Cenozoic displacements along faults. Where extreme brecciation has occurred, the topography resembles "badland" topography. Between these scarps, however, the rocks form a smooth topography. The overall color in this area ranges from grayish pink (5YR8/2) to grayish orange (10YR7-8/2-4).

> Two types of light colored rock are present in this area: The first is, as described by Hulin, virtually devoid of dark minerals. The orthoclase and minor microcline, which form about 25 percent of this rock, are anhedral crystals, slightly sericitized, containing inclusions of apatite, quartz, and plagioclase. The plagioclase forms an estimated 40 percent of the rock and has a general composition of sodic oligoclase; it shows good albite twinning, fair normal to oscillatory-normal zoning, and euhedral to subhedral shapes. Quartz, forming about 35 percent of the rock, is anhedral and contains small crystals of apatite and magnetite. Biotite, much of which is altered to chlorite, forms less than 1 percent, and opaque minerals and apatite are present only in trace amounts.
>
> The second type of light colored rock found here is an aplite. It is probably less abundant that is the first but because of a greater resistance to weathering it outcrops more commonly. It consists of orthoclase, plagioclase, and quartz, with minor microcline, and a trace of chlorite presumably from altered biotite. All the minerals are irregular in shape and size. Some crystals are as large as 1.5 mm but

are generally smaller. The over-all texture is seriate. Myrmekitic structures are not uncommon. The feldspars are slightly altered, especially along cracks, to a clay-like material.

Within this area, darker rocks form about 30 percent of the total. They range in estimated composition from quartz monzonite to granodiorite and tonalite. Biotite, commonly altered in part to chlorite, is the most common dark mineral. Magnetite is sparse, apatite is locally abundant. The plagioclase commonly shows normal to oscillatory normal zoning, and both feldspars are slightly altered to clay or sericite.

Southeastern Outcrops

The second large area of plutonic rocks, in the southeastern corner of the map, is notable for lack of the pink leucocratic and aplitic phases found in the area described above. Instead, near-gray colors predominate although locally iron oxides add a tinge of yellow or orange. Most of this area is deeply weathered and only occasionally can an outcrop of the bedrock be found; in the remaining area the rock is weathered to a coarse plutonic gruss.

Good exposures are scarce, but the predominant rock types here appear to be biotite-monzonite, quartz monzonite, and tonalite. Where exposed along the Blackwater fault, the rocks become much more complex and locally show evidence of silicification.

Although minor in areal extent, an interesting rock type does occur here. It is a hornblende gabbro-aplite complex, shown on the map in section F21.

It consists of euhedral crystals of hornblende, some ranging up to two inches long, and very minor feldspar. In some areas, hornblende appears to form the entire rock. The aplite is present as dikes and apophyses in the gabbro. Chilled zones, one to three inches wide, grade into a pegmatite-like rock toward the middle of the dikes which are as much as five feet wide. All gradations between the hornblende gabbro and aplite are found but these are restricted to the edges of the darker rock areas. In these border-line areas, knotty inclusions of epidote, usually between one-half inch and one inch across, are sometimes present.

No inclusions of the hornblende gabbro were found in the aplite although lenticular zones of hornblende resembling schlieren were found. This evidence, plus the distinct dike-like habit of the aplite, satisfactorily establishes the aplite as the younger of the two.

Other Outcrops

In the northeastern quarter of the Lava Mountains only two small patches of intrusive rock occur. The first, in sections A26 and A27, forms an irregular outcrop approximately 2,000 feet by 3,000 feet. About 90 percent of this area exposes dioritic rocks which are medium- to fine-grained and are brecciated, altered, and silicified. Locally, aplitic phases are present. The remaining 10 percent of the area exposes a grayish-red coarse-grained rock, possibly a quartz monzonite, which weathers to a very coarse gruss. This differs from the pink leucocratic rocks found in the northwestern part of the area in that dark minerals make up perhaps 5 to 10 percent of the total.

The other area of plutonic rock is found in the northeastern corner of the map near the exposures of metamorphic rock. It is a fine-grained diorite or perhaps tonalite. Plagioclase, hornblende, and biotite form the bulk of the rock; quartz is present as interstitial grains and fillings. The plagioclase is in euhedral to subhedral crystals showing good to fair development of albite twins and poor development of Carlsbad twins. Normal zones are found in almost all the plagioclase crystals and alteration of the plagioclase to clay(?) is fairly heavy. Green hornblende is present as subhedral crystals which commonly have been altered to chlorite. Biotite, present as flakes and shreds, has also been partially altered to chlorite.

Age and Relationship to Other Areas

The relationships between the Atolia quartz monzonite and plutonic rocks of other nearby areas is not known. This is partly the result of the lack of detail in the present study and partly a result of the general lack of detail for the plutonic rocks in this part of California.

The age of the Atolia quartz monzonite in this area is known only to be younger than the undated metamorphic section which it intrudes, and older than the middle Pliocene Bedrock Spring formation which overlies it. Hulin (1925) assigned an age of Jurassic on the basis of indirect evidence. The present writer would prefer to keep the date an open question until more direct evidence is available.

TERTIARY SEDIMENTARY ROCKS

Four small outcrops of this rock occur within the mapped area. These are in sections B27 and B33. The unit outcrops as a very light gray (N8) to yellowish gray (5Y8/1) material and is slightly more indurated than the overlying Bedrock Spring formation. The lithology is characteristically a boulder-conglomerate or sandstone with some pyroclastics. The boulders are well rounded, range in size up to 1 foot, and consist of light colored plutonic rocks or banded rhyolitic rocks. The pyroclastic rocks are white (N9) to light orange pink (5YR9/4). The matrix is very coarse-grained sandstone. The section in B27-n is described below:

Thickness (feet)	
11	Arkosic conglomerate, well-bedded. Very light gray (N8) to yellowish gray (5Y8/1). Well-rounded fragments, up to 1 ft across, of quartz-monzonitic rocks, some banded rhyolitic rocks; matrix of very coarse-grained arkosic sandstone forms 95 percent of unit.
18	Arkosic conglomerate, pyroclastics, and tuff; interbedded. Conglomerate colors similar to previous unit, pyroclastics and tuffs white (N9) with streaks of pale brown (5YR6/2). Ratio of clastics to pyroclastics about 1 to 1.
7	Arkosic conglomerate. Well-bedded. Light brown (5YR6-8/4), some very light gray (N8).
33	Sandy tuff. Well-bedded, beds 1-10 in. thick. Yellowish gray (5Y8/1) to very light gray (N8). Sand forms 20 to 60 percent of rock.
69	

Age and Relationship to Other Formations

These rocks are known to be later than the Atolia quartz monzonite and the rhyolitic activity in the area inasmuch as both rocks are found as boulders in the conglomerates. At the location of the measured section, the unit underlies the Bedrock Spring formation with a well-defined 20-degree angular unconformity. At this contact there is a faint suggestion of a fossil soil horizon about 1 foot thick.

No fossils were found in this unit so its age remains unknown except within the limits imposed by the Atolia quartz monzonite, the rhyolitic activity, and the middle Pliocene Bedrock Spring formation. With such a spread it is impossible to make a meaningful correlation with other Tertiary rocks of the Mojave Desert area.

TERTIARY VOLCANICS

Three types of volcanic rocks, known only to be pre-middle Pliocene, occur within the mapped area. The first type is in B33-a and B33-b, the second in E6-l and E6-k, and the third and most extensive in sections A33, A34, and A35.

Type 1

The first type outcrops in various shades of gray, yellowish, and reddish. It is a cliff-forming section of relatively unaltered and well-bedded pyroclastics, tuffaceous sand, and pyroclastic breccia. The Bedrock Spring formation overlies it with an angular unconformity.

Type 2

The second volcanic area is an extremely altered and brecciated zone which weathers to various shades of gray, brownish, and buff and consists of unbedded materials, probably intrusives.

> Lithology and composition -- In hand specimen and thin section, the rocks are seen to consist chiefly of plagioclase, quartz, and groundmass, with minor opaques. The groundmass is predominantly partially crystallized "glass". The plagioclase crystals, ranging in size up to 4 mm, show seriate textures and have weak oscillatory or oscillatory-normal zones and well-developed albite twins; the apparent compositions range from andesine to sodic labradorite.

The quartz occurs generally as fine-grained veins and replacements and probably forms about 15 percent of the rock. Opaque materials, apparently alterations of biotite and hornblende, are not numerous; initially hornblende was more abundant than biotite.

This rock is generally strongly altered. The plagioclase has been replaced by calcite, averaging about 10 percent replacement. The dark minerals have been replaced by opaque iron oxides. Much of the groundmass has been replaced by quartz. The texture shows no lineations and what were once vesicles are now filled by quartz or green opal(?).

Type 3

The third, and most extensive rock in this unit, is bext exposed in sections A33 and A34. Two types make up almost the entire unit: The first, forming perhaps 90 percent of the total, is grayish and weathers to shades of green with brownish orange phenocrysts; the second weathers to almost pure white or yellowish. Both types outcrop as extremely complex areas of resistant jagged rock. The unit is massive and everywhere brecciated by faults and fractures that form no distinct pattern. Apparently it is an intrusive complex.

In hand specimen the darker rock shows a grayish green (5-10GY5-6/1-2) matrix with light brown (5-10YR6/2-4) phenocrysts. The light colored type is white (N9) or yellowish gray (5Y8/1) with only vague suggestions of phenocrysts. Originally the rock probably consisted of plagioclase and amphiboles in a groundmass that formed perhaps three-quarters of the rock. The rock now is heavily altered and crushed.

Lithology and composition -- The plagioclase has been altered to calcite and sericite and minor opaque substances; the ratio of the alteration products is very approximately as follows: Opaques 10 percent, calcite 50 percent, sericite 40 percent. The amphiboles(?) have been largely altered to a serpentine-like mineral, sericite, and opaque substances; the ratio of the alteration products is very roughly as follows: Serpentine 60 percent, sericite 30 percent, and opaques 10 percent. Maximum crystal sizes are: Plagioclase 4 mm, and amphiboles 2 mm. The groundmass is now holocrystalline consisting of patches showing radial and mottled extinction under polarized light, giving the general appearance of fine-grained quartz. Traces of sericite, calcite and serpentine are also found in the groundmass.

A chemical and spectrochemical analysis of the darker rock is given in table 2.

The lighter colored rock type of this unit had an estimated original composition of 20 percent plagioclase, 5 percent amphibole, and 75 percent groundmass. Alteration has now changed the plagioclase into calcite, quartz (chalcedony(?)), and a trace of opaques. The amphibole(?) has been altered to opaque (10 to 50 percent of the original mineral) and zoisite(?). The groundmass now consists of about 98 percent fine-grained quartz(?) with traces of opaques, serpentine, and calcite.

Age and Relationship to Other Formations

All of these described volcanic units are believed to be younger than the Tertiary sandstones (Ts) and the Atolia quartz monzonite (aqm). A contact, found in section A35-q, between type 3 and the quartz monzonite appears to be flat and sedimentary. In the other areas of contact, as in sections A33 and A34, the faulting is too intense to allow any deductions as to their relative ages. The Tertiary sandstones are believed to be older solely because no fragments of these volcanics are found in them. It is very possible that these volcanics are pre-Tertiary; they are much more complexly brecciated than many of the regional Tertiary rocks. However, nowhere in this part of the Mojave area are any unmetamorphosed pre-Tertiary volcanics known. Consequently, an age of Tertiary is preferred -- but not proved.

Modal analyses	Sample number 41-39
Plagioclase megaphenocrysts	---
Plagioclase microphenocrysts	---
Total plagioclase	---
Biotite	---
Hornblende	---
Oxyhornblende	---
Orthopyroxene	---
Clinopyroxene	---
Quartz	---
Opaque minerals	---
Non-opaque minerals	---

Chemical analyses	Sample number 41-39
SiO_2	60.2
Al_2O_3	16.4
Fe_2O_3	1.9
FeO	2.9
MgO	1.4
CaO	4.6
Na_2O	3.4
K_2O	2.5
TiO_2	0.90
P_2O_5	0.22
MnO	0.04
H_2O	3.2
CO_2	2.9
Total	100

Norm (C.I.P.W.)	
Q	18.0
C	---
or	15.0
ab	28.8
an	22.0
di	0.7
hy	5.0
mt	2.8
il	2.6
hm	---
tn	---
ru	---
ap	---
Classification symbol	I.4.3.4

Spectrochemical analyses	
Cr	20
Co	20
Mn	320
Ni	10
Sc	10?
V	50
Fe	3.0%
Cu	30
Ga	10
Ti	2600
B	30
Ba	1100
Be	--
Pb	10
Sr	1000
Yb	2
Y	10?
Zr	100

Table 2: Modal, normative, chemical, and spectrochemical analyses for one sample of the Tertiary volcanics. The modal, normative, and chemical values are percents, the spectrochemical values are parts per million.

The Tertiary volcanics are clearly older than the Bedrock Spring formation as shown by sedimentary relationships in several places. Also fragments of the volcanics -- a distinctive rock type -- are found throughout most of the Bedrock Spring formation in the western and northern parts of the area.

Thus, this unit is younger than the Atolia quartz monzonite, probably younger than the Tertiary sandstones, and definitely older than the mid-Pliocene Bedrock Spring formation.

BEDROCK SPRING FORMATION

The Bedrock Spring formation, a new formation named here, is the major sedimentary rock unit in the Lava Mountains region. It is named after Bedrock Spring in section B31-f, about 1 mile west of the type section.

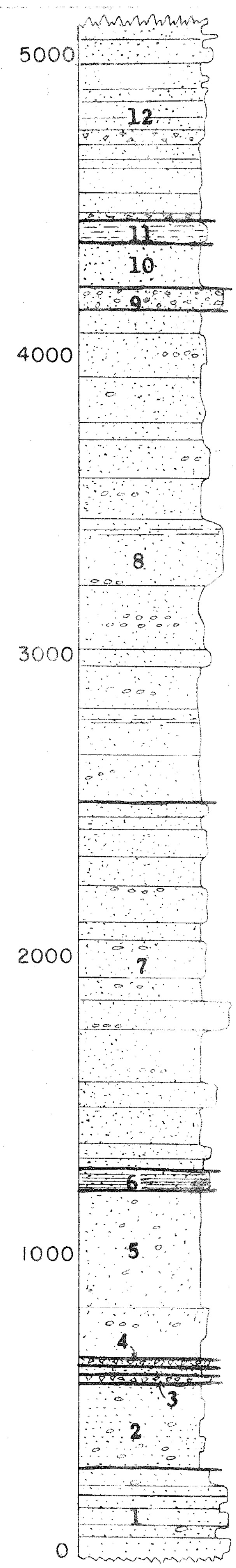
Lithologically, the formation varies from coarse arkosic conglomerates and sandstones that form the bulk of the formation, to finer siltstones, mudstones, and limestones, as well as tuffs, pyroclastics, and volcanic breccias. More than 5,000 feet of section are present. Reliable vertebrate fossils indicate an age of middle Pliocene. The type section is portrayed in figure 4; photographs of rocks from the basal and middle portions of the section are shown in figure 5.

Description of Included Rock Types

Sedimentary clastic rocks (Tbs) --

Sandstones and conglomerates --

The best exposed sections of sandstone and conglomerate are in



12. Sandstone, contains lenses of breccia and conglomerate; some thin tuff beds. Weathers to light green, yellow, or brown. Well bedded.

11. Mudstone, green.

10. Sandstone, conglomeratic lenses. Beds thick to massive.

9. Conglomerate, tuffaceous, matrix of arkosic sandstone. Massive.

8. Sandstone, arkosic; lenses of well rounded dioritic, quartz monzonitic, and rhyolitic pebbles; scattered thin beds of siltstone and mudstone. Generally nonresistant to weathering; most bedding thick to massive.

7. Sandstone, arkosic. Tan to light brown. Generally massive, resistant beds locally present in section.

6. Sandstone, arkosic, lenses of pebbles. Tan to brown. Beds thin to flaggy, resistant.

5. Sandstone and conglomerate. Tan to yellow. Weathers to smooth hillsides.

4. Volcanic breccia, angular fragments of volcanic rock in a pyroclastic matrix. Tan to purple. Resistant to weathering, massive.

3. Pyroclastic breccia. Green to blue-green. Resistant to weathering.

2. Sandstone, arkosic, a very few lenses of pebbles. Yellow to light brown. Massive to thinly bedded.

1. Sandstone, arkosic, well sorted. Pale red. Beds up to 3 ft thick, well defined.

Figure 4. Type section of the Bedrock Spring formation. Thicknesses are in feet.

Figure 5a. The lower part of the Bedrock Spring formation, as exposed in section E5-e, near the base of the type section. The beds weather to a red-brown color in this area.

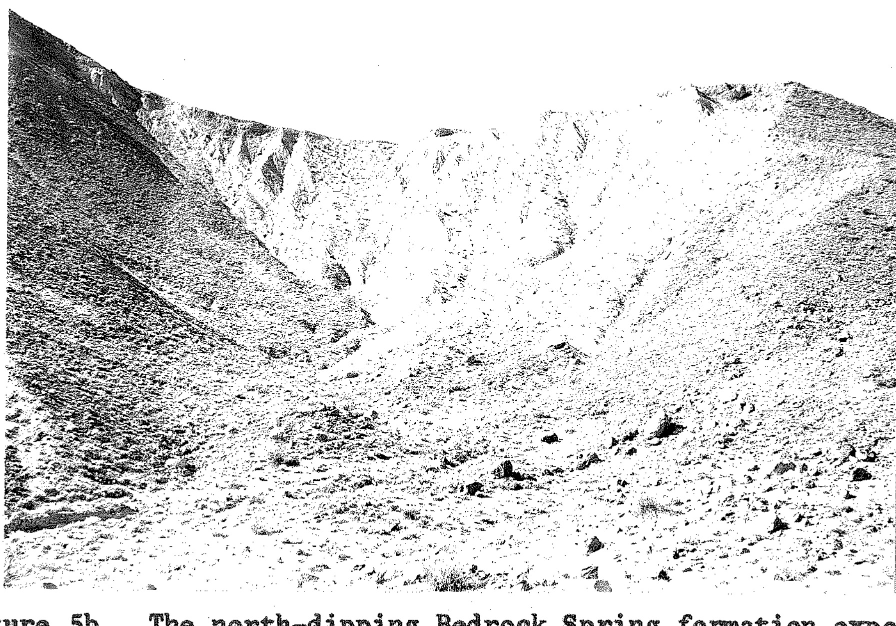


Figure 5b. The north-dipping Bedrock Spring formation exposed in section B30-q, in the middle of the type section. The beds are tan with streaks of red-brown or brown.

the type section and in sections E3 and D2. The rocks generally weather to relatively smooth hills in areas of low relief, and to badland topography in areas where erosion is more intense. The few beds that are well indurated form conspicuous cliffs, ridges, or ledges in what would otherwise be smooth hillsides covered with overburden.

Bedding is difficult to recognize except in the area of best exposure. Where the beds have been indurated or the exposures are good, they are seen to vary from flaggy (e.g. in sections E31-c and E31-f) to massive (e.g. in sections B20 and B29). Few beds can be traced more than 2,000 feet, and most cannot be traced more than 500. Cross bedding structures and channel structures, often with a few larger boulders or cobbles in the bottom of the channel, are found in some of the better exposures. A well exposed section and a detailed view of "typical" sandstone are shown in figure 6. Figure 7a shows the type of landscape in the areas underlain by rocks of this unit.

In most areas the rock colors vary between yellowish gray (5Y7-8/2) and grayish yellow (5Y8/4). A few areas have conspicuously different coloring: The most prominent of these are the "red beds", good examples of which are found in sections E5-e, E5-f, E4-e, and E4-f. Here, the coloring varies between pale red (5YR6-7/2) and moderate red (5R5-7/4). The color seems to be a result of iron oxides but is not obviously a function of grain size, bedding, or any lithologic variable. Red beds are the most abundant in the lower part of the formation. A given bed may change color laterally over a distance of a few hundred feet, grading from red into light green, yellow, or the normal color for this formation. The red coloring does not appear

Figure 6a. The Bedrock Spring formation exposed in section B32-c. Beds dip north at about 10 degrees. This part of the section weathers uniformly to light tan.

Figure 6b. Detail of the lithology shown in the right-foreground of figure 6a. Note the crude graded bedding.

Figure 7a. Aerial view of the north side of the Lava Mountains showing typical outcrops of the Bedrock Spring formation (light colored hillsides). Photograph taken from section E22, looking southwest. Dome Mountain (D) is labeled.

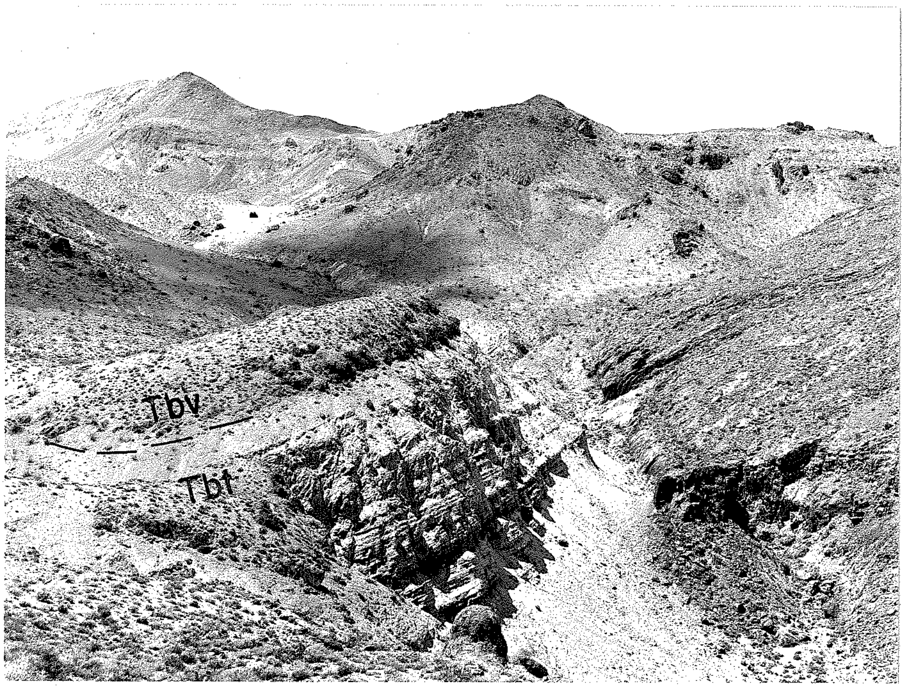


Figure 7b. Pyroclastics (Tbt) and volcanic breccias (Tbt) in the Bedrock Spring formation. Photograph taken in section E5-j, looking northwest. Photograph by R. F. Yerkes.

to be a surface effect, as noted by Hulin (1925, p. 43), inasmuch as material from mine shafts several hundred feet deep show similar coloration.

<u>Lithology and composition</u> -- Generally the sandstones consist of angular fragments showing only crude sorting. The most common size range is between coarse and very coarse sand but finer material is not uncommon. Conglomerate clasts are usually well rounded to subrounded and show little sorting. Fragments larger than two inches are uncommon. They include the following plutonic rocks: pink leucocratic quartz monzonite, pink aplite, gray quartz monzonite, pegmatitic rocks, quartz, and metamorphic rocks, but no hornblende gabbro. Volcanic rocks, which form 10 to 30 percent of the fragments, include purple volcanic porphyries, massive rhyolitic rocks, and rhyolitic rocks showing strong color banding. In many outcrops, there is a small percentage of volcanic rocks that are indistinguishable from the Almond Mountain, Klinker Mountain, and Lava Mountains series of volcanics.

The sandstones and conglomerates are only slightly indurated in most areas; in the "average" outcrop, sand can be gouged out with a pocketknife. The cement appears to be calcite although silicification is locally found (see below).

Silicified sandstones --

Very well indurated sandstones are found in sections D26 and D27 where they have been silicified as a result of intrusive volcanic activity. These rocks possibly should be classed as metamorphic rocks with which they have many physical and petrographic properties in common. The smooth hills are high and steep and the rocks break with a smooth conchoidal fracture. Bedding, where visible, is indicated by linear rows of pebbles. The unit is generally brownish in color, averaging perhaps pale brown (5YR5-7/2-4) although some areas are more orange.

<u>Lithology and composition</u> -- The silicified rock, in sections E26 and E27, consists of about 20 per-

> cent detrital quartz and 40 percent altered feldspar. The remaining 40 percent is fine-grained quartz (and possibly some chalcedony or opal) which now cements the grains together. Minor amounts of sericite(?), serpentine(?), and opaques are also present. Grain sizes range up to 0.7 mm but average about 0.2 mm.

Siltstones and claystones --

Good exposures of siltstones and claystones are found in sections E3-a and E3-g. These rocks weather to low smooth hills, commonly displaying a variety of colors ranging from light green through yellowish to gray. Bedding where exposed is usually distinct and often thin; however, well-exposed rocks of this type are rare. These beds, like most other units in this area, can usually be traced only a few thousand feet along the strike.

> <u>Lithology and composition</u> -- Under a hand lens these rocks appear to consist of silt- and clay-sized fragments with an almost invariable contamination of fine- to coarse-grained sand fragments. In three areas evidence of evaporites was found: The first, in section E3-h, contains efflorescences that taste "salty" and probably consist of halite. The second, in sections B26-a, B26-b, and B26-g, contains many gypsiferous beds. The third, in section B22-g, contains a white residue which was found to be volcanic ash containing traces of a borate; semi-quantitative analysis for B_2O_3 found 0.08 percent (H. Almond, oral communication, 1955).

Limestone --

The best exposed sections of limestone are found in sections B27-h and B26-a. These weather as resistant cliff-forming beds, usually a yellowish or greenish color. The distinct and well-formed beds are generally more than 1 foot thick and some range up to 5 feet. Laterally the limestones grade into other rock types very rapidly and the most continuous bed can be traced only 1,500 feet.

Lithology and composition -- Although no petrography was done on these limestones, in hand specimen they appear to contain large proportions of volcanic ash; presumably this furnishes the green coloration. Some also contain a small percentage of sand and most contain 10 percent or more silt.

Volcanic breccias and flow breccias (Tbv) --

The best examples of this member are found in sections A31, E2, and E4, and are illustrated in figure 7b. The units generally are found as single beds which are more resistant than the surrounding rocks and consequently are well exposed. Colors vary from brownish gray to gray and some have a purplish tint. On the fresh surfaces, the rock is extremely hackly and jagged -- the fragments usually being more resistant than the matrix.

Most of the beds are massive and contain sharp-edged fragments in totally unsystematic orientations. Beds range up to 100 feet in thickness although the average is probably between 25 and 50 feet. Many can be traced for several thousand feet and two may be traced almost a mile along the strike.

Lithology and composition -- The composition of these units is illustrated by the following three megascopic descriptions:

1. Volcanic breccia, consisting of fragments up to 2 inches across, some fairly well-rounded, in a pyroclastic matrix; pebbles and larger fragments form about 90 percent of the total volume. Fragments generally consist of the four following types:
   a) Light brownish gray (5YR6/1) groundmass with phenocrysts of plagioclase, hornblende, and altered biotite.
   b) Medium light gray (N6) groundmass with phenocrysts of zoned plagioclase, hornblende, and euhedral biotite; the plagioclase and hornblende crystals range up to 5 mm in length; the groundmass is glassy to scoriaceous.

c) Light gray (N7) groundmass with phenocrysts of zoned plagioclase, up to 10 mm long, hornblende up to 5 mm long, and euhedral biotite, in a scoriaceous matrix.
d) Medium dark gray (N4) and light olive gray (5Y6/1) groundmass containing phenocrysts of plagioclase, hornblende and altered biotite.

2. Volcanic breccia consisting of fragments, which form about 75 percent of the rock, in a light brownish gray (5YR7/1) pyroclastic matrix. The following four rock types are well represented by the fragments:
   a) Brownish gray (5YR4/1) heavily altered groundmass with phenocrysts of plagioclase, biotite, and pyroxene(?).
   b) Very pale purple (5P8/2) perlitic groundmass with phenocrysts of euhedral biotite and anhedral feldspar.
   c) Medium gray (N5) glassy groundmass with phenocrysts of euhedral biotite and anhedral feldspar.
   d) Very light gray (N8) groundmass of altered glass shards(?) with euhedral phenocrysts of hornblende, biotite, and feldspar.

3. Volcanic breccia consisting of medium light gray (N6) fragments, angular, ranging in size up to 2 inches, in a tuffaceous matrix of the same color. The fragments, all of one rock type, show color banding that results from variations in the composition of the groundmass. Phenocrysts of plagioclase, hornblende, and biotite are visible in the fragments.

The third of these units, the only monolithologic member found in the formation,was chosen to represent the volcanic activity in Bedrock Spring time, so was also subjected to modal, spectrochemical, and chemical analyses. The results are shown in table 3.

The plagioclase is present as euhedral crystals showing a continual gradation of sizes; zones are generally oscillatory-normal although some are normal or mottled; albite twinning is well developed in about half the crystals; the maximum anorthite percentage is 60. Biotite is found in some samples as euhedral crystals with no reaction rim. Oxyhornblende, which may be in part hornblende, is present as euhedral crystals with no reaction rim and very few opaque inclusions. Orthopyroxene, as clear euhedral prisms,

Modal analyses	Sample number 128-32
Plagioclase megaphenocrysts	15.1
Plagioclase microphenocrysts	5.1
Total plagioclase	20.2
Biotite	0.5
Hornblende	6.3
Oxyhornblende	---
Orthopyroxene	1.2
Clinopyroxene	---
Quartz	---
Opaque minerals	1.5
Non-opaque minerals	0.1

Chemical analyses	Sample number 128-32
SiO_2	64.8
Al_2O_3	16.6
Fe_2O_3	1.4
FeO	2.2
MgO	2.0
CaO	4.6
Na_2O	4.5
K_2O	2.0
TiO_2	0.58
P_2O_5	0.20
MnO	0.08
H_2O	1.2
CO_2	0.27
Total	100

Norm (C.I.P.W.)	
Q	18.2
C	---
or	11.6
ab	38.2
an	19.2
di	2.9
hy	5.1
mt	2.1
il	1.2
hm	---
tn	---
ru	---
ap	---
Classification symbol	I.4.3.4

Spectrochemical analyses	
Cr	60?
Co	40
Mn	550
Ni	20
Sc	10
V	70
Fe	2.6%
Cu	10
Ga	10
Ti	2400
B	30
Ba	2400
Be	--
Pb	20
Sr	1600
Yb	1
Y	10
Zr	130

Table 3: Modal, normative, chemical, and spectrochemical analyses for one sample of the volcanic breccias in the Bedrock Spring formation. The modal, normative, and chemical values are percents, the spectrochemical values are parts per million.

has common inclusions of magnetite. A few clinopyroxene crystals are present. The groundmass consists of about 68 percent glass, 30 percent slightly anisotropic "glass", and 2 percent needlelike plagioclase crystals. There is very little opaque material. The color banding is caused by concentrations of opaque dust in the groundmass. Vesicles, mostly microscopic but ranging in size up to 1 mm, are abundant and show a faint alignment. Maximum crystal sizes are: plagioclase, 3 mm; biotite, 3 mm; hornblende, 2.5 mm; orthopyroxene, 0.3 mm.

Tuffs and pyroclastics (Tbt) --

The best exposed samples of this unit are found in sections B24, B31, E4, and E5. Rocks of this member are usually resistant to weathering and consequently form cliffs which have uneven and hackly surfaces caused by the more resistant fragments which stand out in relief. The beds found in sections B31, E4, and E5 weather to a pale green (10G6-7/2) or pale blue green (5BG6-8/2). The unit is commonly massive but stratification within the member is sometimes distinct. Some members are as thick as 100 feet but the average is nearer 20 to 30 feet. Along the strike the beds are about as persistent as the volcanic and flow breccias (Tbv).

The tuffs and pyroclastics found in the vicinity of B24 are no more resistant to weathering than the surrounding sandstones and conglomerates. They weather to shades of pink, yellow, and green. Most portions are very well bedded, and although individual beds cannot be traced for more than a few hundred feet, the pyroclastic-rich zone is persistent for about 3 miles.

Lithology and composition -- The rocks consist predominantly of tuffaceous or pyroclastic material, apparently laid down without sorting. Besides pyroclastic materials, they commonly also contain fragments of very coarse sand consisting of feldspar, quartz, euhedral hornblende, and biotite crystals. Fragments of volcanic rocks are usually also present.

Distribution of Various Rock Types

In the very broadest sense, the rock types that make up the Bedrock Spring formation fall into a pattern. The siltstone, claystone, limestone and volcanic members of this formation are found chiefly along the axis of the Dome Mountain anticline (see fig. 21); sandstones and conglomeratic sandstones outcrop on the limbs of the anticline. The silicified sandstones are restricted almost totally to the area near the intrusive complex.

The concentration of the finer-grained rocks and the volcanic rocks along the anticlinal axis could result from either of the following: 1) Fine-grained rocks and volcanic rocks are characteristic of only the lower part of the Bedrock Spring formation; or 2) the finer facies and volcanics were restricted to the center of the basin throughout the formation's deposition, the later formed anticlinal axis coinciding with the center throughout much of its length. Neither alternative can be discarded. However, because the basin center may well have been approximately where the fold axis now is, and this type of facies zonation is the general case in present day basins, the second alternative is preferred.

Age and Relationship to Other Formations

A large collection of fossils from the Bedrock Spring formation was made in 1952 by R. H. Tedford and Robert Shultz, Jr. Some additional material was collected by T. W. Dibblee, Jr., G. N. White, and the present writer.

G. E. Lewis has identified the vertebrate fossils as follows:

> "I have made comparisons with other collections in several museums. My best guess is that the age of most of the fossil vertebrates in your collection from the Lava Mountains area corresponds to that of the middle to upper parts of the Ogallala group of Nebraska. The Lava Mountains fossil vertebrates are comparable to those found in the Ash Hollow formation of the Nebraska Survey, and seem to be intermediate between those of the Chanac and Kern River formations of California. This age is best considered to be Middle Pliocene (assuming the age of the Villafranchian fauna of Europe, and that of the *Equus* (*Plesippus*) fauna of the Blanco formation, to be earliest Pleistocene in conformity with interpretations given at the 1948 International Geological Congress).
>
> "Significant determinations are:
>
> Order PERISSODACTYLA
> Family Equidae
> *Pliohippus* cf. *P*. *leardi*, from localities LM-6, LM-13, LM-20, and LM-21.
> *Pliohippus* sp., from localities LM-10 and LM-15.
>
> Order ARTIODACTYLA
> Family Camelidae
> ?*Pliauchenia* sp., from localities LM-6, LM-8, LM-11, LM-13, LM-15, LM-16, LM-20, and LM-26.
> ?*Megatylopus* sp., from localities LM-10, LM-16, and LM-21.
>
> Order LAGOMORPHA
> Family Leporidae
> cf. *Hypolagus* sp., from localities LM-15 and LM-16.
>
> Order RODENTIA
> Family Cricetidae
> *Neotomodon* sp., from localities LM-15 and LM-16.
>
> A complete list of determinations is attached."
> (See appendix III).

The approximate stratigraphic positions of the fossil localities and the probable relationships between two fossil-bearing sections are plotted in figure 8.

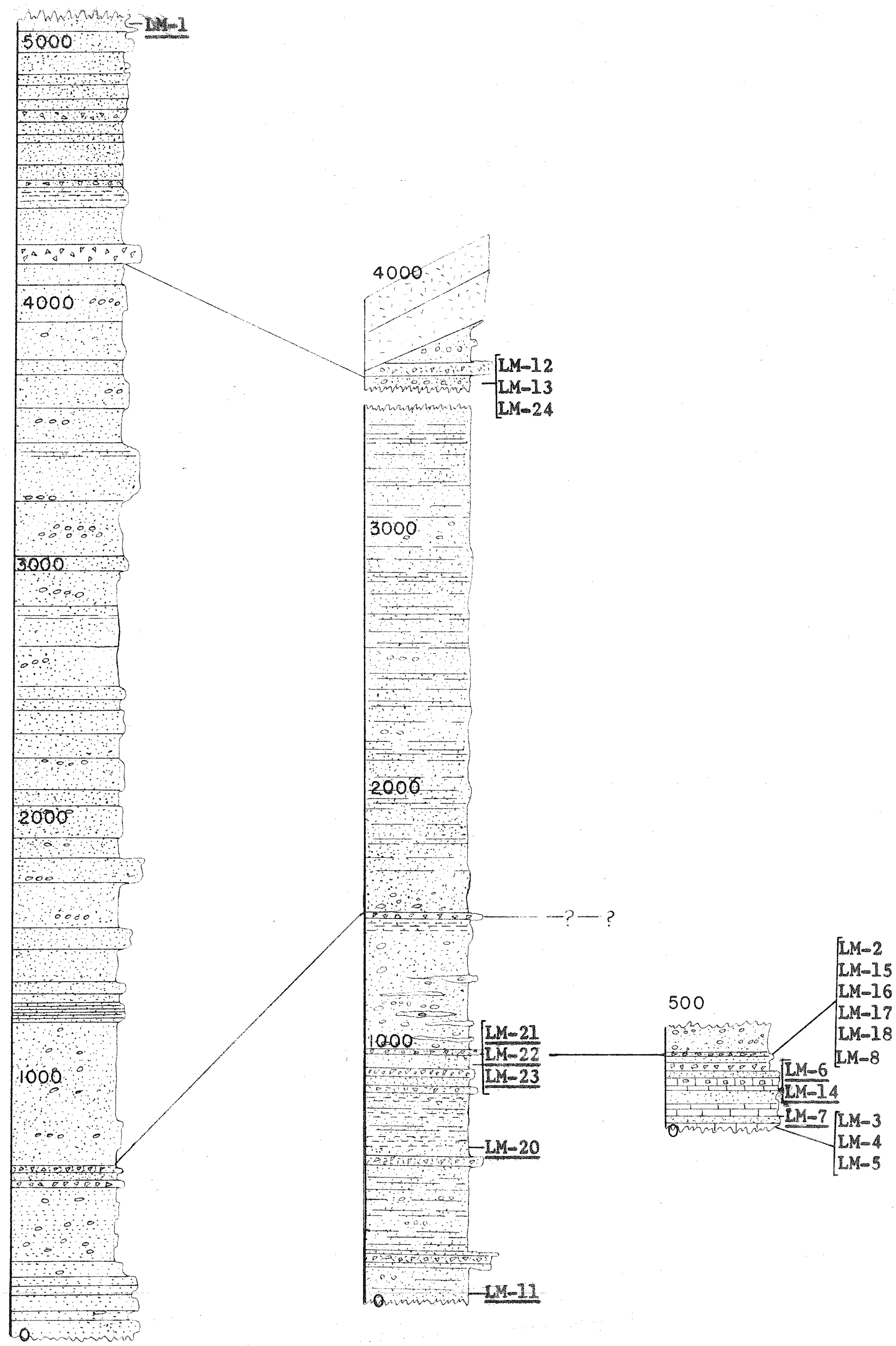


Figure 8. Three measured sections in the Bedrock Spring formation showing the positions of the fossil localities. Those localities that can be traced directly into the measured section are underlined; those only approximately correlated are not. The lines connecting the sections together are the best approximations of "time lines" that can be made on the basis of the mapping done.

The left column is the type section for the Bedrock Spring formation; the middle column is in sections E2 and E3; the right column is in section B27. See plate 4 for the exact location of each. See appendix III for the faunal list for each locality; see plate 4 for the exact location of each locality. All thicknesses are in feet.

Within the northern Mojave Desert, only three other Pliocene faunas are known, all of which are only a few miles south of the Garlock fault. In the Avawatz Mountains (Henshaw, 1939), lower Pliocene rocks are exposed. The rocks about four miles northwest of Mojave are of middle Pliocene age (identifications by Lewis, Stock, and Tedford, as quoted by Hewett, 1955). A limestone from Castle Butte, east of Rosamond, yielded lower Pliocene diatoms (determined by K. E. Lohman, quoted by Hewett, 1954). All of the other vertebrate collections from the Mojave Desert are of middle or upper Miocene age. North of the Garlock fault, in the southwestern Basin Ranges, Pliocene rocks are exposed in the Ricardo formation (Dibblee, 1952) of the El Paso Mountains, 15 miles west of the Lava Mountains, in the Coso Mountains (Schultz, 1937), and in Death Valley (Axelrod, 1940; Curry, 1941; Noble and Wright, 1954).

On the basis of the work done to date, none of the other Pliocene rocks in the northern Mojave Desert or in the southern Basin Ranges are clearly of the same age as the Lava Mountains fauna. This, plus the evidence that the Bedrock Spring formation was deposited in a local basin, makes it clear that no other formations are definitely equivalent. Although future work may well find some that are, within the area covered by the reconnaissance map (plate 1) and in other nearby areas, the writer knows of no similar rock types that cannot be more closely related to rocks of a different age.

ALMOND MOUNTAIN VOLCANICS

The type section of the Almond Mountain volcanics, a new formation here named, is in section E34, on the west side of Almond Mountain for which the formation is named. It is diagrammatically portrayed in figure 9 and is illustrated in figure 10a.

The Almond Mountain volcanics consist of interbedded flow breccias, volcanic breccias, tuffs, tuff breccias, pyroclastics, pyroclastic breccias, and sandstones. At the type section, volcanic breccias form about 97 percent of the formation while tuffs and pyroclastics form only 3 percent. In the exposures to the northeast, however, in sections E24 and F19, flow breccias and volcanic breccias form about 55 percent, tuffs and pyroclastics form 35 percent, and sandstones form 10 percent of the formation.

Description of Included Rock Types

Tuffs and Pyroclastics (Tat) --

The best exposures of this unit, which includes tuffs, tuff breccias, pyroclastics, and pyroclastic breccias, are found in the type section and in section F6. Figure 10b illustrates one of the pyroclastic beds in the type section. The rocks are commonly soft and weather to soft poorly exposed hillsides. Colors include the following:

Light gray (N7-8)
Yellowish gray (5Y7-8/1)
Grayish red purple (5RP4/2)
Very pale red (5R6/1)

A common type of tuff containing pumice fragments weathers to shades varying from pale yellowish orange (10YR8/6) to light olive gray (5Y6/1) and very light gray (N8).

Most of the beds of this unit are several tens of feet thick; generally the pyroclastics are thicker than the tuff units. Within the members, bedding is usually unrecognizable except in the tuffa-

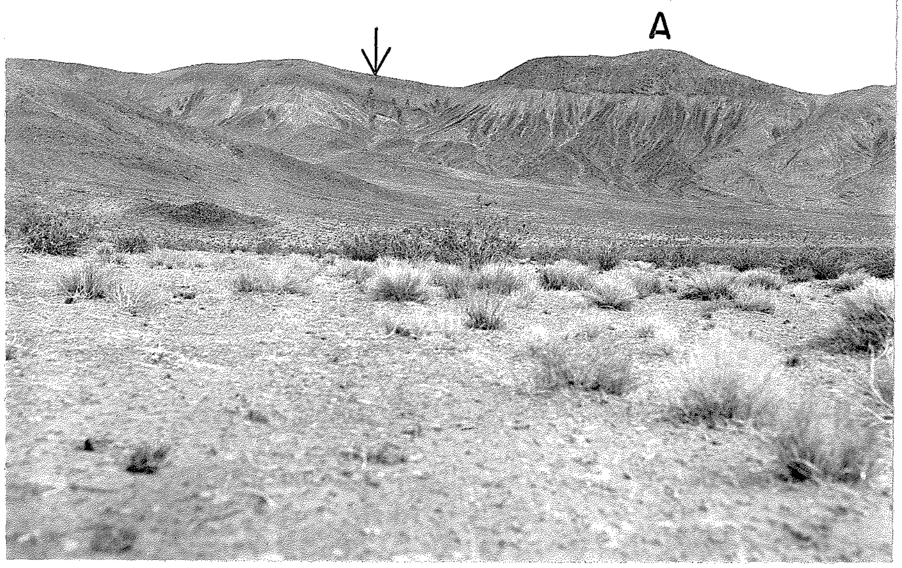
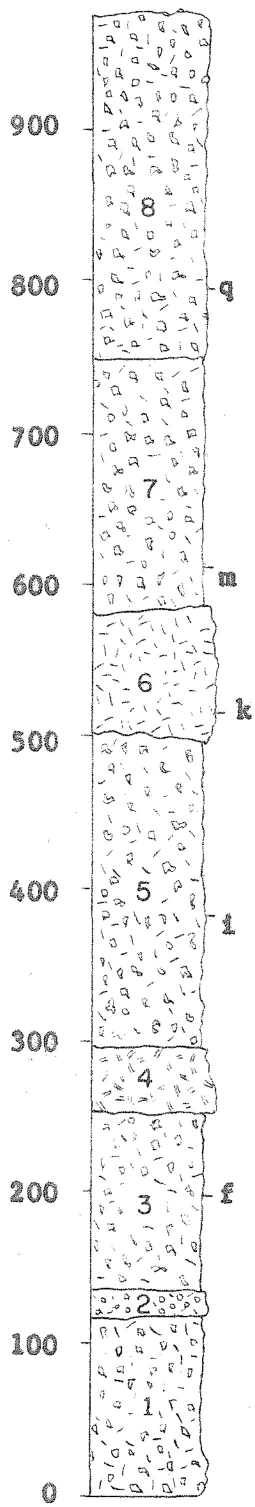


Figure 9a. View of Almond Mountain (A) from the southwest. The location of the type section for the Almond Mountain volcanics is below the arrow.

Figure 9b. Contact of a volcanic breccia bed overlying a white pyroclastic bed. Photograph taken in the lower part of the type section of the Almond Mountain volcanics.



8. Volcanic breccia. Weathers to light gray (N7) and olive gray (5Y4/1). Lithology similar to unit below. Massive, grades into the unit below.

7. Volcanic breccia. Weathers to medium light gray (N6) and pale red purple (5RP6/2). Fragments, up to 5 ft wide, form more than 98 percent of the unit; fragments are angular with large conchoidal cracks. Massive.

6. Andesite sill. Contorted color bands of dark gray (N3) and pale reddish brown (10R5/4). Upper half slightly brecciated.

5. Volcanic breccia, monolithologic. Fragments probably form about 98 percent of the total. Medium gray (N5) in top two-thirds, light brownish gray (5YR6/1) in lower third. Massive.

4. Tuff; small percentage of lava fragments in a tuff matrix. Very light gray (N8), yellowish gray (5Y7/1), and dusky yellow (5Y6-7/4-6); more yellowish in top and bottom thirds. Grades into unit above.

3. Volcanic breccia, nearly monolithologic. Weathers from medium light gray (N6) to reddish brown (10R4/4). Angular fragments up to 6 ft across. Massive.

2. Tuff-conglomerate. Weathers to light gray (N7), pale red (5R6/1), and grayish red purple (5RP4/2). About 30 percent subangular to subrounded fragments of lava, pyroclastics, and pumice, in a tuff matrix. Fragments range up to 18 in., average 3 in. across. Locally well bedded.

1. Volcanic breccia. Weathers to light olive gray (5Y6/1) and brownish gray (5YR5/1). About 85 percent fragments, up to 1 in. in diameter, in a pyroclastic matrix. Massive.

Figure 10. Type section of the Almond Mountain volcanics. Letters show the relative positions of the 124-22 series of samples described in table 4. Thicknesses are in feet.

ceous units containing pumice fragments. In these, bedding is commonly well defined and "textbook" examples of graded bedding can be found. Laterally, rocks of this member commonly grade into other volcanic rock types over distances of a few hundred feet although units recognized as "equivalent" may be traced for 2 or 3 miles.

> Lithology and composition -- The tuffs and pyroclastics can be divided into two general categories. The first, the pumice-bearing tuffs, consist of fragments of pumice, well-rounded and up to an inch in diameter, in a matrix of tuff or tuffaceous sandstone. Fragments, which are generally very light gray (N8) to white (N9), generally form between one-third and two-thirds of the rock. The matrix is usually somewhat darker or more orange.
>
> The pyroclastics and pyroclastic breccias consist of fragments of angular to subrounded volcanic rock in a matrix of unsorted pyroclastic material. The volcanic rock fragments are generally purplish and average 1 to 3 inches across although some measure more than a foot.

Volcanic breccias and flow breccias (Tab) --

The best exposed sections of this unit are found in the type section and in sections F19 and E25. The colors of the weathered outcrops include the following:

Medium light gray (N5-7)
Light olive gray (5Y6/1)
Brownish gray (5YR4-8/1)
Grayish orange (10YR4-7/4)
Pale red (10R6-7/2-4)
Pale red purple (5RP6-7/2)

The units form resistant beds and ledges, the flow breccias being somewhat more resistant than those containing pyroclastic material in the matrix. In most, the fragments are angular, and in some, the fragments have "megaperlite" cracks and fractures.

The units are found as massive beds, commonly a hundred feet thick. Lateral continuity is variable; some members have been distinguishable over a mile or two and others lose their identity in a few hundred feet.

Lithology and composition -- In the majority of the rocks in this unit, the fragments form more than 90 percent of the total although a few contain a much lower percentage. The fragments are without exception volcanics and most generally consist of light gray or purplish rock types. The matrix in the volcanic breccias may include pyroclastic material but the percentage seldom exceeds 5 percent of the rock; the flow breccia matrix is lava which in some cases is of the same composition as the fragments.

The study of 19 thin sections emphasizes the similarity between these rocks. All contain plagioclase phenocrysts and three-quarters of the rocks also contain biotite, oxyhornblende, and orthopyroxene. Only about one-third contain quartz. The plagioclase is found as megaphenocrysts and microphenocrysts in about equal proportions; zone and twin development is variable and about half the rocks have a calcic rim on the plagioclase. Much of the biotite and oxyhornblende show partial or complete alteration to opaque materials, pyroxene, and apparently to plagioclase; the relationship of the included plagioclase is subject to other interpretations, possibly. The orthopyroxenes are essentially unaltered. Clinopyroxene, found in about two-thirds of the rocks, shows partial alteration in well over half of these.

The results of modal, normative, chemical, and spectrochemical analyses are found in table 4.

The microscopic textures of these rocks are variable in detail, but most are slightly vesicular and have a strong lineation resulting from the alignment of the plagioclase microphenocrysts and the oxyhornblende crystals. In most rocks, the plagioclase, oxyhornblende, and biotite crystals range in size up to about 3 mm. The orthopyroxene and clinopyroxene crystals are generally less than 1 mm long.

Plagioclase megaphenocrysts are very commonly clumped together. Sometimes this clustering occurred after the crystal had grown to nearly normal shape and size, but more commonly at an earlier time, so that there has been a mutual interference of growth. Microphenocrysts of plagioclase are also seen as

Modal analyses	Sample number 124-22Q	124-22M	124-22I	124-22F
Plagioclase megaphenocrysts	11.2	6.7	3.3	22.9
Plagioclase microphenocrysts	13.0	11.6	12.0	4.5
Total plagioclase	24.2	18.3	15.3	27.4
Biotite	0.7	0.3	0.3	2.2
Hornblende	---	---	---	---
Oxyhornblende	1.0	0.4	0.1	---
Orthopyroxene	1.0	2.4	2.4	1.7
Clinopyroxene	0.7	0.3	0.6	---
Quartz	t	---	0.1	---
Opaque minerals	3.1	1.3	1.6	1.2
Nonopaque minerals	0.5	0.1	0.8	0.1
Chemical analyses				
SiO_2	64.8	66.9	66.8	65.4
Al_2O_3	16.2	16.2	16.2	16.5
Fe_2O_3	1.9	1.0	1.1	1.2
FeO	1.4	2.0	1.9	2.0
MgO	1.2	1.8	1.2	1.2
CaO	5.0	3.5	3.8	3.9
Na_2O	3.6	3.8	3.9	4.2
K_2O	2.8	2.9	2.7	2.6
TiO_2	0.50	0.50	0.50	0.55
P_2O_5	0.17	0.16	0.16	0.18
MnO	0.05	0.04	0.05	0.05
H_2O	2.2	1.9	2.0	2.1
CO_2	0.11	0.05	0.05	0.05
Total	100	101	100	100

Table 4. Modal and chemical analyses for four samples of the Almond Mountain volcanics. All values are in percents.

Norm (C.I.P.W.)	Sample number			
	124-22Q	124-22M	124-22I	124-22F
Q	21.7	22.6	23.0	20.1
C	---	0.4	---	---
or	16.7	17.2	16.1	15.6
ab	30.4	32.0	33.0	35.6
an	19.7	17.5	18.6	18.4
di	2.6	---	0.2	0.9
hy	2.7	6.6	4.6	4.3
mt	2.8	1.4	1.6	1.9
il	0.9	0.9	1.4	1.1
hm	---	---	---	---
tn	---	---	---	---
ru	---	---	---	---
ap	---	---	---	---
Classification	I.4.3.4	I.4.3.4	I.4.3.4	I.4.3.4

Spectrochemical analyses				
Cr	30	40	30	20
Co	40	40	20	20
Mn	340	300	340	320
Ni	10	10	10	10
Sc	10?	5?	1	5?
V	40	50	40	40
Fe	1.6%	1.9%	1.4%	1.7%
Cu	10	10?	10	10?
Ga	10	10	10	10
Ti	2200	2100	1800	2200
B	50	50	30	40
Ba	2100	1700	1200	1400
Be	---	---	---	---
Pb	10	10	10	10
Sr	1500?	1200	800	1100
Yb	1	1	1	1
Y	10?	5	3	5?
Zr	120?	100	80	100

Table 4 (cont'd). Normative and spectrochemical analyses for four samples of the Almond Mountain volcanics. The normative values are percents, the spectrochemical values are in parts per million.

> attached pairs, but only in a small percentage of the total.

Sandstones (Tas) --

Only one good exposure of this rock type is found in the area mapped. It is in section E24. Here, it outcrops in a canyon as a 50-foot bed of friable material showing only faint bedding. The unit weathers to yellowish gray (5Y8/1) but on a fresh surface it is sometimes more yellow. At this outcrop, the bed is overlain and underlain by members of the tuffs and pyroclastics rock unit. East and south of here it becomes relatively flat lying and its presence can only be inferred from the arkosic float. Sandstone may also be the surface rock type to the north in sections F7, F18, and F19 (shown on the map as Tat), but the preferable interpretation is shown on the map.

> Lithology and composition -- Where the lithology could be studied, this unit was found to be a medium- to very coarse-grained arkosic sandstone containing very few pebbles. Locally the unit is well indurated, probably the result of cementation by calcium carbonate.

Undifferentiated volcanics (Ta) --

This unit -- the "catch-all" unit for this formation -- is shown on the map in areas where the rocks have none of the characteristics of bedded deposits. For the most part it consists of a volcanic rock averaging perhaps light brownish gray (5YR6/1). Most of these units outcrop as high steepsided hills with an almost solid talus on the lower slopes. Most of these areas are probably intrusive complexes. They are found to grade laterally into stratified units in such a manner that in many areas a line contact cannot be drawn between the two.

Lithology and composition -- The mineralogy of the rocks is similar to that in the volcanic breccia and flow breccia unit (Tab). The plagioclase, biotite, oxyhornblende, clinopyroxene, and orthopyroxene are found in most of the rocks and quartz is found in a few. No characteristics seem to be distinctive for this unit except possibly that the biotite and oxyhornblende crystals are very heavily altered. No lineation is present in many of the rocks although most show common to abundant vesicles. Crystal sizes are about the same as those in the volcanic breccias and flow breccias section.

Distribution of Various Rock Types

On the map it can be seen that the proportion of tuffs, pyroclastics, and pyroclastic breccias (Tat) increases with respect to volcanic breccias and flow breccias (Tab) in all directions from Almond Mountain. To the north, the proportion of the finer material increases and along the northern rim of outcrops no volcanic or flow breccias are present. Instead, the pyroclastics are very fine-grained and appear to be deposited some distance from the volcanic source. To the east of Almond Mountain, the volumes of tuffs and pyroclastics increase until they approximately equal the volcanic and flow breccias. In this area, pumiceous tuff thickens toward the east. South and to the east of Almond Mountain, the proportion of pyroclastic material to coarser debris increases gradually. Little is known about the changes to the west of Almond Mountain because of the very poor exposures and the complicating effect of the Brown's Ranch fault zone.

Volcanic Source and Environment of Deposition

If one makes the assumption that the flow breccias and volcanic breccias are deposits that remain closer to their source than pyroclastics and tuffs, the conclusion can be reached that the centers of volcanic activity were near Almond Mountain. Two areas, one to the west of Almond Mountain, in section E32 and E33, and one to the south, in section E34 and G63, are shown on the map as undifferentiated Almond Mountain volcanics (Ta). The characteristics of these rocks, in conjunction with the facies variations, suggest these areas as the sources of the Almond Mountain volcanics.

Age and Relationship to Other Formations

No fossils were found within the deposits of the Almond Mountain volcanics. They clearly rest on top of the middle Pliocene Bedrock Spring formation -- in some places conformably, as in section E11 and E14, and in other areas unconformably, as in sections E1, F6, and F7. Thus it is certainly middle Pliocene or younger in age. The extent to which dissection has occurred and the number of events and mappable units that have been found to be later than this formation suggest upper Pliocene as a plausible age.

KLINKER MOUNTAIN VOLCANICS

This formation has been divided into five members: The lower two make up a volcanic intrusive complex, and the upper three are stratified deposits resting on top of the complex. The type localities for the two lower members are in section D24-m for the greenish-weathering unit (Tkg), and in section D23-c for the purplish-weathering unit (Tkp). The type section for the overlying units is in section D11-f on the north side of Klinker Mountain for which the formation is named.

The intrusive complex includes yellowish green volcanic rocks that have undergone strong alteration, and purplish volcanic rocks that are slightly less altered. The stratified deposits consist of sandstones and conglomerates, volcanic breccias and flow breccias, and tuffs, pyroclastics and pyroclastic breccias. At the type section, the stratified rocks are about 600 feet thick; detrital rocks form about 28 percent, volcanic and flow breccias form about 60 percent, and tuffs and pyroclastics form about 12 percent. Although the thickness of the formation varies markedly, this general proportion of the three rock types is maintained over much of the area.

The outcrop characteristics of the two portions of this formation are very different. The greenish and purplish rocks of the intrusive complex form small steep hills and canyons which combine to make a patternless hummocky topography. The stratified deposits form flat-topped hills with steep sides. They generally weather to medium grays, grading down into deep browns or purplish gray; the tuffs and pyroclastics weather to the lighter colors. These bedded rocks tend to change lithology and thickness very rapidly along the strike although a general succession can usually be recognized over a few square miles.

Description of Included Rock Types

Greenish-weathering volcanic complex (Tkg) --

The best exposed areas of this rock are found in the type locality and in sections D23-k and D23-q. Three types are included: The first is a thinly-bedded pyroclastic rock; the second is a system of more resistant dikes that cut the other two types but are seldom found cutting the overlying units; the third, which forms over 90 percent of the total area, is a brecciated volcanic rock, apparently intrusive for the most part.

The relationship between the three types has not been established. The bedded pyroclastics, which are indicated on the map as clusters of dip and strike symbols, seem to be unsystematically placed with respect to the more common rock type. The dikes are seen to cut the pyroclastics and the altered complex rock but in only one outcrop do they cut the overlying members.

The unit weathers to a distinctive set of colors which include the following:

Olive gray (5Y5/1)
Pale olive (10Y6/2)
Greenish gray (5GY6-8/1)

Lithology and composition -- In hand specimen the rock is characterized by a high degree of alteration. Phenocrysts of plagioclase and mafic minerals can be recognized by shape although most of the original minerals are destroyed. By thin section study, the phenocrysts consist of plagioclase, which is altered in part to calcite and dark minerals, and biotite(?) and hornblende(?) which are almost entirely altered to opaque materials, calcite, chalcedony, chlorite, or serpentine(?). The plagioclase is present as megaphenocrysts and microphenocrysts and twinning seems to show medium development. The apparent composition of the plagioclase probably was between An_{40} and An_{50} for the most part. The groundmass is entirely a fine-grained mottled material that has an undulating extinction. It is probably quartz and possibly other silica minerals. Pyrite is found as disseminated euhedral crystals. In many respects, this rock is comparable to the "propylite" found in many mineralized areas. The term is not used here for this unit solely because of the minor amount of chlorite present -- a mineral considered by many to be a necessary major constituent.

The texture is nonvesicular and the minerals show no directional alignment. Phenocrysts of plagioclase are as large as 5 mm but average 1 or 2 mm. Biotite and hornblende crystals average between 1 and 3 mm across.

The modal, normative, chemical, and spectrochemical compositions are shown in table 5.

<u>Purplish-weathering volcanic complex (Tkp)</u> --

The best exposures of this unit are found in sections D22-r, D23-c, and D23-e. Like the greenish-weathering complex, this unit weathers to an irregular topography of steep-sided hills forming no general topographic pattern. Colors of the fresher outcrops include the following:

Medium gray (N5)
Purplish blue (10PB6-7/2)
Very pale purple (5P7-8/1-2)
Pale reddish purple (5RP4-6/2)

More weathered surfaces are:

Pale red (10R6/2)
Pale brown (5RY5/2)

The rocks outcrop in one of two ways: The softer more altered rocks weather as if they were pyroclastic or tuffaceous. The more resistant rocks, most of which are volcanic necks, occur as low peaks; many of these have steeply-dipping foliation structures.

<u>Lithology and composition</u> -- These rocks are characterized by white plagioclase phenocrysts and, in many, by excellent hexagonal flakes of biotite up to 3 mm across. Microscopic study shows the following: The plagioclase is euhedral, sometimes forming crystals up to 8 mm in length but more commonly 1 to 3 mm long. Andesine is the dominant composition but some is labradorite. Zones range from weak to strong and the degree of twinning is variable. Alteration has attacked many of the plagioclase crystals; calcite is the common alteration product. Biotite is usually present; it is sometimes relatively unaltered although generally it has been changed to iron oxide. Hornblende or oxyhornblende, which is much less abundant than biotite,

Modal analyses	Sample number 29-22
Plagioclase megaphenocrysts	4.2
Plagioclase microphenocrysts	7.3
Total plagioclase	11.5
Biotite	---
Hornblende	---
Oxyhornblende	---
Orthopyroxene	---
Clinopyroxene	----
Quartz	0.4
Opaque minerals	3.2
Non-opaque minerals	0.2

Chemical analyses	Sample number 29-22
SiO_2	65.8
Al_2O_3	16.2
Fe_2O_3	1.4
FeO	1.8
MgO	1.2
CaO	3.9
Na_2O	4.6
K_2O	2.3
TiO_2	0.51
P_2O_5	0.16
MnO	0.05
H_2O	1.8
CO_2	0.64
Total	100

Norm (C.I.P.W.)	
Q	20.5
C	---
or	13.3
ab	38.8
an	17.0
di	2.0
hy	3.0
mt	2.1
il	0.9
hm	---
tn	---
ru	---
ap	---
Classification symbol	I.4.3.4

Spectrochemical analyses	
Cr	50
Co	80
Mn	360
Ni	10
Sc	5
V	40
Fe	1.8%
Cu	10
Ga	10
Ti	2600
B	10
Ba	1900
Be	--
Pb	10
Sr	1400
Yb	1
Y	10
Zr	110

Table 5: Modal, normative, chemical, and spectrochemical analyses for one sample of the greenish-weathering member of the Klinker Mountain volcanics. The modal, normative, and chemical values are percents, the spectrochemical values are parts per million.

is almost always altered to opaque materials. Clinopyroxenes are sometimes present and quartz is not uncommon. In one outcrop, in section D25-m, zeolites, probably stilbite, form several percent of the rock.

Rocks of this unit generally show no lineation and vesicles are uncommon. The groundmass usually consists of 5 or 10 percent crystalline material, the balance consisting of fine-grained anisotropic material, possibly quartz, tridymite, or cristobalite.

The results of modal, normative, chemical, and spectrochemical analyses are shown in table 6.

Relationship to greenish-weathering volcanic complex --

The relationships between the purplish- and greenish weathering members are complex. In gross pattern the purple-weathering rock definitely overlies the greenish-weathering rock, that is, hillsides that expose both types almost always have the purple type above the greenish-weathering type. In more detail, however, it is not uncommon to find "fragments" of the one material apparently included in the other, or "dikes" of one intruding the other. At still closer range, however, there is no sharp contact visible between the two rock types and the color change grades over several millimeters or a few centimeters.

The original mineralogy of both units was probably similar. The type of alteration -- calcite replacing the plagioclase, and serpentine, chlorite, or opaque minerals replacing the biotite and hornblende -- is also similar. The difference is in the degree of alteration. For these reasons, the two units are believed to have originally been the same rock.

The greenish-weathering rocks outcrop in an elongated area which is, in turn, surrounded by purple rocks. This areal pattern, plus the

Modal analyses	Sample number 128-33
Plagioclase megaphenocrysts	5.9
Plagioclase microphenocrysts	7.4
Total plagioclase	13.3
Biotite	---
Hornblende	---
Oxyhornblende	t
Orthopyroxene	t
Clinopyroxene	0.3
Quartz	0.1
Opaque minerals	10.2
Non-opaque minerals	0.2

Chemical analyses	Sample number 128-33
SiO_2	67.7
Al_2O_3	16.5
Fe_2O_3	3.3
FeO	0.14
MgO	0.57
CaO	4.0
Na_2O	4.3
K_2O	2.8
TiO_2	0.54
P_2O_5	0.19
MnO	0.02
H_2O	0.38
CO_2	<0.05
Total	100

Norm (C.I.P.W.)	
Q	23.2
C	---
or	16.7
ab	36.2
an	17.5
di	1.7
hy	0.6
mt	2.1
il	1.1
hm	1.9
tn	---
ru	---
ap	---
Classification symbol	I.4.3.4

Spectrochemical analyses	
Cr	40
Co	30
Mn	210
Ni	20
Sc	2
V	30
Fe	1.6%
Cu	5?
Ga	10
Ti	1800
B	10
Ba	1900
Be	--
Pb	20
Sr	1200
Yb	1
Y	5
Zr	110

Table 6: Modal, normative, chemical, and spectrochemical analyses for one sample of the purplish-weathering member of the Klinker Mountain volcanics. The modal, normative, and chemical values are percents, the spectrochemical values are parts per million.

nature of the alteration, is believed to be the product of hydrothermal waters. The altering solutions were probably high in CO_2, thus the high percentage of calcite, but the overall changes in composition did not drive the rock greatly "out of line" from the other rock compositions plotted in figures 27 and 30. In figure 27, the CaO, and CO_2, and possibly Na_2O, are slightly higher than the average, but no particular elements seem to have been selectively displaced.

Whatever the cause of the color change, it was found to be an easy distinction to make on a map. Furthermore, this contact between the two seems to have had the reputation of being economically important in the past; numerous prospect pits are located along it and rocks from one 400-foot shaft, in section D24-c, shows megascopically visible pyrite mineralization.

Tuffs and pyroclastics (Tkt) --

The best exposures of this unit are found in the type section which is illustrated in figures 11a and 12, and in section E5, and in E6 which is shown in figures 11b and 13. It includes tuffs, tuff breccias, pyroclastics, and pyroclastic breccias. As a rule, this unit is somewhat less resistant to weathering than the flow breccias and volcanic breccias, and somewhat more resistant than the sandstones and conglomerates. The weathered surfaces are usually uneven and cavities tend to form in some of the beds. The colors are quite variable, and include the following:

Very pale green (5G8/2)
Pale grayish yellow green (5GY8/2)
Yellowish gray (5Y7-8/1-2)
Pinkish gray (5YR8/1)

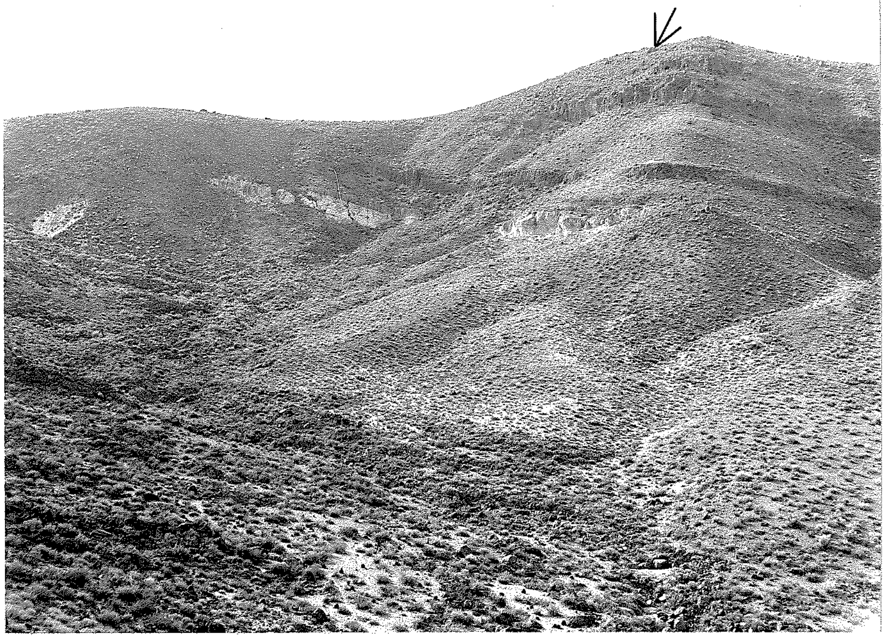
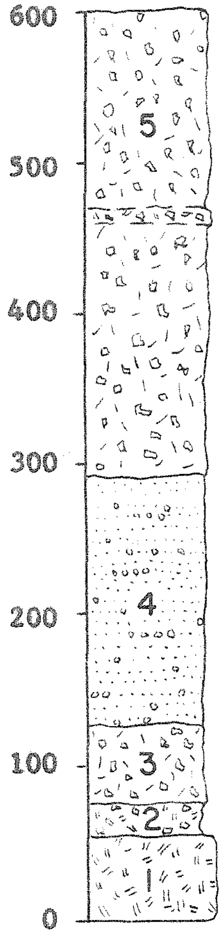


Figure 11a. Type section of the Klinker Mountain volcanics. Measured section, illustrated in figure 12, is below the arrow. View toward the south.

Figure 11b. The section of the Klinker Mountain volcanics sampled for analysis. Samples were taken downhill from the arrow.



5. Volcanic breccia. Light olive gray (5Y6/1). Fragments range in size up to 6 ft across, average perhaps 3 in.; angular to subrounded, with some of the larger boulders well-rounded; gray and purple volcanic rocks form half to three-fourths of the total in a matrix of pyroclastic breccia.

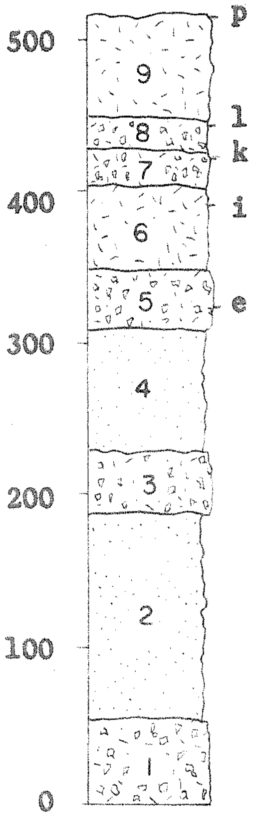
4. Sandstone and conglomerate; poorly exposed except for top 20 ft. Yellowish gray (5Y7/2) to light olive gray (5Y6/1). Where exposed, bedding well defined, average about 2 in. thick. Majority of fragments are volcanic rocks, up to 2 in., averaging one-half in., subangular to well-rounded; probably also contains tuff. Contact with overlying volcanic breccia is sharp and well exposed.

3. Volcanic breccia. Colors similar to those in unit below. Angular to subrounded fragments form 50 to 90 percent of the total; average about 2 in. across. Contact with underlying unit is gradational; upper part of unit is more resistant.

2. Pyroclastic breccia. Light brownish-gray (5YR6/1) to light olive-gray (5Y6/1). Fragments of purple and red-brown volcanic rocks, up to 2 ft across, averaging about 1 in.; subangular to subrounded. Finer in lower part, fragments form 10 to 50 percent of total in a pyroclastic matrix.

1. Pyroclastic tuff. Yellowish-gray (5Y8/1), light olive-gray (5Y6/1) in top 10 ft. About 5 percent subangular to subrounded fragments of purple to red-brown volcanic rocks, some fragments of pyroclastics. Massive. Lower contact with Bedrock Spring formation poorly exposed; contact with overlying pyroclastic breccia well exposed.

Figure 12. Type section of the Klinker Mountain volcanics. Thicknesses are in feet.



9. Lava Mountains andesite. Medium dark gray (N4). Massive

8. Volcanic breccia, monolithologic; fragments up to 2 ft across from about 40 percent of the total, pyroclastic material forms the rest.

7. Volcanic breccia, monolithologic; fragments up to 3 ft across in a pyroclastic matrix. Pale reddish brown (10R4-6/4) to grayish orange pink (5YR7/2). Massive.

6. Flow, andesite. Brownish black (5YR3/1). Weathers to slabs in lower half, blocks in upper half.

5. Volcanic breccia, monolithologic; Medium gray (N4-6) fragments, up to 4 ft across, in a pyroclastic matrix.

4. Sandstone, arkosic, similar to arkosic sandstone below. Light colored tuffaceous sandstone at base and top.

3. Volcanic breccia, heterogeneous volcanic rocks in a matrix of pyroclastic material. Weathers to pinkish gray (5YR8/1). Fragments form about 50 percent of total.

2. Sandstone, arkosic, some stringers of pebbles. Yellowish gray (5Y7-8/1-2). Pebbles are angular to subrounded, and are about 95 percent volcanic, the balance being rhyolitic, quartz monzonitic, and "bull" quartz; the sand is apparently formed mainly of the "pink" leucocratic quartz monzonite. Well bedded in top third, massive in rest.

1. Volcanic breccia; heterogeneous angular volcanic rocks, up to 1 ft across, in a pyroclastic matrix. The matrix weathers to light brownish gray (5YR6/1). Massive.

Figure 13. Section of the Klinker Mountain volcanics exposed in section E6-j. Letters show the relative positions of the 97-38 series of samples described in tables 7 and 8. Thicknesses are in feet.

Grayish orange (10YR7/4)
Pale red purple (5RP6/2)
Very light gray (N7-9)

Beds range in thickness from 5 to 50 feet, thicknesses of 10 to 20 feet being the more common. The majority of these units are massive, but stratification, usually as beds several feet thick, is sometimes seen. Along the strike, a given unit can usually be traced two or three thousand feet and a few can be traced for a mile.

In the eastern exposures of this unit, in the vicinity of the Brown's Ranch fault zone, the rocks are generally fine-grained, show no bedding, and weather as if very soft. The colors are variegated.

> Lithology and composition -- The percentage of coarse fragments in these units varies from 0 to 50 percent but the average is probably between 5 and 15 percent. The fragments are always volcanic rocks, are usually angular or slightly rounded, and measure a few inches across. Some, however, range up to several feet. The volcanic rocks that make up the fragments are most often purplish or gray porphyritic andesites although a few are pumice fragments. The matrix is generally pyroclastic or tuffaceous material with a small percentage of detrital silicates.

Volcanic breccias and flow breccias (Tkb) --

The best exposed examples of this unit are found in sections D10, D11, D15, E5, and E6. In most areas they weather to form resistant hills with talus-covered slopes. Where well exposed, the surface is hackly and jagged, the fragments generally standing out in relief from the less weather-resistant matrix. The colors of the weathered units fall into two rather distinct classes. The first, which is generally lower in the section, is a purplish-weathering volcanic breccia which includes the following colors:

Light bluish gray (5B7/1)

Pale purple (5P6/2)
Grayish red purple (5RP4-5/2)
Moderate red (5R3-6/2-6)
Pale red (10R4-6/2)

The second unit weathers to grayish or grayish brown colors and includes the following:

Light brownish gray (5YR6-7/1-2)
Gray orange pink (10YR7/4)
Light olive gray (5Y4-7/1-4)
Dark greenish gray (5GY4/1)
Medium light gray (N5-8)

The breccias of this unit are almost invariably massive and show no textural evidence of interrupted deposition. Color transitions, however, are sometimes abrupt enough to suggest that some change occurred. Along the strike, the beds are extremely variable with respect to thickness, composition, size of the fragments, matrix, and weathering characteristics. Although many units are shown on the map to extend for several miles, the detailed lithology and appearance commonly change several times in this distance. A given stratigraphic succession of characteristics can seldom be mapped for more than a mile.

Lithology and composition -- In rocks of this unit, the ratio of fragments to matrix varies from 50 to 100 percent although the average is probably between 80 and 90 percent. The matrix consists of both pyroclastic materials and lava, although pyroclastics are more common. The fragments are most commonly gray or purplish rocks, the ratio of the two determining the over-all color of the unit. Most fragments are angular although some units contain rounded material. The average size is between 1 and 6 inches; the maximum is most commonly a foot or two and in some rocks it is as much as 6 feet. There is a crude direct correlation between the percentage of fragments in the unit and the size of those fragments.

The fragments, like most of the other volcanic rocks of this area, are porphyritic rocks with minerals forming one-quarter to one-third of the rock and groundmass forming the rest. Study in thin section indicates the following: Plagioclase, present in all the rock studied, shows no natural division into megaphenocrysts and microphenocrysts in about two-thirds of the thin sections; zones in most of the larger crystals are medium to weak and a calcic rim is found in about one-quarter; twin development is generally weak or medium. Biotite, present in about 90 percent of the thin sections studied, shows nearly complete alteration in about half. Hornblende or oxyhornblende, present in all the sections studied, is almost entirely altered in over half the rocks. Orthopyroxene, present in about two-thirds of the rocks, is nearly fresh in most sections. Clinopyroxene, present in three-quarters of the rocks, is most generally unaltered. Quartz is found in about 80 percent of the sections studied, usually as rounded and embayed crystals, some showing alteration halos of fine clinopyroxene(?). The groundmass composition is variable but on an average consists of half faintly anisotropic "glass", one quarter small acicular crystals or crystallites, and one quarter isotropic glass. Most rocks show a light to medium "dust" of reddish or black opaque materials.

Many of the rocks show a flow lineation in the hornblende or oxyhornblende crystals and in the microphenocrysts of plagioclase; some rocks show an elongation of the vesicles in the same direction. Small vesicles are common in about half the rocks. The crystals of plagioclase generally average 1/2 to 1 mm in length and show maximum lengths of 4 to 8 mm; hornblende, oxyhornblende, and biotite show maximum dimensions of about 1 to 2 mm; orthopyroxene and clinopyroxene seldom are larger than 0.5 mm. Quartz is usually 1 or 2 mm in the maximum dimension.

The chemical, spectrochemical, normative, and modal compositions are given in table 7.

Sandstones and conglomerates (Tks) --

The best exposures of this unit are found in sections D13, E5, and E6. Generally, they are nonresistant rocks which outcrop very

Modal analyses	Sample number 97-38L	97-38K	97-38I	97-38F
Plagioclase megaphenocrysts	9.0	9.6	8.9	10.7
Plagioclase microphenocrysts	9.3	13.9	13.1	11.7
Total plagioclase	18.3	23.6	22.0	22.4
Biotite	1.2	1.0	0.1	0.7
Hornblende	---	---	---	---
Oxyhornblende	0.6	0.8	0.7	0.6
Orthopyroxene	0.9	0.9	1.3	1.1
Clinopyroxene	0.8	0.6	0.6	0.4
Quartz	0.1	0.1	1.1	0.6
Opaque minerals	4.1	8.1	3.3	3.6
Nonopaque minerals	1.0	4.7	0.1	0.4

Chemical analyses	97-38L	97-38K	97-38I	97-38F
SiO_2	62.2	61.0	63.6	62.5
Al_2O_3	16.5	17.0	16.9	16.6
Fe_2O_3	2.4	2.3	1.5	1.8
FeO	1.6	1.9	2.6	2.4
MgO	3.1	2.8	2.8	2.3
CaO	4.6	5.0	4.4	5.0
Na_2O	3.8	3.6	3.9	3.8
K_2O	2.2	2.2	2.8	2.7
TiO_2	0.65	0.69	0.68	0.68
P_2O_5	0.24	0.26	0.25	0.24
MnO	0.06	0.06	0.06	0.06
H_2O	3.1	3.2	1.1	1.8
CO_2	0.05	0.05	0.05	0.05
Total	100.	100.	101	100

Table 7. Modal and chemical analyses for four samples of the stratified rocks of the Klinker Mountain volcanics. All values are percents.

Norm (C.I.P.W.)	Sample number			
	97-38L	97-38K	97-38I	97-38F
Q	17.7	17.4	15.7	18.9
C	---	0.3	---	---
or	12.8	12.8	16.7	16.1
ab	32.0	30.4	33.0	32.0
an	21.7	23.1	20.3	20.3
di	0.9	---	1.3	3.6
hy	7.4	7.4	8.7	5.7
mt	3.2	3.2	2.1	2.6
il	1.2	1.4	1.4	1.4
hm	0.2	---	---	---
tn	---	---	---	---
ru	---	---	---	---
ap	---	0.7	---	---
Classification	II.4.3.4	II.4.3.4	II.4.3.4	II.4.3.4

Spectrochemical analyses

Cr	70	90	100	80
Co	30	40	60	50
Mn	370	460	400	380
Ni	50	60	60	50
Sc	5	10	5	5
V	60	70	80	70
Fe	2.2%	3.0%	2.6%	2.5%
Cu	30	30	30	20
Ga	20	20	10	10
Ti	2200	2700	2700	2000
B	30	30	40	30
Ba	2300	2200	1800	1400
Be	---	---	---	---
Pb	20	10	10	10
Sr	1600	2200	1700	1300
Yb	1	1	1	1
Y	5	10	5	5?
Zr	100	150	120	80

Table 7 (cont'd). Normative and spectrochemical analyses for four samples of the stratified rocks of the Klinker Mountain volcanics. The normative values are percents, the spectrochemical values are in parts per million.

poorly although those which have a higher percentage of volcanic tuffs seem to be more resistant. Besides sandstones and conglomerates, some siltstones and limestones are included in this member. The colors of weathering include the following:

Light brown (5Y6/4)
Yellowish gray (5Y7-8/1-2)
Grayish yellow green (5GY7/2)

The conglomeratic sediments are more brown and the finer sediments tend toward green. In a few small areas, the rocks are approximately pale red (10R6/2). Bedding is generally very faint and is revealed in many outcrops only by stringers of coarse pebbles or beds of finer material. Most of the units are very lenticular and cannot be traced for more than a few thousand feet.

Members of this unit are distinguishable from the sandstones and conglomerates of the Bedrock Spring formation by the higher percentage of volcanic rocks among the pebbles and cobbles. Here, the ratio of volcanic fragments to others is usually about 5 or 10 to 1; in the Bedrock Spring formation, the reverse ratio is more general.

Lithology and composition -- The pebbles in the sandstones and conglomerates of this unit are usually subrounded to subangular and seldom exceed 3 inches in diameter. The majority of the volcanic pebbles are purplish or gray, apparently derived from other members of the Klinker Mountain volcanics. A few other types such as banded rhyolitic rocks are found. Nonvolcanic pebbles include fragments of quartz, metamorphic rock, and Atolia quartz monzonite.

The sandstone is usually a poorly sorted arkose and ranges in size from very coarse to medium grained; in some areas, the rocks are composed of silt to fine sand. Some of the detritus appears to be derived from the pink leucocratic Atolia quartz monzonite inasmuch as the majority of fragments are pink feldspar or clear quartz. Some portions of this member contain an appreciable percentage of tuffaceous material and there are all gradations from pure sandstone to the pure tuffs of the "tuffs and pyroclastics" member of this formation.

In the type section of the Klinker Mountain volcanics, the sandstone and conglomerates contain a higher percentage of pebbles, cobbles, and boulders than do most other exposures of this unit.

In one area, in sections E9-b, f, and m, a thin bed of limestone is found, apparently interbedded with fine-grained clastic rocks of this series. The limestone, which breaks with a conchoidal fracture having a waxy lustre, is about 4 feet thick and is about 10 feet below the base of the Lava Mountains andesite. It weathers to colors averaging yellowish gray (5Y6-8/1-2) and on the fresh surface is a slightly lighter color. Many fragments from this unit contain abundant fossils, apparently ostracodes(?) and mollusks(?). When dissolved in acid, an oily film rises to the surface.

Distribution of Various Rock Types

The five units described above are grouped into two stratigraphic units: The lower two, consisting of the greenish and purplish-weathering members of the volcanic intrusive complex (Tkg and Tkp), underlie the stratified rock units. Within this complex, as discussed above, there is a pseudo-stratigraphic order of the purple rocks overlying the greenish rocks but this is a result of alteration, not of the depositional sequence. The upper three units, comprised of the stratified rocks (Tkt, Tks, and Tkb), show no over-all depositional sequence.

To the north and northeast of Klinker Mountain, the sequence is fairly consistent, namely, that sequence found in the formation type section. North and northeast of Dome Mountain, the section is similar but siltstone is locally the basal member. West of Klinker Mountain, the sequence is very irregular and no stratigraphic order of the various units is apparent. Southwest and south of Klinker Mountain, the volcanic breccias and flow breccias of the Klinker Mountain volcanics directly overlie the intrusive complex.

The areal distribution of the members is systematic in a very gross way. North, northeast and east of the Klinker Mountain type section, the basal volcanic members of the formation are pyroclastics, and the ratio of pyroclastics, tuff, and detrital rocks to volcanic breccias and flow breccias is about 1 to 1. South and slightly west of Dome Mountain the section, although complicated by faulting, seems to have a comparable percentage of sedimentary and pyroclastic material. South and southwest of Klinker Mountain, the formation consists chiefly of coarse volcanic debris; the maximum thickness of the formation is also found in this area. In the vicinity of the Brown's Ranch fault zone, the Klinker Mountain volcanics are almost entirely tuffaceous; the relationships and lithologies are complex and poorly exposed in this area, however.

Thus, the coarsest materials in the Klinker Mountain volcanics are found south and west of Klinker Mountain and the finest materials are near the Brown's Ranch fault zone four miles to the east. The sections between and to the north are interlayered coarse, medium, and fine-grained material. The thickest section corresponds with the coarsest portion; the thinnest exposed sections are the interlayered coarse and fine material. The base of the finest grained materials is not exposed.

Volcanic Source and Environment of Deposition

Inasmuch as the coarsest and thickest portions of the Klinker

Mountain volcanics are found in the western and southern part of the area in which this formation outcrops, it seems probable that the volcanic products came from that area. The most obvious source is the intrusive complex (Tkg and Tkp) exposed in that portion of the map. This hypothesis is strengthened by the similarity between the composition of the layered members of the volcanics and the probable original composition of the intrusive complex rocks. Also, the detailed field relationships along the contact suggest an intrusive contact in part, although the over-all relationships are those of a sedimentary contact.

The Klinker Mountain volcanics are restricted to the area south of the Dome Mountain anticline (see fig. 21) which was present in the form of a ridge at that time (see "Folds"). The formation was probably deposited in a region of moderate relief as shown by the variation in stratigraphy that occur from one exposed section to the next. Most of the sections that show real differences in character are separated by faults that offset the base of the volcanics the most, beds within the section somewhat less, and the overlying Lava Mountains andesite the least. This strongly implies that displacements along the faults occurred before, during, and after the Klinker Mountain volcanics were deposited, and that much of the topographic relief at that time was a result of this activity. The deposition of the volcanic debris was apparently an intermittent activity inasmuch as locally, sedimentary rocks derived in part from the granitic highland or the still-exposed Bedrock Spring formation, were interbedded with the products of explosive volcanic activity.

Age and Relationship to Other Formations

The Klinker Mountain volcanics are believed to be contemporaneous with, and equivalent to, the Almond Mountain volcanics. The two formations can be seen interbedded in sections E2 and E11. Both formations also have the same relationships with respect to the underlying Bedrock Spring formation and the overlying Lava Mountains andesite.

The relationship of the Klinker Mountain volcanics to the underlying Bedrock Spring formation is distinctly that of an unconformable contact in many areas, although not everywhere. Good examples of an unconformity can be seen in sections D2-f, E3-c, E3-k, and E6-r. The relationship to the overlying Lava Mountains andesite is likewise unconformable and good examples can be seen in sections E7-l, D2-m, and D11-n; the latter unconformity is shown in figure 14a. Apparently, in the interval between the deposition of the Bedrock Spring formation and the deposition of the Klinker Mountain volcanics, much of the deformation was folding; in the interval between the Klinker Mountain volcanics and the Lava Mountains andesite, much of the deformation was faulting without appreciable tilt of the fault blocks.

For the reasons outlined under the Almond Mountain volcanics, there is little positive reason to correlate this pair of formations with others that have been mapped in the Mojave Desert region.

LAVA MOUNTAINS ANDESITE

The type section of the Lava Mountains andesite is in section D1-m, and the name is taken from the Lava Mountains where it is well exposed.

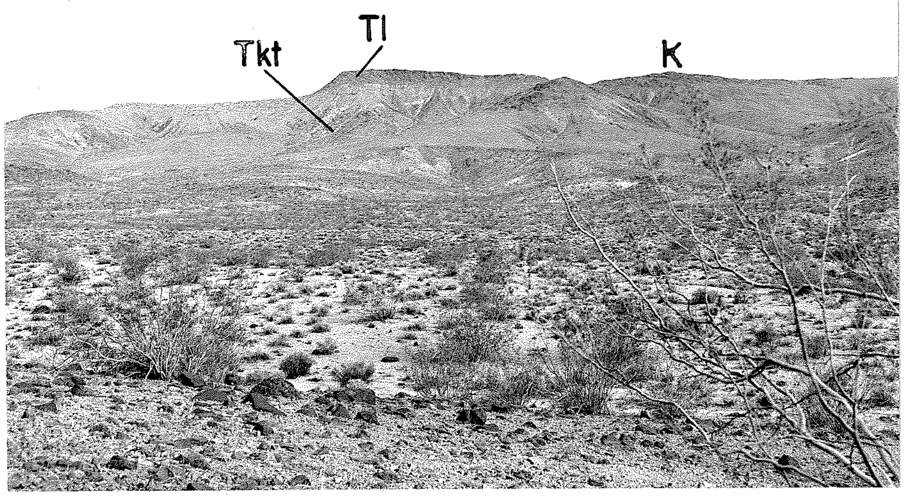


Figure 14a. Klinker Mountain (K) as seen from the west. Note the north-dipping bed of tuff (Tkt) which is unconformably overlain by the Lava Mountains andesite (Tl).

Figure 14b. Typical outcrop of the late Pliocene(?) felsite unit. Photograph taken in section E5-r.

The Lava Mountains andesite is a rather uniform and distinctive rock type. Throughout most of the area it is present as flows which now form the tops of the mesa-like hills. On the edges of these hills, it outcrops as a resistant blocky material that forms dark talus slopes on the hillsides. In hand specimen it most commonly is dark gray with small reddish brown streaks or patches. In other places, variations of this main type are found as reddish brown rocks, as intrusive dikes, sills, and plugs, as flow breccias consisting of angular fragments of the Lava Mountains andesite in a matrix of the same material, and as flow conglomerates containing rounded fragments of Lava Mountains andesite and other volcanic rocks in a matrix of the andesite.

Descriptions of Included Rock Types

Andesite flows (Tl) --

This unit, which forms the bulk of the formation, is present as patches over most of the southern two-thirds of the area. Good exposures are found along the edges of many of the outcrop areas, the best of which are in sections B31, D1, D2, E1, E34, F7, and F18.

Figure 15a shows the typical aspect of the andesite outcrops. On the tops of the mesa-like hills, the typical "outcrop" is a field of boulders lying on fine-grained chocolate brown material. Over many of these flat areas, reliable outcrops are scarce or nonexistent. Around the edges, the rocks are flaggy, jointed, or structureless. Near the base of the flows, the rock commonly weathers to flaggy slabs, an inch or two thick. The attitude of these slabs is usually about parallel to the contact at the base and gradually changes to

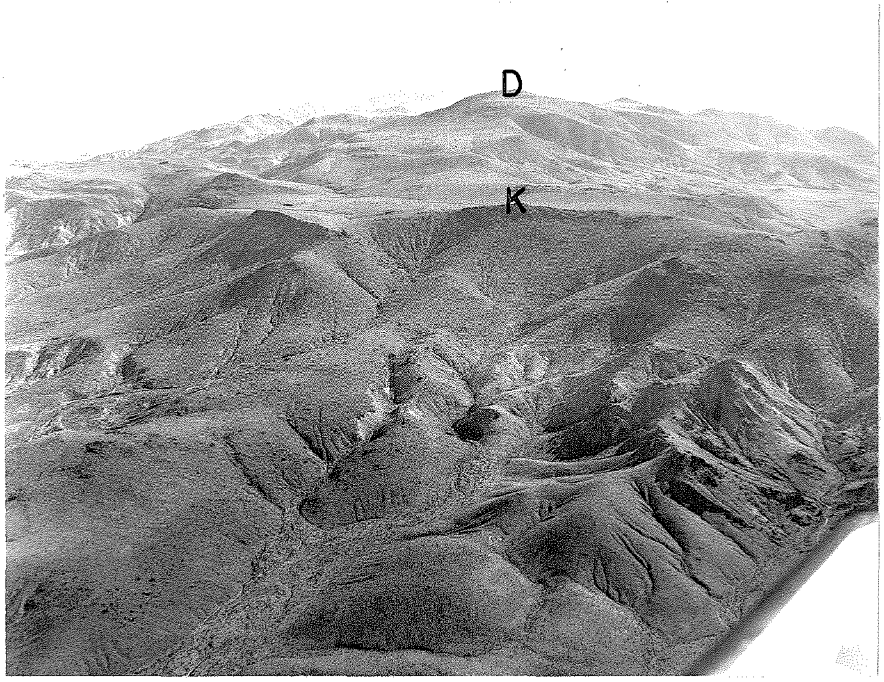


Figure 15a. Aerial view of the top of the Lava Mountains. Klinker Mountain (K) and Dome Mountain (D) are labeled. Note the smooth upper surface of the Lava Mountains andesite which caps the mountains. View toward the east.

Figure 15b. View of the basal contact (C) of the Lava Mountains andesite. Photograph toward the east, from section E8-a.

nearly vertical in the upper part. Above this flaggy zone, perhaps 20 or 30 feet, columnar joints a foot or two across are sometimes present.

The flows generally weather to medium dark gray (N2-4), brownish gray (5YR3-5/1-4), and grayish red (10R3-5/1-4). In an unusually high percentage of the rocks, the groundmass is composed of the same two colors -- dark gray and brownish red -- although the ratio of the two colors varies greatly. Generally, one color forms the major portion, and the other is found as small thin streaks about 1 mm wide and 10 mm long. The less altered rock is typically medium gray (N4-5); the more oxidized portion varies from pale red (10R4-6/2-4) to light brown (5YR5-7/1-6).

Of 117 hand specimens studied, 52 percent contained two colors in the groundmass. Sixty-five percent of the total were all or partly gray, ranging from medium dark gray (N3) to light gray (N7); thirty-nine percent were confined to the middle two shades, medium gray (N4) and light medium gray (N5). Reddish brown colors were found in 48 percent of the samples; in 28 percent, pale red (10R4-6/1-6) formed one of the colors, and in 20 percent, light brown (5YR5-7/1-6) formed one.

Along the strike of this unit, little color variation was found outside of the limits described above. The predominant color often changed from gray to red, but the member remained unrecognizable over distances of several miles.

Lithology and composition -- Microscopic study of 45 thin sections indicates the following: Plagioclase is almost always found as two generations; zones are well developed in the majority of crystals, and twinning is usually medium to strong; over half the thin sections contain calcic rims on over half the plagioclase crystals. Biotite, present in 82 percent of the sections, is strongly altered in more than half. Oxyhornblende, present in 89 percent of the rocks, shows a similar degree of alteration. Clinopyroxene, present in 80 percent of the rocks, is relatively unaltered in two-thirds. Orthopyroxene, present in 69 percent of the rocks, is relatively unaltered in about two-thirds, Quartz, present in 69 percent of the samples, is common in a few and sparse in most of the rocks in which it occurs.

The groundmass varies greatly in character. On the average, about 30 percent of the groundmass consists of microscopic crystals and crystallites, 45 percent anisotropic "glass", and 25 percent isotropic glass. The concentration of opaque materials is likewise very variable, ranging from rocks in which only a thin black dust is present, to rocks in which the groundmass is virtually opaque. The reddish brown rocks contain the highest percentage of opaques. The nature of these opaque materials varies. Some are small euhedral crystals that appear black. Others are irregularly shaped -- featherlike, hairlike, or fibrous -- and commonly appear red in conoscopic light.

In thin section these rocks generally show only slight lineation if any. Many rocks have small but numerous vesicles; some appear to contain a quarter to a third of their volume as vesicles. A few of these vesicles have linings of opal, chalcedony, tridymite, or a yellowish or greenish fibrous anisotropic material. Plagioclase crystals commonly range in size up to 5 or 6 mm in length, biotite and oxyhornblende up to 2 or 3 mm, and pyroxene is usually not over 1 mm in length. Quartz is generally present as crystals 1 to 3 mm across.

Alteration in these rocks is extreme in some and light in others. Usually the plagioclase shows little alteration of the outermost zone although along some of the more marked zonal boundaries, especially at the base of the calcic rim, swarms of inclusions of clear or yellowish glass suggest temporary resorption. Apparently the last major resorption and alteration of the plagioclase megaphenocrysts occurred after the crystals had clustered to form a "glomeroporphyritic" texture. In every instance noted, the resorbed area, and the subsequent calcic rim, was formed only on the outward faces of the crystal group. The faces that were in contact with other crystals were neither resorbed nor coated with a calcic rim.

Biotite and oxyhornblende usually alter to opaque materials. Successive stages of alteration can be represented by the following: 1) a coating of euhedral opaque crystals on the biotite or oxyhornblende crystals only slightly altered; 2) a dense felt of opaque materials in those in which alteration is more advanced; 3) still more thoroughly altered crystals consist almost entirely of fine-grained opaque material with central areas of nonopaque minerals (clinopyroxene(?)); 4) in the most advanced alteration, the opaque materials seem to have started dispersing into the surrounding groundmass. The clinopyroxene and orthopyroxene crystals also alter to opaques from the outside toward the center; often the opaque rim is "preceded" by a zone of reddish or orange discoloration. Reaction rims around quartz usually consist of fine-grained clinopyroxene but these are not always present.

The results of modal, normative, chemical and spectrochemical analyses are found in table 8.

Although the above description applies to the majority of rocks of this category, one distinct variety is also included. It is found in sections E8 and E9 and consists of two phases: First, and most abundant, is a light brownish gray (5YR4-8/1) type; the second is medium light gray (N6) and breaks with a very smooth conchoidal fracture displaying a waxy lustre.

The first consists of 25 to 30 percent phenocrysts of plagioclase, biotite, probably hornblende, and quartz, in a very vesicular matrix. The vesicles are coated with a greenish material. The average megaphenocryst size is about 3 mm, though some crystals are as much as 5 mm long. The second is characterized by an almost total lack of opaque material and a very well developed set of perlitic fractures, most of the circular fractures having radius of less than 1 mm. The green hornblende and biotite are totally free from alteration as is orthopyroxene. Maximum crystal sizes range up to 4 mm for plagioclase and 1 mm for hornblende, biotite and orthopy-

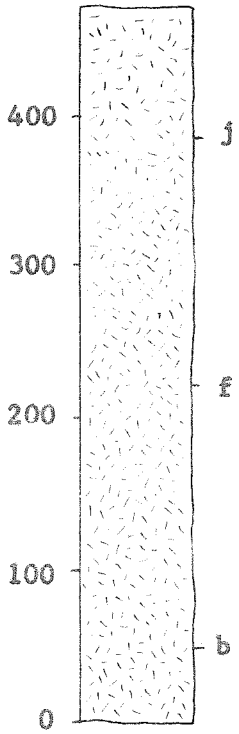
Modal analyses	27-21	27-23	98-7	97-38°	124-23J	124-23F	124-23B	124-22K	181-28
	Sample number								
Plagioclase megaphenocrysts	13.8	8.5	10.9	10.6	12.4	12.5	10.5	4.3	7.9
Plagioclase microphenocrysts	10.7	20.2	10.0	12.2	9.4	6.8	6.8	11.6	8.3
Total plagioclase	24.5	28.7	20.9	22.9	21.8	19.2	17.2	15.9	16.4
Biotite	0.3	0.1	0.5	0.3	0.1	0.3	---	0.5	---
Hornblende	---	0.2	---	---	---	---	---	---	---
Oxyhornblende	0.4	---	2.1	0.1	3.1	7.6	0.7	0.2	t
Orthopyroxene	1.4	0.2	0.2	0.1	0.1	0.9	0.1	2.5	0.7
Clinopyroxene	0.8	2.0	0.3	0.2	---	0.1	---	0.1	0.9
Quartz	0.5	0.1	0.1	0.2	---	0.3	0.1	---	3.2
Opaque minerals	5.4	2.5	6.7	6.0	9.5	2.2	11.4	1.4	8.2
Nonopaque minerals	0.5	0.6	0.7	2.9	0.1	0.2	---	0.5	0.7
Chemical analyses									
SiO_2	64.5	63.3	63.8	65.0	64.2	64.1	64.9	66.1	60.6
Al_2O_3	16.4	16.4	16.7	16.7	16.8	16.7	16.9	16.2	16.2
Fe_2O_3	2.1	1.4	3.8	3.8	3.7	1.8	4.1	2.3	2.8
FeO	1.9	2.8	0.14	0.34	0.44	2.1	0.02	0.88	2.4
MgO	2.3	2.4	2.3	0.75	2.3	2.1	2.0	1.6	3.5
CaO	4.4	5.0	4.7	4.2	4.4	4.1	4.3	3.9	5.8
Na_2O	4.2	4.2	4.1	4.4	4.5	4.0	4.5	4.0	3.8
K_2O	2.3	2.3	2.1	2.6	2.5	2.7	2.5	2.7	2.4
TiO_2	0.66	0.68	0.58	0.68	0.66	0.64	0.66	0.50	0.76
P_2O_5	0.23	0.28	0.29	0.24	0.28	0.26	0.30	0.18	0.28
MnO	0.06	0.06	0.06	0.02	0.06	0.06	0.06	0.04	0.07
H_2O	1.0	1.2	1.2	1.8	0.17	1.4	0.20	1.4	1.2
CO_2	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.21	0.74
Total	100	100	100	101	100	100	100	100	101

Table 8. Modal and chemical analyses of nine samples of the Lava Mountains andesite flows. All values are in percents.

Norm (C.I.P.W.)	Sample number								
	27-21	27-23	98-7	97-38°	124-23J	124-23F	124-23B	124-22K	181-28
Q	18.4	15.9	19.0	21.0	17.6	18.5	17.7	21.7	14.0
C	---	---	---	---	---	0.3	---	---	---
or	13.3	13.3	12.2	15.6	15.0	16.1	15.0	16.1	13.3
ab	35.6	35.6	34.6	37.2	37.2	34.1	38.2	34.1	32.0
an	19.2	19.2	21.1	18.1	18.6	18.6	18.4	18.1	20.3
di	2.2	4.5	0.4	1.3	0.9	---	---	1.1	5.4
hy	5.3	6.6	5.6	1.3	5.1	6.5	5.0	3.5	6.9
mt	3.0	2.1	---	---	---	2.6	---	1.6	4.2
il	1.4	1.4	0.3	0.8	0.9	1.2	---	0.9	1.5
hm	---	---	3.8	3.8	3.7	---	4.2	1.1	---
tn	---	---	1.2	0.8	0.6	---	1.0	---	---
ru	---	---	---	---	---	---	0.3	---	---
ap	---	---	---	---	0.7	0.7	0.7	---	0.7
Classification	I.4.3.4	II.4.3.4	I.4.3.4	I.4.3.4	I.4.3.4	I.4.3.4	I.4.3.4	I.4.3.4	II.4.3.4

Spectrochemical analyses	27-21	27-23	98-7	97-38°	124-23J	124-23F	124-23B	124-22K	181-28
Cr	80	80	70	60	40	40	40	40	70?
Co	60	80	30	20	80	60	40	50	60
Mn	390	420	390	170	420	420	380	280	470
Ni	50	60	60?	50	30	20	30	10	50
Sc	5?	5	10?	5	5	5	5	5	5?
V	60	70	60	70	70	60	60	40	90?
Fe	2.2%	2.2%	2.8%	2.4%	2.8%	2.2%	2.5%	1.6%	3.1%
Cu	20	20	20	30	20	10	20	10	30
Ga	10	10	10	20	20	10	20	10	10
Ti	2600	2400	2100	2800	2500	2100	2600	2100	2400
B	40	40	20	20	30	30	20	40	20
Ba	1700	1600	2000	1800	2000	1400	2000	2000	1900
Be	---	---	---	---	---	---	---	---	---
Pb	10	10	10	10	20	10	10	10	10
Sr	1400	2000?	1600	1400	1500	1200	1800	1000	1600
Yb	<1	<1	<1	<1	<1	<1	1	<1	1
Y	5	5	10	5	10	5?	10	10	5?
Zr	120	110?	100	110	110	80	120	110	90

Table 8 (cont.). Normative and spectrochemical analyses of nine samples of the Lava Mountains andesite flows. The normative values are percents, the spectrochemical values are parts per million.



Andesite. Colors vary between medium dark gray (N4) and pale red (10R6/2); the top and bottom thirds have a higher percentage of the red colors. Excellent foliation in some parts; about horizontal near the base, steeper in the upper part.

Figure 16. Section of Lava Mountains andesite on southwest side of Almond Mountain. Letters show the relative positions of the 124-23 series of samples described in table 8. Thicknesses are in feet.

roxene. The width of devitrification along the cracks varies from 0.5 to 1.5 microns, averaging 0.9 microns (Royal Marshall, oral communication, 1955).

Intrusive sills and dikes (Tli) --

Rocks of this unit include sills and dikes, which are in the western part of the area, and intrusive plugs with a "skirt" of associated flows, which are found in the central portion of the map. The best exposures are found in sections B32, D1, D2, and E5.

The rocks weather generally to dark colors approximating olive gray (5Y3-5/1-2) or dark greenish gray (5GY3-5/1). Some outcrops are nonresistant to weathering and are consequently exposed as zones of dark colored decomposed volcanic material. Other exposures -- these being more common -- are more resistant and form cliffs or steepsided hills. The thicker portions of the sills sometimes form excellent columnar joints a foot or two in diameter. In some areas (as in section D1-p), the vertical columnar joints form many superimposed layers, although these joint-systems lose their identity near the upper and lower contacts. In D1-f and D1-g, is a well exposed gradational contact between one of these intrusives and the arkosic sandstone of the Bedrock Spring formation. A silicified zone, a few inches to a few feet thick, grades into the intrusive over a distance of about 10 mm. In thin section, this gradational zone is seen to consist of a mechanical mixture of angular fragments of clastic rock in a matrix of very fine-grained intrusive rock containing small euhedral plagioclase crystals. The clastic fragments form about 95 percent of the mixture.

Conceivably, this is a micro-model of the method of emplacement for intrusive rocks in relatively-unconsolidated clastic rocks of this type. The fact that no trace of these clastic fragments is found except around the outermost edges of the intruding material, indicates one of the following: 1) the fragments have been entirely assimilated by the time they have traveled a very short distance into the magma, or 2) the clastic mixture is restricted to the outermost layer of the intrusive by the lack of turbulent flow in the molten sill. The fact that the fragments show no rounding from the action of the enclosing magma probably rules out the first alternative. If assimilation was not operative, then the sill must have been emplaced by forceful injection.

In one area, section E5, the rock consists of alternating zones of light olive gray (5Y6/1) separated by thin beds of lighter colored material. They form pseudobeds, uniformly 1-foot thick, which are parallel to the slope and probably to the direction of flowage. In section E5-h, the toe of this flow is well-exposed in the canyon bottom. This feature is shown in figure 17.

The most characteristic megascopic features of all these intrusive sills and dikes are the dusky yellow (5Y6/4-6) coatings in the vesicles which appear as elongated streaks, generally less than 1 mm across. The color of the groundmass includes the following:

Gray (N1-6)
Light olive gray (5Y5-6/1)
Greenish gray (5GY4-6/1-4)
Pale brown (5YR5/1-2)

Lithology and composition -- Thin section examination shows the following: The rock consists of phenocrysts of plagioclase, biotite, oxyhorn-

Figure 17a. Toe of a Lava Mountains andesite flow exposed in section E5-h. Photograph by R. F. Yerkes.

Figure 17b. Detail of the portion of the toe illustrated in figure 17a. Note the "roll-over" structures. Photograph by R. F. Yerkes.

blende, orthopyroxene, clinopyroxene, and sometimes quartz, in a groundmass of microcrystals and anisotropic "glass". The plagioclase, always found as two size groups, is most commonly strongly zoned, and almost always has a calcic rim. Twins show weak to strong development. Most of the biotite is partially altered to opaque materials. The amphibole, green hornblende in the intrusive rocks of the northwestern part of the area, and oxyhornblende in the extrusive "skirts" in the central part of the area, is heavily altered to opaque materials. Clinopyroxene and orthopyroxene are fresh in most rocks but in some have been partially or totally altered to serpentine(?). Quartz is present in a little over half of the rocks examined. The groundmass consists of about 20 percent isotropic glass, the balance being about half microcrystals and half anisotropic "glass"; many samples have numerous disseminated fibers of a light green to colorless mineral which may be serpentine(?), and most have a medium-light "dust" of opaque minerals.

Some of the rocks show a faint lineation in the groundmass. Vesicles, present in most sections, are lined with one or more types of greenish yellow material which apparently includes serpentine, stained chalcedony, opal, tridymite, and/or zeolite; the optical properties of these fibrous or fine-grained minerals vary from low to high birefringence, a refractive index above or below 1.54, and parallel extinction. In one rock, tridymite, chalcedony, and opal were found as successive coatings, all three forming a layer about 0.15 mm thick; the outer contact of the chalcedony was nearly opaque from included dust or cavities. In most of these rocks, the plagioclase phenocrysts range in size up to 6 mm, the biotite up to 3 mm, the hornblende or oxyhornblende up to 3 mm, quartz up to 1 mm, and clinopyroxene and orthopyroxene up to 1 mm. Average sizes are generally 1/2 to 1/3 of these figures.

The modal, chemical, normative, and spectrochemical analyses for two of these rocks are shown in table 9.

Flow breccia (Tlb) --

This unit is best exposed in sections D12-j, D22-j, and D23-m. It outcrops most generally as a jagged resistant rock ranging in color from grayish red (5R3-6/2) to brownish gray (5YR3-6/1) on the

Modal analyses	Sample number 28-17	128-34
Plagioclase megaphenocrysts	9.73	10.74
Plagioclase microphenocrysts	9.67	11.08
Total plagioclase	19.40	21.82
Biotite	0.93	0.41
Hornblende	1.80	---
Oxyhornblende	---	0.14
Orthopyroxene	0.13	0.34
Clinopyroxene	0.20	0.27
Quartz	0.20	0.48
Opaque minerals	1.73	4.38
Nonopaque minerals	6.00	4.65

Chemical analyses	Sample number 28-17	128-34
SiO_2	64.4	63.9
Al_2O_3	16.6	16.3
Fe_2O_3	3.2	3.6
FeO	.78	.44
MgO	1.0	1.5
CaO	4.4	4.4
Na_2O	4.2	4.2
K_2O	2.6	2.6
TiO_2	.62	.64
P_2O_5	.20	.22
MnO	.04	.04
H_2O	2.2	2.3
CO_2	$<.05$	.22
Total	100.	100.

Norm (C.I.P.W.)	28-17	128-34
Q	19.70	18.48
C	---	---
or	15.57	15.57
ab	35.63	35.63
an	18.63	17.79
di	2.59	2.81
hy	1.30	2.50
mt	0.46	---
il	1.22	0.91
hm	2.88	4.00
tn	---	0.39
ru	---	---
ap	---	---
Classification	I.4.3.4	I.4.3.4

Spectrochemical analyses	28-17	128-34
Cr	45	45
Co	24	20
Mn	330	340
Ni	40	40
Sc	6.6	9.6?
V	50	36
Fe	2.0?	1.7?
Cu	18	6?
Ga	12	12?
Ti	2100	2100
B	t?	13
Ba	2300	2200
Be	---	<1
Pb	12	10
Sr	1400	1800
Yb	<1	<1
Y	8.0	8.4
Zr	130	94

Table 9. Modal, normative, chemical and spectrochemical analyses for two samples of the "Intrusive sills and dikes" member of the Lava Mountains andesite. The modal, normative, and chemical values are percents, the spectrochemical values are parts per million.

weathered surfaces although lateral variation is marked. On fresh surfaces it is usually somewhat lighter colored. The fragments show no sorting and range in size from sand-sized fragments up to a foot across; exceptionally, 2-foot fragments are found. Generally, the smaller fragments are angular to subangular, and the larger are subangular to subrounded. In most units the fragments form half to three-quarters of the total rock, the lava matrix forming the balance.

The fragments found in this unit are either similar to the matrix material, a gray rock with a greasy lustre, or a light purple rock. The first is presumably the same composition as the typical Lava Mountains andesite, and the latter two are probably derived from the Klinker Mountain volcanics. The matrix material apparently consists of the Lava Mountains andesite flow rock.

Flow conglomerate (Tlc) --

The best exposures of this unit are found in sections D14-c, D15-b, and D15-d. The rock outcrops as a resistant unit with the well-rounded fragments forming either pits or bumps on the surface. The colors of the matrix range from pale red (10R4-6/2-4) to pale brown (5YR5-6/2-4); the fragments are mostly medium gray (N4-6). The outcrops shown on the map consist of very similar rocks which were probably once part of the same flow. If true, the area west and north of section D13 was a continuous slope and probably dipped west or northwest.

The fragments in this unit usually consist of a gray rock with a greasy lustre. The matrix usually consists of undifferentiated Lava Mountains andesite.

One thin section of a sample from a similar unmapped flow on the north side of Dome Mountain shows the following relationships at the contact between the fragments and matrix. The fresh matrix material contains plagioclase, oxyhornblende, biotite, hypersthene, and minor quartz in a groundmass of about 20 percent anisotropic "glass", 80 percent isotropic glass, and a very heavy "dust" of red semiopaque fragments. The inclusions consist of plagioclase, hornblende, biotite, and hypersthene, in a clear matrix which contains about 3 percent needle-like crystals of plagioclase(?) and almost no opaque materials. Near the contact, one can see that the host rock was assimilating the fragments by mechanically breaking off pieces of mineral or groundmass, irrespective of crystal or groundmass boundaries, rather than by reaction or solution. There is no zone of reaction where the broken-off minerals are in contact with the host rock. The only change in the host rock that occurs in the vicinity of the fragments is an increase in the very fine-grained "dust" of reddish opaque materials.

Distribution of Various Rock Types

Members of the Lava Mountains andesite cover most of the higher hills in the southern two thirds of the mapped area. The andesite flows (Tl) are most abundant in the vicinity of Klinker Mountain, Dome Mountain, Almond Mountain, and in the large area 3 to 5 miles northeast of Almond Mountain. No mappable differences were found between any of these areas although some differences in mineralogy and chemistry can be detected. The flow conglomerates (Tlc) and flow breccias (Tlb) are restricted to the southwestern portion of this map.

The Lava Mountains andesite is relatively uniform in thickness throughout the area. Some flows are as much as 600 feet thick but most are between 200 and 400. Except for a 2-mile strip along the western edge of the map where the flows tend to be somewhat thinner, there is no large area characterized by excessively thick or thin andesite flows.

Volcanic Source and Environment of Deposition

The sources for the flows of the "intrusive" member (Tli) in the central part of the map are probably at the center of each of the moundlike hills that are aligned in an east-trending row.

The source of the andesite flows (Tl) of this formation is problematical. Throughout the field mapping, a continual attempt was made to record the flow structures in these rocks and thus delimit the vents. This approach was found to be fruitless. The outcrops were not adequate except along the edges of the hills, and the attitudes obtained were ambiguous.

As a result, the estimates of source areas can only be inference: The extent of the outcrops and the lack of great variations in thickness suggest that there were many sources for this uniform rock type. The best guess that can be made is that most of the highest outcrops of the rocks of this unit -- the "mounds" in the lava plateaus, and the more or less round hills in the southeastern part of the map -- are all source areas.

Probably the surface on which the andesite flows were deposited was one of low relief, and in places nearly flat. As noted by Hulin (1925), there is evidence that the flows in the northwest part of this area flowed north; the best evidence is in section Dl-c. The pattern of the flow conglomerate suggests that the flows in the western portion flowed west. The surface which received the flows in the central portion of the map was probably about horizontal. Figure 15b shows the almost-flat base of the flows in sections E8 and E9; the flows associated with the plugs along the south edge of sections B31, B32, B33, and B34 apparently spread in all directions from the plugs, a good indication of a nearly-flat surface.

Age and Relationship to Other Formations

The Lava Mountains andesite is in many places clearly unconformable on the Bedrock Spring formation and on the Klinker Mountain and Almond Mountain volcanics. These relationships are well shown in sections A36, B32, D11, and E9. The relationship of the andesite to two younger units can be established: The Christmas Canyon formation of Pleistocene(?) age contains fragments of the Lava Mountains andesite flows (Tl) in fairly high proportions. The Older Gravels (Qg) also contain fragments and boulders of the andesite. The latter deposits, however, rest on surfaces that were present at the time one member of the andesite was extruded. As can be seen in section B32-q, the "intrusive" andesite (Tli) rests on the uphill parts of surfaces that are elsewhere covered by Older Gravels (Qg). On this basis, the Lava Mountains andesites could be considered at least in part Quaternary (thus QTl, etc.), or the gravels could be called in part Pliocene (thus QTg). However, for each formation, the bulk of the evidence indicates the ages assigned to them, and for the sake of map simplicity, the slightly overlapping ages have not been written into the symbols.

Within this part of the Mojave Desert, many volcanic sections have been correlated with these volcanic flows -- under the name of Red Mountain andesite as it was called by Hulin (1925). It seems to the present writer that although many of these correlated flows have a similar lithology and occupy a comparable position with respect to the stratigraphic sequence of the area, there is little positive reason for the correlation. Most of the evidence indicates that the flows of the Lava Mountains andesite were very local and did not extend for more than a few miles from their source in any direction. To be sure, there are numerous sources within this area, but they form a very distinct cluster which is isolated from the other areas of potential correlation by large volcanic-free outcrops of plutonic rocks.

It is an interesting problem, however, in the stratigraphy of the Mojave Desert, that a great many regions do have the same general succession of rock types, viz. 1) sandstones and conglomerates, 2) volcanic breccias, tuffs, and pyroclastics, 3) capping flows of a dark colored rock usually called an andesite, and 4) very young-looking basaltic rock. Although as stated above there is little reason to think these separated areas are correlative in the sense of being once connected and/or contemporaneous, there does seem to be a repetition of the sequence. This strongly suggests to the writer that there is some fundamental process in common that controls the stratigraphic sequence for many of these areas.

The Lava Mountains andesite is definitely younger than the Bedrock Spring formation, of middle-Pliocene age, and the Almond and Klinker Mountain volcanics of late Pliocene(?) age. Some of the most recent flows are probably equivalent to the Quaternary gravels (Qg), although most of the formation is definitely older than the Christmas Canyon formation (Qcc) of Pleistocene(?) age. An age of "very late

Pliocene" is assigned to the Lava Mountains andesite although it is recognized that in part it may extend into the Quaternary.

OTHER VOLCANICS

Late Pliocene(?) Fine-Grained Intrusives

This unit combines five more or less distinguishable intrusive volcanics. Four occur as dikes; a fifth is found as small volcanic plugs.

Type 1 --

The first type, found in sections D1-k and D1-q, weathers to resistant "spines" that project through the softer Bedrock Spring formation. The groundmass color approximates grayish orange pink (5YR8/2). Scattered throughout the groundmass are small irregular patches, a few millimeters across, which are light brown (5YR6/6). The plagioclase crystals appear the same color as the groundmass, and the biotite forms relatively unaltered euhedral books. The orange-stained areas are commonly elongate, some being as much as 20 mm in length; possibly they represent altered acicular hornblende.

Type 2 --

The second type of dike rock is exposed in sections D1-h, E5-e, E6-c, and E6-e. It also weathers to resistant spines projecting through the Bedrock Spring formation. The color of the fresh surface varies from grayish orange pink (5YR7/2) to very pale orange (10YR7-8/2-6). The darker colors commonly have the appearance of stains and form swirling contorted patterns on the fresh surface. Vesicles, which are very abundant, are commonly lenticular and aligned. They are usually coated with a pale yellowish orange (10YR6-8/6) fine-grained material. The only visible minerals are plagioclase crystals up to 4 mm in length.

> In thin section, plagioclase, biotite, and hornblende(?) can be seen in the groundmass of microcrystals of plagioclase(?) and anisotropic material. The plagioclase, present as megaphenocrysts and microphenocrysts, is very weakly zoned and twinned; the composition ranges up to An_{60}. The biotite is almost entirely altered to opaque material, plagioclase, and discolored calcite. The hornblende(?) is entirely altered.

Type 3 --

The third type of dike rock found in the area is restricted to section A35 where it has intruded the Atolia quartz monzonite. All rocks of this unit, which weather to shades of reddish, red brown, and purple, are very strongly brecciated and heavily altered.

Type 4 --

The fourth type of dike rock, found in section A23, weathers to soft, crumbly, dark grayish rock with small white phenocrysts of plagioclase as the only visible mineral. This unit, too, is very strongly brecciated, being only a short distance from the Garlock fault.

Type 5 --

The small volcanic plugs and necks, located in sections D13, D14, and E18, form steepsided round hills, usually weathering to a color approximating moderate red (5R4/4). In detail, cleavage, color banding, or lineation is sometimes visible, generally dipping at high angles; no pattern, however, seems to be the rule. In hand specimen the rock usually appears somewhat coarser grained than the other volcanics of the region; the average size of the plagioclase megaphenocrysts in many samples is between 1 and 2 mm.

> In thin section, the rock is seen to consist of plagioclase, biotite, oxyhornblende, orthopyroxene, clinopyroxene, and quartz, in a groundmass predominantly of microcrystals of plagioclase and anisotropic "glass". The plagioclase shows zones that are commonly well-developed and many have a calcic rim; twins are sparingly developed, and the apparent composition ranges from andesine to calcic labradorite. Most of the biotite is partially altered to opaque materials. Usually, the oxyhornblende is strongly or entirely altered. Orthopyroxene and clinopyroxene, present as small euhedral crystals, is usually free of alteration. Quartz, which ranges from fairly common to abundant, is present as rounded and embayed crystals, some of which show a reaction rim of clinopyroxene. Most samples show a faint lineation in the microphenocryst plagioclase and a slight to fair vesicularity. Maximum crystal sizes are as follows: Plagioclase 4 mm; quartz 2 mm; biotite 2 mm; oxyhornblende 1.5 mm; orthopyroxene and clinopyroxene about 0.75 mm.

Age and relationship to other formations --

The four series of dikes described in this unit are known only to be intrusive into the Bedrock Spring formation and the Atolia quartz monzonite. The small plugs and volcanic necks are probably intrusive into the Klinker Mountain volcanics although they could represent topographic highs that projected into the Klinker Mountain volcanics as they were being deposited. The relationships between these intrusives and the Lava Mountains andesite is not known. For this reason, the rocks are tentatively assigned to late Pliocene(?) but the possibility that they may be in part Pleistocene cannot be discarded.

Late Pliocene(?) Felsite

The best exposed sections of this rock are found in sections B27-p and E5-r. It is characterized by a very strong tendency to spall off as flaggy slabs as shown in figure 14b. The cleavage direction is parallel to thin bands of darker colors and to the alignment of the minerals. Usually, the attitude of this foliation is steep. In sections E5 and E8, the attitudes dip at high angles toward the center of the outcrop; in section B27, the attitudes dip at high angles away from the center of the outcrop. Probably, both of these outcrops are remnants of volcanic plugs.

It commonly weathers to a color approximating light brown (5YR7/4) and forms high steep hills as a result of its great resistance to weathering. Normal to the cleavage, this rock breaks with a smooth conchoidal fracture and the colors of this surface include the following:

Medium light gray (N5-7)
Very pale purple (5P8/2)
Light brownish gray (5YR6-8/1)
Light grayish orange (10YR7-8/4)

Lithology and composition -- Results of thin section examinations show the following: The rock consists of a few plagioclase and biotite megaphenocrysts in a groundmass of very fine-grained microphenocrysts, crystallites, and anisotropic "glass". The plagioclase megaphenocrysts are euhedral, usually with very sharp edges, and show only weak zoning and twinning. The apparent composition of these is variable, ranging from about An_{30} to An_{55}; the average is perhaps An_{45}. The microphenocrysts apparently have a similar composition although some have an apparent composition of An_{65}. Biotite, usually partially or totally altered to opaque materials, is found as very thin "books" which appear in a crosscutting thin sections as streaks about 0.02 mm across. Some oxyhornblende(?) was seen in trace amounts. The groundmass consists predominantly of microscopic crystals, crystallites, and anisotropic "glass";

isotropic glass usually forms less than 20 percent of the material. The groundmass contains a light to medium "dust" of equant black opaque, or red translucent fragments.

In thin section these rocks are notable for the almost perfect alignment of the plagioclase microphenocrysts, crystallites, and the biotite crystals. Some specimens show vesicles but most have none. Plagioclase and biotite crystals are sometimes as much as 3 mm long; the average size of the plagioclase microphenocrysts is perhaps 0.02 mm long.

The results of modal, chemical, spectrochemical, and normative analyses are found in table 10.

Age and Relationship to Other Formations --

In two outcrops, in sections E5-j and E8-a, rocks of this unit are lying on top of the Bedrock Spring formation. Its relationship to all other Tertiary formations is unknown; the only unit containing fragments of this distinctive rock type is the Quaternary gravels (Qg). Thus it is probably late Pliocene or possibly early Pleistocene. Its age is considered to be late Pliocene(?) in this report.

Late Pliocene(?) Tuffs and Pyroclastics

These rocks are restricted to the northeastern quarter of the map. The best exposures are located in sections B23-l and B26-f. The colors vary from shades of green to light red, gray, or brown. Most of the rocks are extremely resistant to weathering and form cliffs and steep-sided hills. Some exposures, especially those along the west side of the outcrop area, show good bedding, but most of the others are massive. Where bedding is visible, the rocks are seen to be extremely faulted and broken.

Most rocks of this unit consist of coarse volcanic debris, apparently unsorted, consisting of well-indurated pyroclastic material

Modal analyses	Sample number 97-39
Plagioclase megaphenocrysts	1.23
Plagioclase microphenocrysts	6.28
Total plagioclase	7.51
Biotite	0.28
Hornblende	---
Oxyhornblende	---
Orthopyroxene	---
Clinopyroxene	---
Quartz	---
Opaque minerals	1.08
Nonopaque minerals	1.15

Chemical analyses	Sample number 97-39
SiO_2	71.5
Al_2O_3	15.6
Fe_2O_3	1.5
FeO	.01
MgO	.02
CaO	2.5
Na_2O	4.0
K_2O	3.3
TiO_2	.24
P_2O_5	.10
MnO	.02
H_2O	1.5
CO_2	<.05
Total	100

Norm (C.I.P.W.)	
Q	30.12
C	0.82
or	19.46
ab	34.06
an	12.51
di	---
hy	---
mt	---
il	0.46
hm	1.44
tn	---
ru	---
ap	---
Classification symbol	I.4.2.4

Spectrochemical analyses	
Cr	12
Co	24
Mn	110?
Ni	1.7
Sc	<1
V	6
Fe	.69?
Cu	1.8
Ga	9.3
Ti	830
B	22
Ba	2600
Be	<1?
Pb	22
Sr	1200
Yb	---
Y	10
Zr	100

Table 10. Modal, normative, chemical, and spectrochemical analysis for one sample of the Pliocene(?) felsite. The modal, normative, and chemical values are percents, the spectrochemical values are parts per million.

forming 75 to 95 percent of the total, the balance being formed of angular volcanic fragments. Some of the well-bedded units also contain detrital material.

Age and relationship to other formations --

This formation is older than the late Pliocene(?) breccias (Tpb) which overlie it. The relationships with the Bedrock Spring formation, however, appear to be intrusive. The most likely explanation for them is that the tuffs and pyroclastics were deposited early in the period of volcanic activity; they were subsequently deformed and intimately mixed with the rocks of the Bedrock Spring formation during the intrusion of the volcanic breccias (Tpb).

It is possible, however, that the tuffs are older than the Bedrock Spring formation and that the outcrops that we now see are exhumed hills that were present at the time the Bedrock Spring was deposited. This explanation, however, demands the unlikely coincidence that the only areas in which these tuffs and pyroclastics had been uncovered should be the only areas in which the late Pliocene(?) volcanic breccias were later deposited. It seems more likely that the pyroclastics and tuffs are connected genetically with the late Pliocene(?) volcanic breccias. Since the latter are definitely younger than the mid-Pliocene Bedrock Spring formation, it is concluded that the tuffs and pyroclastics are also.

The relationship of this unit to the Klinker Mountain volcanics, the Almond Mountain volcanics, and the Lava Mountains andesites is not known.

Late Pliocene(?) Volcanic Breccias

The rocks included in this category are found in two widely separated portions of the map. One group of outcrops is found along the western edge of the area, the other is in the northeastern quarter. They are not intended to be correlative.

Type 1 --

The first unit, restricted to the western edge of the mapped area, is best exposed in sections D3-q, D9-j, and D15-b. It generally shows medium resistance to weathering -- more than the underlying Bedrock Spring formation and less than the overlying Lava Mountains andesite. On hillsides the colors approximate pale red purple (5RP6/2) and light brownish gray (5YR6/1); where well exposed on canyon walls it is slightly more brown.

The composition of this unit varies from a pyroclastic breccia, consisting of 80 percent purplish pyroclastic material containing fragments mostly less than 1 inch across, to a volcanic breccia, with boulders up to 4 feet across forming 80 to 90 percent of the unit. The fragments are predominantly of a purplish volcanic rock but up to 30 percent of them are Lava Mountains andesite. Also, a small percentage of metamorphic fragments, mostly knotty schist, are present.

Age and relationship to other formations --

The relationship of the breccias to the underlying(?) Klinker Mountain volcanics is apparently that of an unconformity, as suggested by the mapped relationships in sections D10-h and D15-a, but the exposures are never quite good enough to be convincing. The relationship of this unit to the underlying Bedrock Spring formation is clearly that of a slight unconformity in one area (D15-g); in others, the contacts are not well enough exposed to be conclusive.

Its position with respect to the Lava Mountains andesite is problematical: The breccias are clearly overlain by flows of the Lava Mountains andesite yet also contains fragments of rock types not known in any of the volcanic formations prior to the Lava Mountains andesite. It is probably older than the most recent flows of the Lava Mountains andesite and younger than the Bedrock Spring formation and the Klinker Mountain volcanics. Consequently, the unit is simply assigned to late Pliocene(?) age.

Type 2 --

The second area of exposed Pliocene volcanic breccias is restricted to the northeastern quarter of the map and is best exposed in sections B22-l, B24-q, and B25-h. The unit weathers as a very resistant cliff-forming rock with a jagged and hackly surface and displays the following colors:

Pale red (5R4-6/2)
Pale red purple (5RP4/2)
Pale brown (5YR4-6/2-4)

The rocks in the western half of the outcrop are, in general, more red than those to the east.

In the western portion of these outcrops, the rocks consist of well-developed flow breccias; the angular fragments are most commonly a fraction of an inch to a few inches across but some are measured in feet. The matrix in these rocks is apparently lava, although it may be a well-indurated pyroclastic or a welded tuff.

The rocks in the eastern half are generally more homogeneous and consist of light gray (N7-8) phenocrysts of plagioclase, measuring up to 5 mm, and some visible biotite and amphibole(?); the matrix is a medium light gray (N6-7) fine-grained material which is very vesicular on a microscopic scale. This unit, too, could be a welded tuff although no detailed work on it was done.

Age and relationship to other formations --

This unit is clearly unconformable on the Bedrock Spring formation and is on top of the Pliocene(?) pyroclastics and tuffs. Its relationship to the Christmas Canyon formation of Pleistocene(?) age can only be inferred: There is a faint "line" on these volcanic breccia hills; above it the rocks are very well exposed, and below it the rocks are still partially covered with their own debris. If one projects the surface defined by the top of the Christmas Canyon formation into the area of the volcanic breccias, the extension corresponds with this "line". It seems reasonable that this was the "alluvium line" at the time the Christmas Canyon formation was being deposited and that the volcanic breccias were resistant remnants of earlier volcanic activity that projected through the Christmas Canyon formation as it was being deposited. If this inference is acceptable, the age of the volcanic breccias is between middle Pliocene and Pleistocene(?). An age of late Pliocene(?) seems plausible.

TERTIARY ROCKS, UNDIFFERENTIATED

Rocks of this unit are found in three areas in the northwestern quarter of the map. All consist of complexly altered, folded, brecciated, and crushed rocks, mostly volcanics. Sedimentary rocks are found as thin beds in some of the area. Two of the areas also have intrusive volcanic rocks included.

The relationship of these units to other formations in the area is unknown. They are assumed to be Tertiary on the basis of induration and general lithology. Most are probably equivalent to some of the Tertiary formations mapped within the area but it is futile to attempt to correlate them.

CHRISTMAS CANYON FORMATION

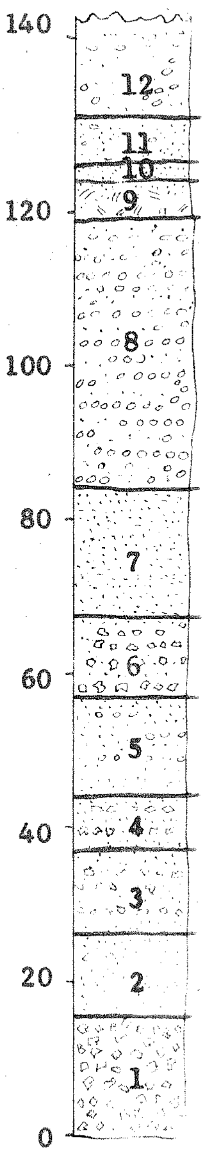
The Christmas Canyon formation, a new formation here named, is restricted to the northeastern portion of the mapped area. The type section is located in section C8-e and the formation is named for Christmas Canyon, about one mile east of the type section. The type section is shown in figures 18 and 19.

The formation consists of two distinct lithologic types. The first, a sandstone unit, is restricted to a strip about one-half mile wide and parallel to the Garlock fault. The type section is located in this facies. The second is a boulder conglomerate which is characterized by large vesicular andesitic, basaltic, and rhyolitic boulders, commonly one to two feet across. This facies is found south of the area occupied by the sandstone facies and north of the Garlock fault.

Sandstones

The rocks of the sandstone unit generally form yellowish gray (5Y7/2) hillsides. For the most part they are relatively unindurated and form "badland topography" over much of the exposed area; in other

Figure 18. The type section of the Christmas Canyon formation is located downhill from the arrow. The rocks in the immediate foreground are typical of the boulder conglomerate facies of the formation. Photograph looks northeast, Searles Lake is in the left distant background.



12. Sandy conglomerate. Pebbles, averaging $\frac{1}{2}$ inch in diameter, range in size up to 12 inches; they consist of volcanic porphyritic rocks, rhyolitic rocks, plutonic rocks, metamorphic rocks, and vesicular andesitic or basaltic rocks which are somewhat larger. Faintly bedded. Grayish-orange (10YR7/4).

11. Very fine- to medium-grained sandstone. Poorly bedded. A few pebbles of rhyolitic and metamorphic rocks. Light grayish orange (10YR8/4).

10. Very fine-grained sandstone. Poorly bedded. Yellowish gray (5Y7/2). Grades into the tuff below.

9. Tuff, pure in lower part. Very light-gray (N8).

8. Conglomerate. Well bedded. Contains fragments of vesicular andesitic and basaltic rocks averaging 2-inches across, ranging up to 6 inches; also fragments of metamorphic limestone, plutonic and rhyolitic rocks. Grayish-orange (10YR6-7/2). Cemented by calcium carbonate.

7. Very fine-grained sandstone. Fairly well bedded. Light grayish-orange (10YR8/4).

6. Alternating breccia and fine- to coarse-grained sandstone containing breccia fragments. Fragments range up to 3 inches, average 1 inch across. A few vesicular andesitic and basaltic fragments. Grayish-orange (10YR7/4).

5. Siltstone to very fine-grained sandstone. Well bedded, with stringers of metamorphic fragments which average $\frac{1}{2}$-inch in diameter and range up to 1 inch in diameter.

4. Alternating beds of breccia and very fine- to medium-grained sandstone. Beds 1 inch to 1 foot thick. Fragments, including some vesicular andesitic and basaltic fragments, average 1 inch in diameter, range up to 3 inches. Grayish orange (10YR7/4) to light olive gray (5Y6/1).

3. Alternating breccia and fine- to coarse-grained sandstone. Fragments average 1 inch across, range up to 3 inches, include vesicular basaltic rocks. Light grayish-orange (10YR8/4).

2. Fine-grained sandstone to siltstone. Metamorphic fragments, as stringers, average $\frac{1}{2}$ inch and range up to 1 inch across. Yellowish-gray (5Y8/1).

1. Breccia of metamorphic rocks, plutonic rocks in varying proportions, and volcanic porphyries; no vesicular andesitic or basaltic fragments. Fragments average $\frac{1}{2}$ inch across, range up to 3 inches. Weathers to pale yellowish-brown (10YR7/2).

Figure 19. Type section of the Christmas Canyon formation. Thicknesses are in feet.

areas they form low rounded hills. The bedding is generally distinct and individual beds, ranging in thickness from less than an inch to a few feet, may be traced laterally for several hundred feet.

The sandstones and siltstones of this unit are poorly sorted and consist of angular fragments of arkosic composition. Many of the beds, especially the finer-grained sandstones and siltstones, contain a high percentage of calcium carbonate which weathers out as white coloring. Locally, as in the type section, tuffaceous beds are found.

The pebbles included in the conglomeratic sandstones and conglomerates, which are interbedded with the finer material, have the following characteristics: They are rounded to subangular and include porphyritic andesitic rocks, metamorphic rocks of the types exposed nearby, rhyolitic rocks showing contorted color banding, plutonic rocks which sometimes include the pink leucocratic phase of the Atolia quartz monzonite, and small vesicular andesitic or basaltic rock pebbles.

Within this unit there are many minor angular discordances between beds. They do not seem to be widespread and are believed to be very local -- perhaps as the result of contemporaneous movement on the Garlock fault.

Boulder Conglomerates

This unit is found south of the sandstone facies and north of the Garlock fault. It forms steepsided hills which are covered with slumped debris. Most of the outcrops are tan to dark brown. Bedding is rarely seen.

In most places, the unit consists of pebbles, cobbles, and boulders in a matrix of very coarse angular sandstone. The pebbles and cobbles include dark colored plutonic rocks, grayish plutonic rocks, limestones, slates, phyllites, quartz, quartzites, andesitic porphyries, and rhyolitic fragments; the boulders are almost entirely composed of banded rhyolitic rocks and vesicular andesitic and basaltic rocks which commonly measure about one foot across. The thickness of this facies seldom exceeds 100 feet and most exposures are about 50 feet thick.

At one locality (in section C17-j), several dozen pebbles of the included volcanic and plutonic rocks were collected. The following megascopic and microscopic descriptions of nine of these may be considered a qualitative sampling of that collection:

> Porphyritic latite. Groundmass color: light olive gray (5R6/1). Phenocrysts of euhedral plagioclase and orthoclase(?) in a groundmass of fine-grained orthoclase(?), plagioclase, and quartz. Groundmass is holocrystalline. Most minerals are partially altered to claylike material.

> Andesite porphyry. Groundmass color: brownish black (5YR2/1). Phenocrysts of plagioclase, almost entirely altered to silica minerals, in a groundmass of tridymite(?) cross-cut by many quartz veins.

> Andesite. Groundmass color: grayish red purple (5RP4/2). Phenocrysts of plagioclase, strongly altered to sericite(?) and a yellowish material, and hornblende, entirely altered to opaque material; a groundmass of fine-grained silica minerals(?) and anisotropic "glass".

> Andesite. Groundmass color: grayish brown (5RY3/2). Phenocrysts of plagioclase, heavily twinned and zoned with a calcic rim, and oxyhornblende partially altered to opaque materials. Groundmass consists of fine needlelike plagioclase crystals, and anisotropic "glass". The groundmass is about 40 percent altered to calcite. A few grains of

quartz are present. This rock appears identical to those in the Lava Mountains andesite.

Vesicular andesite. Groundmass color: dark gray (N3). Phenocrysts of plagioclase, euhedral, faintly zoned and twinned, and clinopyroxene, euhedral, fresh. Groundmass is almost opaque in thin section. Vesicles, forming perhaps 10 percent of the rock, are filled or coated with calcite. This is typical of the "vesicular andesitic and basaltic rock" found throughout this formation.

Andesite or felsite. Groundmass color: dark reddish brown (10R3/4). Phenocrysts of albite, all less than 1 mm long, heavily altered and crushed. Groundmass is nearly opaque and contains numerous small clusters of euhedral(?) to subhedral quartz crystals.

Meta-dacite(?). Groundmass color: light olive gray (5Y6/1). Contains a few small euhedral to angular crystals of plagioclase and quartz, the plagioclase being very heavily altered. The groundmass consists of fine-grained silica minerals(?) and wisplike areas of fine fibrous material, possibly serpentine. Very heavily altered.

Metadiorite. Crystals of orthoclase(?), plagioclase, quartz, and green hornblende. The feldspars are strongly altered to serpentine(?), chlorite(?), sericite(?), and clay. Texture is seriate. Opaque minerals are sparse.

Leucocratic quartz monzonite. Crystals of orthoclase, plagioclase, quartz, and very minor chlorite, presumably after biotite. Some microcline. Rock appears identical to the leucocratic phases of the Atolia quartz monzonite found in the northwestern corner of the mapped area.

Distribution of Various Rock Types

South of the Garlock fault, the finer facies of the Christmas Canyon formation are limited to the half-mile wide strip along the south edge of the fault. The same rock types are exposed north of the Garlock fault in sections C4-j and C4-k, and in a narrow strip along the fault, east of the mapped area. Figure 20a shows this extension.

Conglomerate facies form the remainder of the exposures. The main areas of outcrop are south of the strip of fine-grained material along the Garlock fault, and northeast of the mapped area, on the north side of the fault.

The change between the coarse and fine facies occurred along a line of low metamorphic-rock hills that were elevated along the now-concealed fault shown on the map. Interfingering relationships between the two facies are exposed at several places in the vicinity of the concealed fault, the transition of a given bed occurring over a zone a few feet wide.

Most of the floor of Spangler valley is warped and/or eroded into broad domes and depressions. The rocks exposed in the stream channels and gullies bear a strong resemblance to the Lava Mountains outcrops of the Christmas Canyon formation; it is very possible that the Christmas Canyon formation forms much of the valley fill. Probably some of the deeper parts of the fill in Searles Lake basin are equivalent in age, but the lithologies--down to 875 feet--are very dissimilar (Smith & Pratt, in press, 1956?).

Age and Relationship to Other Formations

In section C8-h, about one-half mile west of Christmas Canyon, there is a well-exposed contact between the underlying metamorphic rocks and the Christmas Canyon formation. Here, a basal breccia, primarily of metamorphic fragments and about 25 feet thick, is seen in sedimentary contact with the metamorphic rocks. This is the only exposure of the contact adequate to prove the absence of major displacement along the concealed fault since the deposition of the Christmas Canyon formation.

The boulder conglomerate facies of the Christmas Canyon formation is clearly unconformable on the Bedrock Spring formation in many places. The relationships with the late Pliocene volcanic units are not directly known; however, the Christmas Canyon formation is inferred to be younger inasmuch as it contains pebbles that are very similar, in both hand specimen and thin section,to the Lava Mountains andesite. The conglomeratic facies also contain the vesicular andesitic and basaltic rocks derived from outcrops several miles to the southeast (see the reconnaissance map, plate 1). These outcrops are probably Pleistocene -- an inference based on the relatively fresh condition of the flow surface. Only basaltic rocks, travertine, and alluvium have been deposited since Christmas Canyon time.

With the possible exception of some of the Older Gravels (Qg), none of the other formations are equivalent in age to the Christmas Canyon formation. East of the mapped area, along the south end of the Slate Range (see fig. 20a), there is a thick section of similar-looking material which may be a continuation of the same formation. To date, however, no mapping has been done to confirm this.

Only one fossil -- a hoof bone -- has been found in the Christmas Canyon formation. This was found, by Richard Tedford and Robert Shultz, Jr., about a thousand feet north of the type section. According to G. Edward Lewis (written communication, 1956): "The size of the hoof bone permits reference either to a large species of *Pliohippus* or a small *Equus*." On the basis of this fossil, which is admittedly inconclusive, plus the evidence afforded by the pebble content of the formation, an age of Pleistocene(?) is assigned.

Environment of Deposition

Apparently the Christmas Canyon formation was deposited in a closed basin. The coarser facies of the formation were alluvial fan deposits and the finer facies playa lake deposits. That the finer sediments were deposited in standing water is suggested by the high calcium carbonate content in some of the beds. Another possible indication of standing water is the presence of numerous calcium carbonate tubes which may be calcified plant roots. Volcanic activity was also present in the area as indicated by local tuff beds, one of which is in the upper part of the type section; this activity, however, was neither frequent nor long lasting.

The only areas that are known to contain the vesicular andesitic and basaltic rocks, plus the banded rhyolitic rocks, are about 5 miles southeast (see plate 1). The other rock types found as pebbles are also compatible with that source area. Thus the portion of the Christmas Canyon formation exposed in the Lava Mountains represents the northwestern toe of a 5-mile alluvial fan.

BASALTIC ROCKS

Several basaltic dikes and very small flows are found in the northeastern part of the area. These weather to resistant ridges and "spines", generally in shades of dark red or dark gray. Some, especially the northern dikes, are volcanic breccias.

In hand specimen the rock was seen to consist of phenocrysts of plagioclase, pyroxene, and olivine(?) which is now entirely altered to iron oxides, in a matrix of vesicular dense material. The vesicles on the outside of the outcrops or breccia fragments commonly contain calcium carbonate; fresh, previously-unexposed vesicles, however, contain none.

Age and Relationship to Other Formations

At the westernmost end of the outcrops, basaltic rocks overlie the coarser facies of the Christmas Canyon formation. Here the basaltic rocks are in the form of a very small flow of volcanic breccia; a pyroclastic(?) matrix forms about 15 percent of the rock, and angular basaltic fragments, up to three feet across but averaging two inches across, form the balance. This unit lies with a horizontal contact on conglomerates of the Christmas Canyon formation which contain rounded vesicular andesitic and basaltic rocks, as well as grayish or purplish porphyritic volcanics and reddish-weathering rhyolitic rocks.

Correlation of these rocks with other basaltic rocks in the Mojave Desert region is treacherous. As pointed out in the discussion of the Lava Mountains andesite, there is a tendency for the sequence of Cenozoic events to end with andesitic and subsequently basaltic extrusion in many widely separated parts of the Mojave desert. However, as also pointed out in that discussion, a similarity of sequence has not been proven to mean a similarity in age. In the Lava Mountains, the basaltic rocks described here are several miles away from the earlier andesitic activity. Consequently, any inferred connection between the two seems unwarranted unless more positive evidence is found.

One feature about these rocks, however, should be noted: These dikes are very closely parallel to the Garlock fault and are approximately in line with the concealed fault to the east which was active in pre-Christmas Canyon formation time. The conclusion that the fault and the dikes are related seems unavoidable. It is curious that along the entire length of the Garlock fault -- in fact, to the writer's knowledge, along the entire length of the San Andreas fault also -- there is no other late Cenozoic volcanic activity. Why these faults, two of the main Cenozoic faults in the western United States, should be virtually devoid of such activity, while rows of late Cenozoic volcanoes have formed along less impressive faults, is an interesting problem.

Probably much of the answer lies in the nature of the faults: Strike-slip faults, such as the Garlock and San Andreas, are probably the results of compressional stresses and consequently afford too tight a conduit for the upward passage of molten lavas. This would be true of reverse faults also. Normal faults may be the most favorable zones of weakness for volcanic lavas. Whether the converse is true, viz., that young volcanic activity along a fault is evidence of normal displacement in recent time, must await independent confirmation. If true, however, the fault which served as a passage for the Quaternary basalts in the Lava Mountains was a normal fault, and its parallelism with the Garlock fault should not be construed to mean a similar displacement.

OLDER GRAVELS

Pediment Gravels

Older gravels are found as cappings on many of the pediments in the central and north-central portions of the area. Good examples are exposed in sections B29, B32, and E9.

Most occur as relatively flat caps of uniform thickness on top of the truncated beds of the Bedrock Spring formation. On exposed surfaces, the gravels generally weather to shades approximating grayish orange pink (5YR7/2), and in general show little resistance to weathering. Bedding is seldom seen and when found, can be traced for only a short distance.

The pebbles, cobbles, and boulders in these gravels were clearly derived, in every instance noted, from the hills within the drainage area of the adjacent streams. The fragments range from subangular to well-rounded, and range in size up to two feet across. They are almost without exception derived from the Klinker Mountain volcanics or the Lava Mountains andesite. The matrix of these gravels is very coarse sand, apparently derived in part from the Bedrock Spring formation and in part from the volcanic outcrops. For this reason the gravels have a more brownish or purplish hue than do the underlying sedimentary rocks.

Members of this unit can be distinguished from members of the conglomeratic facies of the Christmas Canyon formation as follows: Conglomerates of the Christmas Canyon formation always include vesicular andesitic or basaltic rocks and usually rhyolitic rocks; the Older Gravels contain only volcanic rocks with a local source.

Older Alluvium

Older alluvium, here used to designate the alluvial-type deposits that are now being dissected, is found along the sides of most of the canyons and washes. The pebbles and cobbles are generally plutonic rocks and volcanic rocks; the ratio of volcanic to plutonic rocks is about two or three to one. In most areas this alluvium is undeformed although along the Garlock fault zone, some slight tilting was seen.

The rocks are commonly well indurated, apparently as a result of cementation by calcium carbonate. Bedding is well defined but very lenticular. The color of this formation averages about grayish orange pink (5YR7/2).

ALLUVIUM

Alluvium is now being deposited in all the canyons of the Lava Mountains and in large areas north and southeast. The composition, as might be expected, is that of an arkosic gravel. The pebbles and cobbles of volcanic rocks are clearly derived from the Pliocene volcanic formations, and the pebbles of plutonic rocks are mostly derived from the Bedrock Spring formation.

TRAVERTINE

Searles Lake Shorelines

Along the shoreline of Pleistocene Searles Lake (Gale, 1915) a few deposits of travertine are found. Most of these are very small, measuring only a few feet in each dimension. No "pinnacles" comparable to those at the south end of Searles Lake are present.

One interesting outcrop of travertine occurs in section B12-e where the Christmas Canyon formation has been uplifted along the Garlock fault. Here, travertine has been deposited on the north-sloping fault scarp. Thus the scarp was formed prior to the high-water period in Searles Lake. According to Libby (1954), the top of the "parting mud" in Searles Lake has an age of about 10,500 years; this "parting mud" is clearly contemporaneous with the last major influx of water into Searles Lake. Blackwelder (1954) has postulated that the highest shoreline on Searles Lake is not the result of the last (Tioga) glacial period, but is the result of the earlier (Tahoe) period. The writer feels, on the basis of preliminary work on the problem, that the reverse is true, namely, that the high shorelines are the product of the last glacial period. In either event, the age of 10,500 years is a minimum for the travertine on the Garlock fault scarp; it may be much older. Consequently, the last major displacement on the Garlock fault in this area, was more than 10,500 years ago.

Along the West Edge of Lava Mountains

Along the west edge of Lava Mountains five separate outcrops of calcareous material that resemble travertine were found. These are in sections D3-m, D3-n, D10-k, D22-d, and D27-g. The travertine(?) weathers to shades varying between light olive gray (5Y6-8/1) and grayish orange pink (5YR7-8/2). On the fresh surface it is usually somewhat lighter. The texture consists of cryptocrystalline limestone commonly having a "vesicular" appearance. On the weathered surface, structures of contorted bands and layering stand out in relief.

These four outcrops occur at similar elevations: 3550, 3500, 3550, 3350, and 3400, respectively. It seems remotely possible that these are remnants of an old lake shore which has since been tilted south. However, no further work was done to corroborate or disprove this hypothesis.

Along Brown's Ranch Fault Zone

Two small tabular outcrops of travertine occur in the Brown's Ranch fault zone in section E17-k. Both of these are yellowish gray (5Y8/1) and contain pebbles of the surrounding volcanic rock types. The larger one shows structures considered by some to be caused by algae. The outcrop, which measures about 150 feet by 50 feet, is elongated parallel to the direction of faulting and shows faint vertical lineation. The smaller travertine outcrop is of a similar lithology and measures about 200 feet along the strike and 25 feet thick; it has horizontal structures as the predominant texture. Both were probably deposited as "aprons" of travertine by springs associated with the fault zone.

The age of these travertine deposits is uncertain. The upper contact appears to grade into the overlying Klinker Mountain volcanics and Lava Mountains andesite, respectively. This effect suggests that the travertine was contemporaneous with the volcanics of the late Pliocene. However, the same relationships are also found along the upper contacts of some Recent spring deposits that are clearly younger than the enclosing rocks. With these in mind, one can only consider the travertine deposits in the Brown's Ranch fault zone to be of any age between the late Pliocene and recent.

TECTONIC STRUCTURES

Within the Lava Mountains area, three fault systems converge. The Garlock fault and its associated faults trend N. 75° E. along the north side of the area. The Blackwater fault, trending N. 45° W., dominates the southeastern part of the region. The Brown's Ranch fault zone, which has an average trend of about N. 55° E., dominates the central and southwestern parts of the area. The Garlock fault has left-lateral displacement; the displacements along the Blackwater fault and Brown's Ranch fault zone are less clear-cut but probably are right- and left-lateral, respectively. The Dome Mountain anticline, the major fold within the area, trends nearly parallel to the Garlock fault throughout most of its length.

Most of the structures within this region conform to the patterns set by these major units. The problems in theoretical tectonics posed by such an area are great; unfortunately, only some of the answers are immediately forthcoming.

FAULTS

Garlock Fault

The Garlock fault is located along the north edge of the mapped area. Inasmuch as throughout most of its length, alluvium is on at least one side, it is nowhere "exposed" in the usual sense of the word but it is more noticeable in sections A23, B12, C7, and C8. Figure 20 shows the fault as seen from the air.

Figure 20a. View of the Garlock fault (G) and the Searles Lake shorelines (S) exposed in the northeastern corner of plate 2. Christmas Canyon (C) is in the foreground. View looking east. Photograph by R. C. Frampton.

Figure 20b. View of the Garlock fault (G) and the Thrust fault (T) on the north side of the Lava Mountains. View looking west.

<u>Displacement</u> --

Although much of the Garlock fault has never been geologically mapped in detail, its position is visible on a topographic map. At its western extremity, about 85 miles southwest of the Lava Mountains, the fault trends approximately N. 60° E.; in the Lava Mountains it trends N. 75° E.; at the south end of Panamint Valley, approximately 15 miles to the east, the fault trends east; from that point eastward the trend gradually changes to S. 85° E. until it loses its identity near the Avawatz Mountains -- a critical area not yet mapped.

In the Lava Mountains area, the type and amount of recent displacement are fairly distinct. Stream courses, especially in sections A22, A23, and A28, show consistent offsets, with the south side shifted relatively east. The largest offset of this type seen in the area is 200 feet. These displacements are, of course, only those occurring in late Cenozoic time. The more significant figure -- the amount of total displacement and its nature -- is as much more difficult to determine as it is of greater importance.

Descriptions of various portions of the Garlock fault have been published by Hulin (1925), Wiese and Fine (1950), Dibblee (1952), and Muehlberger (1954). All agree that the displacement on this fault is left lateral; conclusions vary as to the extent of this displacement. Hulin (1925) postulated a displacement of about 5 miles, based on the displaced contact between the Paleozoic section and plutonic rocks. Wiese and Fine (1950) demonstrated a 2-mile displacement on a fault parallel to the Garlock fault. Muehlberger (1954) reported stream channels that were offset 2,000 feet and Cenozoic rocks that were displaced $1\frac{1}{2}$ miles. In the Lava Mountains, offset stream channels furnish the only evidence of displacements on the Garlock fault.

Age --

The length of time during which the Garlock fault has been active is unknown but the histories of the areas south and north of this shear have been different since middle Tertiary time. This inference is based on the lack of Tertiary rocks older than middle Miocene in the Mojave Desert region, whereas older sections are found north of the Garlock fault. Smith (1951) dated a thrust fault along the north side of the Garlock fault as pre-lower Miocene; this thrust probably resulted from activity on the Garlock fault.

Within the Lava Mountains area, the only indication of pre-Quaternary activity on the Garlock fault comes from the fragments of pink leucocratic quartz monzonite found in the Bedrock Spring formation. They came from the northwestern outcrops of that rock which very probably had been elevated along the Garlock fault. If true, this portion of the fault is at least as old as middle Pliocene.

The last major displacement on the Garlock fault is clearly more than 10,500 years ago. This date is based on the presence of Searles Lake travertine on the north-facing scarp of the Garlock fault in section B12-e, as described in the section on travertine. That the high-water stage of Searles Lake is younger than the scarp is somewhat corroborated by inspection of aerial photographs which show that the shoreline, in the vicinity of Christmas Canyon, has not been offset by the fault (see figure 20a). This evidence is not conclusive, however, because the angle between the shoreline and the fault is very small.

Faults Parallel to Garlock Fault

Within this area only two major faults parallel the Garlock fault. The first of these is in B7 and B8, and was discussed along with the Christmas Canyon formation. This fault, which is inferred to exist because of the rapid facies change in the Christmas Canyon formation, was active primarily in pre-Christmas Canyon time. Since that time renewed movement may have occurred, but it has been relatively minor.

The second and larger of these faults is exposed along the south side of the Atolia quartz monzonite outcrop in the northwestern portion of the map. This fault, which separates Atolia quartz monzonite from younger rocks throughout much of its length is nearly vertical in its eastern half and dips 60° - 70° south in its western portion. Thus it is a normal fault. The amount of displacement along this fault is not known, but the apparent horizontal displacement of the base of the Bedrock Spring formation is about 4,000 feet with the south side moved relatively east. But inasmuch as the rocks that underlie the formation in the two areas are different, the offset contact cannot be attributed entirely to horizontal displacement. The vertical displacement is not known except that the Bedrock Spring formation in this area is only about 100 feet thick north of the fault, and probably is a few thousand feet thick on the south. Displacement on this fault probably occurred primarily in pre-Lava Mountains andesite time as is shown by the undisturbed flow overlying the fault trace at its western end.

Blackwater Fault

As shown on plate 1, the Blackwater fault is a long, nearly straight fault that enters the area from the southeast. Within the portion shown on that map, the trend shifts from N.20° W. at the south edge to about N. 45° W. in the Lava Mountains. On such a small scale map, the fault appears to be a few long breaks; in detail, as seen on plate 2, it consists of an anastomosing row of fractures, few more than two or three miles long.

Displacement --

Southeast of the Lava Mountains, the movement was both right lateral and dip-slip, with the position of the upthrown block alternating from side to side (see plate 1). Within the Lava Mountains the upthrown side of the fault is on the southwest and, in section F17-b, it dips 60° NE. Therefore it is a normal fault. Right lateral displacement is suggested by drag on the northeast-trending faults in D1 and F6, and on resistant beds in the Bedrock Spring formation which are bent nearly into alignment with the fault. These beds dip more steeply near the fault than a short distance away.

Further evidence of strike slip displacement is found about 10 miles southeast of the mapped area. Here, in the granitic portion (i) shown on the reconnaissance map (plate 1), a series of east-trending aplitic and rhyolitic dikes are truncated by a fault parallel to the main break. These dikes, which dip at high angles, are not found on the northeast side of this secondary fault, thus suggesting that they have been horizontally displaced beyond the outcrop area.

In the southeast corner of the Lava Mountains area, the Blackwater fault has formed prominent scarps. Northwest of F6, no signs of recent activity are present. In view of this, it is believed that the Blackwater fault has been offset by the northeast-trending strike-slip fault that is well exposed in E2. If movement on the latter is similar to the Garlock fault -- and it seems to be -- the offset extension should be found to the southwest. About a mile in this direction, in section B35-p, the map shows a concealed northwest-trending fault that is inferred on the basis of the following evidence:

1. A marked lithologic change in the Bedrock Spring formation is found along this line. The lithology changes from the characteristic coarse clastic facies on the southwest, to siltstones, claystones, limestones, and gypsum-bearing beds on the northeast.

2. The eastern limit of the Klinker Mountain volcanics and the Lava Mountains andesite is approximated by this line.

3. The late Pliocene(?) volcanic rocks northeast of this line are markedly different from the Pliocene volcanic rocks to the southwest.

4. Small faults -- mostly too small to be mapped -- become more numerous in the vicinity of the postulated fault.

5. Marker beds and contacts all disappear at or near this line.

6. The terrain on which the Bedrock Spring formation was deposited was apparently Tertiary sandstones and volcanics southwest of this line, and Atolia quartz monzonite to the northeast.

<u>Age</u> --

If the postulated offset extension of the Blackwater fault is valid, then there was activity along this line in Bedrock Spring time. Possibly it was active even earlier, so that erosion of any Tertiary sandstones and volcanics on the northeast side could have taken place prior to the deposition of the Bedrock Spring formation.

The most recent displacements on the fault vary from place to place. In some areas, Quaternary gravels have not been offset whereas in others, alluvium has been displaced.

Faults Parallel to Blackwater Fault

The most important faults of this group are in sections E2 and E3. Here, they offset units of the Bedrock Spring formation which dip at angles ranging from 20 degrees to nearly vertical.

Displacement --

The trend is somewhat variable in this area ranging from N. 15° W. to N. 85° W. These faults offset good marker contacts in the Bedrock Spring formation and consequently allow a detailed analysis of the displacement. This displacement has been right lateral and strike-slip, as indicated by the greater apparent offset of the beds with high dips as compared to beds with low dips.

Age --

It is clear from the offsets just described that folding had occurred in the Bedrock Spring formation before the right-lateral displacement took place. Since that displacement, about a thousand feet of left-lateral offset has occurred on the Brown's Ranch fault zone where it truncates the southern end of this northwest-trending group.

One small fault (in D31-q) which is parallel to the Blackwater fault was active during Bedrock Spring time. This is shown by the layer of clastic Bedrock Spring material (Tbs) that separates the tuff (Tbt) and volcanic breccia (Tbv) members on the northeast side but which is absent on the southwest. Apparently this fault formed a small scarp and clastic deposition occurred only on the northeast side for a short period of time.

Thus, activity along the faults of this group occurred during and after the deposition of the Bedrock Spring formation. Since the last major displacement along the Brown's Ranch fault zone, there has been no renewed activity on them.

Brown's Ranch Fault Zone

The northeast-trending faults in the central portion of the map are here called the Brown's Ranch fault zone after Brown's Ranch in section G5. The best exposures of this zone are found in section E17-r where a grayish orange (10YR7/4) zone of fault breccia, about 500 feet thick, is exposed. It consists of angular siliceous fragments embedded in a siliceous matrix, and the unit forms resistant jagged outcrops. Southwest of this exposure, however, the zone appears to consist of soft material, part of the tuffaceous member of the Klinker Mountain volcanics. In this portion there are also some "beds" of siliceous fault breccia which are believed to be the result of preferential cementation along certain horizons subsequent to brecciation, rather than sedimentary "beds" of fault gouge material.

Displacement --

The Brown's Ranch fault zone trends N. 45°-65° E. At its northeastern end, the trend shifts northward. To the southwest, it is headed toward the mineralized Atolia tungsten district. It will be interesting to see, when detailed mapping has been carried that far, if the mineralized tungsten veins, which trend approximately N. 75° E. (Lemon and Dorr, 1940), represent extensions of this fault zone.

In the vicinity of the main fault zone, a single fault surface was found (in section E20-c) which dipped 70° SE. and had slickensides plunging east at 60°. Larger-scale features are exposed in E10 and E11 where the faults vary in dip between vertical and 60° NW., and the relative displacements in every example are up on the northwest side. Conversely, in sections E21 and E22, the same fault zone -- here with vertical dips -- displaces beds relatively down on the northwest side. It is common to get such changeable displacements on strike-slip faults, and these suggestions of lateral displacement are believed to be more reliable criteria than the single fault surface described above. This permissive evidence, when combined with the evidence described in the section on "Faults parallel to the Blackwater fault", is taken to indicate left lateral displacements on the faults of this zone.

Age --

Faults of the Brown's Ranch fault zone have displaced portions of the Klinker Mountain and Almond Mountain volcanics and the Lava Mountains andesite; there is no evidence of activity prior to the deposition of these rocks. Displacements have also occurred after the activity on the northwest-trending faults in sections E2 and E3, and probably on the Blackwater fault. Major displacements have not occurred since the deposition of the older gravels (Qg) in sections

E9 and E15. However, one mile to the southeast, a fault of this group has formed small scarps about 10 feet high in the older alluvium; on aerial photographs, this fault can be traced southwest into the alluvium.

Apparently the Brown's Ranch fault zone was very active in the period between the deposition of the late Pliocene volcanic units and the Quaternary older gravels; the Blackwater fault and its subsidiaries were most active prior to this time. Some offsets have occurred along the Brown's Ranch fault zone in Quaternary time but they were relatively minor.

Faults Parallel to the Brown's Ranch Fault Zone

Most of the faults north and west of the Brown's Ranch fault zone have a similar trend and many of the same characteristics. The best exposed of these are in D1-h, E4-l, E5-q, E6-p, and E6-q. Faults of this trend are numerically the most abundant in the Lava Mountains area. It might appear that the heaviest concentration is in a belt trending northwest from the Brown's Ranch fault zone but this is chiefly because of excellent exposures in this stretch. The area to the north and east, which shows almost no faults, is probably as extensively faulted but the exposures are too poor to reveal the breaks.

Displacement --

Most of the faults in this category trend between N. 40° E. and N. 55° E. The attitudes are variable; some dip toward the northwest, others toward the southeast, and many are vertical. No one type appears predominant.

The displacements on the faults are generally dip-slip. As these faults were active during the deposition of the Lava Mountains andesite, the Klinker Mountain volcanics and possibly the Bedrock Spring formation, the stratigraphic sections on the two sides of a fault are often dissimilar. Many of the faults in the western third of the region have displaced the base of the Klinker Mountain volcanics relatively downward on the southeast side prior to the deposition of the Lava Mountains andesite. As a result, the andesite now rests on increasingly thick sections of Klinker Mountain volcanics toward the southeast. Displacements in the Lava Mountains andesite are irregular. Some faults are traceable across the entire area covered by Lava Mountains andesite. Other faults displace the edge of a given flow but cannot be traced across the area covered by that flow. Still other faults in this group do not in any way affect the andesite, although the Klinker Mountain volcanics may be offset several hundred feet.

<u>Age</u> --

It is not known whether these faults were active prior to, or during, the deposition of the Bedrock Spring formation. The first mappable displacement involves the basal members of the Klinker Mountain volcanics. The most recent displacement on many of these faults was prior to the extrusion of the Lava Mountains andesite, but others have also displaced these flows. No faults of this group displace Quaternary deposits.

Thrust Faults

A small thrust fault is well exposed in sections A23 and A24. Here, Atolia quartz monzonite clearly overlies red sandstones and siltstones; the attitude of the fault contact varies widely as shown on the map.

The rocks that underlie this fault consist of well-bedded fine-grained sandstones and siltstones which weather to grayish orange pink (5YR7/2). These rocks, which are only slightly indurated, lack some of the characteristics of the Bedrock Spring formation, namely, the rhyolitic, intermediate volcanic, and pink leucocratic quartz monzonite pebbles. Consequently, there is doubt that this unit is actually part of, and contemporaneous with, the Bedrock Spring formation.

To the writer's knowledge, this is the only exposure of a thrust fault within the mapped area. Hulin (1925) postulated that this thrust was connected with a fault along the north side of the Rand Mountains, but nothing within this mapped area can add support to that theory. This thrust is truncated on the west by the Garlock fault; to the east, it disappears under alluvium.

There is a possibility that the eastern extension of this fault swings southward under the alluvium and connects with the rapidly curving fault that ends in A25-h. This hypothesis has been discarded because of the low angle of dip of the thrust fault and the nearly vertical dip of the other fault. If this connection is not made, one has the problem of explaining why a thrust fault is not found in the Bedrock Spring formation to the east or southeast. The answer may be one of three things: 1) The fault was formed prior to the deposition of the Bedrock Spring formation, the red sandstones and siltstones being older; 2) the fault does extend into the Bedrock Spring formation but has not been detected because of the very poor exposures in that area; or 3) the fault simply dies out.

FOLDS

The main fold within the Lava Mountains is here called the Dome Mountain anticline, after Dome Mountain which lies about 1 mile south of the fold near its western end. The fold axis is about parallel to the Garlock fault throughout most of its length, as shown in figure 21. The plunge is variable. Pre-Bedrock Spring rocks are exposed at several places along the axis.

Folding began along this line at least as early as Bedrock Spring time and continued through Lava Mountains andesite time. The Bedrock Spring formation was deformed along this line prior to the deposition of the volcanics, the deformation apparently forming a topographic ridge which prevented the deposition of the Klinker Mountain or Almond Mountain volcanics north of the axis. Between the deposition of the volcanics and the Lava Mountains andesite, little folding occurred. Warping and tilting resumed, at least locally, after the extrusion of the andesite.

Several other folds can be traced on the map but they are relatively short and form no consistent pattern. Most of these are broad folds that plunge from the sides of the Dome Mountain anticline. A syncline is present in the eastern end of the fine-grained facies of the Christmas Canyon formation.

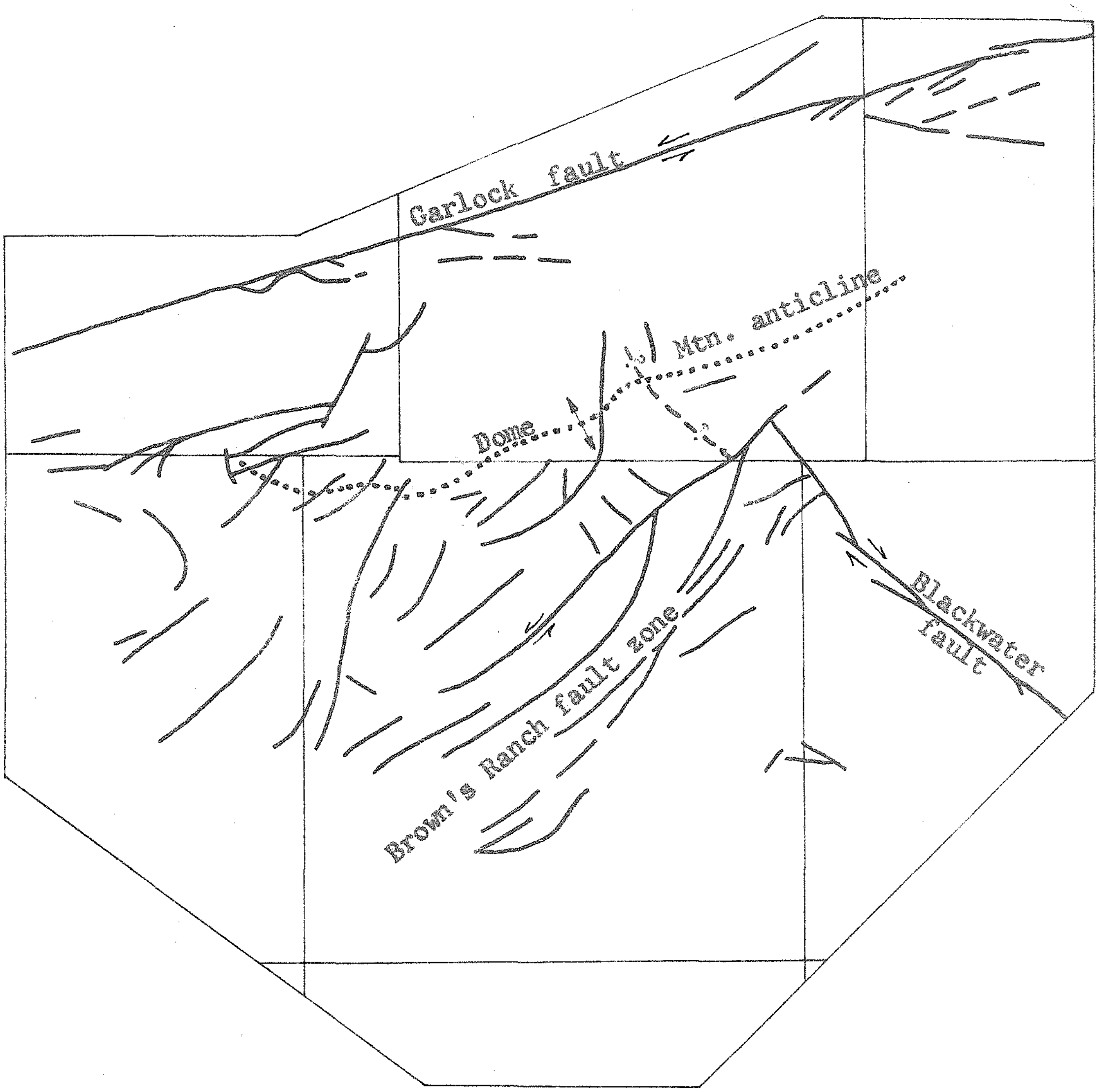


Figure 21. Generalized diagram of plate 2 showing the fault pattern in the Lava Mountains and the position of the Dome Mountain anticline.

SIGNIFICANCE OF THE STRUCTURAL PATTERN

Previous considerations of the structural pattern of the northern Mojave Desert have taken into account only faults of the Garlock and the Blackwater types. Hewett (1955) shows the faults that were mapped at the time of his writing or were suspected on the basis of aerial photographs. The faults on his map fall into three categories: 1) those in the southwestern two-thirds of the "Mojave Block" which have a strong northwestern trend; 2) those in the northeastern third of the "Mojave Block" which show no consistent system; and 3) those north of the Garlock fault which show parallelism with the big north-northwest faults of Owens, Panamint and Death Valleys. The junction point of these three areas is at the Lava Mountains.

Faults that trend parallel to the Brown's Ranch fault zone are sparsely represented on Hewett's map. A few are shown in the vicinities of Randsburg, the Calico Mountains, and Superior Valley, but they are uncommon and are only found outside of the zone characterized by northwest faults. North of the Garlock fault, several northeast faults are known.

In Lava Mountains area, the Brown's Ranch fault zone represents the most persistent structural trend. The Blackwater fault, in spite of its impressive continuity to the southeast, is not a major fault system in the Lava Mountains. Likewise, the Garlock fault, the master fault for this portion of California, is not as well represented by parallel and obviously related faults as might be expected. This peculiar anomaly demands an explanation.

In studying structures of this type, two main questions must first be answered: What are the directions and amounts of displacement along the faults, and what is the sequence in which these displacements took place? The evidence within the Lava Mountains area for the types and amounts of displacement on the various faults is contradictory. The Garlock fault shows satisfactory evidence of left-lateral displacement but only for very late Cenozoic time. Displacement on the Blackwater fault is inferred to be right-lateral on the bases of drag and the displacement on faults with a similar trend. The displacement along faults of the Brown's Ranch fault system have been postulated as strike-slip within the main fault zone, but the parallel faults to the northwest apparently have a major dip-slip component.

The sequence in which these displacements took place is even less clear cut: The relative age between contiguous faults can be established in several places, but all three fault systems give evidence of renewed activity from time to time up to the present. It is impossible to assign only one age of activity to any given fault system.

The periods of renewed activity may have resulted from displacements along previously formed faults -- already established as zones of crustal weakness -- as a result of stresses that normally were relieved along other fault systems. To distinguish such offsets -- which might be called "passive" displacements -- from the "active" displacements caused by tectonic stresses, is highly subjective. Probably the best criterion available is the magnitude of the displacement, the "active" displacements being greater than the "passive". On this basis, most of the larger offsets of pre-Quaternary rocks could be classed as "active" and the small scarps in the Quaternary gravels and alluvium could well be the result of "passive" displacements.

Within the limited reliability of this criterion, the sequence of the last "active" displacements is believed to be:

1. Blackwater fault system
2. Brown's Ranch fault system
3. Garlock fault

Conclusions

Considering the regional and local structural pattern, the most likely explanation of the tectonic pattern is as follows: The Blackwater and Brown's Ranch fault systems have been essentially inactive throughout the Pleistocene. This conclusion is based on the probable offset of the Blackwater fault by a fault of the Brown's Ranch system which, in turn, is known to have been active primarily in pre-Lava Mountains andesite time. The Garlock fault has been inactive for 10,500 years or more.

The faults of the Brown's Ranch system are probably the present expression of faults that originated parallel to the Garlock fault but have been rotated 15°-30° by drag along that fault. This origin would explain: 1) the apparent absence of fractures that seemingly should have formed parallel to the Garlock fault throughout its long history; 2) the tendency for many of the faults of the Brown's Ranch group to "bend" toward the north as they approach the Garlock fault; and 3) the broad curve in the earlier-formed Blackwater fault which is in the direction one would expect from large-scale drag along a left lateral fault.

Whether these features can all be explained by one process must await more knowledge of the geology of this portion of the desert. On the basis of what is now known of the Lava Mountains area, the above explanation is believed the most adequate.

VOLCANIC STRUCTURES

Within the areas of volcanic rocks, especially in the areas exposing Lava Mountains andesite, five types of igneous structures were mapped: Linear structures, platy structures, color bands, foliation, and columnar joints.

At each outcrop, the reading was made on the structure believed to be the best indicator of the direction of flowage in the lava. Linear or platy structures involving the phenocrysts are believed the most reliable but were seldom found. Most generally these are defined by the acicular hornblende or the smaller plagioclase crystals. Platy minerals, such as biotite and tabular plagioclase crystals, sometimes align themselves so that a two-dimensional surface is defined. Two-dimensional planes are more commonly defined by the color banding. In the Lava Mountains andesite, this usually consists of reddish brown bands in a field of dark gray, or vice versa. Within the Almond Mountain and Klinker Mountain volcanics, banding is also common but in brecciated lavas these attitudes of course become meaningless.

The most common structure in these volcanic rocks is foliation. This could result from several causes, such as tectonic activity, cooling history, or the alignment of the microcrystals and phenocrysts. In all the rocks that were subsequently studied by thin section, it was found to be caused by the last. Columnar joints are shown only if the jointing was exceptionally good or if no other igneous structure was available for this immediate area.

INTRUSIVE STRUCTURES AND EXTRUSIVE STRUCTURES

The purpose in recording these igneous structures was to try to find patterns that would indicate whether a given area of rock was a flow or an intrusive. Work along these lines has been done by several (for example; Williams, 1942; McCulloh, 1952). Williams' work on late Cenozoic flows in the Crater Lake area indicated that around the edges, most attitudes dipped steeply toward the center of the flow, although many exceptions were found in the examples shown. Around the vent, he found a general concentric pattern which dipped steeply toward the center of the plug. McCulloh found, in volcanic rocks of the Calico Mountains, that this pattern of concentricity was very common and on this basis concluded that many of the outcrops of the rocks in question were the remnants of intrusive plugs.

In the Lava Mountains area, no consistent pattern was found. The nearest things to "good" flow structures are found in sections E5-b, E5-g, E5-h, E8-h, E8-j, E8-q, E9-b, E9-g, and E9-l. Those in section E5 tend to have the color banding parallel to the flow surface; those in sections E8 and E9 illustrate the tendency for attitudes to be steep along the edges and convergent toward the middle of the flow. The best intrusive structures are found in sections B27-q, B27-t, B34-d, E5-j, E5-q, E5-r, E8-f, and E8-g.

DEFORMATION ASSOCIATED WITH VOLCANIC ACTIVITY

Throughout the area there seems to be no consistent type of deformation associated with volcanic intrusion. Around some of the exposures that are believed to be intrusive plugs, there is local "punching up", but others seem to show no such tendency. Still others suggest small-scale subsidence in the surrounding sedimentary rocks. Many of the dikes in the western part of the area show local deformation and "punching up" in the immediate vicinity but this effect dies out within a few tens of feet.

GEOMORPHOLOGY

PEDIMENTS

The remnants of one or more pediments are found in the northern half of the Lava Mountains area. For the purpose of description, the remnants have been grouped into three units on the basis of the composition of the capping material. This grouping may separate surfaces that originally were portions of the same pediment; it is unlikely, however, that any one of the three groups include parts of different pediments.

These surfaces are called pediments because they were gently dipping erosional surfaces cut on older rocks. The largest remnant was cut on Atolia quartz monzonite and probably never had more than a few feet of debris on its surface. The other pediments were cut on the deformed beds of the Bedrock Spring formation; these surfaces are now capped by as much as 50 feet of material so some should properly be considered as buried pediments. For simplicity, however, all are called pediments in this report.

The largest pediment remnant, the large outcrop of Atolia quartz monzonite in the northwestern part of plate 2, is illustrated in figure 22. Prior to dissection, it probably consisted of a gentle north-sloping surface covered with a thin layer of weathered granitic debris. The southern edge was along the fault that now separates the quartz monzonite from Tertiary rocks. There is no evidence indicating where the north boundary might have been. West of the mapped area, the plutonic rock is overlain by Tertiary rocks and this was probably an area of more relief. At present, the surface is slightly warped: The eastern half plunges toward the east-northeast; the western half is in the form of a gentle west-southwest plunging trough although this shape may be largely the product of renewed erosion.

In the north-central portion of the map, several pediment relicts are present which dip toward the north or northeast at 2 to 5 degrees. Figure 23a shows some of these surfaces. The capping material was, in every instance noted, derived from rocks that are on the uphill projection of the surface. The underlying rocks, for the most part, are those of the Bedrock Spring formation and beds dipping up to 60° are truncated by the erosional surface.

In the northeastern quarter of the map, the remains of an arched pediment are found. It was buried by the Christmas Canyon formation which remains as a capping up to 50 feet thick. Most of this pediment was cut on the Bedrock Spring formation but the northeasternmost part was cut on metamorphic rocks and the Atolia quartz monzonite. Apparently, this latter surface was an area of slight relief in Christmas Canyon time, whereas the area underlain by the Bedrock

Figure 22a. View of the pediment, cut on Atolia quartz monzonite, silhouetted against the lighter hills. View from the northwest.

Figure 22b. Aerial view of the same pediment (p) illustrated in figure 22a. The thrust fault (t) is at the base of the foreground hills.

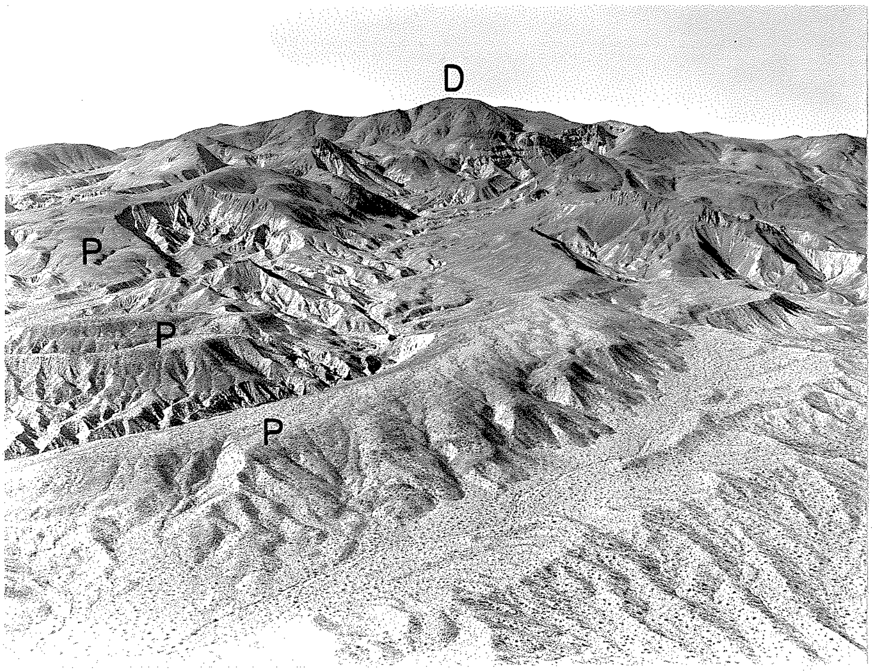


Figure 23a. View of the pediment relicts (p) shown in the north-central portion of plate 2. Dome Mountain (D) is on the skyline; view toward the southwest.

Figure 23b. View of the northwestern outcrops of the Lava Mountains andesite (Tl) which form flat caps on the hills. The area of lower relief to the west is Atolia quartz monzonite. View toward the east.

Spring formation was relatively smooth.

After the deposition of the Christmas Canyon formation, this pediment was warped into a broad anticline; the axis is about two miles south of the Garlock fault and trends parallel to that fault. Inasmuch as the debris in the Pleistocene(?) Christmas Canyon formation was all derived from the southeast, the warping can be dated as Quaternary. This deformation took place fast enough to block the northwest drainage across the Lava Mountains which previously had been a part of the Searles Lake drainage system.

Age

The pediments in the north-central portion of the map are probably contemporaneous with the late phases of the Lava Mountains andesite. The pediments in the northeastern portion of the map are nearly contemporaneous with the Christmas Canyon formation which rests on them. There is no indication of the age of the pediment cut on the Atolia quartz monzonite.

There seems to be no satisfactory way to determine the relative ages of three groups of surfaces but all of the pediments were probably formed between the very late Pliocene and the middle or late Pleistocene. As noted in the section on the Christmas Canyon formation, the pebbles of Lava Mountains andesite found in that formation are from the andesite flows (Tl), not the "intrusive" member (Tli) which is the phase actually contemporaneous with the pediment surface. Consequently, there is no pebble type common to both pediment cappings.

All three pediment groups have had distinctive tectonic histories since their formation: the pediment cut on Atolia quartz monzonite has been relatively uplifted nearly 1,000 feet since its formation; the pediment in the northeast quarter of the map has been arched into a broad anticline; the pediment remnants in the north central part of the area appear to be unchanged since their formation. If this criterion were reliable, the relative ages of pedimentation would be in that order. However, in a region as tectonically active as this, the degree of deformation means little, but no better criteria are available.

SHORELINES

Searles Lake

Along the northeastern edge of the area, excellent shorelines were cut during the highest stand of Searles Lake at an elevation of about 2,250 feet, 630 feet above the present lake surface (see fig. 20a). Throughout much of their length, they take the form of benches 10 or 20 feet wide with wave-cut cliffs 5 or 10 feet high. Travertine is deposited along some parts of this near-shore area but is not restricted to the highest shoreline. As explained in the section on Travertine, these shorelines are more than 10,500 years old, but are more recent than the last displacement on the Garlock fault in this area.

Cuddeback Lake

A very faint shoreline(?) is visible on the north shore of Cuddeback Lake (in E32 and G4) at an elevation of 2,660 feet, approximately 110 feet above the present playa level. This shoreline is indicated only by a very faint line on the hillsides along the top of a slight concentration of fine-grained sand. From close range, the shoreline is extremely vague, but from a half mile away, the line is more easily seen. With nothing but this nebulous evidence it would be risky to postulate a shoreline. The strongest argument is that similar lines occur on two hills at the same elevation -- a highly unlikely occurrence if they were formed by any means other than the one suggested.

The age of this shoreline(?) is not known but presumably it was formed during one of the pluvial periods. If this strand is the highest one, and it probably is, most likely it is the same age as the top shoreline of Searles Lake. The age of that shoreline is debated but most agree that it is of Tahoe or Tioga age. The present writer prefers Tioga for the Searles Lake strand on the basis of incomplete studies; by inference, the shorelines of Cuddeback would also be of Tioga age.

ECONOMIC GEOLOGY

METALS

Gold mining has been attempted in only one part of the Lava Mountains area -- in Christmas Canyon. Here, two adits, the longer about 200 feet, extend into the Atolia quartz monzonite and two shafts connect the adits with the surface. To the writer's knowledge, no commercial ore was ever taken from the mine which has been inactive since about 1930. Some of the prospect pits within the Lava Mountains were probably made in the search for gold inasmuch as the claim notices associated with them were dated in the early 1900's -- 5 to 10 years after gold was discovered at Randsburg.

The majority of mines and prospect pits in the region east of City Well resulted from the search for silver -- an outgrowth of the California Rand ("Kelly") silver mine discovered in 1919. One of these, the North Rand mine located in section D27-h, was described by Hulin (1925). It consists of a 400-foot incline which dips south at about 60°; it is apparently all in the greenish-weathering member of the Klinker Mountain volcanics. This mine reportedly (Joe Foisie, Johannesburg, oral communication, 1955) had commercial ore near the surface but none at depth. Material on the dump consists of altered tuff and sandstone containing small crystals of pyrite disseminated throughout the rock and concentrated along some of the fractures. Another mine, just south of the mapped area, about 1/2 mile southwest of the North Rand mine, is reported to have a shaft about 500 feet deep which was too hot to continue deeper (Joe Foisie, oral communication, 1955).

In section D24-q, a shaft estimated to be 400 feet deep, is located at the contact between the greenish-weathering and the purplish-weathering members of the Klinker Mountain volcanics. Samples from the dump are fine-grained, grayish yellow green (5GY8/2) volcanic rocks that contain disseminated pyrite.

A flurry of mercury prospecting occurred approximately at the same time as the search for silver. The writer knows of no production from this area. The "Steam Well", in section D25, was drilled as a mercury prospect.

RADIOACTIVE DEPOSITS

On the north side of the mapped area, along the Garlock fault, is the "Alpha Beta Gamma Mine" -- a large prospect for radioactive minerals. It is reported to have a radioactive count of 3X background (Walker, Lovering, and Stephens, 1956). At present, no further activity is apparent.

WATER

The water supply for the towns of Randsburg and Johannesburg comes from the wells in the southwest corner on the map. Two of these wells, reported by Thompson (1929), were 380 and 400 feet deep and had water standing at 375 and 390 feet, respectively. The water, which is good quality, must be pumped about 6 miles with a vertical lift of about 150 feet; the sale price is about one cent per gallon.

Bedrock Spring, in the northeastern part of the area, was reportedly (Joe Foisie, oral communication, 1955) dug for water around 1900 by the members of the Spangler family. It consists of an adit, about 10 feet long, projecting into volcanic rock with a few inches of brackish standing water on the floor. No springs or evidence of near-surface water were found throughout the rest of the mapped area.

Within the area shown on the map, there are no highly favorable areas for groundwater accumulation. The areas that drain west and south -- and thus would be potential water sources for Randsburg and Johannesburg -- are not large. The north drainage area is more favorable. The collection area is larger and the Garlock fault might be a groundwater barrier that brings water nearer the surface; there are, however, no signs of near surface water along the fault. Any water that was found in this area might be highly saline from contact with the locally-saline Christmas Canyon and Bedrock Spring formation, and from disseminated salines deposited in the alluvium by the higher stands of Searles Lake.

"STEAM WELL"

In section D25, a well drilled as a prospect for mercury around 1920 brings "live" steam to the surface. It is reported to be 110 feet deep (Joe Foisie, oral communication, 1955) and has given off steam continually for a number of years. No chemical analyses of this steam are available but a general odor of H_2S is present.

This well probably lies on the extension of the Brown's Ranch fault zone and the excessive heat apparently results from hot waters that have worked upward along this zone. The heat is presumably of volcanic origin but whether it is a residuum from the late Pliocene volcanic episode, or a present day result of the same factors that caused that volcanic activity is unknown.

GRAVEL

Gravel has been quarried in Christmas Canyon since about 1948, for use as road metal on the nearby blacktop road. To the writer's knowledge this is the only gravel in the area that has been commercially exploited.

GEOLOGIC HISTORY

The sequence of geologic events, from oldest to youngest, that have left a record in the Lava Mountains is as follows:

1. Marine(?) deposition of limestones, siltstones, and sandstones (m).

2. Intrusion of Atolia quartz monzonite (aqm) into the overlying rocks, deforming and metamorphosing the limestones, siltstones and sandstones (m).

3. Deposition of arkosic boulder conglomerates (Ts).

4. Intrusion and extrusion of volcanic rocks (Tv).

5. Deformation and erosion of all existing rocks.

6. Deposition of the Bedrock Spring formation (Tbs, etc.). Some intermittent volcanic activity, deformation, and erosion within this time.

7. Local deformation of the pre-existing rocks -- mostly as folding. First folding along the Dome Mountain anticline.

8. Extrusion of Almond Mountain (Tab, etc.) and Klinker Mountain volcanics (Tkb, etc.), mostly as explosive eruptions of tuff, pyroclastic, and volcanic debris.

9. Deformation -- much of it as faulting without appreciable tilting of the fault blocks -- and erosion.

10. Extrusion of the Lava Mountains andesite (Tl, etc.).

11. Deformation and erosion.

12. Formation of pediments in the western half of the area and deposition of gravels (Qg) on some of these pediments.

13. Deposition of the Christmas Canyon formation (Qcc) on a south-sloping pediment. Debris derived from southeast of the mapped area deposited on an alluvial fan which graded into a playa approximately along the line of the Garlock fault.

14. Intrusion of basalt dikes (Qb).

15. Arching of the northeastern portion of the Lava Mountains, thus blocking and reversing the drainage.

16. Deposition of alluvium (Qal).

17. Last main displacement along the Garlock fault, causing the scarps now visible.

18. Deposition of travertine along shorelines formed by Searles Lake along the north, 10,500 or more years ago. Shoreline(?) on the north side of Cuddeback Lake possibly also formed.

Item 12 may be contemporaneous with items 13, 14, or 15.

Part III: Volcanic petrology

In the following section, the volcanic rocks of the Lava Mountains are surveyed for trends in the chemical and petrographic characteristics. The trends that are found seem best explained by the following theory:

The volcanic melt was formed by the complete refusion of crustal quartz monzonitic rocks prior to the deposition of the middle Pliocene Bedrock Spring formation. The magma body erupted explosively several times during the middle Pliocene. In late Pliocene time, volcanism became more frequent as a result of the conduits formed by the active faulting of this period; the lavas became more homogeneous as a result of the continuous mixing within the magma body; and the eruptions changed from explosive to effusive when the thermal gradient had steepened sufficiently to allow the magmas to reach the surface without being solidified and brecciated in the conduit. There is no evidence to indicate that fractional crystallization occurred in the magma chamber.

PETROGRAPHY

QUALITATIVE

Textures

The volcanic rocks within the Lava Mountains area present a wide range of textural variation grading from sandy tuffs, through tuffs, pyroclastics, and pyroclastic breccias, and into dense tabular flows and mound-like intrusives. In a general way, the changes with respect to stratigraphic position parallel this order. The volcanic rocks of the Bedrock Spring formation are tuffs, pyroclastics, and volcanic breccias. The volcanic rocks in the lower parts of the

Almond Mountain and Klinker Mountain volcanics are tuffs, pyroclastics, and pyroclastic breccias; these, in turn, grade upward into massive volcanic breccias and brecciated flows. The overlying Lava Mountains andesite consists of large tabular flows that commonly cover several square miles without significant variation in lithology.

The volcanic rocks of all formations contain megascopic phenocrysts plus others that can be seen only with a microscope. All contain megascopic plagioclase and most include biotite, oxyhornblende (or hornblende), and opaque minerals; some quartz is visible in most rocks. The microphenocrysts are usually plagioclase, pyroxene, and opaques. The groundmass, as seen under the microscope, consists of small needlelike crystals of plagioclase(?), anisotropic "glass", and isotropic glass. The texture of almost all the volcanics studied is hyalopilitic although some nearly grade into intersertal.

Many rocks show an alignment of some minerals: Plagioclase microcrystals and microphenocrysts show a fair tendency to be parallel. Biotite shows this tendency only rarely. Oxyhornblende is present as acicular crystals in some rocks and these show a strong susceptibility to alignment. The pyroxenes seldom show any preferred orientation. Quartz, being present as irregular crystals, shows none.

Vesicles are present in many of the rocks, usually in microscopic sizes, with the average dimension most commonly between 0.1 and 0.5 mm; vesicles larger than 1 mm are uncommon. A few of these vesicles show a tendency to be elongated.

Mineralogy

Plagioclase

Composition -- At the outset of the work on the volcanic rocks, much time was spent in trying to determine the composition of the plagioclase. On the basis of a statement by Krump and Ketner, quoted by Emmons (1953, p. 12), curves constructed for high temperature plagioclase were not used. Their argument was, in effect, that the scatter of optical properties in ordinary feldspars more than bridged the differences between the low and the high temperature sets of curves. Consequently, the standard curves found in Winchell and Winchell (1952) were used.

Virtually all of the plagioclase compositions are based on the maximum extinction angle perpendicular to 010 (Michel-Levy method). The extinction angles of Carlsbad twins in conjunction with albite twins are not believed reliable: In the smaller plagioclase crystals it is not uncommon to see two once-independent crystals that have become attached on their side faces (see fig. 24a). If this had happened during the early stages of growth of the larger plagioclase crystals, and they had continued to enlarge while attached in that position, the results would look much like Carlsbad twins but would, of course, not have the rigid interrelationships necessary to make the extinction angle curves valid.

A few determinations of refractive index were also made to test the extinction angle compositions. Typical results are as follows:

Sample	Maximum composition (Ext. angles)	Range of compositions (Refractive index)
124-22F	An 51	An 30-44
124-22I	An 47	An 39-47
124-22J	An 64	An 22-50
124-22M	?	An 36-56
124-22Q	An 60	An 28-52
124-23B	An 49	An 25-45
124-23F	An 50	An 28-50
124-23J	An 65	An 30-42

These results show that the maximum anorthite percentages are roughly comparable as determined by either method, although the extinction angle method generally gives higher results. In part, these higher values result from more measurements on a given thin section. The lower limit of the An content, indeterminable by extinction angles, commonly differs from the upper limit by An 15-25. This range is supported by the variations in optic sign in crystals from the same rocks; in almost every rock, both optically positive and negative plagioclase are present.

Index determinations on feldspar fragments have limited usefulness; one cannot be sure whether the fragment being measured came from the core or the rim of a zoned crystal, or from a megaphenocryst or a microphenocryst. In view of this limitation, it was decided not to determine a maximum and minimum figure for each rock. If this information were to be obtained, a Universal stage would have to be used.

On the basis of these data, it is clear that the plagioclase compositions vary from about An_{30} to An_{60}; exceptionally, the An content is as low as 20 and as high as 70. For the calculations used in this report, the average plagioclase composition is considered to be An_{50} ($NaAlSi_3O_8 \cdot CaAl_2Si_2O_8$).

Zones -- In almost every volcanic rock studied the plagioclase was found to be complexly zoned. The most common type was oscillatory normal, although normal zones and reverse zones were found. Also, what might be called "mottled" zones were common, especially on the inner portion of the crystals.

The most characteristic zonal feature was the recurrence of an outer calcic rim (see figs. 24a and 24b). This rim, which formed the outer 5 to 20 percent of the crystal radius, often rested on a crystal that showed rounding and resorption. Its composition was most generally between 5 and 10 percent more calcic than the feldspar on which it rested, and very commonly approximated the composition of the crystal center. The calcic rim itself usually showed smooth normal zoning.

Another common form of zoning might be called "graded zoning". It consisted of as many as five generations of zones, each zone consisting of a calcic inner portion grading out smoothly to a more sodic outer portion; the contact between this sodic portion and the overlying calcic portion was always abrupt, whereas the calcic to sodic transition was smooth.

Within any given thin section, there was usually no characteristic number of generations of zones, nor did any rock unit show an overall trend.

The range covered by zones in megaphenocrysts is usually An_5 to An_{10}, although exceptionally 10 to 25 percent differences may be

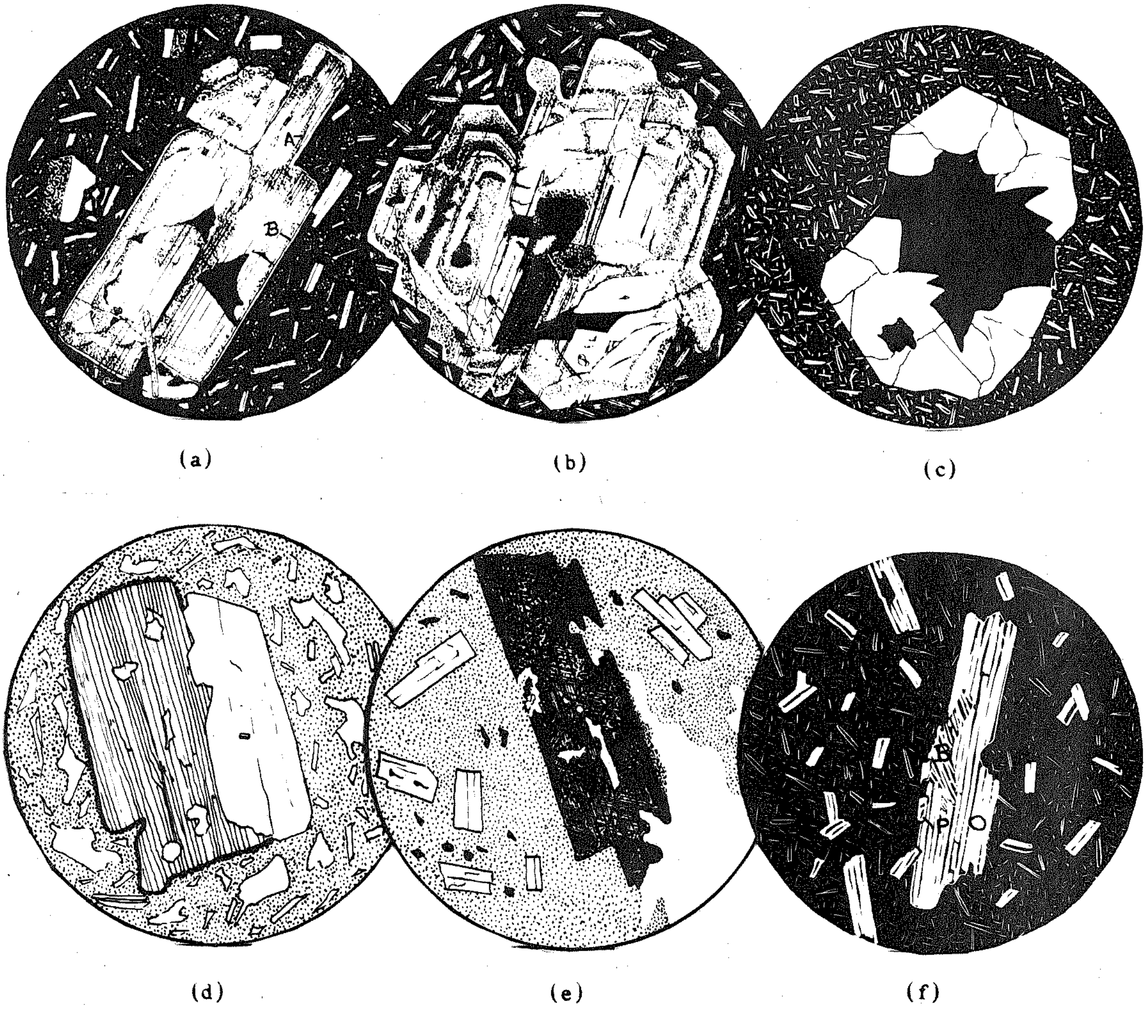


Figure 24. Sketches of mineral relationships as seen under the petrographic microscope. Five are of the Lava Mountains andesite; (e) is of the late Pliocene(?) felsite. Sketches (d) and (e) are in plane-polarized light; the others are with crossed-nicols. All fields are about 2 mm across. Sketches by E. Goss.

(a) Cluster of plagioclase crystals in sample 97-38°. Note that the once-independent crystals have become joined along a crystal face prior to the formation of the outermost two zones (A and B) which are restricted to the outward faces of the crystal group. The outermost zone (B) is a typical "calcic rim".

(b) Cluster of zoned plagioclase crystals in sample 29-6. Outermost zone, which envelops the group, is about the composition of the core of the large crystal; the intervening parts of the crystal are more sodic.

(c) Quartz crystals, in a glassy groundmass, in sample 27-14. The nearly straight edges are believed to be remnants of euhedral crystals that grew in the melt.

(d) Biotite and plagioclase crystals in sample 124-22J. The biotite has been slightly altered to opaque materials along the edge not protected by plagioclase; this indicates that the alteration occurred after the two minerals had become attached, and probably after the lava had solidified.

(e) Biotite crystal in sample 97-31. The crystal is slightly altered to opaques around edges, discolored over rest of the crystal. Note the "percussion figures".

(f) Inclusion of biotite (B) and plagioclase(P) in oxyhornblende (O). Sample 184-6. The irregular shape of the included biotite suggests that it was partially resorbed.

noted between the inner and outer portions of the crystals. Most microphenocrysts show a very faint smooth normal zoning, covering a range of less than An_5. There seems to be none of the tendency found by Larsen (1938A) for andesine to be more heavily zoned than other types. However, those crystals that are strongly zoned do commonly have poor twin development. Evidence of resorption is more commonly associated with reversed zones than with normal zones, but reversed zones are by no means "always discontinuous" as claimed by Phemister (1932).

Twinning -- Albite twins are the most common types found in these feldspars. Usually the twin lamellae are not notably even or uniformly developed. In some examples, zones seem to inhibit the formation of these twin lamellae and in others they seem to have no effect. Although Carlsbad twins, as explained above, were not believed to be reliable and consequently were not systematically studied, most of the twins that appeared to follow the Carlsbad law had an undulating twin plane. Other twin types were not uncommonly found. Most of these appeared to be pericline twins.

The twin types found in these volcanic rocks generally corroborate the findings of Gori (1950). However, in the Lava Mountains rocks, the apparent ratio of albite and pericline twins (Gori's "A-twins") to all other types of twins (his "C-twins") corresponds to albite or oligoclase in the volcanic rocks measured by him. The overall ratio of twinned ("A + C") to untwinned ("U") feldspars found in Gori's work on igneous rocks is about the same as that found here, although the Lava Mountains rocks tend to have the higher percentage of untwinned plagioclase in the microphenocrysts, rather than in megaphenocrysts as he found.

Habit -- The megaphenocrysts are characteristically present as stubby prisms with a length-to-breadth ratio of about 2 to 1. The microphenocrysts are more elongate, generally approximating a 4 to 1 ratio. Both types appear to be elongated parallel to the a axis. In most rocks, the megaphenocrysts are euhedral, although many have slightly rounded crystal corners. The microphenocrysts are, almost without exception, euhedral sharp-cornered crystals.

Megaphenocrysts tend to form crystal clumps with some of the member crystals nearly perfect in shape while others have only partially developed faces. A typical cluster of such crystals is seen in figures 24a and 24b. Microphenocrysts show less tendency to become attached. Apparently the clumping occurred prior to the last crystallization of megaphenocryst feldspar; the outermost rim, which is commonly calcic, always envelops the entire group rather than any one of the member crystals.

Inclusions -- Almost all crystals of plagioclase, especially the megaphenocrysts, have inclusions of clear or yellowish glass as formless blebs or as runic texture. Also, small acicular or prismatic apatite crystals, generally less than 0.1 mm long are common. Occasionally, inclusions of opaques (probably magnetite), oxyhornblende, pyroxene, biotite, chalcedony(?), zircon(?), or rutile(?), are also found.

Alteration -- In most of the rocks studied, the feldspar was relatively unaltered. Evidence of slight alteration and partial resorption was found commonly within the crystal -- apparently having occurred during an interruption in the crystallization -- but alteration including the outermost rim of the crystal was rare. Only in the rock units that were extensively altered had the feldspars been replaced. In these, most of the feldspar crystals had been partially replaced by calcite, usually in the form of optically-oriented stringers laced through the crystal. Fine-grained opaque material, sericite(?), and fine fibrous anisotropic minerals were also common alteration products.

Biotite

Composition -- On the basis of the pleochroic formula and the refractive index of flat lying cleavage flakes, most of the biotite in the Lava Mountains volcanic rocks is annite, the high Fe, low Mg and Al member of the group. The pleochroism is very strong, as noted in the next section, and the refractive index varies from 1.67 to 1.73.

Many mineralogy reference books (e.g. Winchell and Winchell, 1952; Rogers and Kerr, 1942; Larsen and Berman, 1934) do not acknowledge the existence of natural biotite with a cleavage-flake index of more than 1.68. Field studies have reported such minerals, however. Larsen, and others (1937), found biotites of this type and noted that those with the highest index were from the less siliceous rocks such as latitic andesites and quartz latites.

Laboratory work by Kozu and Yoshiki (1929) proved that similar high-index biotites could be formed by heating normal crystals to temperatures of 1,000 C. In their experiments, the biotite began appreciably to change index at about 400 C and continued at a fairly uniform rate to the highest temperature measured. At 1,000 C, Z = 1.703. They also found that naturally-occurring high-index biotite showed no marked changes in properties within this range of heating.

Color and pleochroism -- In thin section these biotites commonly show an uneven coloring with the darker colors found along the cleavage planes or fractures. The darker portions of the biotite flakes have a higher index than the lighter ones and thus presumably are related effects. It is a curious thing that this mineral, which is by no means first reported here, has not been studied in more detail. Many of the indications are that it is analogous to oxyhornblende. If "oxybiotite" is ever defined as a legitimate mineral, these rocks should probably be included among those containing it.

Pleochroism is usually strong, the most common formula is the following:

X = grayish orange (10YR7-8/4-6)
Y = pale brown (5YR4/2)
Z = grayish brown (5YR3/2)

The results of several pleochroic determinations on biotite from rocks of the Lava Mountains andesite are plotted in figure 25.

Habit -- In most rocks, the biotite is present as hexagonal packets of thin plates, measuring one to two mm in the wide dimension. Some rocks, such as the late Pliocene(?) Felsite (Tpf), seem to have biotite present only as very thin wafers or shreds (see fig. 24e).

Inclusions -- Inclusions of opaque material are common. Many of these appear to be magnetite. Plagioclase, twinned and zoned, is also found,

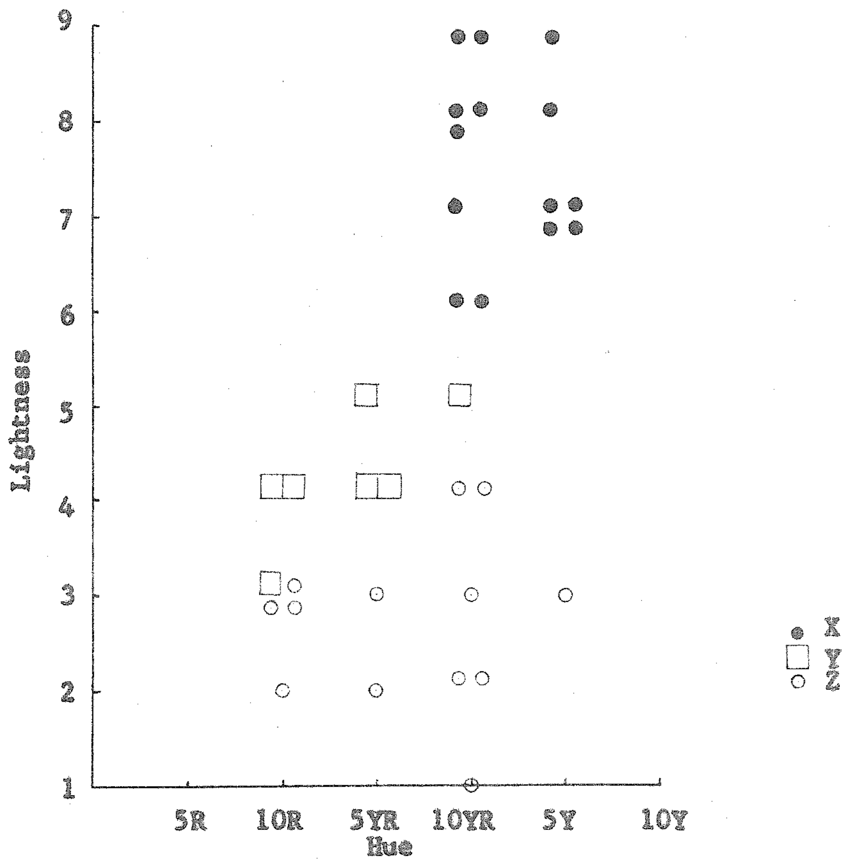


Figure 25. Graph showing the pleochroic formulae of biotite in randomly selected samples. The color terms are those of the Rock Color Chart (Goddard, 1948). "Hue" is a measure of the "redness" (5R), "orangeness" (5YR), or "yellowness" (5Y). "Lightness" is a measure of the relative amount of black (1) or white (9) mixed with the color. "Chroma" (or "saturation") is not plotted.

and some of the plagioclase inclusions themselves contain included magnetite. A few biotite crystals also contain oxyhornblende and pyroxene (clinopyroxene?), but it is possible that they are alteration products rather than original inclusions.

Alteration -- In the majority of rocks, alteration has partially to completely destroyed the biotite crystals. The first phases of alteration usually resulted in a number of equant minerals, probably magnetite, scattered around the outer rim of the crystal or embedded in its edges. More intensive alteration commonly obliterated the euhedral outline of the opaque minerals, and plagioclase and pyroxene(?) became common. The alteration of biotite seems to have been a very late stage process; where biotite and plagioclase are in contact, there has been no alteration of the biotite edges where protected by the plagioclase (see fig. 24d).

Amphiboles

Composition -- In the Lava Mountains rocks, oxyhornblende forms the most abundant amphibole type although common hornblende, or green hornblende, is locally found. The distinction between oxyhornblende and hornblende is apparently arbitrary and there seems to be little agreement among reference books as to where the line should be drawn. Winchell and Winchell (1951) cite theoretical compositions of four "end members", none of which contains any magnesium. According to them, the optic angle ranges from 0 to 15°, and Nz up to 1.80. Rogers and Kerr (1942) cite the optic angle range as 0 to 12° and the Nz up to 1.76; they give no definite formula for the mineral. Larsen and

Berman (1934) used the equivalent term "basaltic hornblende" for "those members containing appreciable Ti with less Mg + Fe than hastingsite and less (OH) than the normal amphiboles". The optical properties of minerals so defined vary; axial angles range up to 21° and N_z ranges up to 1.718. The minerals included by their definition contain more Mg than Fe.

Most references point out that the more normal types of oxyhornblende have extinction angles near zero. Only in exceptional examples do the angles approach the upper limit. In the Lava Mountains rocks, the main change in the pleochroic formula occurred between crystals having extinction angles around 10°. Inasmuch as color is one of the more obvious differences between the two amphiboles, but is difficult to measure quantitatively, the associated extinction angle of 10° was used as the dividing line between the two.

Hornblende, which, for emphasis is sometimes called green hornblende in this report, is restricted to those rocks that are intrusive or those that were quickly chilled upon extrusion. The intrusive dikes of the Lava Mountains andesite (Tli) contain the majority of these examples. Most have extinction angles of about 15°, and indices of hornblende from one typical rock are Nx = 1.675 and Nz = 1.700.

On the basis of the optical data, the approximate composition of the green hornblende is:

$$Ca_2\ Mg_{1.5}\ Fe^{2+}_{3.5}\ Si_8\ O_{24}\ H_2$$

Oxyhornblende is the more abundant type of amphibole. Most of the crystals have extinction angles between 5 to 10°; very few have extinction angles of 0°. On oxyhornblende from two rocks, some of the refractive indices were measured: The first gave readings of Ny = 1.715?, Nz = 1.729, $Z \wedge C = 3^{\circ}$. The second gave a reading of Ny = 1.701 and $Z \wedge C = 10^{\circ}$. With such meager data, it would be difficult to assign a composition to these minerals. It is even more difficult, however, because of the conflicting information in the literature.

Regardless of the reference used, however, it seems clear that the properties of the minerals in the Lava Mountains rock are those of partially dehydrated hornblende. If one applies these insufficient data to the conflicting curves found in the literature, the approximate composition of these minerals may be considered as:

$$Ca_2\ Mg_{3.5}\ Fe^{2+}_{0.9}\ Fe^{3+}_{0.6}\ Si_8\ O_{22.6}\ (OH)_{1.4}$$

Color and Pleochroism -- The hornblende is generally green or straw colored. All variations in color are found between the green or yellow types and the colors normally associated with oxyhornblende. Oxyhornblende from one suite of rocks was examined for pleochroic formulae. The results are shown in figure 26. From this, the following approximate pleochroic formula can be derived:

X = Light moderate yellow (5Y8/6)
Y = Dark yellowish orange (10YR6/6)
Z = Moderate brown (5YR4/6)

Habit -- Both hornblende and oxyhornblende are found as elongated prismatic crystals, which in cross-section have a lozenge-shape. They seldom are more than 3 mm long and most are between 0.5 mm and 1.5 mm long.

Inclusions -- Inclusions are common, the most frequent being euhedral opaque minerals, probably magnetite. Biotite, apatite, and clinopyro-

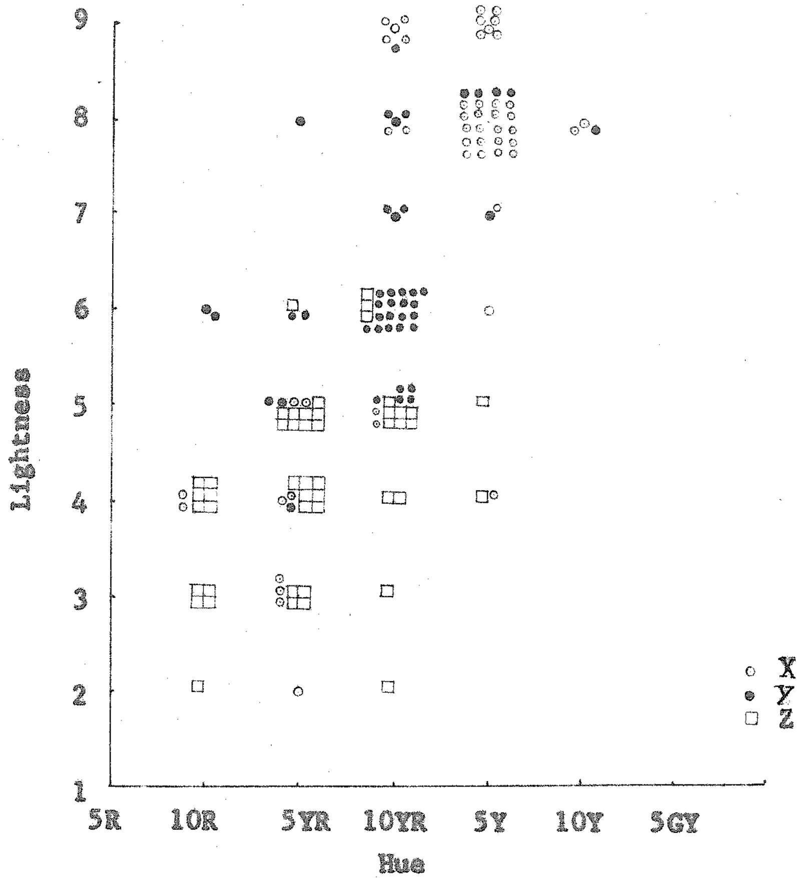


Figure 26. Graph showing the pleochroic formulae of randomly selected amphiboles, mostly oxyhornblende. The meanings of the coordinates are as in figure 25.

xene (itself containing magnetite(?)) are also common (see fig. 24f). Plagioclase crystals, possibly of secondary origin, are found.

Alteration -- The most frequently found alteration products are opaque materials. Others such as plagioclase, epidote(?), and fine-grained pyroxene(?) are also present. In one rock the green hornblende was partly altered to chlorite (penninite(?)) and calcite.

Cause of Transition from Hornblende to Oxyhornblende --

The correlation between the optics of hornblende and the temperature to which it is heated has been noticed by several workers (Belovsky, 1891; Weinschenk, 1912; Graham, 1926; and Kozu, Yoshiki, and Kani, 1927A, B). In Kozu's studies, common hornblende was subjected to ever-increasing heat in an atmosphere of air. Between 700 and 800 C, the extinction angle diminished from 12^{o} to 0.3^{o} and Nz increased from 1.687 to 1.720. Above and below these temperatures the changes were slight. At about 750 C, a marked increase in the rate of weight loss (calibrated as percent of weight loss per degree C) was also noticed. Oxyhornblende, also subjected to similar treatment, showed little change in optical properties when heated although the rate of weight loss changed slightly at 750 C. When the oxyhornblende was heated to 1,000 C in a nitrogen atmosphere, the crystal began to change color around the edges; at 1,050 C it became entirely altered to an opaque black substance; at 1,100 C some anisotropic banding was noticed; at 1,200 C crystals of pyroxene(?) were seen in the fused material.

Although it is difficult to draw geological conclusions from laboratory experiments, it seems clear from these investigations that at about 750 C, common hornblende changes to oxyhornblende at normal atmospheric conditions.

That hornblende can reach the surface and be extruded before alteration to oxyhornblende occurs is shown by the hornblende-bearing perlite in the basal parts of the flow in section E9a. The temperature of these flows must have been well above 750 C inasmuch as most of the flow does contain oxyhornblende. Thus the conditions necessary to keep alteration from occurring must exist until the very late stages of solidification. Probably the transformation temperature is susceptible to the slightly higher water vapor pressures found in a melt. Laboratory studies under such conditions are necessary to confirm this.

Orthopyroxene --

The orthopyroxene in these rocks is hypersthene. In all of the rocks examined, the orthopyroxene is optically negative and the optic angle is medium to high. According to Winchell and Winchell (1951, p. 406, fig. 283), these properties are found in crystals containing about 60 percent enstatite and 40 percent ferrosilite. In most rocks, the crystals are slightly pleochroic, the formula being:

X = very pale orange (10YR8/2)
Y = Z = clear, to very slightly bluish

Most of the crystals are stubby prisms showing well-developed prism faces and very faintly-developed terminations. Many contain inclusions of euhedral opaque minerals, probably magnetite. Alteration, if present, has usually changed the mineral to a fine-grained opaque material or a fibrous greenish material, probably bastite.

Some crystals are stained orange or light brown around the edges, and such colors commonly "precede" the opaque alteration products toward the center of the crystal.

Clinopyroxene --

The volcanic rocks in the Lava Mountains contain only a few percent clinopyroxene. In some rocks, the optic angle and extinction angle suggest that the clinopyroxene is pigeonite while in others, augite or diopside are indicated. Not enough crystals are ever present in one thin section to furnish the variety of orientations necessary to be sure of the species. Another result of the shortage of sample material is that no refractive index determinations could be made. Consequently, all pyroxenes with an inclined extinction have simply been called "clinopyroxene" rather than try to name the species on the basis of inadequate data.

Clinopyroxenes are found in two habits: The more common is that of the orthopyroxenes, namely, stubby prisms. The second, which is much less common, is as clusters of small, well-terminated crystals that radiate inward from the walls of a cavity.

A few crystals contain inclusions of well-shaped magnetite(?) crystals. When altered, clinopyroxene generally reverts to fine-grained opaque minerals or to bastite.

Quartz --

A fraction of a percent of quartz is found in the majority of rocks in the area. Its most common form is that of irregularly embayed fragments, some of which have a reaction rim of fine-grained clinopyroxene. What look like slightly rounded crystal outlines are sometimes present (see fig. 24c), but resorption has usually obliterated the diagnostic features. A few crystals contain round or oval-shaped inclusions of yellowish or clear glass, and in some crystals very small "needles" of apatite can be seen.

Opaque material --

Four types of opaque material are present: The first consists of euhedral equant crystals that appear as squares in thin section; probably most are magnetite, although pyrite, chromite, and ilmenite may be present in appreciable percentages. The second consists of irregular dust-like fragments that appear in conoscopic light to be black. The third type appears as clumps of finer-grained material which most commonly were semiopaque and appeared a deep red in conoscopic light. The fourth type is present as fibrous and hairlike fragments that are deep red or brown in conoscopic light.

Nonopaque materials --

Minerals that were noted but not specifically described above include the following: calcite, zeolite, apatite, opal, chalcedony, and bastite. Minerals that were tentatively identified are: tridymite, chlorophaeite, epidote, serpentine, and olivine.

Groundmass --

Most rocks in this area have a semicrystalline groundmass that consists predominantly of microcrystals, crystallites, and anisotropic "glass" with lesser amounts of isotropic glass. The glass is most often clear, slightly yellowish, or greenish.

The crystallites and microcrystals appear to be plagioclase although no confirming optics could be measured. The opaque material, which usually forms a light to heavy "dust", includes the black equant fragments and the fine-grained materials described above.

In figure 27, the refractive index of the glassy portion is plotted against the silica percentages of the whole rock and of the calculated groundmass. All the indices are between 1.50 and 1.53. According to George (1924), this would indicate a silica range of 57 to 72 percent. This happens to be about right but within this range there is little correlation between the refractive index and the silica percentage of the whole rock. The silica in the calculated groundmass shows a statistical correlation but one point would not be a reliable test.

QUANTITATIVE

General Characteristics of the Suite

It is clear from the previous section that the qualitative mineralogy shows no systematic variations throughout this suite. Table 11 indicates that most of the rocks in the Lava Mountains are also quantitatively somewhat similar. Plagioclase is always present; the total percentage varies from 10 to 30 percent and averages about 20 percent. Biotite locally forms over 2 percent of the rock but more generally about 0.5 percent. Oxyhornblende (or hornblende) sometimes forms 5 or 10 percent of the total in fresh rocks but the average is less than 1 percent; it is usually about twice as abundant as biotite but either may be absent. Orthopyroxene and clinopyroxene are never more abundant than about 2.5 percent of the rock and also are locally absent.

	Maximum	Minimum	Average
Plagioclase megaphenocrysts	22.9	3.3	9.9
Plagioclase microphenocrysts	20.2	4.5	10.3
Total plagioclase	28.7	11.5	20.2
Biotite	2.2	--	0.5
Hornblende	6.3	--	0.1
Oxyhornblende	7.6	--	0.8
Orthopyroxene	2.5	--	0.9
Clinopyroxene	2.0	--	0.4
Quartz	3.2	--	0.4
Opaques	11.4	1.2	4.6
Nonopaques	6.0	--	1.3
Groundmass	78.9	60.2	70.2

Table 11. Shows the maximum, minimum, and average values of the modal analyses on rocks from the Lava Mountains. All values are percents. Calculations excluded sample 97-39, the Pliocene(?) felsite.

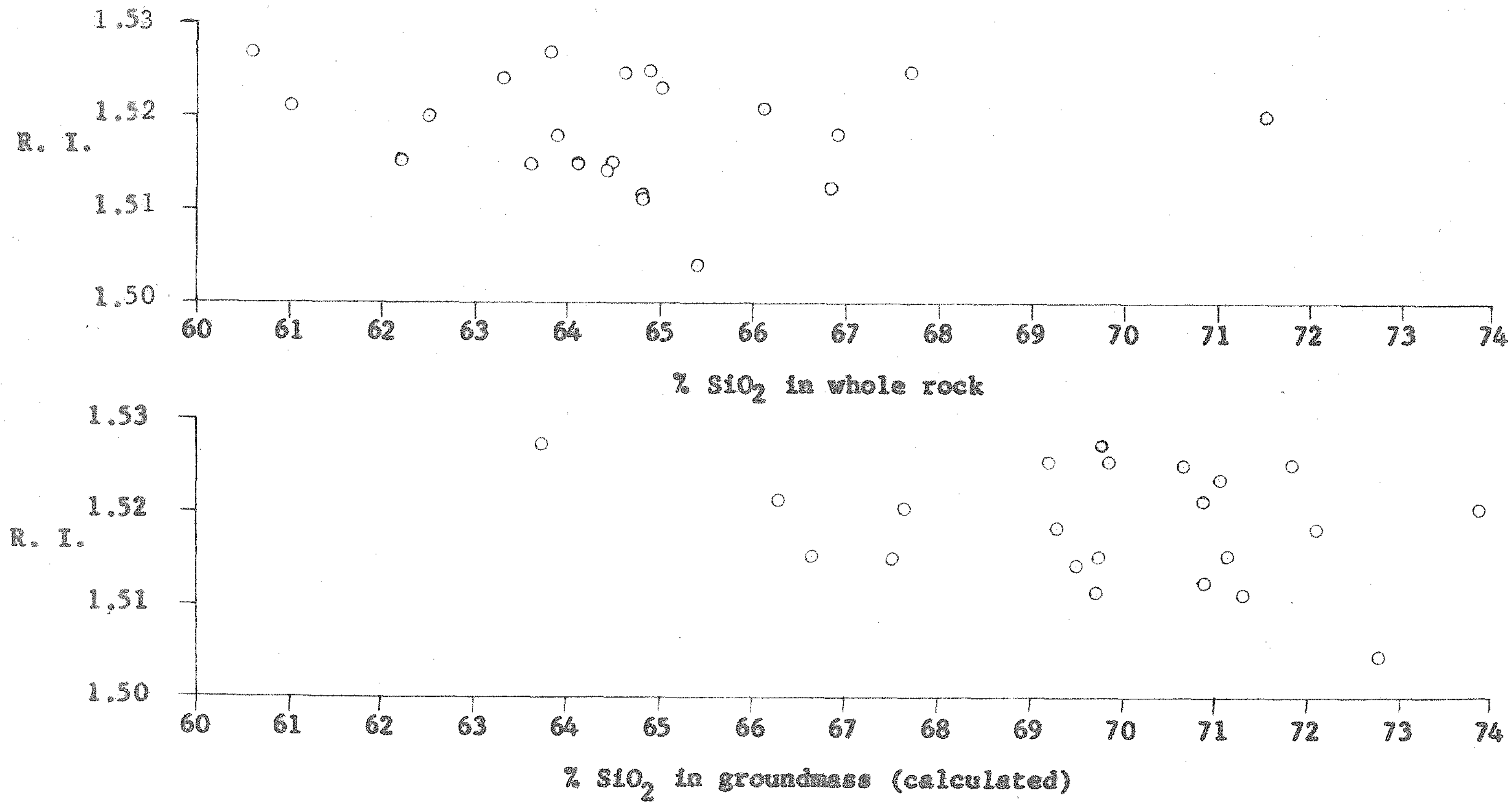


Figure 27. Relationship of the silica content to the refractive index of the glass. The upper figure relates the index of the glass to the silica of the whole rock. The lower figure relates the index to the silica in the (calculated) groundmass. The silica values are percents.

Quartz exceptionally forms over 3 percent but the average is much less. Opaque materials are always present and form between 1 and 10 percent of the total; these figures, however, are probably too high because of the tendency for fine-grained opaque minerals embedded within in the thin section to be projected onto the top surface -- the surface on which the point count is theoretically being made -- as if they were actually a part of that surface. Other minerals make up as much as 6 percent of the rock but average only a few percent. The groundmass in all rocks is the most abundant material and forms from 60 to 90 percent of the total volume.

Characteristics of Suites from Other Volcanic Areas

Within the Mojave Desert, two studies of volcanic rocks have been completed: Work by T. H. McCulloh (1957?), in the Calico Mountains, deals partly with volcanic rocks similar to those in the Lava Mountains; his Pliocene(?) "Lane Mountain formation" includes some volcanics that are similar to those described in this report. The second study, also unpublished, was made by R. G. Schmidt on the volcanic rocks in the Barstow area; his results are not yet available.

Outside of the Mojave Desert, more studies have been made: Along the north edge of the Los Angeles area, work by Shelton (1955) showed the Miocene volcanics to range from basalts to rhyolites. Eaton (1956) described rocks somewhat similar to Shelton's along the south edge of the Los Angeles basin. Yerkes (1956?) found the Miocene volcanics in the eastern Los Angeles basin to be altered andesitic and basaltic rocks.

In the Cascade Range a number of careful studies have been made on the volcanic rocks of the region (Anderson, 1941; Coombs, 1936; Fuller, 1931; Thayer, 1937; Verhoogen, 1937; Williams, 1932, 1933, 1934, 1935, 1942). The bulk of rocks studied by these men are more basic than those in the Lava Mountains. Andesitic and basaltic rocks, containing hypersthene, augite, and in some, olivine, are areally abundant in the late Tertiary series; dacitic and rhyolitic rocks are less abundant and tended to be restricted to explosive volcanic episodes which commonly occurred during the later stages of eruption.

In the Basin Ranges and southern Rocky Mountains area, several studies of the volcanic rocks have been made. Work by Hunt (1938) dealt with a sequence of rocks ranging from sheet basalts to rhyolites; although some of the rocks are similar to those in the Lava Mountains area, the size of the region being investigated -- and consequently the scope of his conclusions -- was many times larger. Williams (1936), working in the Navajo-Hopi country, found the Cenozoic volcanics to be a high soda and potash sequence with scarce biotite and hornblende.

The San Juan region, Colorado, as described by Cross and Larsen (1935) and by Larsen and others (1936, 1937, 1938A, 1938B), contains many features which are identical to those in the Lava Mountains. Larsen noted that hypersthene was generally restricted to rocks with more than 54 percent but less than 65 percent silica; olivine was found in rocks containing less than 56 percent silica; amphiboles were found only in rocks containing more than 53 percent silica; biotite began to be found in rocks with more than 58 percent silica. Feldspars, which were complexly twinned and zoned in most rocks, seemed to bear virtually no relationship to the chemical character of the rock in which they were found; the plagioclase within a given rock commonly varied through a range of An_{30-50}. Plagioclase zones generally had a difference of 10 to 30 percent in anorthite content between the core and the rim, and reverse zoning was about as common as normal zoning. Orthoclase and sanidine were found in the more acid volcanics. Magnetite and ilmenite were most common in basaltic rocks; andesitic rocks more commonly contained iron that had been altered to a red oxide although if the rocks were glassy, it was present as black oxides. The petrographic relationships indicated that the "change in state [of black opaque materials to red] obviously took place with the crystallization of the groundmass". Quartz, tridymite, and cristobalite were present in about equal quantities. Quartz was found in both the groundmass and as phenocrysts; tridymite was in the groundmass of the acid rocks, as a cement in tuffs, and in cavities of the basic rocks; cristobalite was found as rounded balls on the walls of andesitic- and basaltic-rock cavities and in the groundmass of certain rocks.

In Mexico, extensive studies have been made by many on the petrology of Paricutin volcano. The more intensive of these was by Wilcox (1954) with a supporting regional study by Williams (1950). Williams noted the virtual absence of hornblende and biotite in the rocks of the region, and Wilcox confirmed this for Paricutin extrusives by detailed modal analyses.

The major difference between the volcanic rocks of the areas cited and those of the Lava Mountains is the paucity of the hydrous minerals -- oxyhornblende (or hornblende) and biotite. There is the converse shortage of the anhydrous equivalents -- pyroxenes -- in the Lava Mountains rocks. Whether this is a very local characteristic, or one found over most of this part of the country, will have to await the completion of work in other nearby regions. Except for this contrast, the petrographic similarity between these rocks and other comparable rocks from western North America is striking.

Variation with Age

The variation in mineral composition with respect to stratigraphic position is shown in figures 28 and 29. Samples collected from measured sections in the Almond Mountain and Klinker Mountain volcanics and the Lava Mountains andesite are plotted in stratigraphic order to show the variation in mineral content. These graphs show three things: First, the amount of variation between the volcanic strata of a single formation (Tkb or Tab); second, the variation between two formations of the same age and similar lithology but five miles apart (Tkb vs. Tab); and third, the variation within a seemingly homogeneous unit (Tl).

Within the Almond Mountain and Klinker Mountain volcanics, there are faint trends correlative with the stratigraphic position. The trends within one formation, however, are not repeated by the other. Furthermore, the variations within the overlying Lava Mountains andesite make it clear that any one sample maybe markedly nonrepresentative of that unit.

For these reasons, it is impossible to demonstrate intraformational trends in the modal compositions. On the basis of either section alone, variations are found that might be considered "fundamental". When corroboration is sought in the other formation, how-

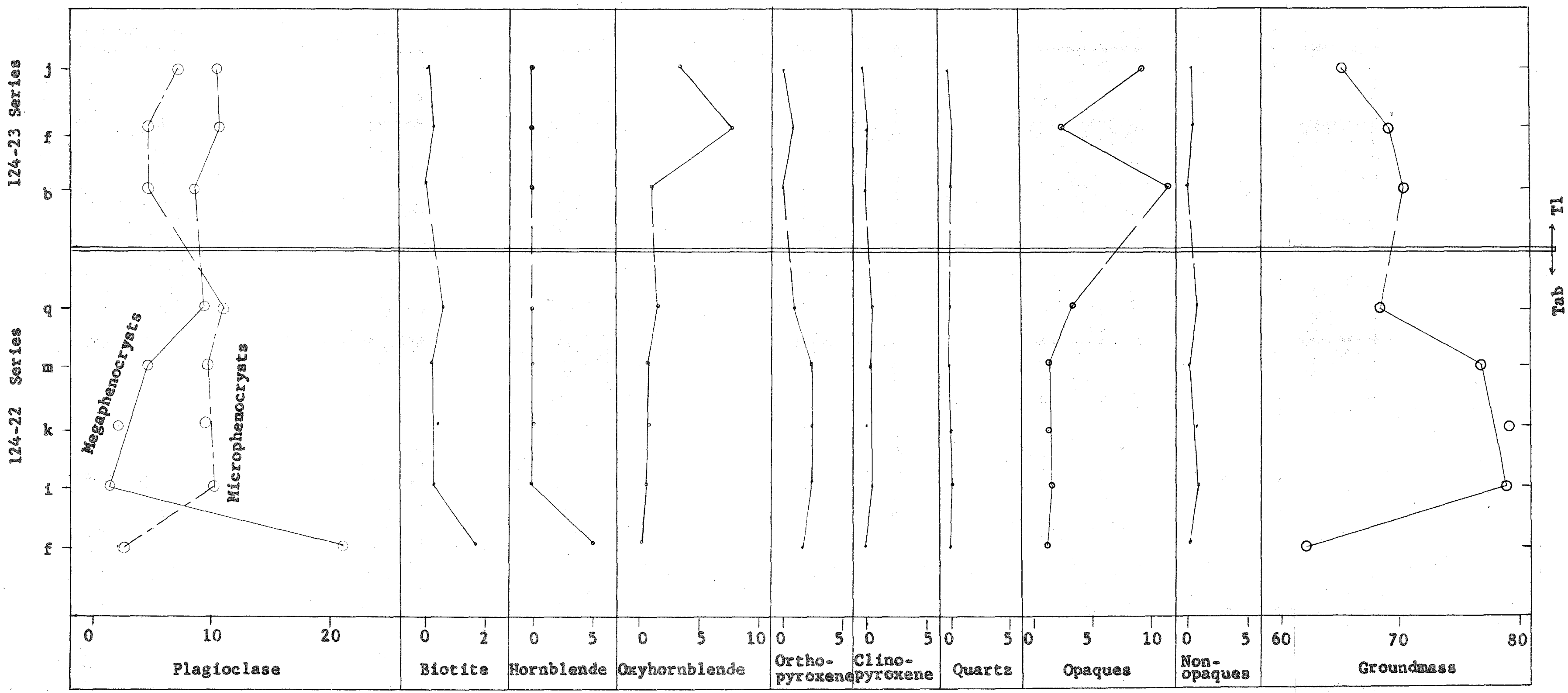


Figure 28. Diagram showing the variations in the mode as a function of the stratigraphic position of the samples. All values are percents. The relative stratigraphic positions of the samples are shown in figures 10 and 16. The radii of the circles represent the average analytical errors calculated in Appendix I.

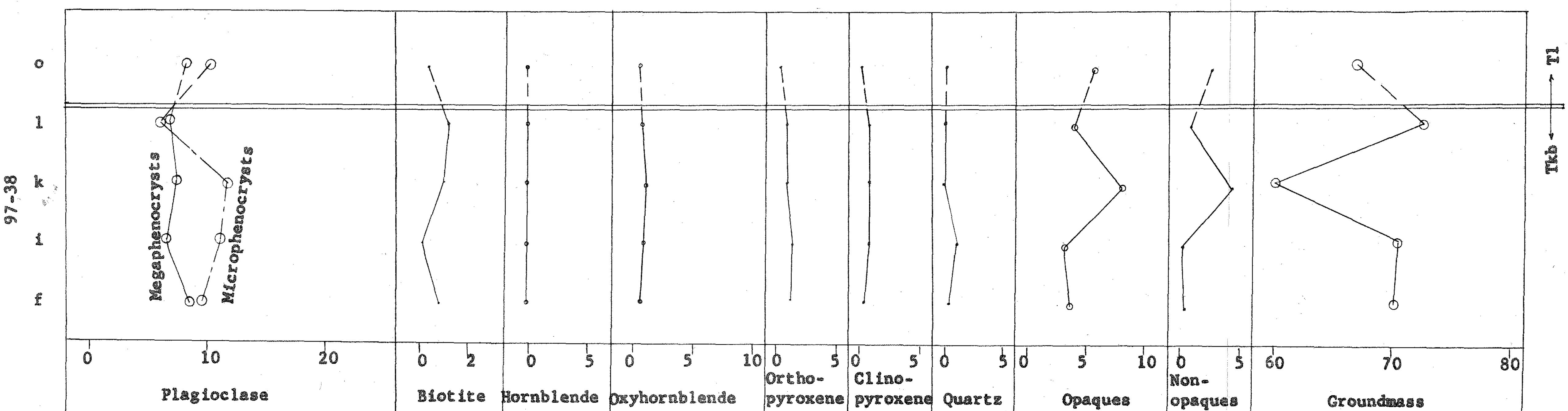


Figure 29. Diagram showing the variations in the mode as a function of the stratigraphic position of the samples. All values are percents. The relative stratigraphic positions of the samples are shown in figure 13. The radii of the circles represent the average analytical errors calculated in Appendix I.

ever, it is not found.

Average modes for each of the four Pliocene volcanic formations are listed in table 12 and are plotted in figure 30. This graph suggests the following modal trends from the base of the section toward the top: 1) The percentage of microphenocrysts of plagioclase tends to increase, while the megaphenocrysts decrease; 2) the percentage of hornblende appears to decrease while oxyhornblende increases slightly; (3) the percentage of opaques tends to increase slightly; 4) the groundmass percentage diminishes faintly. No trend, however, is detectable for the pyroxenes and only the faintest trend is visible for quartz.

These data must be used cautiously. The lower row of points (Tbv) are based on a single specimen, while the middle and top row are based on averages of 4 to 10 specimens each. Also the averages for Almond Mountain and Klinker Mountain volcanics, in a great many of the curves, fall a short distance apart, and some more than straddle the difference between the top and the bottom formation. Thus, the modal differences between formations are not great. If the sampling error is large -- and it may be -- no modal variation can be demonstrated.

SUMMARY OF PETROGRAPHY

The volcanic rocks are all plagioclase andesite porphyries. Most also contain oxyhornblende and biotite phenocrysts, and some contain minor quartz. Under a microscope, orthopyroxenes and clinopyroxenes are visible; the groundmass is slightly crystalline to glassy. The mineral composition and content show no strong trends correlative with

	Tbv	Tkb	Tab	Tl & Tli
Plagioclase megaphenocrysts	15.06	9.54	11.03	10.75
Plagioclase microphenocrysts	5.11	12.01	10.31	10.53
Total plagioclase	20.17	21.55	21.34	21.28
Biotite	.53	.76	.88	.30
Hornblende	6.30	--	1.27	.20
Oxyhornblende	--	.66	.40	1.41
Orthopyroxene	1.19	1.07	1.88	.43
Clinopyroxene	--	.59	.37	.47
Quartz	--	.47	.04	.52
Opaque minerals	1.46	4.78	1.81	5.80
Nonopaque minerals	0.07	1.52	.35	1.64

Table 12. Average modal compositions of the volcanic rocks from the Bedrock Spring formation (Tbv; one sample), Klinker Mountain volcanics (Tkb; six samples), Almond Mountain volcanics (Tab; four samples), and the Lava Mountains andesite (Tl and Tli; eleven samples). All values are volume percents.

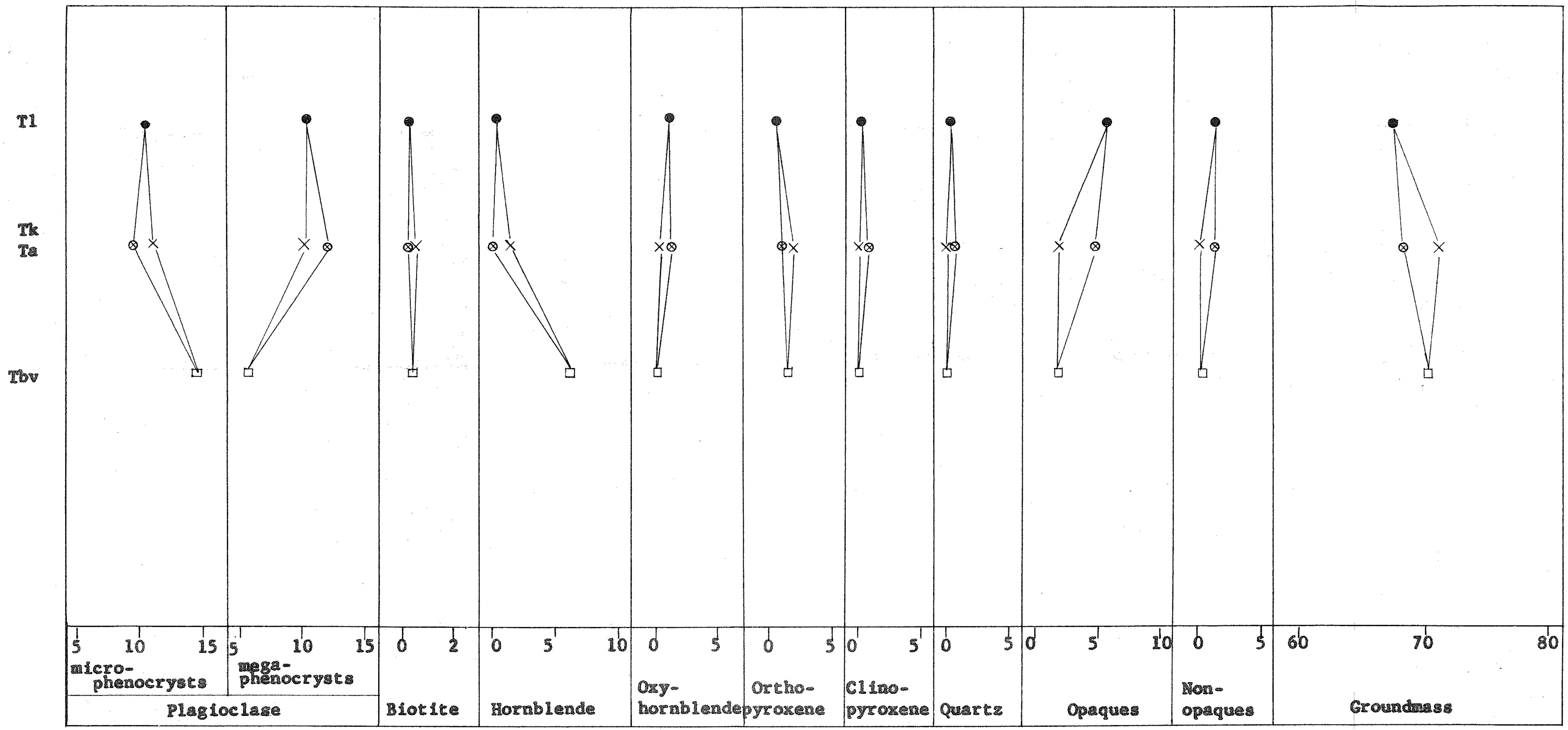


Figure 30. Graph showing the stratigraphic variation in the average modes for the four Pliocene formations listed in table 12. Symbols are as follows: □ = Bedrock Spring formation; × = Almond Mountain volcanics; ⊗ = Klinker Mountain volcanics; ● = Lava Mountains volcanics.

their stratigraphic position. Neither within the formations, nor between formations, are there strong and irreversible trends; the most recent rocks and the older rocks show very little difference in composition. Only the textures change: The earlier volcanic rocks are without exception the products of explosive eruptions whereas the latest rocks resulted from effusive activity.

PETROCHEMISTRY

GENERAL CHARACTERISTICS OF THE SUITE

Major Element Composition

Results of the twenty-four chemical analyses are plotted against the SiO_2 content in figure 31. Although these by no means form a smooth line, they do define statistical trends as well as most suites of analyzed rocks. The curves for Al_2O_3, total Fe as Fe_2O_3, Na_2O, K_2O, TiO_2, P_2O_5, and MnO show the clearest trends; the curves for MgO and CaO show a somewhat less; H_2O and CO_2 show little trend.

By extrapolation, the alkali-lime index (Peacock, 1931), that percentage of SiO_2 at which $Na_2O + K_2O = CaO$, is about 58. According to Peacock's classification, these rocks would be calc-alkalic.

Volcanic petrologists who use the chemical composition as a basis for classification would probably consider the rocks of this suite as dacites. Although this does not seem a sound basis for a primary classification, it does emphasize the inadequate representation of the magma by the early crystallizing minerals.

As a result of this tendency for the minerals with basic affinities to crystallize first, the residual liquid becomes more acid as the crystallization proceeds. At the time the process is arrested by

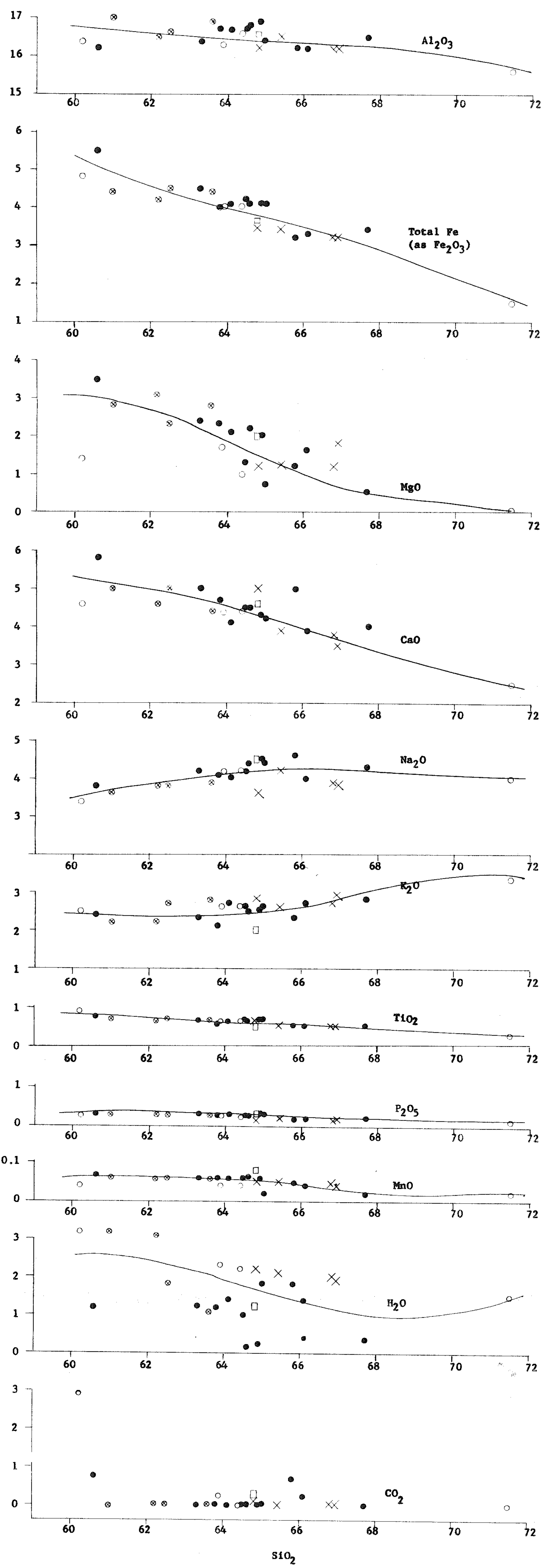


Figure 31. Variation diagram showing the relationships between the major elements and the silica of the host rock.

Symbols:
- ● Lava Mountains andesite
- ⊗ Klinker Mountain volcanics
- × Almond Mountain volcanics
- □ Bedrock Spring formation
- ○ Other volcanics

solidification, the residual liquid that has not been removed from the system is found as the groundmass.

To confirm this relationship for this suite of rocks, the composition of the groundmass had to be determined. It is nearly impossible in rocks of this type to physically separate the groundmass from the crystals. Consequently, the composition of the groundmass had to be calculated from the data obtained from modal analyses and from petrography. In these calculations, the following mineral formulas and densities were used:

Mineral	Formula	Density used in converting to weight-percent
Plagioclase	$NaAlSi_3O_8 \cdot CaAl_2Si_2O_8$ (An_{50})	2.68
Biotite	$K_2Fe^{2+}_6Al_2Si_6O_{24}H_4$ (Annite)	3.20
Hornblende	$Ca_2Mg_{1.5}Fe^{2+}_{3.5}Si_8O_{24}H_2$	3.30
Oxyhornblende	$Ca_2Mg_{3.5}Fe^{2+}_{0.9}Fe^{3+}_{0.6}Si_8O_{22.6}(OH)_{1.4}$	3.40
Orthopyroxene	$Mg_{0.6}Fe_{0.4}SiO_6$ (hypersthene)	3.50
Clinopyroxene	$CaMgSi_2O_6$ (diopside)	3.50
Quartz	SiO_2	2.65
Opaques	$Fe_3O_4 \cdot Fe_2O_3$	5.00
Nonopaques	(included in groundmass)	2.50
Groundmass		2.50

The resulting compositions are shown in figure 32 as a function of the silica percentage in the groundmass. Figure 33 compares the variation curves for the groundmass with those from the total rock analyses.

Normative Composition

The C.I.P.W. norms of the analysed rocks are given along with

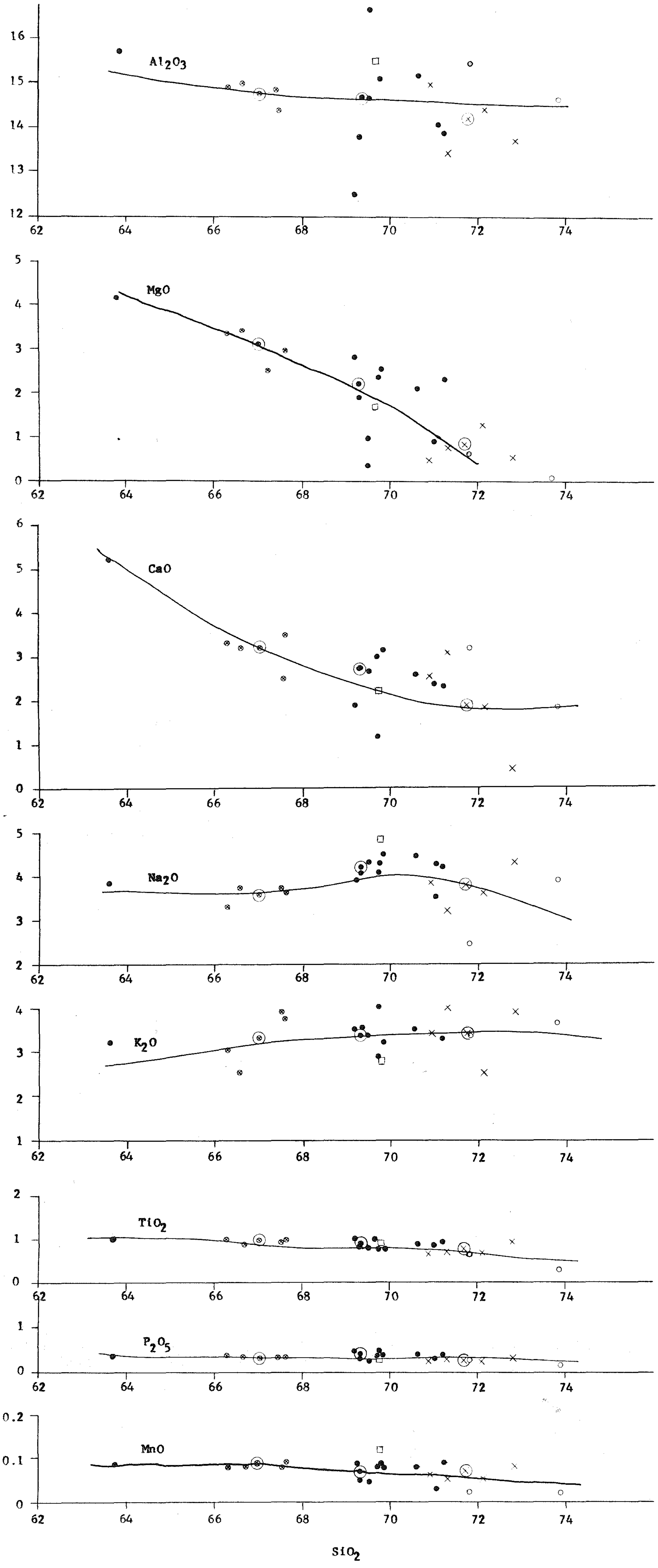


Figure 32. Variation diagrams for the calculated groundmass compositions, showing the relationships of the major elements to the silica in the groundmass.
Symbols:
● Lava Mountains andesite
⊗ Klinker Mountain volcanics
× Almond Mountain volcanics
□ Bedrock Spring formation
○ Other volcanic units
The average value of each group is enclosed in a large circle.

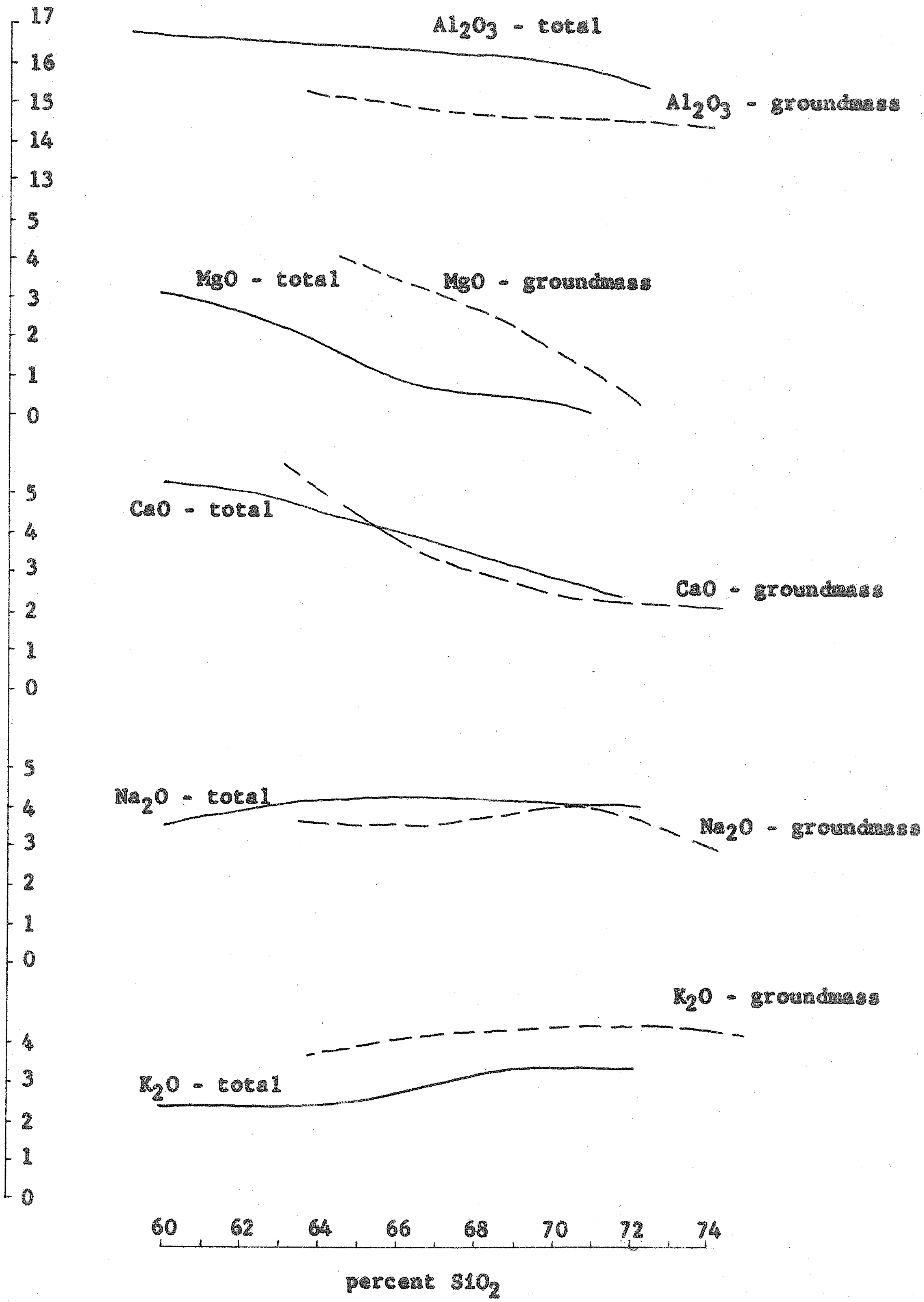


Figure 33. Variation curves for the total rock and for the calculated groundmass. The total rock curves are taken from figure 31; the groundmass curves are from figure 32. All values are percents.

the chemical analyses in the section on Detailed Stratigraphy. The norms are calculated by the method described by Washington (1917). Nineteen of the rocks are "yellowstonose" with a symbol I.4.3.4; four are "tonalose" with a symbol II.4.3.4; one -- the Pliocene(?) felsite -- is "lassenose" with a symbol I.4.2.4.

The lack of variety in the rocks of Lava Mountains suite is emphasized by the small number of C.I.P.W. normative rock names needed to describe them -- that classification not noted for its tendency to group chemically dissimilar rocks. The difference between "yellowstonose" and "tonalose" is solely in the class number (I and II). This portion of the symbol is a function of the ratio of quartz plus feldspars to dark minerals; the higher the Roman numeral, the higher the percentage of normative dark minerals. The similarities between these rocks (excepting "lassenose") are more impressive: The identical order, rang, and subrang result from similar ratios of normative quartz to feldspar, alkalies to lime, and potash to soda. The "lassenose" is anomalous because of the higher ratio of alkalis to lime than in the rest of the rocks.

Minor Element Composition

A total of thirty-six elements were sought in the spectrochemical analyses. Three of these, Fe, Mn, and Ti, were also included in the major element analyses.

Those elements detected in virtually all of the rocks are: B, Ba, Co, Cr, Cu, Fe, Ga, Mn, Ni, Pb, Sc, Sr, Ti, V, Y, Yb, and Zr.

Those elements that were sought but not detected in any rocks are: Ag, As, Bi, Ce, Hg, In, La, Nd, Pt, Sb, Sn, U, and Zn.

Elements that were questionably detected in some rocks are the following: Ge (in 128-34, 97-38K, and 97-38I), Li (in 29-22), Mo (in 124-22K, 97-38I), and Nb (in most samples).

In figure 34, the values obtained for the minor elements are plotted against the silica content of the host rock. Fairly straight line relationships are found for B, Ga, Mn, Pb, Sc, Sr, Ti, V, and Zr?. Three elements -- Cr, Ni, and Cu, -- show a "steplike" curve, the break coming between 64 and 65 percent SiO_2. There is no strong trend for Co, Ba, and Yb.

COMPARISONS WITH OTHER VOLCANIC AREAS

Other volcanic rocks studied in western North America show no great chemical similarity to the Lava Mountains suite. The Lava Mountains rocks have an alkali-lime index of 58. By comparison, rocks on the northeast side of the Los Angeles region, in the Glendora area (Shelton, 1955), have an index of 65; in the Paricutin region they have an index of 60 (Williams, 1950), and Paricutin itself has an index of 62 (Wilcox, 1954). Rocks in the Clear Lake area, California, have an index of 62 (Anderson, 1936), and those in Medicine Lake Highland, California, have an index of 60.5 (Anderson, 1941); in the Cascade Range, values include 62 for Crater Lake, 63.9 for Mt. Lassen, 63.7 for Mt. Shasta, and 62.3 for Mt. St. Helens (quoted in Williams, 1942). Thus, it can be seen that the Lava Mountains suite is deficient in calcium as compared to most volcanic areas studied on the west coast of North America.

Spectrochemical analyses of volcanic rocks from California have been published by Nockolds and Allen (1953, 1954). Hawaiian rocks

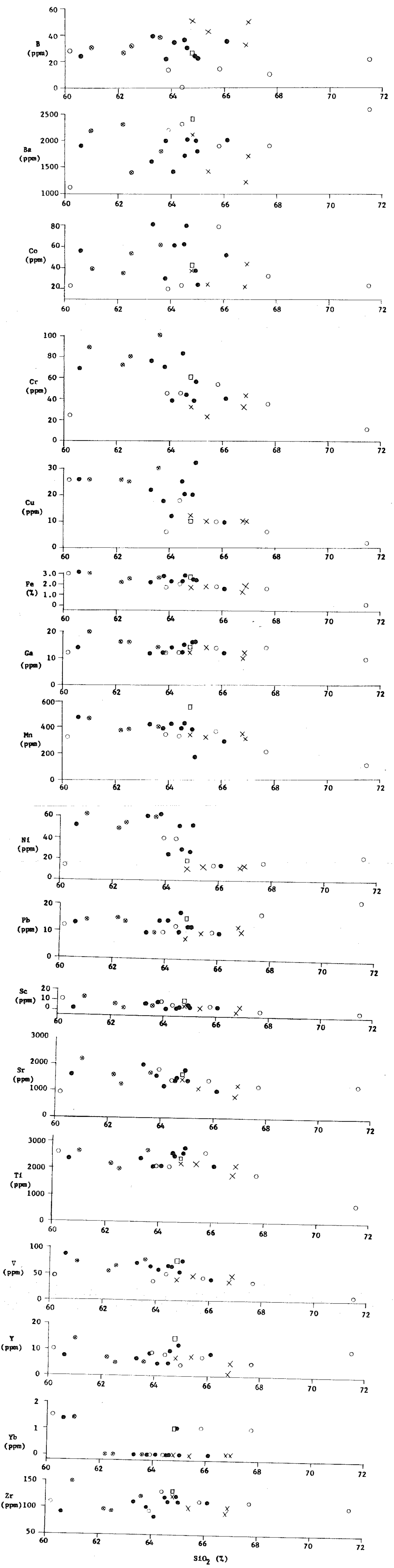


Figure 34. Variation diagrams showing the relationships between the elements analysed spectrochemically and the SiO_2 of the host rock.

Symbols:
- ● Lava Mountains andesite
- ⊗ Klinker Mountain volcanics
- × Almond Mountain volcanics
- □ Bedrock Spring formation
- ○ Other volcanic rocks

were analyzed spectrochemically by Wager and Mitchell (1953); a suite from northeast Ireland was analyzed and evaluated by Patterson (1951); Paleozoic spilites and quartz porphyries from the Alps were analyzed by Amstutz (1953). Unfortunately, these analyses were not made in the same laboratory as the Lava Mountains analyses, so the absolute values cannot be compared with any significance.

Most of these areas have several types of volcanic rocks represented. Although any one type may have only a small range of compositions, the several types combine to give a wider spread of compositions represented in each area. The Lava Mountains contain essentially only one volcanic rock type. This very limited range is the major distinction between this area and those mentioned above.

RELATIONSHIP BETWEEN CHEMICAL AND MODAL COMPOSITIONS

In working with coarse-grained halocrystalline rocks, the mineralogy understandably gives a good approximation of what major and minor elements are present. The crystal structures set semirigid limits on what elements can or cannot be included. In partially glassy rocks, where crystals form only a percentage of the total, the major and minor element content should show less correlation. In glassy rocks it should show none.

The volcanic rocks from the Lava Mountains show little relationship between the major elements and the mineral contents. There seems to be no correlation between the amounts of Mg or Fe and the mafic minerals of the rock -- biotite, amphibole, and opaques. An attempt to correlate the amounts of Co, V, Ni, and Cr, with the biotite, hornblende, oxyhornblende, and opaque mineral content of the rocks was likewise fruitless. These trace elements might be expected on the basis of their atomic radii (Cr^{3+} = 0.64; Ni^{2+} = 0.78; V^{3+} = 0.65, and Co^{2+} = 0.82) to be readily substituted in minerals containing Fe^{2+}, Fe^{3+}, and Mg^{2+} (radii of 0.83, 0.67, and 0.78, respectively). However, attempts to correlate these mafic minerals with elements is hazardous: All three minerals tend to alter to opaques during the final stages of solidification and these opaques cannot be accurately measured by modal analysis methods (see Petrography, Quantitative).

Plagioclase, the most abundant mineral in the rock, shows no quantitative relationship to Ca or Na. Figure 35 shows the relationships between total plagioclase and Ba, Sr, and Pb. The Ba shows no trend. The Sr shows a faint increase as the percentage of total plagioclase increases. The Pb shows a well-defined decrease as the total plagioclase percentage increases.

The lack of relationship between the amount of plagioclase and barium is not surprising; barium (radius 1.43; this and all other radii from Rankama and Sahama, p. 794, 1950) can most easily substitute for K (radius 1.33) in the feldspar lattice. Inasmuch as no potash feldspar is present, the only probable substitution would be for the small percentage of K in the plagioclase and in the biotite.

Strontium, which increases almost proportionally, probably substitutes for the Ca (radius 1.06) in the anorthite molecule; although Rankama and Sahama gives a radius of 1.27 for Sr, more recent work, quoted by Amstutz (1953), indicates a radius of 1.12 for Sr. Thus, it is more likely to substitute for Ca than K.

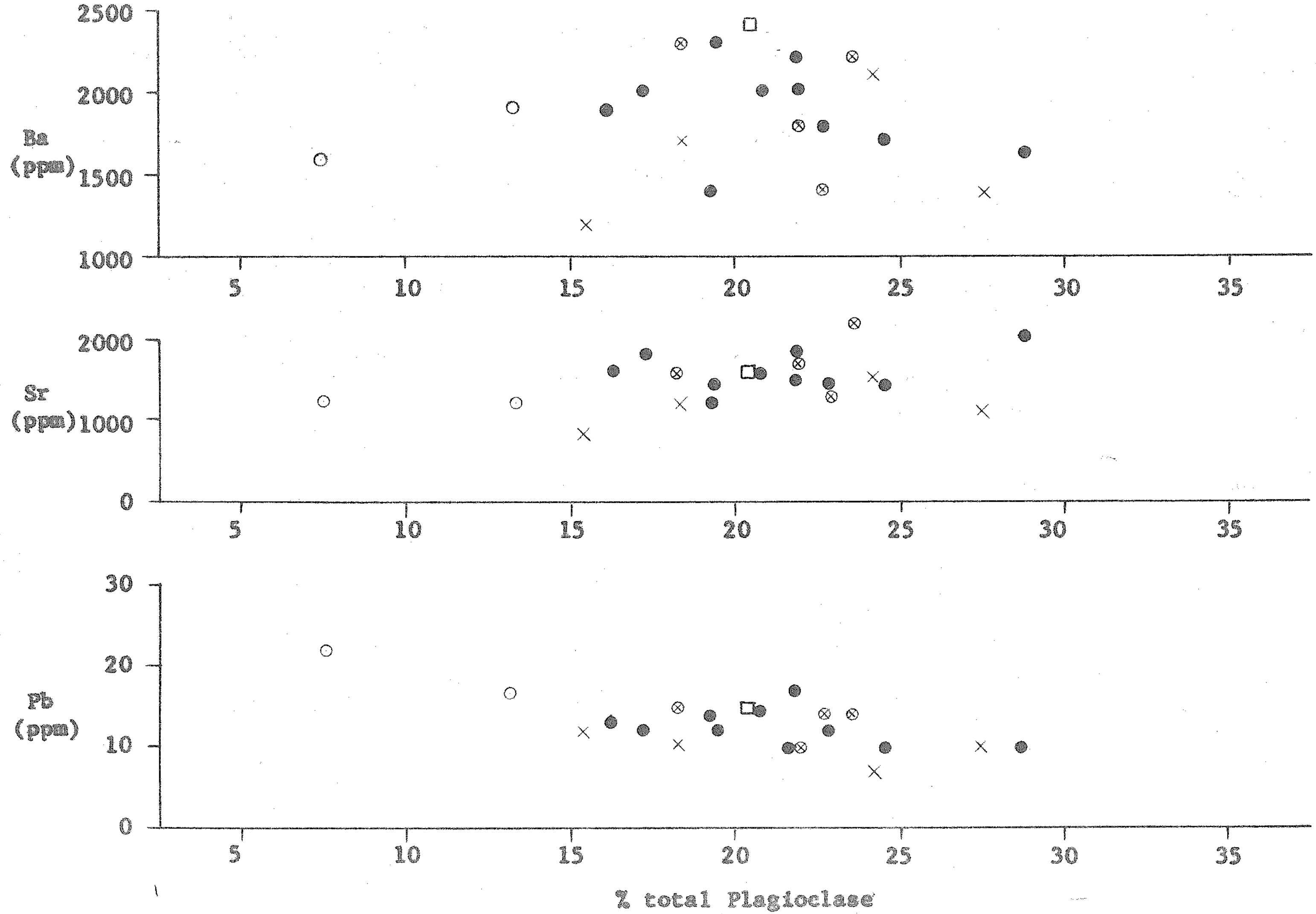


Figure 35. Diagram showing the relationships between the percentage of total plagioclase and Ba, Sr, and Pb. Symbols as in figure 34.

The negative correlation between lead and plagioclase remains unexplained. The radius of Pb (0.84, and 1.20) suggests K as the most likely material to be substituted. Also, as Amstutz (1953) pointed out, the smaller radius can fit in the holes between octahedral and tetrahedral lattices of silicate structures. Neither of these explanations, however, seem to explain this apparent decrease in total Pb with the increase in total plagioclase.

CHEMICAL CHANGES WITH RESPECT TO AGE

Within Formations

The variations in the major element content of successive volcanic units within the same formation are shown in figures 36 and 37. The Almond Mountain volcanics (Tab) show a tendency to decrease in Al_2O_3 and Na_2O, while moving up the section, and an increase is suggested for CaO; only SiO_2, total Fe, and MgO show no marked trends. The contemporaneous Klinker Mountain volcanics (Tkb) show a very faint tendency to decrease in SiO_2, total Fe, K_2O(?), and CaO, as one moves up the stratigraphic column; vague trends towards increasing amounts are found for Al_2O_3, MgO, and Na_2O.

The points not included by the connecting lines in figure 36 are analyses of a Lava Mountains andesite sill that intruded the section at this position. It is interesting that for every component (except Al_2O_3), the sill rock composition is intermediate between the host and the overlying Lava Mountains andesite. Presumably this resulted from a limited assimilation of the host rock by the sill.

The analyses within the Lava Mountains andesite, in figure 36, show the amount of chemical variation that must be expected within a single

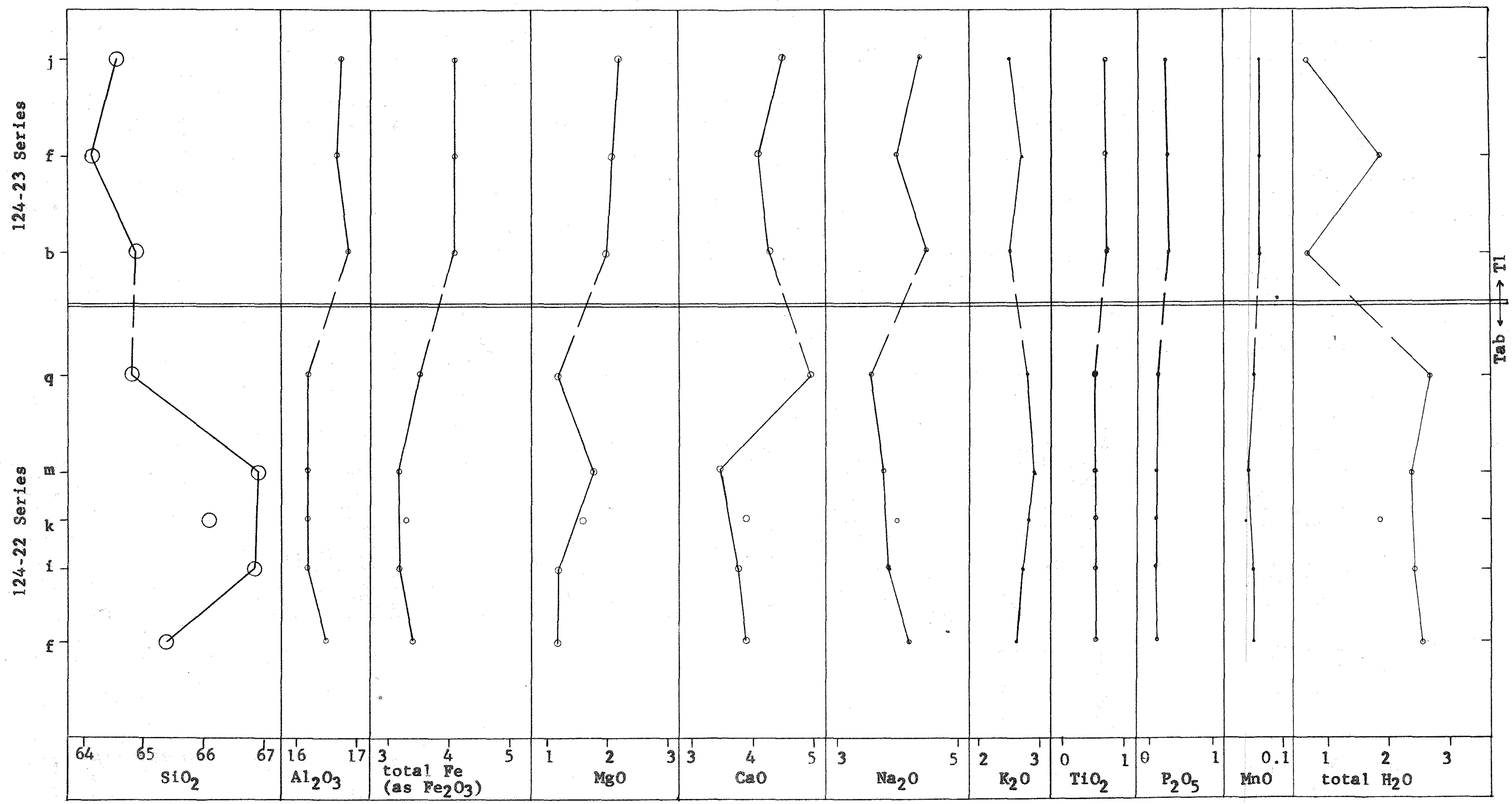


Figure 36. Diagram showing the variations in the major elements as a function of their stratigraphic position. The element values are in percent. The relative stratigraphic positions of the samples are shown in figures 10 and 16. The radii of the circles represent the average analytical errors calculated in Appendix I.

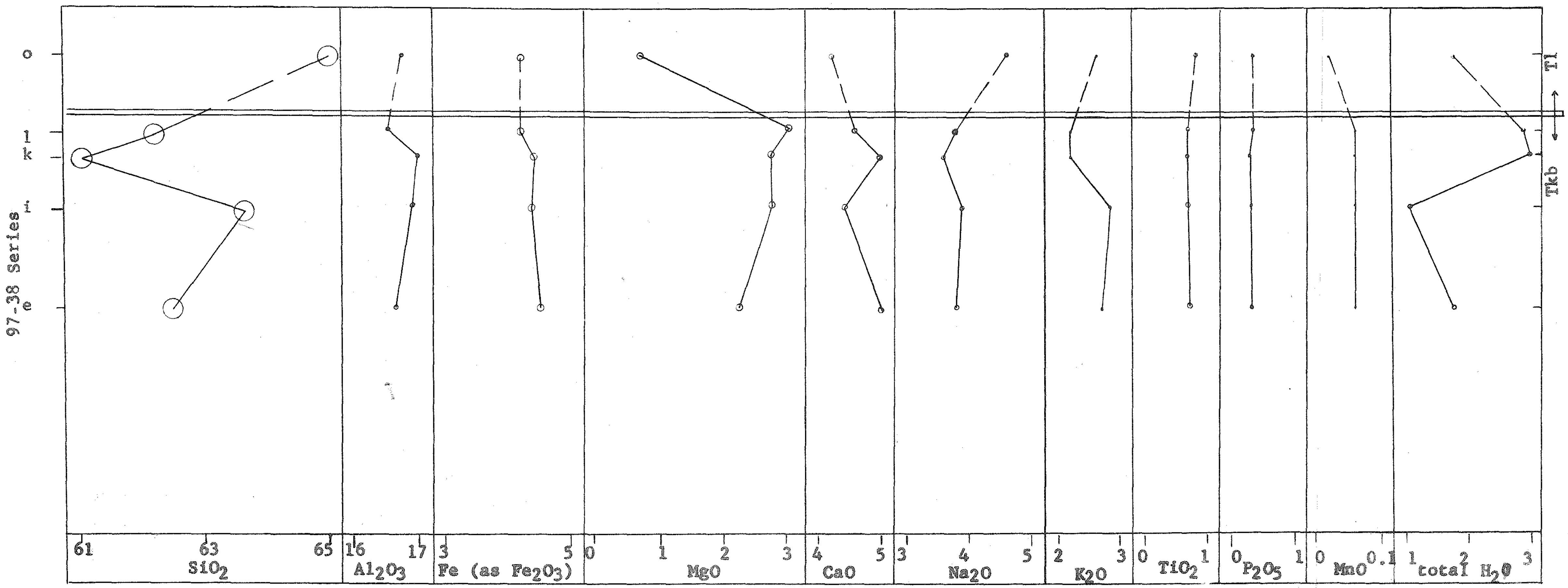


Figure 37. Diagram showing the variations in the major elements as a function of the stratigraphic position of the sample. The element values are in percent. The relative stratigraphic positions of the samples are shown in figure 13. The radii of the circles represent the average analytical errors calculated in Appendix I.

mappable unit. These three samples were collected on the same hillside from rocks that are mapped as the same unit, primarily to test the reproducibility of data from one part of a flow to another. The only petrographic difference between the middle sample and the others is that it is relatively fresh and unaltered, whereas the other two rocks have undergone extensive alteration to opaque materials. It would appear that the alteration, which changed the Fe-bearing minerals to opaque substances, has changed the apparent concentration of some, but not all, of the elements.

In figures 38, 39, 40, and 41, the results of the spectrochemical analyses are plotted against the sample position in stratigraphic section. In figures 38 and 39, Almond Mountain volcanics (Tab) show a faint tendency for Ba(?), Cr, Sc, Sr, and Ti to increase toward the higher part of the section. In this direction, Pb and V tend to diminish. There is no marked change in the others. In the overlying Lava Mountains andesite (Tl), the upper and lower of the three samples show a marked increase in Sc, Sr, Ti, Y, Zr, Ba, Cu, and possibly Ga.

In figures 40 and 41, the Klinker Mountain volcanics (Tkb) increase in Ba, Ga, Sc, Sr, Ti, Y, and Zr toward the upper part of the section. The B, Cr(?), Cu, Mn, Ni, Pb, V, and Yb show no strong trends. A faint decrease is found for Co.

Between Formations

Tables 13, 14, and 15 show the average values for the chemical, normative, and spectrochemical compositions of the volcanic-bearing formations. They show, rather convincingly, that there are no major shifts from one formation to the next.

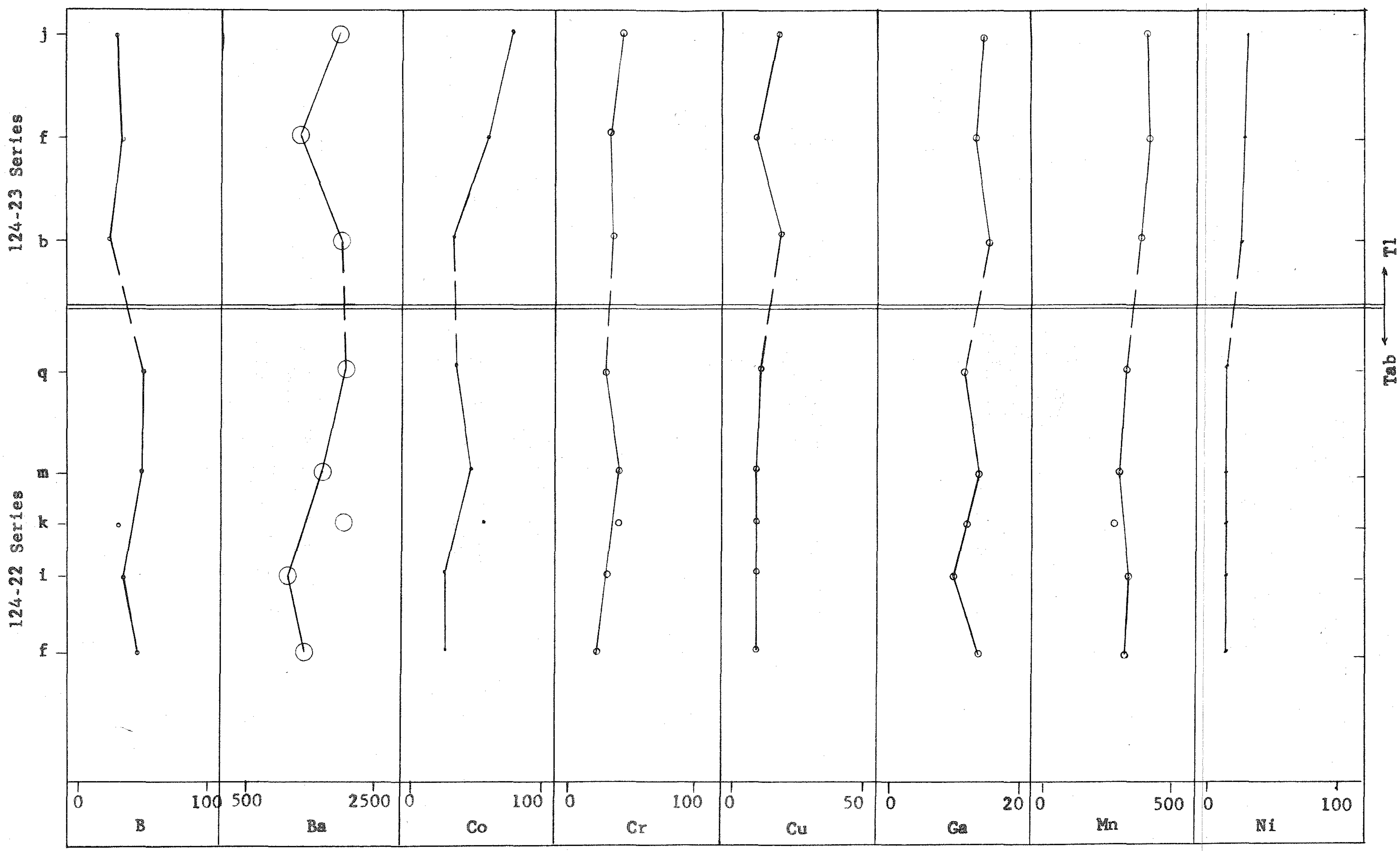


Figure 38. Diagram showing the variations in the amounts of B, Ba, Co, Cr, Cu, Ga, Mn, and Ni as a function of the stratigraphic position of the samples. All element values are parts per million. The relative stratigraphic positions of the samples are shown in figures 10 and 16. The radii of the circles represent the average analytical errors calculated in Appendix I.

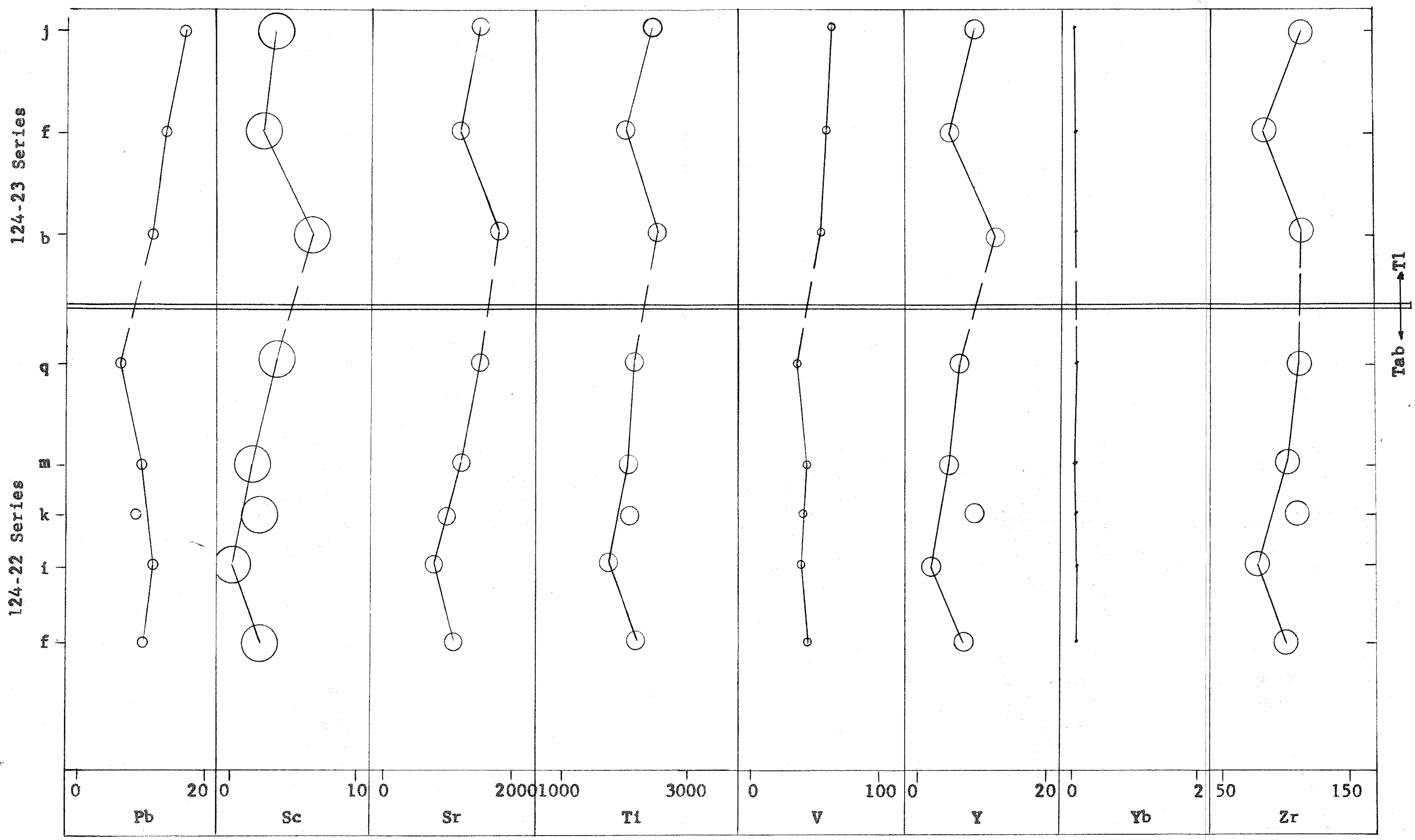


Figure 39. Diagram showing the variations in the amounts of Pb, Sc, Sr, Ti, V, Y, Yb, and Zr as a function of the stratigraphic position of the samples. All element values are in parts per million. The relative stratigraphic positions of the samples are shown in figures 10 and 16. The radii of the circles represent the average analytical errors calculated in Appendix I.

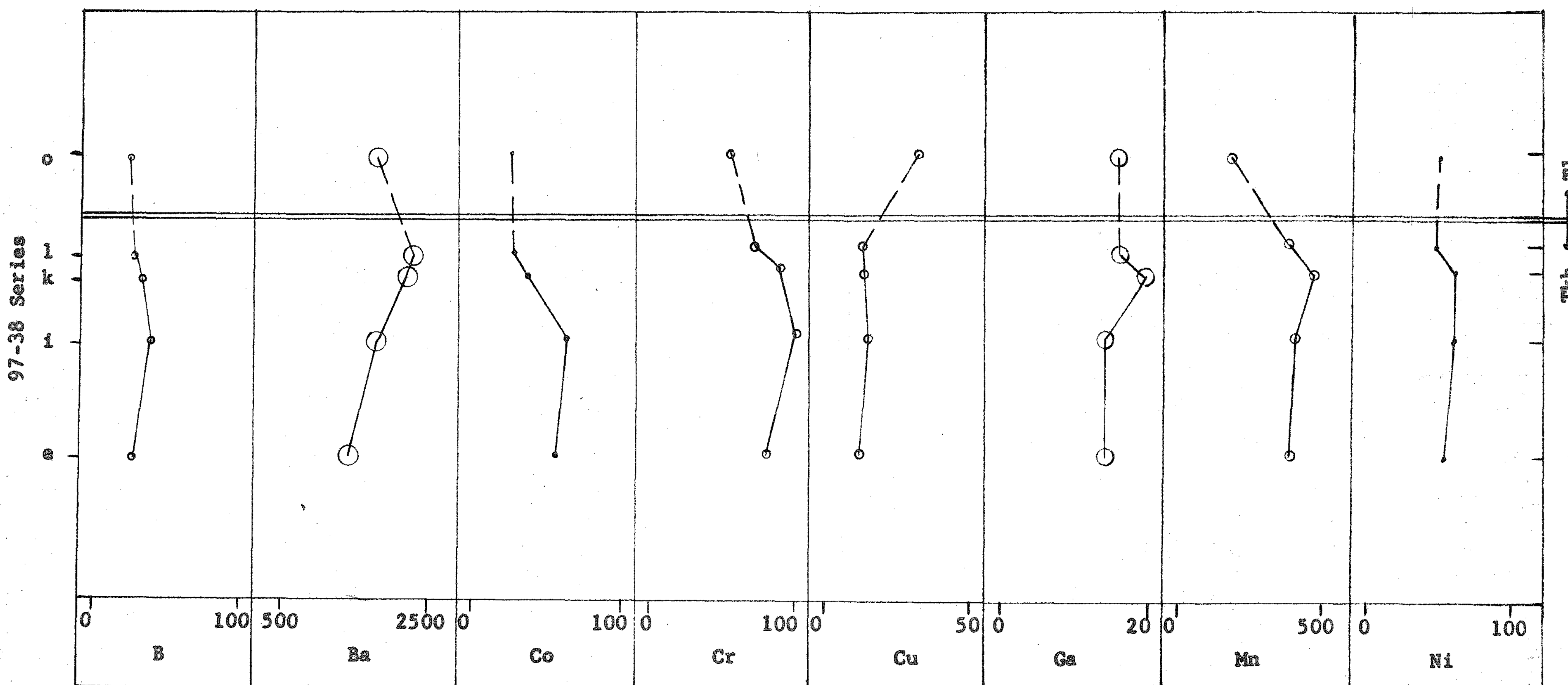


Figure 40. Diagram showing the variations in B, Ba, Co, Cr, Cu, Ga, Mn, and Ni as a function of the stratigraphic position of the samples. All elements values are in parts per million. The relative stratigraphic positions of the samples are shown in figure 13. The radii of the circles represent the average analytical errors calculated in Appendix I.

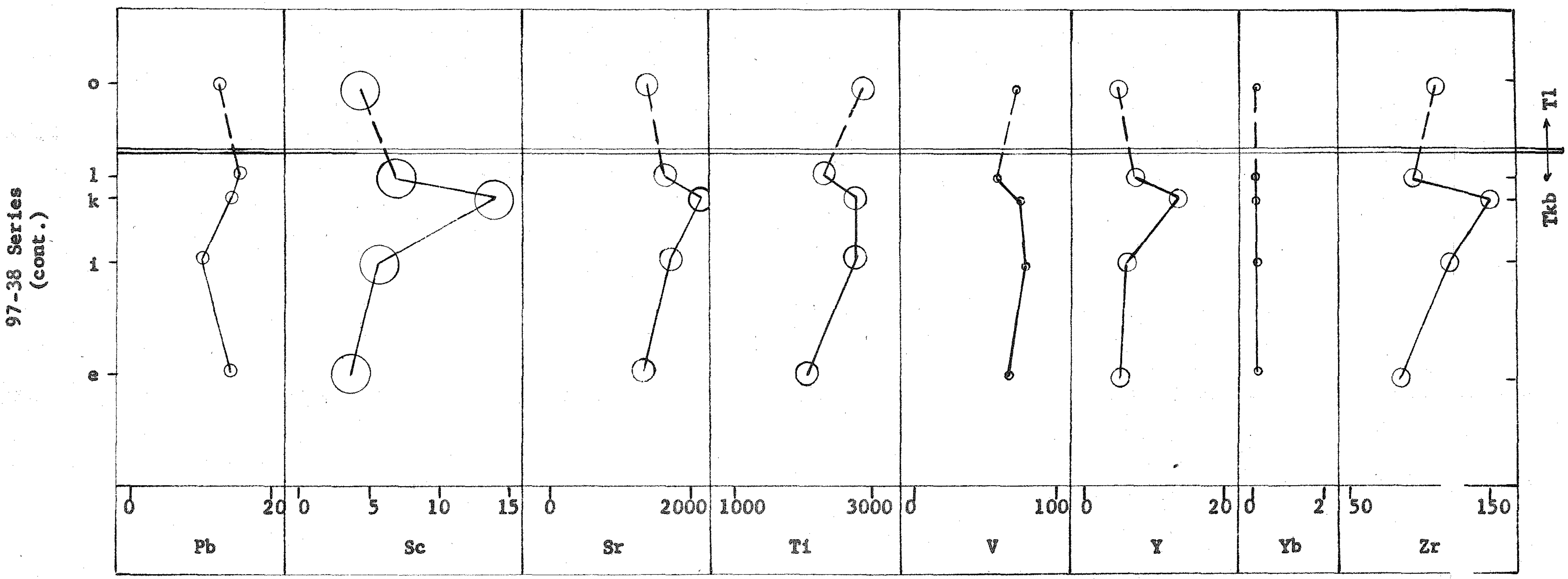


Figure 41. Diagram showing the variations in Pb, Sc, Sr, Ti, V, Y, Yb, and Zr as a function of the stratigraphic position of the samples. All element values are in parts per million. The relative stratigraphic positions of the samples are shown in figure 13. The radii of the circles represent the average analytical error calculated in Appendix I.

	Tbv	Tkb	Tab	Tl and Tli
SiO_2	64.8	62.3	66.0	63.9
Al_2O_3	16.6	16.8	16.3	16.6
Fe_2O_3	1.4	2.0	1.3	3.0
FeO	2.2	2.1	1.8	1.1
MgO	2.0	2.8	1.4	2.0
CaO	4.6	4.7	4.1	4.6
Na_2O	4.5	3.8	3.9	3.9
K_2O	2.0	2.5	2.8	2.5
TiO_2	0.58	0.68	0.51	0.66
P_2O_5	0.20	0.25	0.17	0.26
MnO	0.08	0.06	0.05	0.05
H_2O	1.2	2.3	2.1	1.2
CO_2	0.27	<0.05	<0.2	<0.05

Table 13. Average chemical compositions of the volcanic rocks from the Bedrock Spring formation (Tbv; one sample), Klinker Mountain volcanics (Tkb; six samples), Almond Mountain volcanics (Tab; four samples), and Lava Mountains andesite (Tl and Tli; eleven samples. All values are percents.

	Tbv	Tkb	Tab	Tl and Tli
Q	18.34	17.43	21.83	18.35
C	---	0.08	0.10	0.03
or	11.68	14.60	16.40	14.66
ab	38.25	31.83	32.75	35.44
an	19.18	21.33	18.56	18.90
di	2.87	1.44	0.94	0.93
hy	5.09	7.32	4.54	4.51
mt	2.09	2.79	1.91	1.27
il	1.22	1.33	1.07	0.95
hm	---	0.04	---	2.14
tn	---	---	---	0.36
ru	---	---	---	0.03
ap	---	0.17	---	0.24
Classification	I.4.3.4	II.4.3.4	I.4.3.4	I.4.3.4

Table 14. Average normative (C.I.P.W.) compositions of the volcanic rocks from the Bedrock Spring formation (Tbs; one sample), Klinker Mountain volcanics (Tkb; six samples), Almond Mountain volcanics (Tab; four samples) and Lava Mountains andesite (Tl and Tli; eleven samples). All values are percents.

	Tbv	Tkb	Tab	Tl and Tli
Cr	60?	85	30	56
Co	42	46	31	47
Mn	550	402	325	370
Ni	18	56	12	44
Sc	10	7.6	4.4	5.7
V	74	69	42	62
Fe	2.6%	2.6%	1.7%	2.4%
Cu	10	27	10.5	20
Ga	14	16	13	14
Ti	2400	2400	2100	2400
B	26	30	44	24
Ba	2400	1925	1600	1900
Be	--	--	--	--
Pb	15	12	9.8	12
Sr	1600	1700	1150	1570
Yb	1	<1	<1	<1
X	14	8.0	5.5?	7.4
Zr	130	113	100	110

Table 15. Average spectrochemical compositions of the volcanic rocks from the Bedrock Spring formation (Tbv; one sample), Klinker Mountain volcanics (Tkb; six samples), Almond Mountain volcanics (Tab; four samples), Lava Mountains andesite (Tl and Tli; eleven samples). Values for Fe are percent, all others are parts per million.

The chemical differences between the Almond Mountain and Klinker Mountain volcanics and the overlying Lava Mountains andesite are illustrated in figures 36 and 37. The Lava Mountains andesite, shown overlying the Almond Mountain volcanics (in figure 36), appears to be relatively higher in Al_2O_3, total Fe, MgO, CaO, Na_2O, TiO_2, P_2O_5, and MnO; it appears to be lower in SiO_2, K_2O, and H_2O.. The single sample of the Lava Mountains andesite which rests on the Klinker Mountain volcanics section, in figure 37, can only be taken as a questionable indicator of change; it seems to be relatively higher in SiO_2, Na_2O, and TiO_2 and lower in total Fe(?), MgO, and CaO. These relative differences are almost exactly reversed in the two analogous sections. Consequently, none of the "trends" can be cited as widespread results of the sequence.

The changes in minor element compositions between the Almond Mountain volcanics and the Lava Mountains andesite are shown in figures 38 and 39. These show the overlying andesite to have larger amounts of Co, Cr(?), Cu(?), Ga, Mn, Ni, Pb, Sc, Sr, Ti, and V; only B shows a tendency to be lower. The other elements show no trends.

SUMMARY OF PETROCHEMISTRY

The chemical compositions of the volcanic rocks in the Lava Mountains area show little variation from place to place and from formation to formation. The alkali-lime index is about 58, indicating the suite to be calc-alkalic. Most of the rocks have normative (C.I.P.W.) compositions of "yellowstonose" (I.4.3.4.), a few are "tonalose" (II.4.3.40, and one is "lassenose" (I.4.2.4). These indicate that there is little difference in the relative amounts of the major constituents.

The results of spectrochemical analyses show trends with respect to silica content and certain minerals. The major elements, likewise, showed trends with respect to silica, but none with respect to the minerals. Neither the major nor the minor elements follow trends which can be attributed to the stratigraphic position of the host rock.

PETROGENESIS

HYPOTHESES SUGGESTED BY OTHERS

Mechanisms for the origin of volcanic magmas have been proposed by many. Most postulate the melts to be a result of one or more of the following:

1. A primary olivine basaltic magma.
2. A primary tholeiitic magma.
3. A primary olivine basalt magma, contaminated by other rocks or magmas, generally more acid.
4. A primary tholeiitic magma, contaminated by other rocks or magmas.
5. Partial refusion of the granitic layer.
6. Total refusion of the granitic layer.

The concept of a primary olivine basalt magma was first proposed by Bowen (1928), and the possibility of a tholeiitic magma was proposed by Kennedy (1933, 1938); the relative merits of these were reviewed by Tilley (1950). Many, such as Larsen (1938B), have felt that although deep-seated magmas may have played a fundamental role, they also must have partially assimilated other rocks and/or magmas -- with subsequent good mixing -- to get the products seen at the surface. Others call solely on partial refusion of the underlying rocks.

Powers (1955) proposed a partial refusion of the peridotite layer underlying the Hawaiian Islands; others, working in continental areas, have called on partial refusion of the underlying granitic layers.

Once formed, a magma may be altered by fractional crystallization as proposed by Bowen (1928). Wager and Mitchell (1951) demonstrated that fractional crystallization of a primary olivine gabbroic magma, with subsequent settling out of heavier minerals, was responsible for the rocks found in their study. Macdonald (1949) invoked crystal settling to explain the rocks in the Hawaiian Islands.

The mechanics and sequence of eruption have been studied by many but most of the work has been done on basaltic volcanoes. In the Mount Taylor volcanic area of New Mexico, Hunt (1938) found the sequence of extrusion to be: 1) sheet basalt; 2) rhyolite; 3) trachyte; 4) latite; 5) andesite porphyry; 6) sheet basalt. The tuffs, trachyte, and latite members issued from a central pipe or crater, whereas the andesite porphyry flowed from fissures radiating from the pipe; the sheet basalt erupted from "small volcanoes" around the mountain.

Cross and Larsen (1935) described a complex volcanic history in the San Juan area, Colorado, which is characterized by repeated outpourings of rhyolites, quartz latites and andesites, separated by extensive periods of erosion, and culminated by "great floods of basaltic magma with subordinate pyroclastic eruptions". The petrography of these rocks was later studied extensively (Larsen and others, 1936; 1937; 1938A; 1938B). They concluded that the lavas were probably derived from partial assimilation of other rocks or by the mixing of two magmas, and that the resulting melts underwent thorough mixing before eruption. Ransom, Emmons, and Garrey (1910) studied the Bullfrog District, Nevada, volcanic series which contains 16 rhyolite flows, 5 basalt flows, 1 quartz latite flow, 1 quartz basalt, and 2 tuffs; the sequence of basic lavas following acid was repeated five times, and the quartz latite and quartz basalt erupted only after the uppermost basalt had been extruded.

Work in the volcanic regions of northern California, Oregon, and Washington, mostly within the same volcanic province, shows the following results: Anderson (1936) found clear evidence of contamination of the original lavas, both from the rock immediately underlying the flows and from xenoliths of acid and basic differentiates at depth. He also (1941) found no regularity in the sequence of extrusion: 1) andesites plus basalts, 2) basalt, 3) andesite plus rhyolite, 4) shield-forming andesite with minor basalt; 5) perlitic rhyolite, and 6) basalt, andesite, dacite and rhyolite extruded more or less simultaneously.

Coombs (1936) noted that in the Mt. Rainier volcanics, pyroclastics were most abundant in the upper part of the section and flows in the lower part. Fuller (1931) determined the following sequence at Steens Mountain, Oregon: 1) intrusive basalt and rhyolite, 2) acid tuffs and flows, 3) dacitic flows, 4) andesitic breccias and flows up to 15,000 feet thick, 5) basaltic flows, up to 3,000 feet thick, 6) acid, intermediate, and basic flows and tuffs in a complex sequence up to 500 feet thick. Thayer (1937) noted that andesites and basalts formed the bulk of the volcanic rocks in the portion of the Cascades that he studied but that more acid rocks were locally present. Verhoogen (1937) and a series of papers by Williams (1932, 1933, 1934, 1935, and 1942) discussed the sequence, mechanics of eruption, and caldera formation in some of the higher peaks in the Cascade Range.

On the recently-formed Paricutin volcano, numerous studies have been made. Krauskopf (1946A, 1946B, 1948A, 1948B) and Krauskopf and Williams (1946) have cataloged the activity and lava movements of the volcano. In one paper (Krauskopf, 1948A), a mechanism of eruption was suggested in which the lava to be extruded stood high in its conduit and the main gaseous phase bubbled out through the crater while the liquid portion spilled through fissures on the side of the volcano. White (1945) thought that the volcano's activity formed a cyclic pattern, but Wilcox (1954) and Williams (1950) point out that this tendency was shortlived. Williams, however, did note that most of the explosive activity occurred during the first twelve months' eruptions and that subsequent activity was more commonly effusive. Wilcox (1954), as a result of studying the very definite trend in the composition of the rocks extruded as a function of time, postulated a magma cupola at a depth of perhaps 12 kilometers; the lava erupted by Paricutin was believed to be from a fissure on the side of this cupola, and the steadily changing composition was a result of the thermal convection within the cupola.

SUMMARY AND CONCLUSIONS

To explain the origin of the volcanic rocks in the Lava Mountains area, two types of evidence must be reconciled: 1) the trends toward more homogeneous lavas, more effusive character, and more frequent eruptions as the volcanic sequence progressed; 2) the distinct lack of trends in the mineral and chemical compositions of the same lavas.

The trend toward more homogeneous lavas is apparently the result of normal mixing by convection and diffusion. Processes that tend to diversify the lavas, such as fractionation or crystal settling, may have been operative but subordinate.

One explanation for the increasing trend toward effusive outpourings is as follows: In middle Pliocene time, there may have been a relatively low thermal gradient in the Lava Mountains area. If true, the volcanic lavas that started toward the surface were solidified in the conduit; renewed pressures from below then brecciated the rocks and forced them to the surface as explosive eruptions. With the passage of time, the heat from the lava reservoir steepened the thermal gradient in the area. By latest Pliocene time, the overlying rock had been heated sufficiently to allow the Lava Mountains andesite to reach the surface still fluid.

The increased frequency of eruptions is probably a result, in part, of the active faulting during the advanced stages of volcanic activity. A second factor may have been the ever-steepening thermal gradient which allowed a larger percentage of the lava pipes to reach the surface before solidifying.

The lack of trends in the mineral and chemical content of the lavas is probably due to a lack of differentiation, crystal settling, or assimilation. Any one or combination of these processes will almost inevitably cause shifts in the mineral or chemical contents.

That no shift is present indicates that none of the processes acted in a systematic manner on this magma reservoir

One major question about these volcanic rocks remains unanswered: the mechanism for forming the melt.

The composition of the original magma was probably about that as we now see it; it seems likely that if diverse magmas had been formed at an earlier time, there should be evidence within the area of the reciprocal composition. The fact that there is not is negative evidence, but seems to be the better of the alternatives.

That primary olivine or tholeiitic magmas were this source is, of course, impossible as the compositions are wrong. Primary basaltic magmas which have assimilated more acid rocks are also an unsuitable source; the Lava Mountains rocks are too silicic to represent reasonable mixtures of basalts and any other major rocks.

Complete refusion of the quartz monzonitic rocks of the area appears to be the most likely source for the volcanic lavas. The chemical compositions of the plutonics are probably similar although no analyses exist to test this assumption. Only partial assimilation of these plutonic rocks may have occurred, but the apparent composition of the plutonics is so close to that of the volcanic rocks that nearly complete fusion must have occurred.

Appendix I: Precision of analytical methods

	Sample number							
	124-23B			124-23F		124-23J		
	1st count	2d count	3d count	1st count	2d count	1st count	2d count	3d count
Plagioclase megaphenocrysts	10.43	7.51	10.48	11.52	12.46	8.99	11.34	12.39
Total plagioclase	17.50	17.15	17.25	22.00	19.22	17.57	21.98	21.84
Plagioclase microphenocrysts	7.07	9.64	6.77	10.48	6.76	8.58	10.64	9.42
Biotite	---	---	---	---	0.33	---	---	0.07
Hornblende	---	---	---	---	---	---	---	---
Oxyhornblende	1.93	0.96	0.70	8.16	7.63	2.88	1.82	3.10
Orthopyroxene	---	---	0.06	1.20	0.94	0.07	0.21	0.07
Clinopyroxene	---	---	---	---	0.07	---	---	---
Quartz	---	---	0.06	---	0.28	---	---	---
Opaques	10.13	11.18	11.44	1.44	2.21	10.71	9.45	9.49
Nonopaques	---	0.12	---	0.16	0.20	---	0.42	0.13
Groundmass	70.42	70.57	70.47	67.04	69.11	68.77	66.04	65.32
Total	99.98	99.98	99.98	100.00	99.99	100.00	100.00	99.99

Table I-1. Shows the reproducibility of modal analyses. All values have been left unrounded.

	Sample number						
	124-23B		124-23F		124-23J		Average
	M	D	M	D	M	D	D
Plagioclase megaphenocrysts	9.47	1.31	11.99	0.47	10.91	1.28	1.02
Total plagioclase	17.30	0.13	20.61	1.39	20.46	1.93	1.15
Plagioclase microphenocrysts	7.83	1.21	8.62	1.86	9.55	0.73	1.26
Biotite	---	---	0.16	0.16	0.02	0.03	0.10
Hornblende	---	---	---	---	---	---	---
Oxyhornblende	1.20	0.49	7.90	0.27	2.60	0.52	0.43
Orthopyroxene	0.02	0.03	1.07	0.13	0.12	0.06	0.07
Clinopyroxene	---	---	0.04	0.04	---	---	0.04
Quartz	0.02	0.03	0.14	0.14	---	---	0.08
Opaques	10.92	0.52	1.82	0.39	9.88	0.58	0.50
Nonopaques	0.04	0.05	0.18	0.02	0.18	0.16	0.08
Groundmass	70.49	0.03	68.08	1.03	66.71	1.37	0.81

Table I-2. The arithmetic mean and the mean deviation for the modal analyses listed in I-1. The symbols are as follows:

$$M = \text{Mean value} = \frac{\sum X}{N}$$

$$D = \text{Mean deviation} = \frac{\sum |M - X|}{N}$$

Where X = the value of the observation
N = the number of observations

Sample		B	Ba	Be	Co	Cr	Cu	Ga	Mn	Ni	Pb	Sc	Sr	Ti	V	Y	Yb	Zr	Fe(%)
124-22Q	M	50	2100	--	37	32	12	12	340	11	7.2	6.9?	1500?	2200	38	7.0	<1	120?	1.6
	D	5.5	270	--	6	7.2	1.2	0.8	28	1.2	1.3	--	--	180	3.8	--	0	--	0.2
	%	11	13	--	16	23	10	6.5	8.2	11	18	--	--	8.2	10	--	0	--	12
97-38I	M	39	1800	--	61	100	30	14	400	60	10	5.8	1700	2700	79	5.8	<1	120	2.6
	D	3.8	250	--	4.7	8.5	1	0.8	5	5	2.0	1.8	200	320	12	1.3	0?	16	0.4
	%	9.8	14	--	7.7	12	3	5.7	1.2	8.3	20	31	12	2	15	22	0?	13	15
28-17	M	t?	2300	--	24	45	18	12	330	40	12	6.6	1400	2100	50	8.0	<1	130	2.0
	D	5.8?	330	<1	1.7	7.2	4.2	3.2	50	5	1.9	2.5	330	300	9.7	1.8	<1	31	0.27
	%	?	14	?	8.1	16	23	27	15	12	16	38	24	14	19	22	?	24	13
41-39	M	28	1100	--	22	24	26	12	320	14	12	5.5	990	2600	48	10?	1.5	110	3.0
	D	1.5	370	--	1.5	3.5	3.2	0.75	22	0.5	4.5	4.8	210	150	2.9	6.2	0.25	17	0.1
	%	5.4	34	--	6.8	15	12	6.2	6.9	3.6	38	82	21	5.8	5.9	62	17	15	3.3
124-22K	M	35	2000	--	52	40	9.4	12	280	13	9.5	4.5	1000	2100	40	8.3	<1	110	1.6
	D	7.8	230	--	2.9	2.7	0.62	0.75	12	0.25	2.0	2.8	256	250	1.5	3.1	0.25	22	0.1
	%	22	11	--	5.6	6.8	6.6	6.2	4.3	1.9	21	62	26	12	3.8	37	?	20	6.2
Ave.	D	4.9	290	--	3.0	5.8	2.0	1.3	23	2.4	2.3	2.9	250	240	6.0	3.1	0.25	22	0.22
Ave.	%	12	17	--	8.8	15	11	10	7.1	7.4	23	53	21	10	11	36	?	20	10

Table I-3. The mean value, mean deviation, and percent error for the spectrochemical values obtained from five rocks. Sample 28-17 was analyzed six times; the other samples were analyzed four times. The symbols M and D are the same as for table I-2; the percent error, %, is the quotient of D/M.

	Sample number												
	97-39		124-23J		128-34		97-39		124-23J		128-34		Average
	(1)	(2)	(1)	(2)	(1)	(2)	M	D	M	D	M	D	D
SiO_2	71.2	71.8	64.2	65.0	63.9	63.9	71.5	0.3	64.6	0.4	63.9	0.0	0.23
Al_2O_3	15.6	15.7	16.8	16.9	16.3	16.3	15.6	0.05	16.8	0.05	16.3	0.0	0.03
Fe_2O_3	1.5	1.5	3.7	3.6	3.6	3.5	1.5	0.0	3.6	0.05	3.6	0.05	0.03
FeO	0.02	0.00	0.44	0.46	0.36	0.44	0.01	0.01	0.45	0.01	0.40	0.04	0.03
MgO	0.07	0.34	2.3	2.2	1.3	1.7	0.20	0.13	2.2	0.05	1.5	0.2	0.13
CO	2.7	2.3	4.4	4.6	4.4	4.4	2.5	0.2	4.5	0.1	4.4	0.0	0.10
Na_2O	4.1	4.0	4.5	4.4	4.2	4.2	4.0	0.05	4.4	0.005	4.2	0.0	0.02
K_2O	3.3	3.3	2.5	2.5	2.6	2.6	3.3	0.0	2.5	0.0	2.6	0.0	0.00
TiO_2	0.24	0.24	0.66	0.66	0.62	0.66	0.24	0.0	0.66	0.0	0.64	0.02	0.01
P_2O_5	0.10	0.11	0.28	0.28	0.21	0.22	0.10	0.005	0.28	0.0	0.22	0.005	0.003
MnO	0.02	0.02	0.06	0.06	0.04	0.04	0.02	0.0	0.06	0.0	0.04	0.0	0.00
H_2O	1.4	1.6	0.17	0.18	2.4	2.2	1.5	0.1	0.18	0.005	2.3	0.1	0.68
CO_2	<0.05	<0.05	<0.05	0.10	0.22	0.22	<0.05	0.0	<0.05?	<0.05?	0.22	0.0	0.02

Table I-4. Shows the reproducibility of the chemical analyses. Each of the three rocks was submitted in duplicate, the second sample under a different number. The meanings of M and D are the same as for table I-2.

Appendix II: Spectrochemical values for "G-I" and "W-I".

	G-1					W-1						
	Plate 534		Plate 535		Ave.	Plate 534			Plate 535			Ave.
B	?	?	--	--	--	?	?	?	5	6	3	5
Ba	1700	1700	1700	1700	1700	320	320	300	420	340	420	360
Be	3	2	--	--	--	--	--	--	--	--	--	--
Co	1	<1	--	--	--	66	72	48	64	54	56	60
Cr	15	10	12	13	12	160	180	110	110	96	120	130
Cu	20	19	26	14	20	170	160	160	160	160	150	160
Ga	19	16	21	18	18	5.4	5.6	4.0	7.0	4.6	4.0	5.1
Mn	140	160	210	200	180	1200	1400	1200	1700	1600	1600	1400
Nb	65	17	<4	<4	?	--	--	--	--	--	--	--
Ni	--	--	--	--	--	120	140	100	130	100	110	120
Pb	50	54	62	56	56	--	--	--	--	--	--	--
Sc	3	4	3	4	4	80	68	62	74	46	72	67
Sr	540	700	630	630	620	680	720	780	740	660	860	740
Ti	1300	1300	1500	1500	1400	400	3800	4200	5000	4200	4700	4300
V	22	19	22	20	21	150	130	130	260	200	260	190
Y	35?	14	8	12	11	36	28	24	28	18	36	28
Yb	--	--	1	<1	<1	3.6	5.0	3.2	2.4	1.9	2.3	3.1
Zr	240	190	210	240	220	190	190	120	170	140	150	160
% Fe	1.4	1.3	0.60	0.78	1.0	8.0	10	7.0	4.9	3.4	3.6	6.7

Table II. Table showing the experimental values (unrounded) for standard-samples G-i and W-1. The readings were made on the same plates and using the same curves as were the data for the Lava Mountains rocks. For descriptions of these standard samples, see Fairbairn and others, (1951).

Appendix III: Vertebrate fauna, listed by localities

IDENTIFICATIONS OF THE LAVA MOUNTAINS FAUNA BY LOCALITY

Asterisks (*) indicate critical fossils for dating.
See plate 4 for positions of the localities.
All identifications by G. Edward Lewis

LM-1	?*Pliohippus* cf. *P. leardi* ?*Megatylopus* sp. ?*Pliauchenia* sp. fragment of canid jaw mastodon tooth enamel fragments
LM-2	?*Pliohippus* cf. *P. leardi* camelid, undetermined *Testudo mohavense*
LM-3	?*Megatylopus* sp. *Merycodus* sp.
LM-4	?*Pliohippus* cf. *P. leardi* ?*Megatylopus* sp. ?*Pliauchenia* sp.
LM-5	?*Pliohippus* cf. *P. leardi* ?*Megatylopus* sp.
LM-6	**Pliohippus* cf. *P. leardi* ?*Pliauchenia* sp. *Merycodus* sp.
LM-7	Mammal, ungulate, undetermined *Testudo mohavense*
LM-8	*?*Pliauchenia* undetermined fragments
LM-9	?*Pliohippus* cf. *P. leardi* ?*Megatylopus* sp. artiodactyls, undetermined
LM-10	*Pliohippus* sp. ?*Megatylopus* sp.
LM-11	?*Pliauchenia* sp.

LM-13	*_Pliohippus_ cf. _P. leardi_ *?_Pliauchenia_ sp. ?_Merycodus_ sp. _Testudo mohavense_
LM-14	rhinoceros, undetermined small camel, undetermined ?_Merycodus_ sp. _Testudo mohavense_
LM-15	cf. _Hypolagus_ sp. _Neotomodon_ sp. *_Pliohippus_ sp. ?_Pliauchenia_ sp.
LM-16	cf. _Hypolagus_ sp. _Neotomodon_ sp. _Leptocyon vafer_ _Merycodus_ sp. ?_Megatylopus_ sp. ?_Pliauchenia_ sp.
LM-17	?_Pliohippus_ sp. ?_Pliauchenia_ sp. small camel, undetermined
LM-18	?_Pliauchenia_ sp.
LM-19	cf. _Pliohippus_ sp. or _Equus_ (s.l.) sp.
LM-20	*_Pliohippus_ cf. _P. leardi_ *?_Pliauchenia_ sp. small camel, undetermined ?_Merycodus_ sp. carnivore metapodial fragment, undetermined
LM-21	cf. Aphelops sp. *_Pliohippus_ cf. _P. leardi_ *?_Megatylopus_ sp. cervid metapodial fragment, undetermined carnivore metapodial fragment, undetermined
LM-22	mammal vertebrae, undetermined
LM-23	cf. _Merycodus_ sp.
LM-24	mammalian pelvis fragments, undetermined

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